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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:

$$\mathrm{UCS} = 143{,}000e^{-0.035t} \quad (1)$$

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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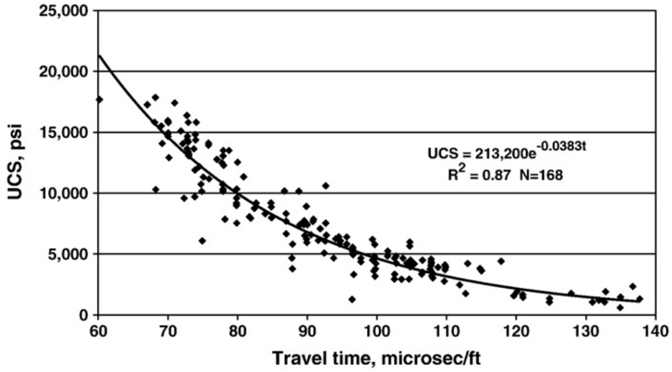

Fig. 1. Sonic travel time versus UCS data from the Australian German Creek seam. Data after McNally (1987).

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

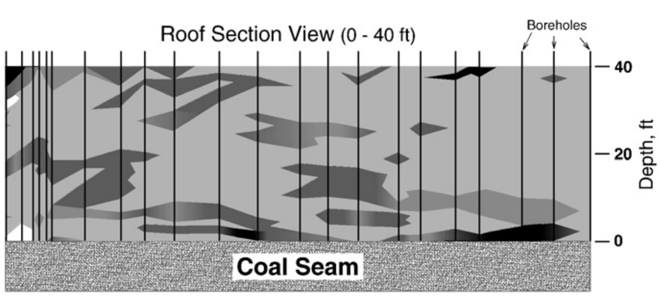

Fig. 2. Contour plot of UCS of the immediate roof above a gateroad at the Crinum mine, Queensland, Australia (after Payne, 2008). UCS data computed from sonic travel time log data, with black representing the weakest roof and light gray to white the strongest roof. Vertical scale 0 to 40 ft. Plot width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

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.

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.

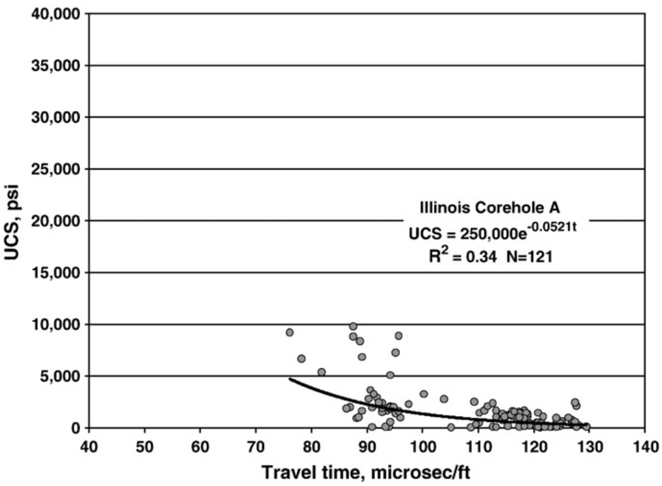

Fig. 3. Illinois corehole A. Sonic travel time versus UCS, with best fit relationship.

time consuming, but can provide a very detailed picture of rock strength in a zone of particular interest, such as the immediate roof of a coal seam. However, it can be difficult to obtain adequate coverage over intervals of weak rocks where it may be difficult to obtain good point load measurements.

In the work conducted for this paper Technique 3 was not used. Instead a mix of Techniques 1 and 2 was used depending upon the amount of core and testing time available. The results obtained from each of the three techniques will be described in the "Discussion and results" section.

4. Sonic log errors

A major source of errors in a UCS/sonic travel time correlation is from errors in the measured sonic travel times. Sonic tools are designed to detect the arrival of the first signal of the sonic wavetrain (the first arrival of the compressional wave), which consists of a series of roughly sinusoidal waves at the tool's operating frequency. The peaks arrive at intervals of approximately 42 µs. The detectors measure the amplitude of the arriving signal and the time of the arrival is recorded when a threshold signal amplitude is detected. For tools containing two receivers the difference between the arrival times at the two receivers is computed and presented as the travel time. If however, the amplitude of the first arrival is too small to trigger the detector, it is possible for the detector to trigger on the second, or a later arrival. If this happens to only one of the detectors, it can cause travel time shifts in 42 µs steps. This type of error is usually referred to as a cycle skip. Typically the far detector is affected and the shift is toward longer travel times, but cycle skipping by the near receiver (less likely, but still possible) can lead to reduced travel times. Cycle skipping can be caused by misalignment or decentralization of the tool with the axis of the hole, either of which will cause destructive interference of the sonic signal and reduction of the signal amplitude. Other causes of cycle skipping include incorrect tool gain settings, gas flowing into the hole (causing both attenuation of signal and increased travel times) and noise from the tool or centralizers scraping on the wall of the hole and attenuation across joints or fractures. The presence of joints and fractures can sometimes cause cycle skipping, although the sources of cycle skips are usually not identifiable. The sonic tool is sometimes suggested as an instrument for identifying joints and fractures through the observation of cycle skipping or the shape of the sonic wavetrain, but there is no generally accepted technique for identifying fractures or joints using standard sonic logging tools.

5. Discussion and results

NIOSH collected data from seven coreholes (Fig. 4), two in Illinois, two in southwestern Pennsylvania, one in north central Colorado, one in southern West Virginia and one in western Kentucky. In the eastern coreholes the sonic logs core were run by Geological Logging Systems, a Division of Marshall Miller & Associates, using a Century Geophysical Corp model 9321 sonic tool. The Colorado logs were run by Century Geophysical Corp, also using the 9321 model sonic tool. The 9321 is an uncompensated sonic tool with one transmitter and two receivers, and is typical of the sonic tools available for minerals industry use.

Although the UCS data were not restricted to any one source, all of the UCS data collected for this paper were obtained from cores provided to NIOSH by cooperating mining companies and point load tested by NIOSH personnel. In all cases except the Colorado corehole the core was collected in the field by NIOSH personnel. The point load data were obtained using a point load tester manufactured by GCTS (Tempe, AZ). The GCTS tester consists of a hand pump, a hydraulic cylinder and two 60° cone shaped platens to break the samples. It incorporates a pressure transducer and potentiometric position transducer, along with hardware and software to allow recording of sample loading and deformation by a laptop computer. Sample deformation was measured for all of the samples tested for this paper and all strength calculations were made using the sample heights at the time of failure.

The testing and calculations followed the procedures outlined in the ISRM recommended method for determination of point load strengths (ISRM, 1985). The equation proposed by Rusnak and Mark (2000), which was based upon approximately 10,000 point load and UCS tests of coal measure rock, was used to convert point load data to UCS:

$$UCS = 21 * I_{s50} \tag{2}$$

Where I_{s50} is determined from the point load test using the standard ISRM procedures.

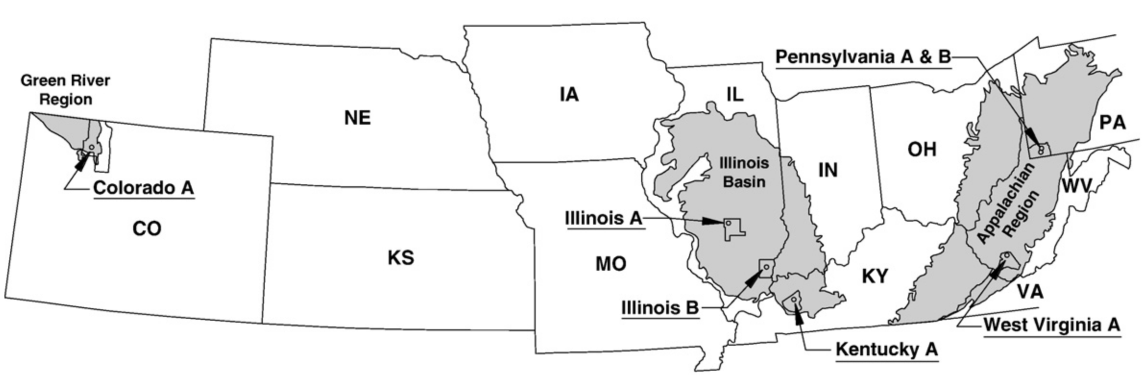

Fig. 4. Location map of the coring sites from which core and log data were collected for this paper.

Table 1
Depths of samples from each corehole.

	Depth range (ft)			
	Min	Max	Average	Median
Illinois A	576.2	599.3	587.8	589.1
West Virginia A	185.1	410.3	300.3	300.7
Pennsylvania A	46.3	542.8	292.2	282.8
Illinois B	1008.4	1142.1	1068.1	1041.3
Pennsylvania B	349.5	735.3	577.2	605.9
Colorado A	965.1	1034.4	984.7	975.6
Kentucky A	800	940.1	872.1	887.3

The GCTS hardware and software were upgraded in late 2007, after testing the core from Illinois corehole A, with an increased sensitivity pressure transducer, longer stroke position sensor and a higher resolution analog to digital data card. The upgrades were primarily needed to allow more accurate estimates of the strength of very weak rocks, such as those commonly found in the Illinois basin, and to facilitate the measurement of the dimensions of larger diameter core samples. The Illinois basin and Colorado cores were 3 in. in diameter and obtained through rotary drilling with coring of selected intervals, while the eastern cores (West Virginia and Pennsylvania) were 2 in. in diameter and obtained by wireline continuous coring.

Most, but not all, of the cores collected in the study were from intervals adjacent to coalbeds to be mined. However the depths of the samples vary over a wide range so Table 1 has been included to provide data on the distribution of sample depths.

Fig. 3 and 5 through 10 show sonic travel time, in μs/ft graphed versus uniaxial compressive strength, as determined from point load data, for each of the seven coreholes. For all seven coreholes most of the points represent a UCS measurement from a single core sample versus the sonic log travel time reading at that depth, but in a few cases they represent the average of a group of UCS readings (2 to 5) plotted versus the sonic log reading at the midpoint of the group. Averaging was always performed over intervals less than or equal to 1 foot in length, in order to match the sonic response to the UCS data. The majority of the data points represent single UCS measurements.

Table 2 summarizes the correlation equations, coefficients of determination, and numbers of samples for each corehole and for several groupings of the data, including the three Illinois basin coreholes, the two Pennsylvania coreholes, the six eastern US coreholes, and a composite of all seven coreholes. The composite equation reported in 2008 (Oyler, et. al., 2008) using data from three coreholes and the general McNally equation (units converted from MPa to psi) are also included in the table for comparison. All of the graphs are reproduced in Fig. 11 to show the spread in the strength estimates from the different data sets. Where data points have been included on the graphs the smaller filled circles represent data used in the correlation, while the larger open circles represent carbonaceous shale samples, which have not been included in the data used to compute the least squares exponential correlation equations, and which will be discussed in greater detail later in this paper.

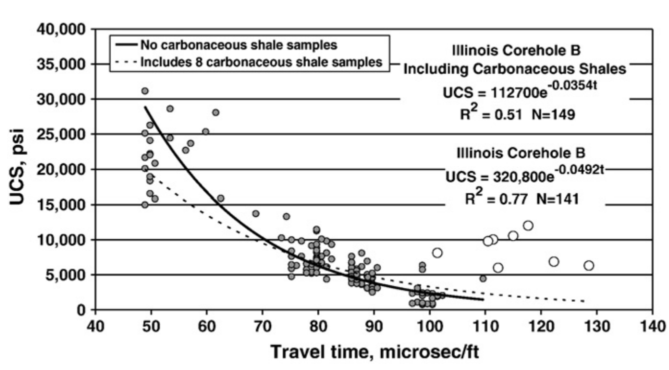

Fig. 5. Illinois corehole B. The large open circles are data from carbonaceous shales. The dashed correlation curve uses all the data, including the carbonaceous shale samples. The solid correlation curve does not use the carbonaceous shale samples. Data points represent point load tests and sonic travel time measurements from individual tests.

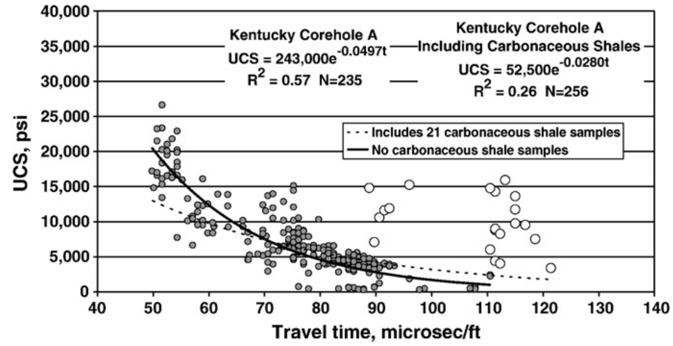

Fig. 6. Kentucky corehole A. The large open circles are data from carbonaceous shales. The dashed correlation curve uses all the data, including the carbonaceous shale samples. The solid correlation curve does not use the carbonaceous shale samples. Data points represent point load tests and sonic travel time measurements from individual tests.

Fig. 12 summarizes the correlations computed for all test data collected. The general Australian McNally equation (McNally, 1987), converted from MPa to psi, has been added for comparison. The equation for the combined data set

$$\mathrm{UCS} = 329,100e^{-0.0505t} \tag{3}$$

is similar in shape and range to the Australian equations. This composite correlation has a coefficient of determination (R^2) of 0.72 and is based upon 1015 data points (a few derived from averaging several samples). In Eq. (3), UCS is the computed rock strength in psi, and t is the travel time read directly from a sonic log, in μs/ft. Fig. 11 summarizes all of the correlations in graphical form, allowing comparison of the various correlations. Table 3 reproduces the regression statistics for Eq. (3), obtained by transforming the exponential equation to a linear one by taking the natural log of both sides of the equation and taking the natural log of the measured UCS values. In table 3 the Intercept Coefficient, 12.704 is the natural log of the constant coefficient of Eq. (3); 329,100. Similar statistical analyses were run for the other data sets, but have not been reproduced in this paper. With the exception of the general McNally equation and the correlation from Colorado A, the correlations show a tight grouping for travel times over 80 μs/ft and a wider spread for lower travel times. This is a helpful trend, since greater accuracy in estimating UCS values is more critical when evaluating weak rocks, and not as critical with stronger rocks.

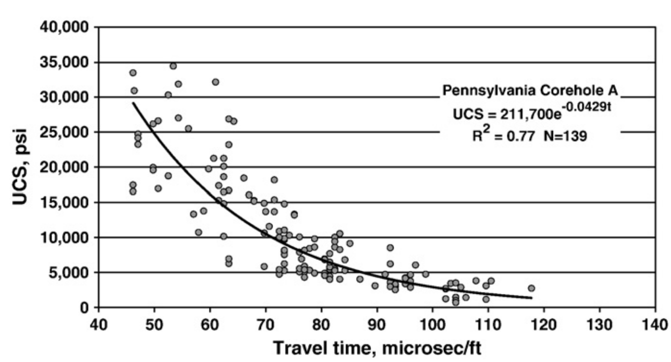

Fig. 7. Pennsylvania corehole A. Filled circles represent individual sample points.

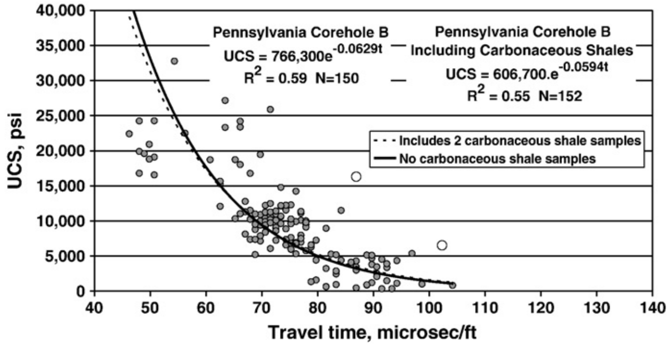

Fig. 8. Pennsylvania corehole B. The large open circles are data from carbonaceous shales. The dashed correlation curve uses all the data, including the carbonaceous shale samples. The solid correlation curve does not use the carbonaceous shale samples. Data points represent point load tests and sonic travel time measurements from individual tests, with six samples averaged in groups of three.

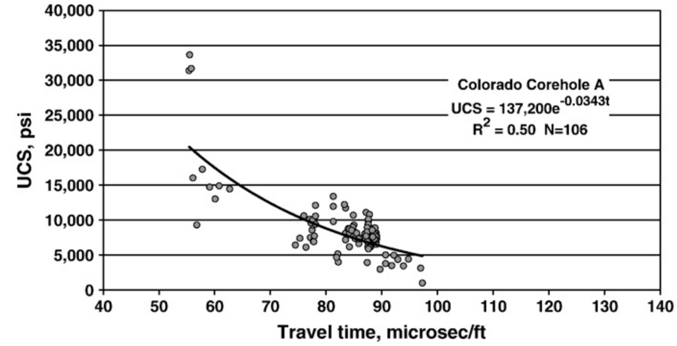

Fig. 10. Colorado corehole A. Filled circles represent individual sample points.

5.1. Carbonaceous shales

Although some spread was observed in the measured UCS values of all rock types when compared to the travel time readings, carbonaceous shales were found to frequently exhibit much higher measured UCS values than other types of rock for the observed travel times. This anomalous response was not noted until the fourth corehole, Illinois B, from which data were collected in August 2008. Prior to that hole almost no carbonaceous shale had been encountered. The large open circles in Figs. 5, 6, 8 and 12 show the carbonaceous shale data. The travel times for the samples from Illinois corehole B ranged from 100 to130 µs/ft, while the strengths ranged from 6000 to 12,000 psi. Normally shales with those travel times would range in strength from a few hundred to 4000 psi. In late 2009 core was collected from above the Herrin (#11) and Springfield (#9) in western Kentucky (Kentucky A, Fig. 6). Again anomalous correlations were observed for carbonaceous shales.

Most of the anomalous carbonaceous shale samples tested during this project were from two marine carbonaceous shales found in the Illinois basin, the Anna shale, found directly above the Herrin #6 (#11 in Kentucky) and the Turner Mine shale, found directly above the Springfield #5 (#9 in Kentucky). The tested UCS values of samples of both of these shales were much higher than would be predicted from the sonic log travel times. Fig. 13 shows a set of typical carbonaceous shale samples, in this case from corehole Kentucky A. Five of the samples are from the Anna shale; the upper right sample is from the Turner Mine shale. The samples were chosen to illustrate the wide range of strengths possible in the carbonaceous shales, and the lack of visual indication of the strength of the samples. The travel time data of the pictured samples cover a narrow range of 110 to 119 µs/ft. The correlation equation predicts UCS values between 670 and 1030 psi. The actual strengths were between 2400 and 15,900 psi.

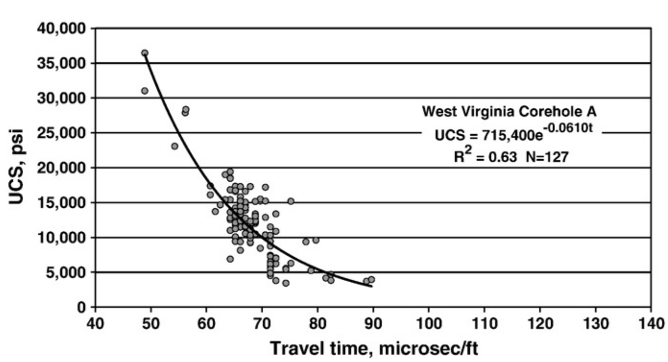

Fig. 9. West Virginia corehole A. Filled circles represent individual sample points.

Samples from carbonaceous shale directly above the Bakerstown coal, from a Pennsylvania corehole, were also tested during the preparation of this paper. The average UCS value for the 16 samples tested in the 2 ft interval was 8000 psi, with a standard deviation of 1300 psi. The high UCS values suggested that the sonic response in this shale is also anomalous, but no sonic data were available for this interval so the results are inconclusive.

One possible source of the anomalous response of carbonaceous shales is the amount of organic material contained in them. The possibility of correlating organic material content to geophysical log response was not pursued in this study, but has been studied by other researchers (Fertl et al., 1986) using a wide range of geophysical logs. Variation in the organic matter content could help explain the wide range of and high UCS values observed from carbonaceous shales tested in this study.

Two observations can be made from the data. First, the carbonaceous shales should be excluded from the data when developing a general sonic travel time-to-UCS correlation because they clearly form a distinct, anomalous rock type. Second, it appears that carbonaceous shales are usually stronger than the general correlation would predict, so it would be conservative to use the general correlations to design support systems in roof containing the shales.

5.2. Application to roof design

The primary purpose of this paper is to lay out for the reader the development of a tool to be used to aid in roof control design. The use of sonic log data combined with the correlations developed in this paper can provide continuous estimates of the UCS of the rocks in the

Table 2
Sonic travel time versus UCS (from point load data) correlation[a].

Corehole or group	Coefficient *A*[b]	Coefficient *B*	R^2	*N*
Illinois A	250,000	−0.0521	0.34	121
Illinois B	320,800	−0.0492	0.77	141
Kentucky A	243,000	−0.0497	0.57	235
Colorado A	137,200	−0.0343	0.50	106
Pennsylvania A	211,700	−0.0429	0.77	139
Pennsylvania B	765,000	−0.0627	0.59	150
West Virginia A	715,400	−0.0610	0.63	127
All coreholes (7)[c]	329,100	−0.0505	0.72	1015
Eastern coreholes (6)	339,600	−0.0515	0.75	909
Illinois basin (3)	270,000	−0.0497	0.75	493
Pennsylvania (2)	298,500	−0.0488	0.63	289
2008 composite (3)[d]	468,000	−0.054	0.87	316
McNally[e]	143,000	−0.035	N/A	N/A

[a] Correlations do not include carbonaceous shale sample data.
[b] *A* and *B* are coefficients of an equation of the form, $UCS = Ae^{-Bt}$.
[c] Number in parentheses indicates the number of coreholes included in the data set.
[d] Correlation of unaveraged Illinois A sample data, Pennsylvania A and West Virginia A data, as reported by Oyler et al. (2008).
[e] From McNally (1987). Equation converted from metric units (MPa) to psi.

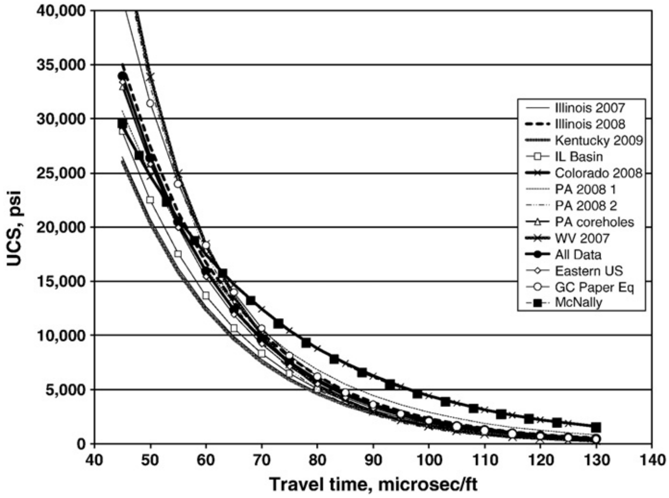

Fig. 11. Graphed correlation equations for data from each of the seven coreholes and including an Illinois basin correlation, Pennsylvania correlation, Eastern US correlation, a correlation using all seven coreholes, and a previously published correlation based upon three of the coreholes (Oyler, et al., 2008). The general McNally Australian equation (in psi units) (McNally, 1987) is shown for comparison.

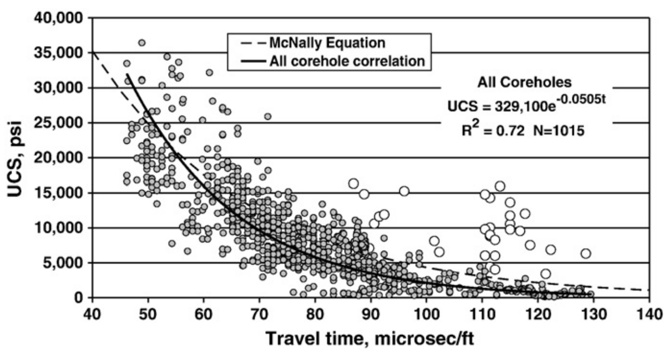

Fig. 12. Correlation using data from all seven coreholes. The large open circles are data from carbonaceous shale samples not used in computing the correlation equation shown. The general McNally equation (McNally, 1987) is shown by the dashed curve.

immediate mine roof. These UCS estimates can also be used to map roof strata and may aid in interpolation of and/or prediction of changes in roof conditions. The UCS obtained from sonic logs is also one of the key input parameters for the Coal Mine Roof Rating (Mark and Molinda, 2005).

This paper does not attempt to determine whether local UCS/travel time correlations on a mine-by-mine basis, as is Australian practice, or correlations using basin wide or regional data give better results. The authors have presented regional correlations rather than local correlations because it was possible to do the former and not the latter and because we believe that the regional correlations can be useful, but we cannot be completely certain that local mine-by-mine correlations would not give better results.

The paper also does not attempt to provide guidelines for using UCS data, whether estimated from sonic logs or from testing of rock samples, for the design of mine roof support systems. Current Australian research (Hatherly, et al., 2005; Hatherly, et al., 2007) is focused on employing the full suite of geophysical logs, including density, sonic, gamma ray and neutron logs, to develop a more complete strata characterization. This work has resulted in the development of the Geophysical Strata Rating (GSR), which has been calibrated by comparison with the Coal Mine Roof Rating (CMRR), but is derived solely from geophysical log data (Hatherly, 2006). NIOSH is currently conducting a study to compare CMRR unit ratings determined using data from core samples to the geophysical log derived GSR ratings. Both ratings attempt to take into account moisture sensitivity, bedding and other factors besides rock strength.

6. Conclusions

The study demonstrated that sonic travel time logs can be used to estimate the UCS of US coal measure rocks. It appears that both the geological conditions and the available geophysical logging technology in the US are suitable for developing and using the sonic travel time versus unconfined compressive strength correlations. The results were consistent across several coal provinces and represent the broad range of rock encountered over the major US coalfields, although the western data are limited. The general correlation shown in Eq. (3) and repeated below in Eq. (4) appears to apply to coal measure rocks throughout the coalfields of the continental United States.

$$\mathrm{UCS} = 329,100e^{-0.0505t} \tag{4}$$

Carbonaceous shales present in the Illinois basin and possibly present in the Appalachian or other regions, were the only rock type that did not fit the general equation. Additional work is warranted to understand the reasons why the tested UCS of carbonaceous shales is significantly higher than would be expected based on the travel times measured in the shales. Coal samples were generally not tested, partially due to lack of availability, and were also not included in the correlations.

The ability to use sonic logs to estimate rock strength provides the US coal industry with a powerful new tool for improving ground control design. The availability of uniaxial compressive strength data is essential to effective roof support selection, gate entry design, and many other aspects of ground control. Widespread use of sonic logs

Table 3
Regression statistics for the data from all 7 coreholes[a].

R-squared	Adj *R*-squared	MSE	*F*	# Obs		
0.7231	0.7229	0.5333	2645.8	1015		
Source	*df*	SS	MS			
Model	1	752.4890	752.4890			
Residual	1013	288.1109	0.284414			
Total	1014	1040.5999				
	Coefficient[b]	Std. err.	*t* stat	*P*-value	95% conf. int.	
Intercept	12.70397818	0.080478	157.8565	0	12.5461	12.8619
X variable	−0.0504562	0.00098	−51.43691	0.0000	−0.05238	−0.04853

[a] Exponential equation transformed to a linear equation by taking the natural log of both sides of the equation and performing a linear regression using the natural log of the UCS values (ln(UCS)).
[b] The intercept coefficient is $\ln(A) = 12.704$, the natural log of the exponential coefficient (A); $A = 329{,}100$.

Fig. 13. Carbonaceous shale samples from corehole Kentucky A. The samples have been tested and the halves oriented to show a top view and a view of the failure surface. All samples are from the Anna shale, except the top right sample, which is from the Turner Mine shale. The samples were chosen to illustrate the wide range of UCS values observed in the carbonaceous shales, despite a narrow range of logged travel times. Depths in feet, UCS in psi and Delta T in μs/ft.

during the exploration phase could vastly increase the quantity of geotechnical data that is available for mine design.

The study also suggests that high-quality sonic logs are essential if the technique is to be successful. Careful attention to the details of the logging process, including use of appropriate logging tools, use of effective logging tool centralizers, accurate depth correlations and elimination of logging errors, such as “cycle skips”, can all help to improve the correlations.

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