Correlation of Sonic Travel Time to the Uniaxial Compressive Strength of U.S. Coal Measure Rocks

David C. Oyler, Research Engineer
Christopher Mark, Principal Research Engineer
Gregory M. Molinda, Lead Research Scientist
NIOSH-Pittsburgh Research Laboratory
Pittsburgh, PA

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 strength data for use in all aspects of ground control design. However, the technique depends upon reliable correlations between the unconfined compressive strength (UCS) and the sonic velocity. This paper describes research recently conducted by the National Institute for Occupational Safety and Health (NIOSH) aimed at developing a correlation for use by the U.S. mining industry. At three coreholes in Illinois, Pennsylvania, and southern West Virginia, sonic velocity logs were compared with 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 the following equation, where UCS is in psi and t is the travel time of the P-wave in microsec/ft.

$$UCS = 468{,}000 \text{ x } e^{-0.054t} \qquad (1)$$

The r-squared value for this equation is 0.87, indicating that a strong correlation between sonic travel time and UCS can be achieved with this technique. The paper also addresses the steps that are necessary to ensure that high-quality sonic logs are obtained for use in estimating UCS.

ACKNOWLEDGEMENTS

The authors would like to thank Collin Henke of Patriot Coal, Murali Gadde of Peabody Energy, and Brian Schaeffer of Foundation Coal for providing drill core for testing and access to drill sites.

INTRODUCTION AND BACKGROUND

Sonic logging has been routinely used for many years in Australia to obtain estimates of coal mine roof rock strength for use in roof support design (McNally, 1987 and 1990). The estimates are obtained through measurements of the travel time of the compressional or P wave, determined by running sonic geophysical logs in coreholes, which are then correlated with uniaxial compressive strength 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:

$$UCS = 143{,}000 \text{ x } e^{-0.035t} \qquad (2)$$

where UCS is in psi and t is the travel time of the P-wave in microsec/ft. Figure 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 (Hatherly, 2002; Larkin, 2000 and Ward and Riley, 2000). These correlations allow for continuous mapping of the roof rock UCS in each borehole (Gordon, 2000 and Guo et al., 2000). 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 velocity data can be obtained from logs of 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.

For example, at the Crinum Mine in Queensland, 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. After several panels, it became clear that areas of difficult ground corresponded closely with regions of low sonic velocity and estimated UCS<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 (figure 2). These contour plots are used to select bolting densities and the location of secondary support (Payne, 2008).

Current Australian research (Hatherly and Medhurst, 2000; Hatherly, 2002; Medhurst and Hatherly, 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

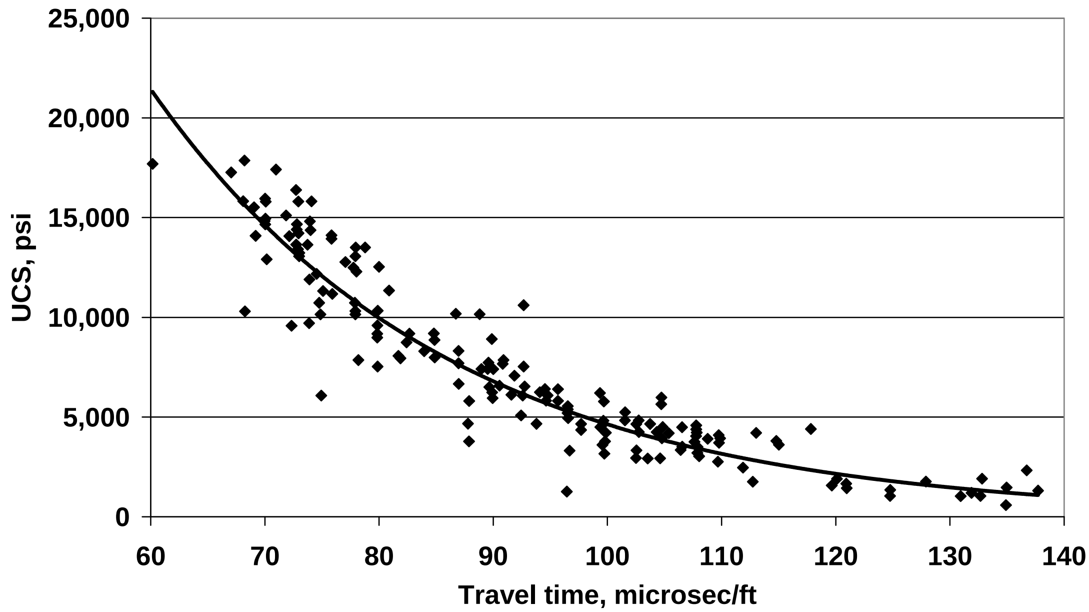

Figure 1. Sonic travel time versus UCS data from the Australian German Creek seam. Data after McNally (1987).

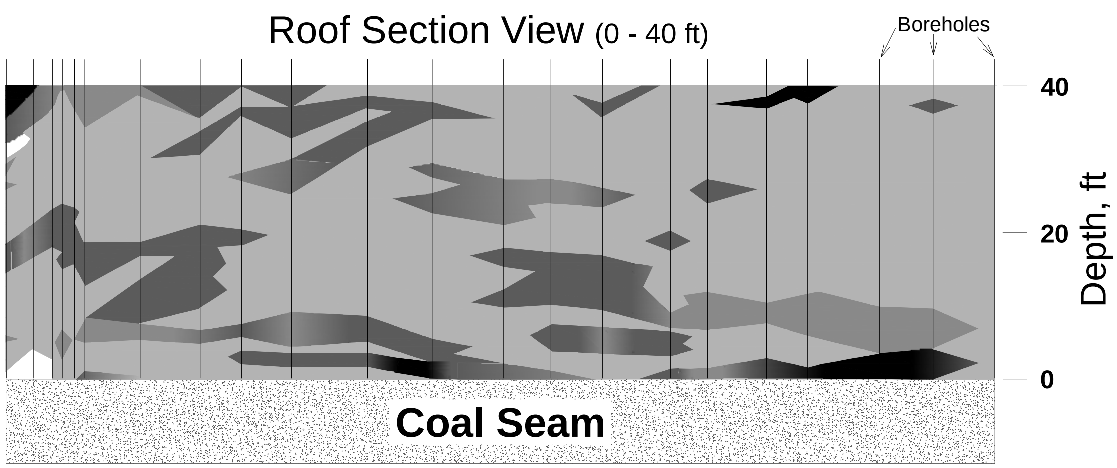

Figure 2. Contour plot of UCS of the immediate roof above a gateroad at the Crinum mine, Queensland, Australia (Payne, 2008). UCS data computed from sonic travel time log data, with black representing the weakest roof and light gray to white the strongest roof. Vertical scale 0 to 40 ft. Plot width approximately 8,000 ft (after Payne, 2008).

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 CMRR, but is derived solely from geophysical log data (Hatherly, 2006).

In contrast to the Australian situation, only limited research has been conducted in the U.S. in this area (see, for example Feddock, et al., 2003). 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 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.

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 (figure 3). The difference in arrival times of the sonic wave train received by two detectors is then used to determine the sonic velocity. Generally sonic data are displayed in travel time per foot, with typical travel times for sedimentary rocks ranging from 40 to 140 microsec/ft. Sonic travel times for sedimentary rocks are generally bounded by the P wave travel times in quartz (sandstone matrix), calcite (limestone matrix) and water which are respectively, 55.6, 45.5 and 190 microsec/ft (Schlumberger, 1991). Travel times for coal and shales are not necessarily limited by the quartz and calcite travel times (although they may be influenced if they contain these minerals), but still generally fall within the 40 to 140 microsec/ft travel time range.

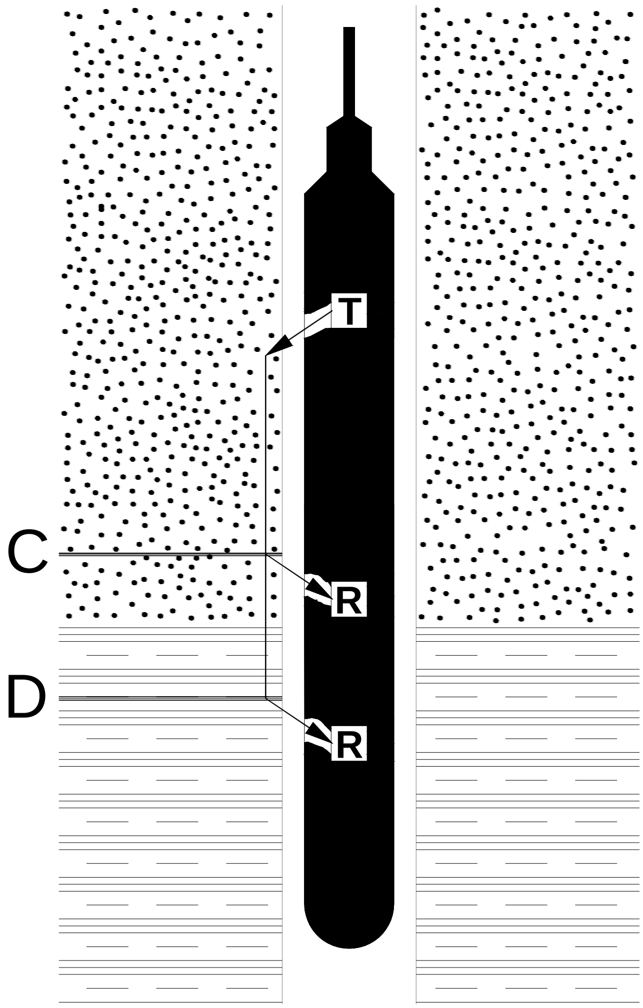

Figure 3. Single transmitter, two-receiver sonic tool geometry showing the path of the sound wave. The difference between the travel times from the transmitter (T) to the far and near receivers (R) is the travel time. The tool vertical resolution is the distance C to D.

If the signal from a sonic receiver is graphed versus time, it appears as a more-or-less sinusoidal wave. The waveform includes both compressional (P) and shear (S) waves, but the velocity usually displayed on logs is determined from the first arrival, which is the compressional wave, the fastest component of the waveform. Sonic logging tools collect a large quantity of data, only a small portion of which is actually required to determine the P wave velocity. There are two generally accepted ways to display the sonic waveform; which is frequently displayed on the logs. The most common display technique is described as a variable density display, while the other is an actual sonic waveform. However, the variable density display is also sometimes described as a waveform display.

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, that is they generally have two transmitters and 4 receivers and the data received can be used to correct for tool misalignment in the hole. They frequently have a spacing between the receivers of 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 U.S. are usually 1 ft, although tools with multiple spacings and slightly shorter spacings (20 cm or 8 inches) 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 obvious. On the other, hand more frequent sampling does not improve the vertical resolution, which is probably a more serious problem in ground control applications.

Finally, it is important to note that since the logging tool measures the sound wave's travel time between two receivers, the velocity it records is actually the *average velocity* of all the rock layers contained within that 1- or 2-ft interval. UCS test specimens, on the other hand, are only several inches long. Figure 3 illustrates this averaging of the travel time. The figure shows a single transmitter, two-receiver tool positioned with the tool measure point centered on the contact between a thick uniform shale and sandstone. Each measurement reads the time required for the P wave to travel from C to D. If we assume that the travel times in the shale and sandstone are, respectively, 100 microsec/ft and 60 microsec/ft, then, at the position shown, the tool reading would be 80 microsec/ft. As the tool moves uphole, the reading decreases until the lower receiver enters the sandstone, at which point the tool reading is 60 microsec/ft. This "averaging" that is inherent in the design of the tool has several important implications that are discussed below.

CORRELATING SONIC AND POINT LOAD UCS DATA

While simple in concept, successful correlation of sonic velocity to UCS measurements requires careful attention to many details of the logging process.

Depth Correlation and Correction

Before accurate correlations of sonic and point load derived UCS data can be obtained, the depths of the core and sonic logs must be in agreement. Typically it can be expected that the driller's and logger's depths will not necessarily agree without adjustment of one set of depths. As long ago as 1987, McNally reported on several of the potential sources of error in correlating sonic logs to core strength data. McNally identified five possible sources of depth errors:

- Loss of core;
- Core stumps left in the hole and assigned to a later run;
- Core swelling (primarily making correction of other error sources more difficult);
- Use of different depth reference points by the driller and logger, and;
- Ordinary errors in measurement and transcription by the driller or core logger.

When correlating core and log depths, it can be useful to begin by placing all of the geophysical logs run on a single depth scale. Typically, a density log with natural gamma ray and caliper is the standard coal log. The sonic log is usually recorded on a separate run with a second natural gamma ray log, and the two gamma ray logs are used to correlate the density, gamma ray, and caliper logs to the sonic travel time curve. The geophysical log depths usually agree, but there can sometimes be small differences of depth between the two logs. Thin limestones, coalbeds and clean (low radioactivity) sandstones make good markers for matching core and geophysical log depths. Comparison of the thickness of the intervals as determined by the density, sonic and gamma ray logs to the length of core of a uniform lithology of known properties (for instance a limestone of low porosity which would be expected to have low radioactivity), can also help in making depth corrections. Thin coals are especially helpful in this respect. It is usually the case that depth discrepancies between the logs and core will be relatively consistent, and will change slowly with depth. This is especially likely to be the case if the discrepancies are derived from errors in the logger's measuring wheel. Arithmetic errors, transcription errors and loss of core are more likely to be caused by the driller and jumps in the depth discrepancies can be expected at the depths where the errors took place.

Vertical Resolution Differences Between Log and Test Specimens

McNally also pointed out that 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 our 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 tool that was used to run all three 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 all three 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 sonic readings 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.
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 from the near receiver to the far receiver.

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; it 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 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.

In the work conducted for this project, technique 1 was originally used on the data from all three coreholes, but the results of applying technique 2 to the West Virginia and Pennsylvania core data suggest that it can provide more reliable correlations. Technique 3 was used on the Illinois core, where only 24 ft of core was available. The results obtained from each of the three techniques will be described in the "Discussion and Results" section.

Sonic Log Errors

Another source of error is from errors in the measured sonic travel times. Sonic tools are designed to detect the arrival of the first signal of the wavetrain, which is roughly a series of sinusoidal waves at the tool's operating frequency. The peaks arrive at intervals of approximately 42 microsec. 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 the amplitude of the first arrival is too small to trigger the detector, however, 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 microsec 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 eccentering of the tool (the axis of the tool and hole not being parallel), and decentralization of the tool in the hole, both of which lead to 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 attenuation across joints or fractures. The presence of joints and fractures can sometimes be detected through observation of cycle skipping, although the sources of cycle skips are usually not identified. Noise from the tool or centralizers scraping on the wall of the hole can create high frequency noise which can cause early triggering of either detector. Again, this can lead to either increased or decreased travel times, depending upon which detector is affected. Better centralizers and lower logging speeds can sometimes reduce the problem, but errors caused by noise are probably more difficult to diagnose than cycle skipping. Noise and attenuation of the signal can also cause errors in detection of the first arrival which can lead to travel time errors. These can be of lower magnitude than errors caused by cycle skipping. Since attenuation is more likely to affect the far detector, attenuation errors usually cause longer travel times.

Because cycle skips are so distinctive, they are easier to identify than errors due to attenuation or noise. Because the sonic tool averages the travel time of an interval of rock equal in length to the receiver spacing, most changes in travel time are gradual and smooth, even when the tool is traveling through the boundaries of formations of drastically different sonic velocities. Cycle skipping usually causes distinctive sharp changes in travel time that are of greater magnitude and take place more quickly than legitimate changes in travel time. Errors caused by attenuation or noise can be more difficult to identify on a log, but one good method of identifying them, and for checking the tool calibration, is to run the log in fluid filled steel casing (when available). A properly calibrated sonic log should read 57 microsec/ft in steel casing (of any diameter), and the travel time should be constant (except at casing joints).

Because of the analog nature of the sonic wavetrain (even though the data are probably transmitted up hole digitally), the data may be processed by adjusting the gain factors of one or more amplifiers or pre-amplifiers. Proper setting of these gain factors is important to obtaining an accurate log. Where the logging engineer is not familiar with the proper settings, or where conditions are unusual, it may be worthwhile to make logging runs (despite additional cost) at several gain settings to determine the optimum settings. Generally it is probably easier to determine the proper gain settings by examining logs of several gain settings side-by-side, so it may make sense to either run the entire log at several gain settings or to run short portions of the log at different settings, then print the test runs and examine them for the correct setting to run the final log. In this project several gain checks were made on all three holes, but the best settings in all three cases were eventually found to be the logging company's standard settings. Confirmation of this fact was considered to be worth the extra logging costs.

Water Loss from Previously Mined Coalbeds

A problem not discussed by NcNally is the loss of water in the hole due to the effects of subsidence or from mined coalbeds above the seam of interest. Water loss does not cause measurement errors, but it does prevent the measurement of travel time data in intervals above the water level. This is a common problem in southern West Virginia and eastern Kentucky, but it can occur in all U.S. coal fields. Potential damage to boreholes can also force mining companies to run density logs through pipe to avoid the risk of losing a gamma ray source in a corehole. Although not the subject of this paper, density logs run through drill pipe cannot be accurately calibrated. While it does not affect sonic velocity logs, the practice of running density logs through pipe would make it difficult to use some of the advanced geophysical techniques for determining roof rock properties currently being developed in Australia (Hatherly et al., 2007).

There are several possible solutions to the problem of fluid loss, depending upon the severity of the loss. If the loss rate is not severe and the water level is high enough, it may be acceptable to simply log less of the hole. It may also be possible to add fluid during the logging operation to maintain an acceptable fluid level. If the rate of fluid loss is greater, it may be necessary to use drilling mud to reduce the rate to manageable levels. Finally, in extreme cases it may be necessary to case off the zones of fluid loss. This adds the expense of running additional casing in the hole and may also require the use of multiple core rigs and larger bit sizes. In some cases, where reducing fluid loss rates may require running casing through mineable coal seams, this may not be acceptable. In these cases it may be more cost effective to abandon the use of sonic data and continue laboratory testing of core samples.

DISCUSSION AND RESULTS

NIOSH collected data from three coreholes, one located in Fayette County, Illinois, one in Wyoming County, West Virginia and the third located in Greene County, Pennsylvania. In all three cases the sonic logs core were run by Geological Logging Systems, a Division of Marshall Miller & Associates[1], using a Century Geophysical Corp model 9321 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. 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 report 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 International Society for Rock Mechanics (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 PLT and UCS tests of coal measure rock, was used to convert point load data to UCS, where Is_{50} is determined from the point load test using the standard ISRM procedures.

$$UCS = 21 \times Is_{50} \tag{3}$$

The GCTS hardware and software were upgraded after the Illinois corehole 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 corehole and to measure the dimensions of larger diameter core samples, such as the 3-in diameter core from the Illinois corehole. Most of the samples from the West Virginia and Pennsylvania coreholes were not as weak as those encountered in the Illinois rocks and the cores in both cases were nominally 2 inches in diameter.

Figures 4, 5 and 6 show sonic travel time, in microsec/ft graphed versus uniaxial compressive strength, as determined from point load data, for the Illinois, West Virginia and Pennsylvania coreholes, respectively. In all three cases the graph points represent individual point load tests correlated to the closest individual sonic travel time measurement. The coefficients of determination (r^2) for the Illinois, West Virginia and Pennsylvania data were 0.34, 0.63 and 0.77 and the number of samples were 121, 127 and 139, respectively. The samples from the Pennsylvania corehole were divided by rock type into three groups, limestones, sandstones and shales and claystones, as shown in figure 6. There were few siltstones in the corehole, although there were many zones of interbedded thin shales and sandstones. These zones were

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

avoided because of the anticipated difficulty in correlating the UCS values of short homogeneous samples with the log responses of a foot of heterogeneous rock.

In the case of the West Virginia and Pennsylvania coreholes sufficient core was available to attempt to follow technique 1, although in some cases rock from thin zones or samples from near bed boundaries were tested.

In the Illinois case, only 24 ft of core were available for testing and the available range of rock strengths and sonic velocities was limited (the travel times ranged from 76 to 129 microsec/ft and the UCS values from 80 to 9,800 psi). The limited amount of available core from this site did, however, allow for more complete testing of the core. Ultimately 122 tests were conducted in the 24 ft; roughly one test per 2.5 in. Since much of the rock tested was thinly bedded, and since each sonic travel time measurement essentially averages the strength of a 1- ft-long interval of the rock in the hole, it was anticipated that a point-by-

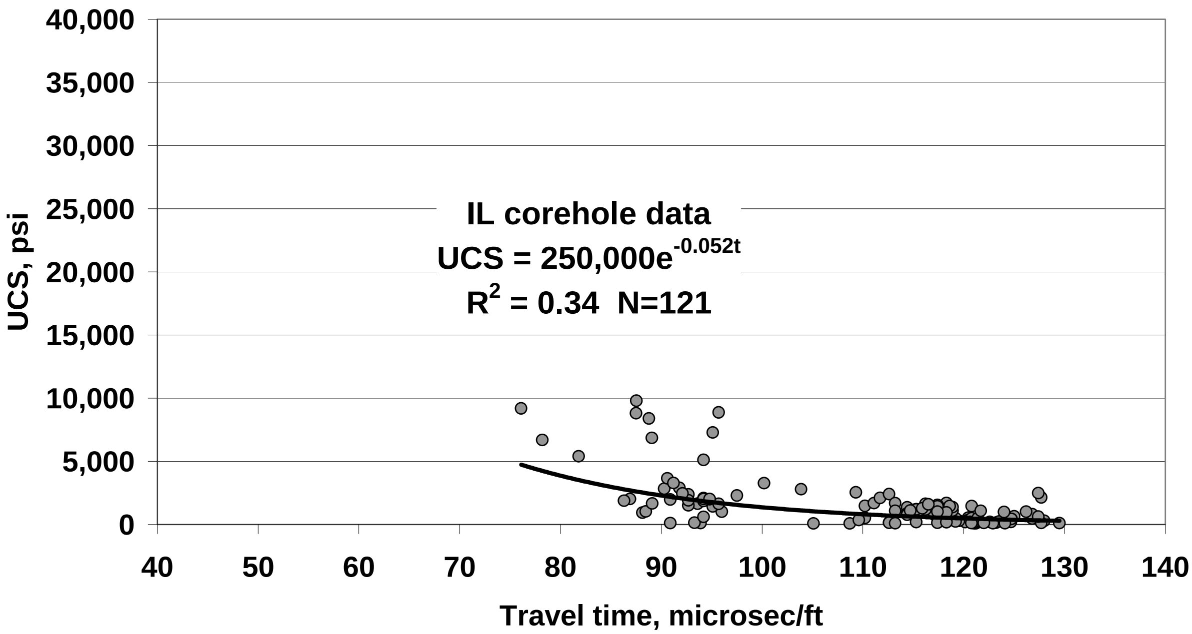

Figure 4. Illinois core sonic travel time versus UCS, with best fit relationship. Data points represent individual sample point load tests and sonic travel time measurements.

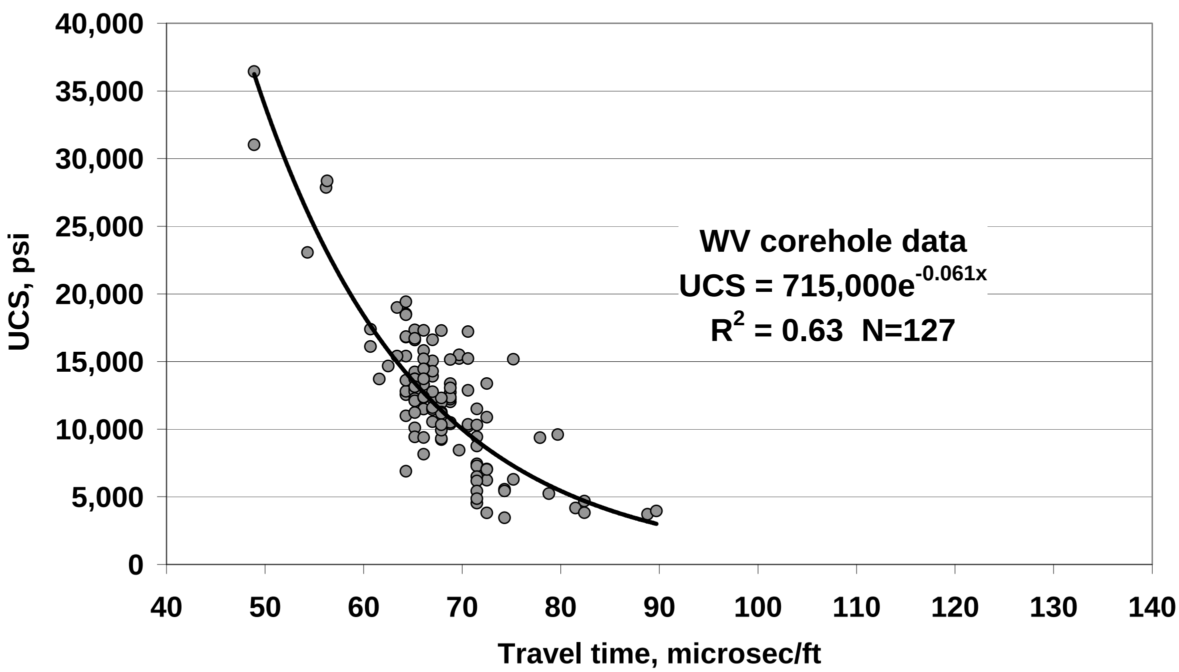

Figure 5. West Virginia core sonic travel time versus UCS, with best fit relationship. Data points represent individual sample point load tests and sonic travel time measurements.

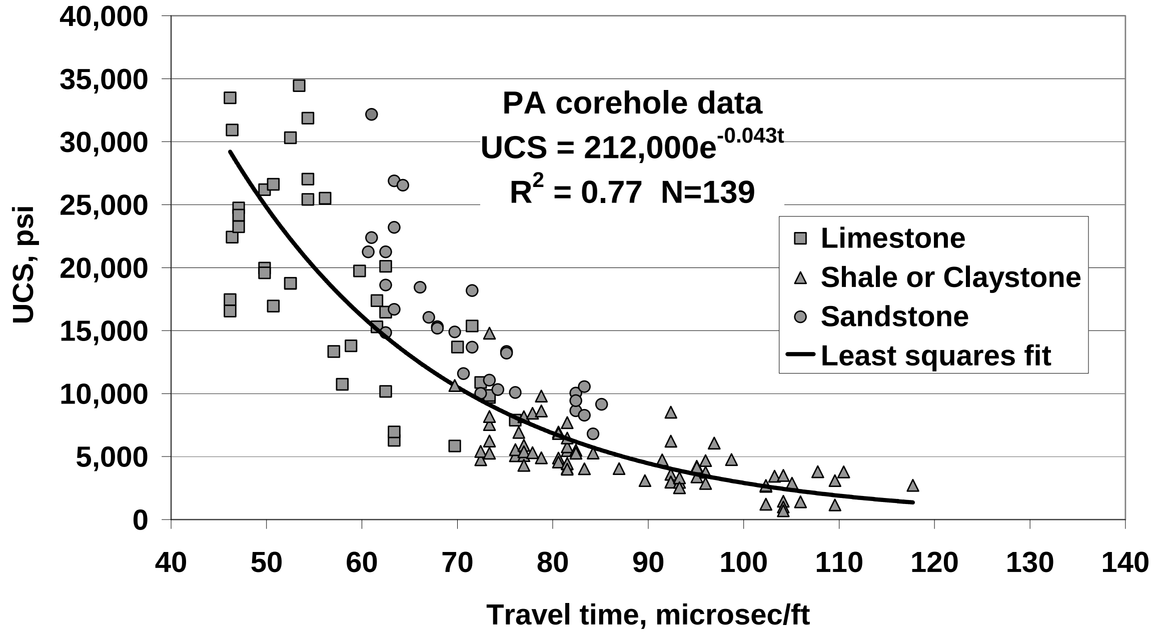

Figure 6. Pennsylvania core sonic travel time versus UCS, with best fit relationship. Data points represent individual sample point load tests and sonic travel time measurements. Lithology indicated for each sample.

point comparison of the UCS to the sonic travel time would result in a poor correlation.

The Illinois data were also graphed using a 5 point moving average (technique 3). Instead of a single point load reading representing an average interval of 2.5 in and the sonic log averaging the travel time of a roughly 13 in interval, the averaged point load readings approximate the average response of 9.3 in of rock. However, the actual intervals between tests varied considerably, with a standard deviation of 4.3 in. The use of the moving average increased the coefficient of determination (r^2) for the Illinois data from 0.34 to 0.54. This improvement was primarily due to the averaging of UCS sample properties across bed boundaries by the use of the moving average, which produces in the UCS data the same effect the 1-ft vertical resolution of the sonic tool has on the travel time measurements. Due to the averaging the number of samples in the regression was reduced from 121 to 117.

The West Virginia and Pennsylvania data were averaged using technique 2. Where multiple point load tests had been performed within a single rock unit, the UCS estimates were averaged and new regressions computed using the averaged UCS estimates. The original testing procedure was not specifically designed with technique 2 in mind and although the results showed some improvement in the correlations, the results were probably not optimized. The improvement in the r^2 value in the West Virginia case was from 0.63 to 0.71, while the Pennsylvania r^2 value changed minimally from 0.77 to 0.78. The number of samples in the regressions was reduced, as a result of the averaging, to 106 and 93 for the West Virginia and Pennsylvania regressions, respectively.

The large difference between the improvement in the West Virginia and Pennsylvania data (less than 0.01 versus 0.08), most likely indicates the range of improvement to be expected from using technique 2, but other factors might have been influential. The most likely factor was the initial range of the data, which was much wider for the Pennsylvania data (the travel times ranged from 46 to 118 microsec/ft for the Pennsylvania data, but only from 49 to 90 microsec/ft for the West Virginia data). In general a wider range of travel times will improve the r^2. It is likely the Pennsylvania case was already closer to the optimum correlation prior to averaging, and the West Virginia core had more room for improvement. The selection of tests averaged might also have had an effect, but this seems less likely, since more tests were averaged from the Pennsylvania cores and no particular effort was made in either case to optimize the selection of test zones for improving the correlation. The decision to average the data was not made in either case until after all of the testing was completed. The low coefficient of determination (r^2) for the Illinois data also appears to be partly due to the narrow range of the data, between 76 and 130 microsec/ft. Had a wider range of rock strengths been present, particularly including higher strength (low travel time) rocks, the initial r^2 probably would have been larger.

The large number of tests of the Illinois core allowed the sonic log and UCS data to be plotted versus depth and compared as shown in Figure 7. The sonic log has been inverted in Figure 7 and presented as a velocity curve in ft/sec, and the UCS data have been graphed using data averaged using a 5-point moving average. The UCS scale has also been adjusted to overlay the two curves in the weak shale intervals. A thin limestone, centered at 599 ft, was used to correlate the two curves. The curves agree fairly well except between 588.5 to 592.5 ft where the UCS data suggest a weaker rock than does the sonic velocity curve.

Figure 8 summarizes all of the test data collected in a single graph using the 5 point moving average data from the Illinois corehole and including the averaged data points for the West Virginia and Pennsylvania coreholes. The general Australian McNally equation (McNally, 1987), converted from MPa to psi, has been added for comparison. The averaged data from all three coreholes have also been combined and a regression equation for the combined data included on the graph. Although the individual r^2 values for the Illinois, West Virginia and Pennsylvania coreholes are 0.54, 0.71 and 0.78, respectively, the r^2 for the combined data set is 0.87. The equation for the combined data set:

$$UCS = 468{,}000e^{-0.054t} \qquad (4)$$

is similar in shape and range to the Australian equations, which further supports its validity. It appears that both the geological conditions and the available geophysical logging technology in the U.S. are suitable for developing and using the sonic travel time versus unconfined compressive strength correlations, much as the Australian mining industry has already done.

CONCLUSIONS

The study demonstrated that sonic travel time logs can be used to estimate the UCS of U.S. coal measure rocks. The results were consistent across three distinct data sets, representing three

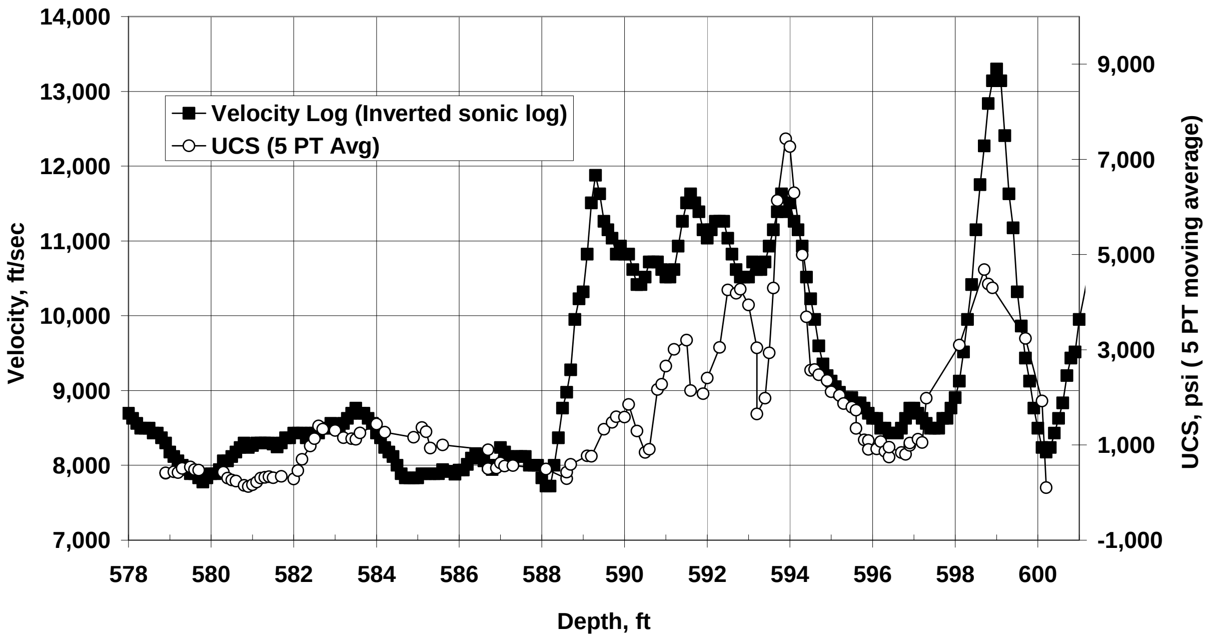

Figure 7. Sonic log of the Illinois core interval with the travel time log inverted and plotted as a velocity curve (ft/sec). The 5 point moving average UCS data (from point load tests) have been plotted with the scales chosen to overlay the curves in shale and give the curves similar sensitivities.

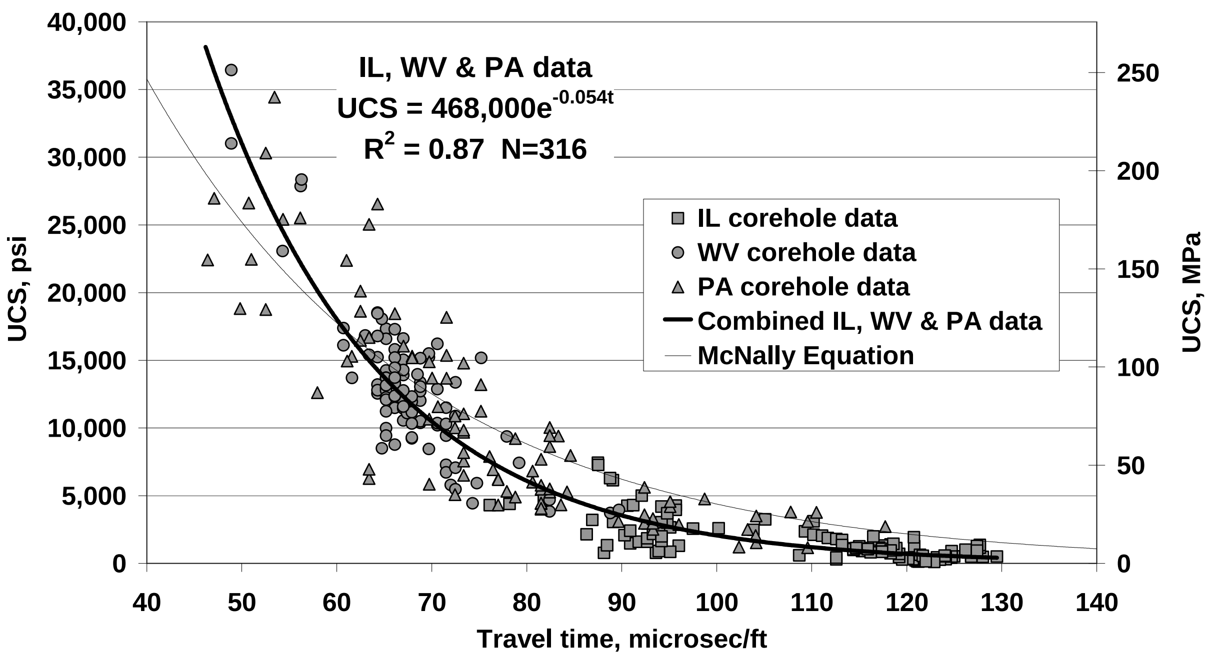

Figure 8. Best fit relationship for the entire data set of the Illinois, West Virginia and Pennsylvania core data. The original Australian McNally equation (in psi units) is shown for comparison.

separate coal provinces and representing the broad range of rock encountered in the eastern and midwestern coal fields.

The ability to use sonic logs to estimate rock strength provides the U.S. coal industry with a powerful new tool for improving ground control design. The UCS is essential to provide effective roof support selection, gate entry design, and many other aspects of ground control. Widespread use of sonic logs 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, making accurate depth correlations and eliminating logging errors, such as “cycle skips”, can all help to improve the correlations.

Disclaimer

The findings and conclusions in this paper 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.

REFERENCES

1. **Feddock, J., Waters, P., Padgett, P., Unrug, K., and Popp, J. ,**(2003). Determination of Rock Strength Properties Using Geophysical and Ultrasonic Logging in Exploration Drill Holes. Proceedings of the 22nd International Ground Control in Mining Conference, Morgantown, WV, pp. 157-161.

2. **Gordon, N.,** (2000). Strata Characterisation at Kestrel Mine. Proceedings of the Geological Society of Australia Bowen Basin Symposium, Rockhampton, QLD, pp. 125-132.

3. **Guo, H., Zhou, B., Poulsen, B. and Biggs, M.,** (2000). 3D Overburden Geotechnical Characterisation for Longwall Mining at Southern Colliery. Proceedings of the Geological Society of Australia Bowen Basin Symposium, Rockhampton, QLD, pp. 67-72.

4. **Hatherly, P.,** (2002). Rock Strength Assessment from Geophysical Logging. Proceedings of the 8th International Symposium on Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications, Toronto, Ontario, Canada.

5.. **Hatherly, P.,** (2006). Reflections on the Application of Geophysics to Ground Control. Proceedings of the 25th International Ground Control in Mining Conference, Morgantown, WV, pp. 78-85.

6. **Hatherly, P. and Medhurst, T.,** (2000). Quantitative Geotechnical Data by Full Waveform Sonic Logging. Proceedings of the Geological Society of Australia Bowen Basin Symposium. Rockhampton, QLD, pp. 91-96.

7. **Hatherly, P.J., Medhurst, T.P., and MacGregor, S.A.,** (2007). A Rock Mass Rating Scheme for Clastic Sediments Based on Geophysical Logs. Proceedings of the International Workshop on Rock Mass Classification in Underground Mining, NIOSH Publication No. 2007-128, IC 9498, pp. 57-63.

8. **ISRM,** (1985). International Society of Rock Mechanics Commission on Testing Methods. Suggested Method for Determining Point Load Strength, Int. J. Rock Mech. Min. Sci. and Geomech. Abstr. *22*:51-60.

9. **Larkin, B.,** (2000). Validating and Using Downhole Geophysical Logs to Determine Geotechnical Characteristics. Proceedings of the Geological Society of Australia Bowen Basin Symposium. Rockhampton, QLD, pp. 443-451.

10. **McNally, G.H.,** (1987). Geotechnical Applications and Interpretation of Downhole Geophysical Logs. ACIRL Coal Research Report 87-7, November, p. 62. ISBN 0 86772 329 7.

11. **McNally, G.H.,** (1990). The Prediction of Geotechnical Rock Properties from Sonic and Neutron Logs. Exploration Geophysics *21*:65-71.

12. **Medhurst, T. and Hatherly, P.,** (2005). Geotechnical Strata Characterisation Using Geophysical Borehole Logs. Proceedings of the 24th International Ground Control in Mining Conference, Morgantown, WV, pp. 179-186.

13. **Payne, D.,** (2008). Crinum Mine, 15 Longwalls 40 Million Tonnes 45 Roof Falls- What Did We Learn? Proceedings of the 8th Underground Coal Operators’ Conference, Wollongong, NSW, Australia, pp. 22-43.

14. **Rusnak, J.A., and Mark, C.,** (2000). Using the Point Load Test to Determine the Uniaxial Compressive Strength of Coal Measure Rock. Proceedings of the 19th International Ground Control in Mining Conference, Morgantown, WV, pp. 362-371.

15. **Schlumberger Log Interpretation Principles/ Applications,** (1991).

16. **Ward, B and Riley, M.,** (2000). The Geotechnical and Hydrogeological Setting for the Kilburne Prospect, Callide Coal Basin. Proceedings of the Geological Society of Australia Bowen Basin Symposium. Rockhampton, QLD, pp. 115-124.