COMPARATIVE ANALYSIS OF MOISTURE SENSITIVITY INDEX TESTS FOR COAL MINE ROOF

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ABSTRACT

Moisture deterioration of clay-rich roof rocks causes high numbers of roof falls in coal mines in humid summer months. Rocks with high moisture content are generally weaker and can further deteriorate when subjected to wetting and drying cycles. As a result, it is important to evaluate the moisture-sensitivity of roof rock prior to mining. The National Institute for Occupational Safety and Health (NIOSH) has evaluated three moisture-sensitivity index tests on roof rocks from 23 U.S. coal mines. The three tests were the University of Kentucky Weatherability test (*Weatherability* test), the Consol Energy Water Sensitivity test (*Water Sensitivity* test), and the NIOSH Immersion test (*Immersion* test). Of these three tests, the *Weatherability* and *Water Sensitivity* tests are more reliable in classifying the moisture-sensitivity of roof rocks.

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.

INTRODUCTION

During the past 5 years, over 2,200 U.S. coal miners have been injured by rock falls. Despite reductions in the rate of occurrence, the number of injuries remains at over 400 annually. There have also been 82 ground fall fatalities since 1995, and of these, 15 have been attributed to skin failure (Mark and Pappas, 2009). Skin failures involve rocks that fall between roof supports. The reasons for roof skin failures include weak bedding planes, slickensided surfaces, and moisture-deterioration of mudstones (Molinda et al., 2008, Molinda and Klemetti, 2008). This report addresses the moisture-deterioration of clay-rich roof rocks.

Coal-forming environments are usually near sea level and resemble modern day coastal and flat-lying locales. As such, quiet water deposition often prevails, resulting in predominantly clay-rich mudrocks which form the roof of coal mines. Some of these rocks are highly reactive to moisture and can deteriorate with exposure, resulting in poor roof conditions and roof falls. A large body of evidence exists detailing the hazardous effects of moisture on clay-rich mudrocks (Molinda, et al., 2006, Molinda and Klemetti, 2008). An extensive literature review can be found in Molinda, et al. (2006) giving detailed information on the following concepts. It is well known that during humid summer months roof fall rates increase. In addition, roof swelling and damage has been measured with instrumentation. As a result, mine operators have successfully responded with high coverage skin controls, including roof screen and spray-on sealants.

For mine planning and support design, it is critical to conduct an accurate assessment of the moisture-sensitivity of roof rocks in both the exploration and mining phases. Laboratory testing of core samples can provide the first evaluation of the future roof integrity. Tests for rock moisture-sensitivity can range from simple immersion to slake durability to strain-gaging rock samples in highly controlled humidity chambers. Individual tests have benefits and disadvantages related to cost, difficulty, and accuracy in correctly simulating the mining environment.

The purpose of this research is to evaluate three commonly used moisture-sensitivity tests for similarities and differences in determining the relative deterioration of roof rock samples. The three tests evaluated are the *Immersion* test as modified by Molinda and Mark (1994) from Sickler's Submersion test (Sickler, 1986), the *Weatherability* test proposed by Unrug (1997), and the *Water Sensitivity* test, a modified slake durability test proposed by Hasenfus and Su (2005).

MOISTURE SENSITIVITY TESTING

Samples of roof rock were collected from coal mines throughout the U.S. The moisture reactivity of these samples was tested using the three tests mentioned previously. The results from each test will be compared along with their advantages and disadvantages.

The three tests require approximately the same preparation and sample size, thus for this study the same procedures were used for collecting and preparing the samples for all test procedures. The majority of samples for this research were taken from roof slabs collected underground, but in two cases exploration cores were used. The slabs and exploration cores were collected from within the primary support horizon of the mine roof. A number of mines had several samples collected throughout the mine to represent variable roof geology.

All the specimens from the roof slabs were prepared by breaking, cutting, or coring the collected samples. All test procedures allowed all three methods of specimen preparation. The exploration cores were cut into approximately 2-in specimens. The specimens were weighed to ensure that they fell within the specifications of each specific test procedure. The specimens were then tested using one of the three test methods. The specimen results were averaged to give a sample result for each test.

The *Immersion* test was performed on specimens from 43 samples from 17 mines. The *Weatherability* test was conducted on specimens from 50 samples from 24 mines. The *Water Sensitivity* test was performed on specimens from 31 samples from 18 mines. The results of the tests using these samples are presented. The samples with all three test results were then compared to determine which they indicates the likelihood of moisture deterioration. Additionally, the tests are compared with one another when both tests are performed on the splits from the same sample. The following account is a description of each of the test procedures.

The Immersion Test

The *Immersion* test (Molinda and Mark, 1994) is the simplest and most straight forward of the three tests. It is a more qualitative than quantitative test, leading to more variation of results due to human interpretation. As shown in figure 1, the *Immersion* test only requires fist-sized specimens, beakers, and water. The *Immersion* test procedure is as follows:

1. Select sample(s) - ~ hand sized.
2. Test for hand breakability.
3. Rinse specimen (to remove surface dirt, dust, etc.).
4. Immerse in water for 24 hours.
5. Observe and rate water appearance, talus formation, and cracking of the sample.
6. Sum rating for Immersion Index.
7. Retest for hand breakability.
8. Determine the Breakability Index.

9. The final Immersion Test Index is the greater of the Breakability Index or the Immersion Index.

The final Immersion Test Index is a value between 0 and 15. A detailed description of the Immersion test indices and procedures can be found in Mark et al. (2002).

Figure 1. Immersion test showing specimen deterioration and original sample.

The Weatherability Test

The *Weatherability* test is a three part test, requiring specimens either from cores or roof slabs weighing between 500 and 2,000 grams (Unrug, 1997). This test is more quantitative than the Immersion test and requires more time and equipment to perform. This test requires a special testing apparatus, consisting of a tank with grates on the bottom to lift the samples off the floor of the tank and a fan, as shown in figure 2. A programmable data logger is used to control the wetting and drying cycles. A schematic of the testing apparatus can be found in earlier works of Unrug (1997). This apparatus allows for the specimens to be subjected to cyclic immersion and drying. This wetting and drying cycle simulates the seasonal wetting and drying that attacks the coal mine roof. The *Weatherability* test procedure is as follows:

1. Oven-dry (70-80 degrees Celsius) specimens to constant weight (i.e. no longer losing moisture and record weight.
2. Place samples in apparatus, label, and photograph.
3. Soak samples for 1 hour.
4. Air dry samples for 6 hours.
5. Repeat steps 3 and 4 for a total of 3 cycles.
6. Take photographs for comparison.
7. Oven dry specimens to constant weight and record weight of the largest intact fragment.

Figure 2. University of Kentucky Weatherability test setup.

This *Weatherability* test procedure was modified slightly. The initial drying period was removed due to the limited impact on the overall result while reducing the time required to complete the test. Secondly, the specimen size requirements were relaxed to include specimens as small as 100 grams, while aiming for 500 gram specimens. This size reduction did not appear to impact the results of the test and allowed for a larger number of samples to be tested.

The resulting Weatherability Index is a ratio of the degraded material, based on the largest remaining intact fragment's weight, to the initial specimen's weight. The Weatherability Index is calculated as follows:

$$\mathrm{WAI} = \frac{\mathrm{W_{ini}} - \mathrm{W_{rem}}}{\mathrm{W_{ini}}} \times 100 \qquad (1)$$

Where:

WAI = Weatherability Index, %

W_{ini} = Initial weight of specimen, grams, and

W_{rem} = Weight of the largest remaining fragment of a specimen, grams

The Water Sensitivity Test

The *Water Sensitivity* test involves more time, physical handling and mechanical manipulation than the two other tests used in this study, but the equipment is simple. This test requires the use of two sieve sizes, a 19-mm and a 2-mm. This test is also quantitative in nature (Hasenfus, 2005). The selection of specimens is similar to the other tests in that specimens are fist-sized, weighing 300-500 grams. The *Water Sensitivity* test procedure is as follows:

1. Weigh specimens.
2. Oven dry specimens (100-105 degrees Celsius) for 24 to 48 hours.
3. Weigh specimens (W_d).
4. Immerse in water for 24 to 48 hours.
5. Wet sieve (stacked sieves +19-mm and +2-mm) and retain +19-mm and +2-mm portions as shown in figure 3.
6. Oven dry (100-105 degrees Celsius) separate +19-mm and +2-mm portions 24 to 48 hours.
7. Weigh remnant sample portions separately (W_{19} and W_2).

Figure 3. Wet sieving of the sample during the Consol Energy Water Sensitivity test procedure.

The resulting Water Sensitivity indices are ratios of the weight of the material that passes each screen to the initial weight as determined via the remnant weights. The water sensitivity indices are calculated as follows:

$$\mathrm{WS}_{19} = 100 \times (\mathrm{W_d} - \mathrm{W}_{19}) / \mathrm{W_d} \quad (19\text{ - mm index}) \qquad (2)$$

$$WS_2 = 100 \times (W_d - W_2)/W_d \quad (2\text{-mm index}) \qquad (3)$$

Where:

WS_{19} = water sensitivity index for 19 – mm screen,
WS_2 = water sensitivity index for 2 – mm screen,
W_d = initial dry weight of specimen,
W_{19} = weight of remaining fragments on 19 – mm screen, and
W_2 = weight of remaining fragments on 2 – mm screen.

Moisture Sensitivity Test Results

The moisture sensitivity results are presented in three ways: (1) individual test procedure results, (2) compilation of all test procedure results, and (3) comparative analysis of test procedure results. Average results for all the specimens from the same sample tested are reported in all cases. As an example, one roof slab from a coal mine would be drilled to produce 10 specimens. The moisture sensitivity values for each of the specimens were averaged and reported as the sample moisture sensitivity. The samples were collected and prepared as discussed previously. Only those samples that were tested in all procedures are included for comparison purposes. The first assessment is a distribution of the results from each test separately. The *Weatherability* test, then the *Water Sensitivity* test, and finally the *Immersion* test results are presented.

The distribution of average sample test results for the *Weatherability* test can be seen in figure 4. A total of 50 samples were tested. According to Molinda et al. (2006), rocks are moderately to highly sensitive to moisture if the index for this test is above 40%. There were 17 samples (34 %) that tested on average above 40%, which designates moderate to high moisture sensitivity as designated by the redline in figure 4.

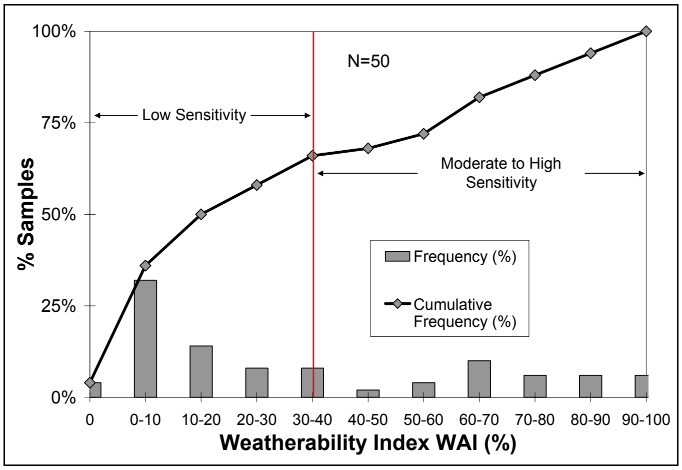

Figure 4. University of Kentucky Weatherability test results.

The *Water Sensitivity* results can be seen in figure 5. A total of 31 samples were tested. The WS_{19} index was used since it is the primary measure of moisture sensitivity. The WS_2 index provides additional indication of the clay content in the sample. The test procedure indicates a moderate level of water sensitivity when the WS_{19} index falls above 25% and a high level of water sensitivity above 58%. The red lines in figure 5 indicate these partitions. A total of 11 samples (35% of the total samples tested) were in the moderate to severe range.

The results from the Immersion test are shown in figure 6. A total of 43 samples were tested. There are two lines on the chart representing different moisture sensitivity levels. The first red line at a Total Immersion Index of 5 represents moderate sensitivity and the second red line at a Total Immersion Index of 9 represents high sensitivity to moisture (Mark et al., 2002). This test resulted in 47 % samples in the moderate sensitivity range and 14% in the high sensitivity range.

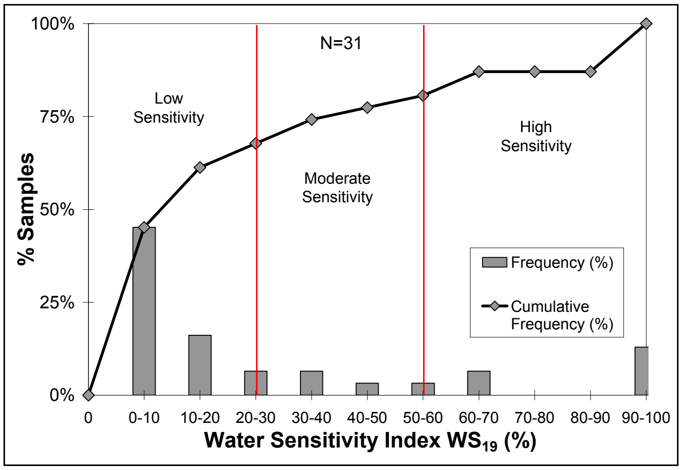

Figure 5. Consol Energy Water Sensitivity test results.

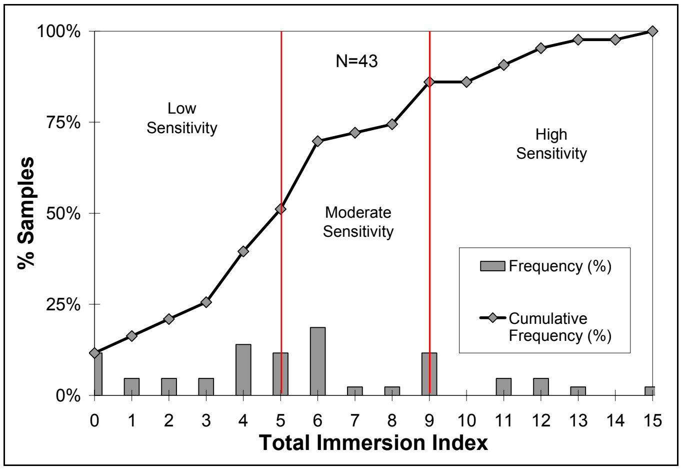

Figure 6. Immersion test results.

The results of each of the three tests show the wide variation of moisture sensitivity that can be found throughout coal mines across the country. A compilation of the results from all three test methods is presented next. It only includes the samples which were tested using all three test procedures. In this way, the results of the three tests on splits of the same sample can be compared side by side.

The sample results (N=22) shown in figure 7 are the average of all specimens from the same sample tested using all three test procedures. Some results represent multiple roof samples from the same mine. The results for the Immersion test in figure 7 have been multiplied by a factor of 6.67 to adjust the rating scale to 0-100 to match the other two tests. In general, each test showed similar sensitivity to moisture for a given sample. In only 2 of the 22 samples, the resulting moisture sensitivities were off by 2 or more categories. In 6 of the 22 samples, the moisture sensitivity fell in the same category. Overall, the three tests showed similar results when the moisture sensitivity was either extremely high or low. In 14 of the 22 samples, the *Immersion* test recorded the highest sensitivity to moisture when compared to the results from the other two test procedures. When the results fell in the moderate range, the *Immersion* test typically showed greater deterioration of the roof rock samples. This indicates that the *Immersion* test can overestimate the moisture deterioration in a specimen.

Figures 8-10 compare the test results from each test method against each of the other test methods. Only the samples which were tested using both methods are presented in these three figures. In each figure, there are two intersecting lines which partition the moderate to high moisture sensitivity values for each test, according to test procedures. The samples which resulted in low moisture sensitivity indexes for both tests can be found in the lower left corner. This indicates agreement between the 2 tests. The samples which resulted in moderate to high moisture sensitivity indexes for both tests can be found in the upper right corner. This also indicates agreement between the tests. The remaining samples had conflicting test results.

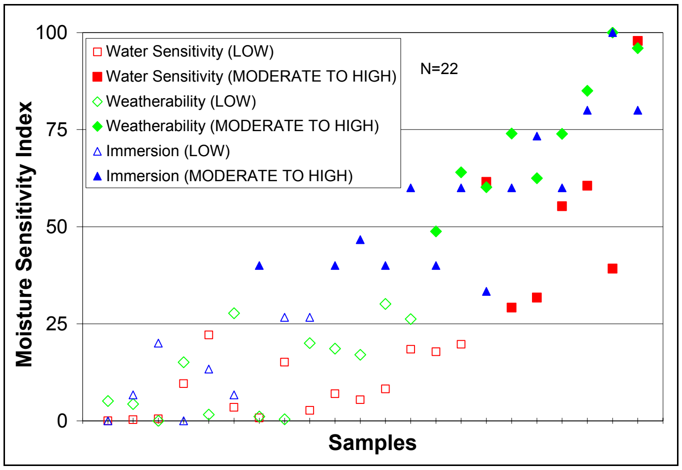

Figure 7. Compilation of the three moisture sensitivity test results:; the Weatherability test, the Water Sensitivity test, and the Immersion test conducted from splits of the same sample are presented.

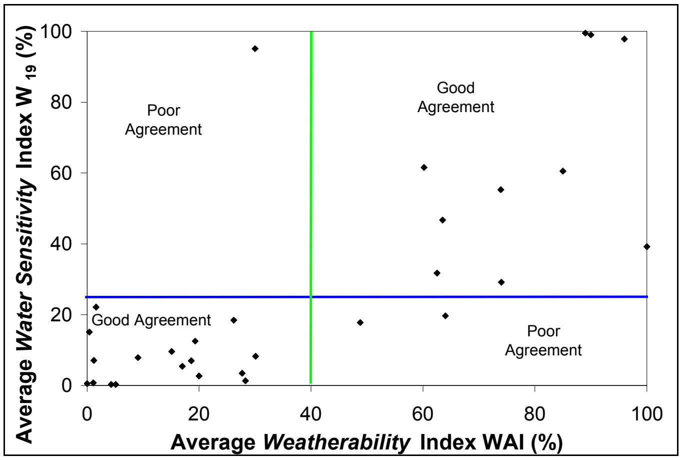

Figure 8. Comparison of moisture sensitivity results from the Water Sensitivity test and the Weatherability test conducted on splits from the same sample.

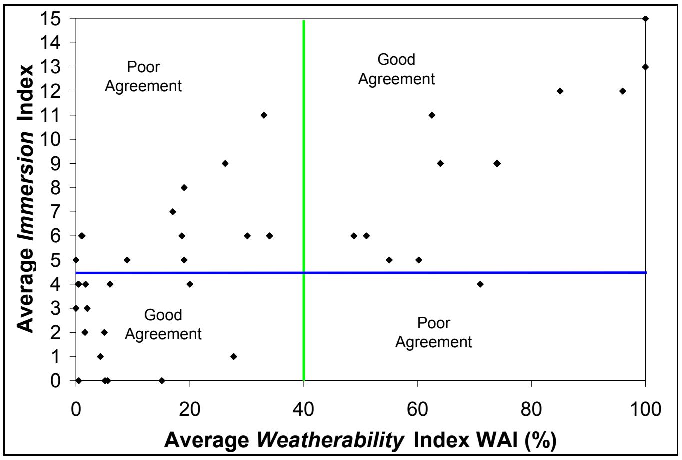

Figure 9. Comparison of moisture sensitivity results from the Immersion test and the Weatherability test conducted on splits from the same sample.

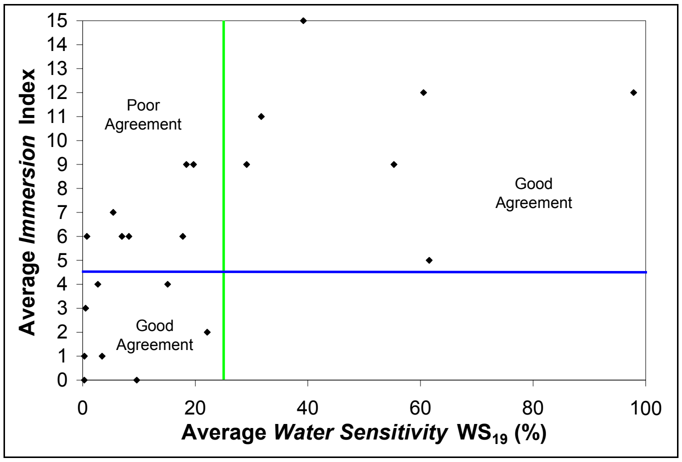

Figure 10. Comparison of moisture sensitivity results from the Immersion test and the Water Sensitivity test conducted on splits from the same sample.

The first is a comparison between the *Water Sensitivity* test and the *Weatherability* test (figure 8). This plot shows a good correlation between the moisture sensitivity measures from the two tests. Three samples (10%) produced conflicting moisture sensitivities and 27 samples (90%) showed similar moisture sensitivity with 17 (57%) having low moisture sensitivity and 10 (33%) moderate to high moisture sensitive. This agreement indicates that these two tests provide similar results.

Figure 9 compares the *Immersion* test and the *Weatherability* test. The comparison shows fewer samples with the same results and substantially more conflicting results (13 or 33%). There were 15 samples (39%) showing low moisture sensitivity in both tests and 11 samples (28%) showing moderate to high moisture sensitivities. These two tests rarely produced consistent test results for a single sample. These results indicate that there is a higher risk of overestimating the moisture sensitivity when using the *Immersion* test, as compared to the *Weatherability* test. The variation is likely due to the subjective observations required by the *Immersion* test.

The third figure compares the *Immersion* test and the *Water Sensitivity* test. Figure 10 shows a similar trend to figure 9 in that given the same sample, the two tests can produce conflicting levels of moisture sensitivity. There were 8 (36%) not sensitive or slightly sensitive to moisture and 7 (32%) moderate to highly sensitive to moisture according to both tests. The *Immersion* test and *Water Sensitivity* test had 7 (32%) conflicting results from the samples tested. Again, the *Immersion* test was more likely to overestimate the moisture sensitivity of roof rock, as compared to the *Water Sensitivity* test. Conflicting results seen could be due to the mechanical interaction with the samples during the *Water Sensitivity* test, or again, errors in observations made for the *Immersion* test.

The *Weatherability* test and the *Water Sensitivity* test correlate with each other. Thus, either the *Weatherability* test or the *Water Sensitivity* test will produce similar conclusions when assessing the potential moisture deterioration of the roof.

TEST RESULTS FROM SPECIFIC COAL MINES

To evaluate the variability in moisture sensitivity that can be observed within a single rock type at a given mine, the *Weatherability* test was performed on 89 specimens prepared from 11 samples collected from the immediate roof at various locations throughout a mine in central Ohio. The immediate roof rock was a gray silty shale. Figure 11 is a distribution of the results The average of the tests was 49%. While a majority (65%) of the values fall into the moisture-sensitive range (>40%), there are a number of specimens that are not highly reactive to moisture. This extreme variability is due to natural variations in rock composition and is not apparent upon visual inspection. From an exploration standpoint, it is unlikely that enough core samples could be obtained to demonstrate this degree of variability. For this reason, in roof rocks that are highly variable, it is important to sample and test more frequently.

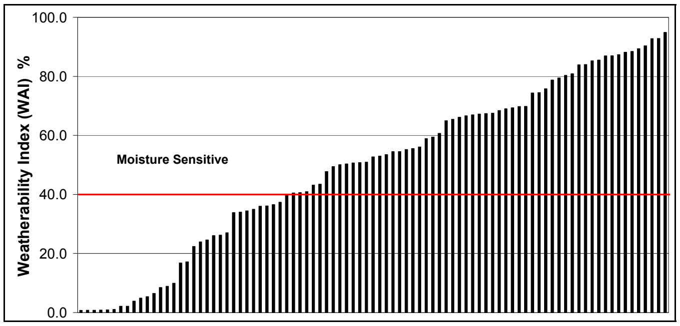

Figure 11. Variability in the moisture sensitivity of roof rock from a central Ohio mine (Samples ranked by Weatherability Index WAI).

CONCLUSIONS

Roof deterioration due to moisture sensitivity continues to cause roof falls and requires extensive entry rehabilitation. Diagnostic testing, both at the exploration phase and during underground mining, would provide data for support design. Three index tests for moisture sensitivity have been evaluated. Of the three tests, the *Weatherability* test and the *Water Sensitivity* test have been shown to provide reasonable agreement in estimating the potential for moisture deterioration of the roof. While still providing a baseline estimate of moisture sensitivity, the *Immersion* test tends to overestimate the likelihood for future deterioration of the roof. One approach would be to perform the *Immersion* test first. If the results show moisture sensitivity, then use one of the other tests.

Depending on the lithologic composition of the rock, significant variability can be present within roof samples from a coal mine, or even a single specimen. Some potential causes of this variability are clay mineralogy, grain size, lamination spacing, and cement. As a result, large numbers of tests are preferred when roof variability is high. For this reason a number of tests of splits from a single roof rock may be required to capture this variability. The *Weatherability* test has the advantage because batch testing of up to 30 samples at a time is possible. The *Water Sensitivity* test can utilize batching of similar sample quantities during the drying and wetting periods, but sieving must be done individually.

If, during the testing regime moisture sensitivity is detected, there are several engineering controls which can aid in the safe recovery of the coal. These controls include screen, sealants, increased support density, leaving top coal, removing moisture sensitive roof rock, narrower entries, shorter panel life, rib meshing, and conditioning the air.

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