NEW DEVELOPMENTS WITH THE COAL MINE ROOF RATING

Christopher Mark, *Chief, Rock Mechanics Section*
Gregory M. Molinda, *Research Geologist*
Timothy M. Barton, *Mining Engineer*
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, Pennsylvania USA

ABSTRACT

The Coal Mine Roof Rating (CMRR) was first presented at this Conference nine years ago. Since its introduction, the CMRR has been incorporated into many aspects of mine planning, including longwall pillar design, roof support selection, feasibility studies, and extended cut evaluation. It has also become truly international, with involvement in mine designs and funded research projects in South Africa, Canada, and Australia.

The purpose of this paper is to bring the mining community up to date with recent improvements and applications of the CMRR. The most important new development is a streamlined process for determining the CMRR from exploratory drill core. Just three types of information are now required:

- Fracture spacing (or RQD)
- Uniaxial compressive strength (or axial Point Load Testing)
- Diametral Point Load Testing

The moisture sensitivity adjustment has also been changed, and new research has related the immersion test to slake durability.

Most recently, the CMRR has been implemented in a computer program, which can be obtained from NIOSH free of charge. The program facilitates calculation of the CMRR from either underground or drillcore data. Values from many locations can be saved in a single file, and an interface with Autocad allows CMRR contour plots to be integrated into mine planning.

INTRODUCTION

Roof falls continue to be the greatest single hazard faced by underground coal miners. One reason is that mines are not built of manmade materials like steel or concrete, but rather of rock, just as nature made it. The structural integrity of a coal mine's roof is greatly affected by natural weaknesses, including bedding planes, fractures, and small faults. The engineering properties of rock cannot be specified in advance, and can vary widely from mine to mine and even within individual mines.

Engineers require quantitative data on the strength of rock masses for design. Traditional geologic reports contain valuable descriptive information but few engineering properties. Laboratory tests, on the other hand, are inadequate because the strength of a small specimen is only indirectly related to the strength of the rock mass.

The Coal Mine Roof Rating (CMRR) was developed nearly 10 years ago to try to fill this gap (1, 2). The CMRR weighs the geotechnical factors that contribute to roof competence, and combines them on single rating scale of zero to 100. The CMRR integrates years of research into geologic hazards in coal mining with the worldwide experience with rock mass classification systems. To verify the procedure, field data were collected from nearly 100 mines in every major coalfield in the U.S.

The CMRR makes it possible to compare ground control experience from different coalfields, even when the geological conditions are very different. This has allowed the collection of large case history databases, which have been the basis of design procedures to solve a wide variety of ground control problems.

Two recent developments should facilitate the integration of the CMRR into geologic exploration and mine design:

- The procedures for collecting CMRR data from drill core have been greatly simplified, and;
- A computer program that speeds calculation and interfaces with mine mapping software is now available.

MODIFIED PROCEDURES FOR DRILL CORE

The CMRR can be determined from underground exposures such as roof falls and overcasts, or from exploratory drill core. In either case, the main parameters measured are:

- The *uniaxial compressive strength* (UCS) of the intact rock;
- The *intensity (spacing and persistence) of discontinuities* such as bedding planes and slickensides;
- The *shear strength (cohesion and roughness) of discontinuities,* and;
- The *moisture sensitivity* of the rock.

The CMRR is calculated in a two-step process. First, the mine roof is divided into lithologic/structural units, and Unit Ratings are determined for each. Then the CMRR is determined by combining the Unit Ratings and applying appropriate adjustment factors. The second step is the same regardless of whether the Unit Ratings were from data collected underground or from core.

The procedures for gathering data and calculating the CMRR from underground exposures have remained essentially unchanged since they were first proposed in 1993. Procedures to determine Unit Ratings from drill core were originally presented by Mark and Molinda in 1996. These have now been streamlined and updated based on recent research.

The new drill core equation is:

Unit Rating = UCS Rating + Discontinuity Rating.

Where:

- The UCS may be determined either by traditional laboratory tests or from Axial Point Load Tests, and;
- The Discontinuity Rating is the **lower** of the *Diametral PLT Rating* or the *Discontinuity Spacing Rating*.

Unconfined Compressive Strength Rating

Laboratory testing is generally considered the standard method of determining the UCS. Unfortunately, laboratory tests are expensive because the samples must be carefully prepared. The variability in the results is also high, with the standard deviation typically about one-third of the mean for coal measure rocks (3).

As an alternative, the CMRR recommends the Point Load Test (PLT) for drill core. The PLT has been accepted in geotechnical practice for nearly 30 years (4). An advantage of the PLT is that numerous tests can be performed, because the procedures are simple and inexpensive because minimal sample preparation is required. The apparatus is also inexpensive and portable. The International Society for Rock Mechanics (5) has developed standard procedures for testing and data reduction.

Another advantage of the PLT is that both *diametral* and *axial* tests can be performed on core. In a diametral test, the load is applied parallel to bedding (figure 1). The diametral test is therefore an indirect measure of the lateral strength, or bedding plane shear strength.

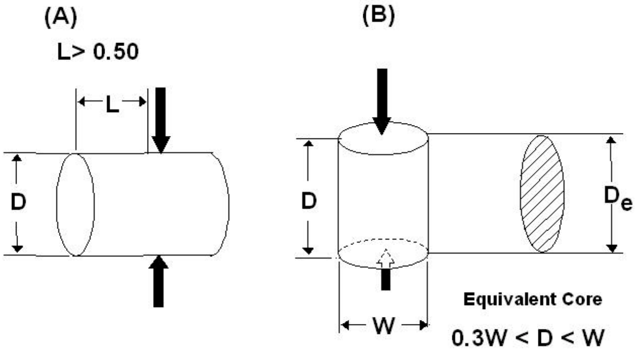

Figure 1. Diametral and Axial Point Load Tests.

The axial PLT is used to measure the UCS. The Point Load Index (Is_{50}) is converted to UCS by the following equation:

$$UCS = K\,(Is_{50}) \qquad (1)$$

Where K is the Conversion Factor. Mark and Molinda (6) originally adopted the K values proposed by Vallejo (7) for the CMRR, which were K=12.5 for clay-rich rocks, and K=17.4 for silty and sandy rocks. Vallejo's study involved a relatively small sample base, however.

To better determine the appropriate value of K for use in the CMRR, a comprehensive study involving more than 10,000 tests of coal measure rocks from 6 states was conducted (6). The study found that K=21 worked for the entire range of rock types and geographic regions (figure 2). The study also found that the variability of the PLT measurements, as measured by the standard deviation, was no greater than for UCS tests.

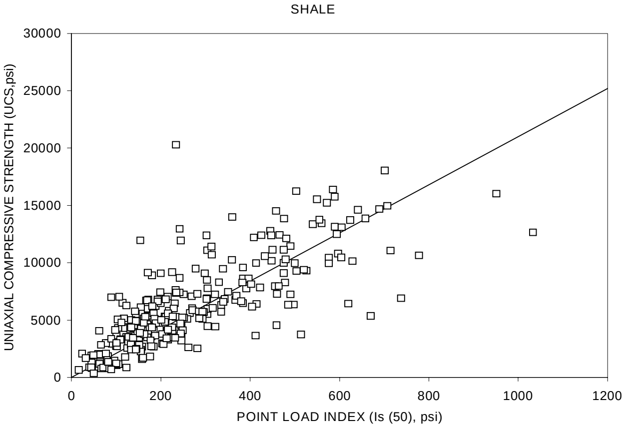

Figure 2. Relationship between Axial PLT and UCS tests for shale (3).

Figure 3 shows the UCS/Axial PLT rating scale used in the CMRR program.

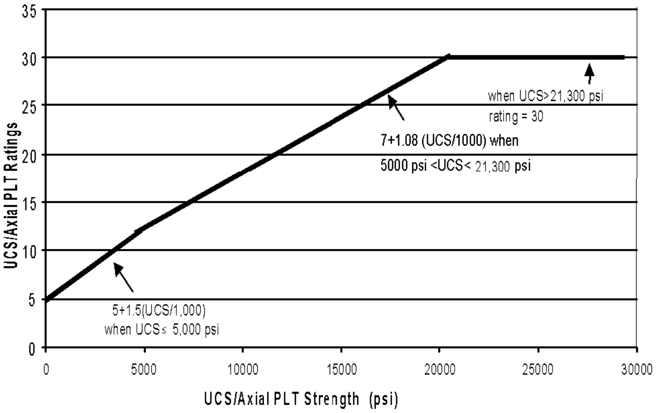

Figure 3. CMRR rating scale for Axial Point Load or UCS tests.

Discontinuity Spacing Rating

Most standard geotechnical core logging procedures include some measure of the natural breaks in the core. The two most commonly employed are the *fracture spacing* and the *RQD*. Fracture spacing is easily determined by counting the core breaks in a particular unit, and then dividing by the thickness of the unit. The RQD is obtained by dividing combined length of core pieces that are greater than four inches in length by the full length of the core run.

Both measures have their advocates in the geotechnical community. Priest and Hudson (8) suggested that the two can be related by the following formula:

$$RQD = 100\, e^{-0.1L}\,(0.1L+1) \qquad (2)$$

Where L=number of discontinuities per meter.

As input, the CMRR uses both the RQD and the fracture spacing. When the fracture spacing is greater than about 1 ft, the RQD is not very sensitive, so the fracture spacing is used directly. At the other extreme, when the core is highly broken or lost, the RQD appears to be the better measure. Either measure may be used in the intermediate range.

The program uses the following equations to calculate the Discontinuity Spacing Rating (DSR) of core from RQD and the fracture spacing. The equations were derived from the original CMRR rating tables.

$$DSR = 10.5 \ln (RQD) - 11.6 \qquad (3a)$$

or

$$= 5.64 \ln (\text{fracture spacing, inches}) + 24 \qquad (3b)$$

The minimum value of the DSR is 20, and the maximum is 48 (see figure 4).

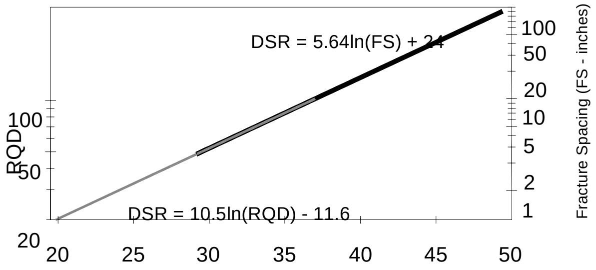

Figure 4. CMRR rating scale for Fracture Spacing or RQD.

Diametral PLT Rating

One problem with both the fracture spacing and the RQD is that they actually measure the strength of discontinuities as well as their spacing. Weak discontinuities may break apart during drilling, while strong ones might withstand the rigors of the drilling process.

The problem is particularly acute with layered rocks such as shales. Such rocks may be recovered intact, with RQD=100, yet their lateral strength may be one-sixth of their axial (6). Since the most severe loading applied to coal mine roof is normally lateral, caused by horizontal stress, bedding plane shear strength is a critical parameter.

Unfortunately, bedding plane shear strength is almost never tested directly in the US. The diametral PLT is a convenient index test that may be used as a substitute. Because the precise relationship between bedding plane shear strength and the PLT is not known, and since it seems unlikely that the same K-factor used to convert the axial test to the UCS would apply, the new CMRR uses the Point Load Index (IS_{50}) directly. The Diametral PLT rating values were derived from the original CMRR tables and the data presented by Mark and Molinda (6), and are shown in figure 5.

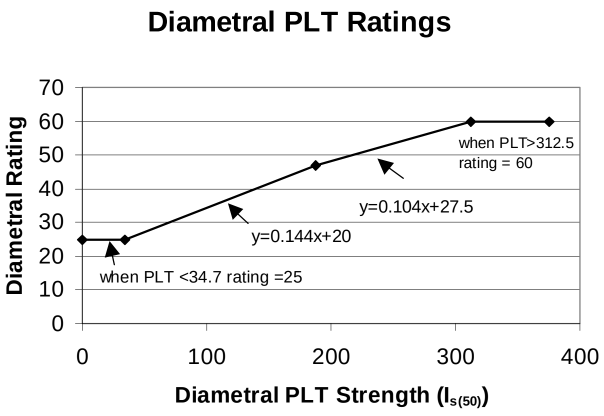

Figure 5. CMRR rating scale for Diametral Point Load tests.

If the diametral test results show that the rock fabric or laminations are low strength, it would be illogical to give the rock high marks for discontinuity spacing. Therefore, the **Discontinuity Rating** is the **lower** of the Diametral PLT Rating or the Discontinuity Spacing Rating.

The Unit Rating is simply the Discontinuity Rating plus the UCS Rating.

OTHER MODIFICATIONS TO THE CMRR

Moisture Sensitivity Deduction

Moisture sensitivity can affect roof stability in several ways. The rock itself may be weakened, or may slake or slough. In extreme cases, rock may disintegrate completely and turn to mud when exposed to groundwater. Clay minerals can also expand, causing swelling pressures in the roof.

In the original CMRR, the maximum deduction for moisture sensitivity was 25 points. In practice, this deduction proved to be too large. The new maximum deduction is 15 points. An adjusted Immersion Test data sheet is shown in figure 6. The moisture sensitivity ratings are then determined using table 1. If immersion test results are not available, moisture sensitivity can sometimes be estimated visually in underground exposures.

Table 1. Moisture Sensitivity Ratings

Moisture Sensitivity	Immersion Index	Rating
Not Sensitive	0-1	0
Slightly Sensitive	2-4	-3
Moderately Sensitive	5-9	-7
Severely Sensitive	>9	-15

Note: Apply to Unit Rating only when the roof is damp or water is leaking through the bolted internal.

IMMERSION TEST

Mine ______________________ Date ______________________

Unit No. ____________________ Tester ______________________

Sample Description (Lithology, bedding, etc.):

Immersion

Observation Rating
Rating
Appearance of Water

Clear = 0 ______
Misty = -1
Cloudy = -3

Talus Formation
None = 0
Minor = -1
Major = -3 ______

Cracking of Sample
None = 0
Minor/Random = -1
Major/Preferred Orientation =-3 ______
Specimen Breakdown = -9

Total Immersion Index ______

Breakability

Observation

No Change 0
Small Change-2
Large Change -6

Breakability Index ______

Procedure for Immersion Test

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 1 hour.

Figure 6. Data sheet for the Immersion Test.

Usually, some time is required for contact with humid mine air to affect rock strength. In short-term applications, therefore, it may not be appropriate to apply the moisture sensitivity deduction. The CMRR program now reports both the Unit Rating and the CMRR **with** and **without** the moisture sensitivity deduction.

Relationship Between Immersion and Slake Durability Tests

The CMRR employs the simple immersion test to measure moisture sensitivity. While numerous other tests have been proposed, the closest thing to a standard moisture sensitivity index is probably the Slake Durability Test (SDT). Hoek (4) recommended the SDT as a basic geomechanical test, ISRM standard procedures have been developed for it, and it is an integral part of Bieniawski's Rock Mass Rating (RMR).

The SDT is intended for use in establishing the rate of breakdown in a rock mass in which stability is suspected to vary with time. To perform the test, 10 lumps of rock, each weighing about 0.1 lbs, are oven dried, weighed, and then rotated through a water bath for 10 minutes. The repeated wetting and drying, together with the mild abrasion that takes place during the test, causes moisture sensitive rocks to break down. The slake durability index is the final dry weight of the sample expressed as a percentage of the original dry weight (4).

Research was conducted to explore the relationship between the SDT and the immersion test. Rock samples were collected underground from a variety of mine settings, carefully wrapped to maintain in situ moisture content, and tested in the laboratory. A total of 96 tests were run on 16 distinct rock types from 9 mines.

The results are shown in Figure 7. Table 2 indicates how the results from either test can be used for input to the CMRR:

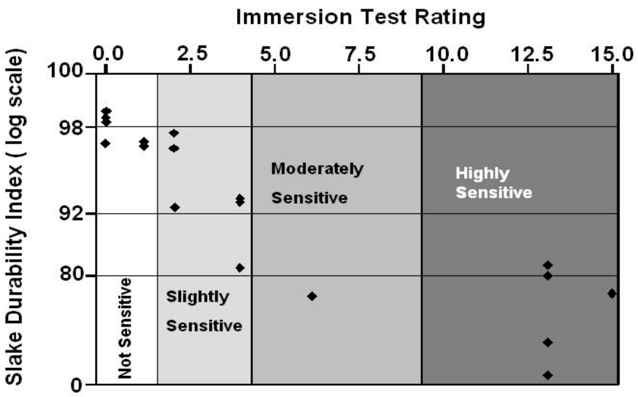

Figure 7. Comparison of the Slake Durability and Immersion Tests.

Table 2. Moisture Sensitivity Classes from Immersion and Slake Durability Tests

Moisture Sensitivity Class	Immersion Index	Slake Durability Index
Not Sensitive	0-1	100-98
Slightly Sensitive	2-4	98-92
Moderately Sensitive	5-9	92-80
Severely Sensitive	>9	<80

From the testing conducted to date, there is a good correlation between the two tests for the Not Sensitive and Slightly Sensitive classes. The correlation is less reliable for distinguishing “moderately sensitive” rocks from “severely sensitive” rocks.

Relationship Between Ball Peen Hammer Test and the UCS/Axial PLT

The Ball Peen Hammer Test, originally proposed by Williamson (9), has been the CMRR standard test for underground data collection. Mark and Molinda (4) compared results for both tests, and found a good correlation. In that comparison, however, the PLT results were converted to UCS using the Vallejo conversion factors.

Figure 8 shows the comparison between the two tests, using an expanded data set and converting the PLT data to UCS with K=21. In 17 of the total of 21 pairs (or 81% of the cases), the difference between the two measurements was 4 points or less. To account for the changed K, the original Williamson rock classes have been slightly adjusted, as shown in table 3:

Table 3. Approximate UCS Ranges from Ball Peen Hammer Tests

Ball Peen Hammer Class	Williamson UCS Range (psi)	CMRR UCS Range (psi)
Molds	<1,000	<2,000
Craters	1,000-3,000	2,000-5,000
Dents	3,000-8,000	5,000-10,000
Pits	8,000-15,000	10,000-17,000
Rebounds	>15,000	>17,000

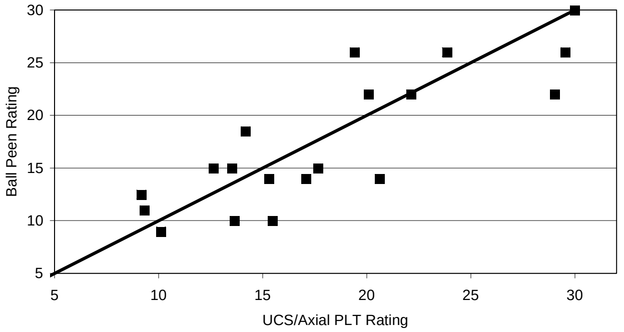

Figure 8. Comparison of Axial Point Load and Ball Peen Tests.

Strong Bed Adjustment

One of the most important concepts in the CMRR is that the strongest bed within the bolted interval often determines the performance of mine roof. The strong bed adjustment (SBADJ) in the CMRR depends upon:

- The Strong Bed Difference (SBD), which is the difference between the strong bed’s Unit Rating and the thickness-weighted average of all the Unit Ratings within the bolted interval;
- The thickness of the strong bed (THSB, ft), and;
- The thickness of the weak rock suspended from the strong bed (THWR, ft).

In the original CMRR, the SBADJ was determined using a table. For improved accuracy and to facilitate implementation of the table in the computer program, equation (4) was derived using multiple regression:

$$\mathrm{SBADJ} = [(0.22\ \mathrm{SBD}*\mathrm{THSB}) - 2.5] * [1 - (0.1\ (\mathrm{THWR} - 1.7))] \quad (4)$$

The SBADJ ranges from 0 up to 90% of the SBD. Other rules that apply are that the maximum THSB that can be entered into the equation is 4 ft, and the allowable range of the THWR is 1.7-8.5 ft. The THSB must also be at least 1 ft, because experience has shown that thinner units cannot be counted on to reinforce the roof, and may actually weaken it because they can concentrate horizontal stress.

THE CMRR COMPUTER PROGRAM

The CMRR program is designed to facilitate the entry, storage, and processing of field data. Either core or underground data can be entered, and calculations are updated instantly when a change is made. This allows the user to vary parameters, such as the bolt length, to see their effect on the final CMRR.

Figure 9 shows the underground data entry screen. Drop-down menus are used to enter the data for each of the parameters. In the core data screen (figure 10), the user has the option of entering PLT test data, and having the program automatically determine the mean UCS and diametral $Is_{(50)}$. Otherwise, the user can enter the mean strength values directly.

An important feature of the new program is a built-in interface with Autocad. Data from up to 200 locations can be entered and saved in a single file, along with their location coordinates. The program can create a file for export that includes both the calculated CMRR values and the locations. A CMRR layer can then be created in Autocad for use in mine planning.

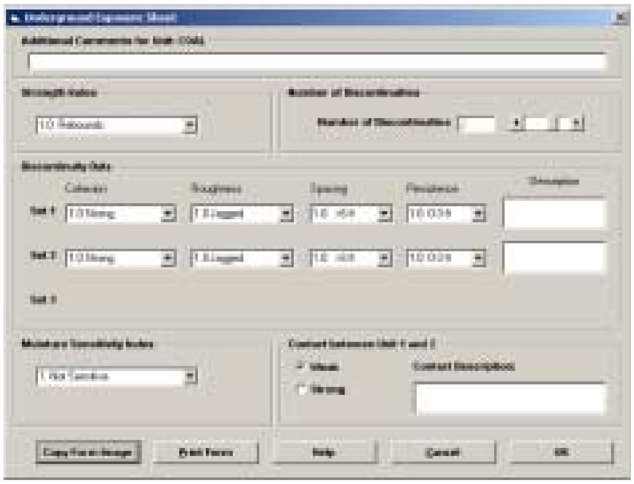

Figure 9. Underground data entry screen from the CMRR Program.

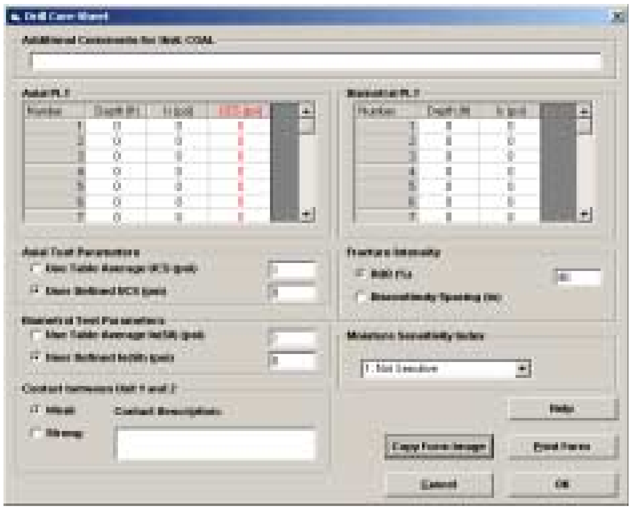

Figure 10. Drill core data screen from the CMRR Program.

RECENT APPLICATIONS OF THE CMRR

During the past 8 years a number of mine planning design tools have been based on the CMRR. The first, and perhaps the best known, was its incorporation into the ALPS pillar design program (10). A large database of longwall case histories was collected from throughout the US, and subjected to statistical analysis. The results showed that when the roof was strong (CMRR>65), longwall chain pillars with an ALPS SF as low as 0.7 could provide satisfactory tailgate conditions. On the other hand, when the roof was weak (CMRR<45), the ALPS SF might need to be as high as 1.3.

Some more recent examples are described below.

Longwall Tailgate Design (Australia)

ALPS was the starting point for an Australian Coal Industry Research Project ACARP) whose goal was to develop an Australian chain pillar design methodology (11). The project aimed to calibrate ALPS for the different geotechnical and mine layouts used in Australia. Ultimately, case history data were collected from 60% of Australian longwall mines.

The study found strong relationships between the CMRR, the tailgate SF, and the installed level of primary support. Design equations were developed that reflected these trends. The final product, called the Analysis of Longwall Tailgate Serviceability (ALTS), was implemented in a computer program and has become widely used in Australia.

Roof Bolt Selection

To help develop scientific guidelines for selecting roof bolt systems, NIOSH conducted a study of roof fall rates at 37 U.S. mines (12, 13). The study evaluated five different roof bolt variables, including length, tension, grout length, capacity, and pattern. Roof spans and the CMRR were also measured. Performance was measured in terms of the number of roof falls that occurred per 10,000 ft of drivage.

The study found that the depth of cover (which correlates with stress) and the roof quality (measured by the Coal Mine Roof Rating (CMRR)) were the most important parameters in determining roof bolting requirements. Intersection span was also critical. The study's findings led to guidelines that can be used to select the proper span, bolt lengths, and bolt capacity based on the CMRR. The results have been implemented into a computer program called Analysis of Roof Bolt Systems (ARBS).

Longwall Mining through Open Entries and Recovery Rooms

Unusual circumstances may require that a longwall retreat into or through a previously driven room. The operation is usually completed successfully, but there have been a number of spectacular failures. To help determine what factors contribute to such failures, an international data base of 131 case histories was compiled (14).

The study found that the CMRR and the density of standing support were the two most important parameters in predicting severe weighting-type failures. These failures only occurred when the CMRR was less than 55, and when the support density was less than 70 psi. When the CMRR was 40 or less, all the successful cases employed a standing support density of at least 145 psi.

Roof Fall Evaluations (South Africa)

The CMRR featured prominently in an important research project sponsored by the Safety in Mine Research Advisory Committee (SIMRAC) and other leading industry, labor, and government organizations in South Africa. The goal of the project was to investigate the causes of fatal roof failures in South African coal mines. A team of recognized experts visited a broad spectrum of mines and collected data at 182 roof fall sites. The study found that roof falls were more likely where the roof was less competent in terms of the CMRR. Another finding was that the CMRR correlated well with roadway widths. Based on data presented by Mark (15), (see figure 11), the study also concluded "in South African coal mines, less support is used for comparable roof conditions than either the USA or Australia. This supports previous conclusions that in South African coal mines, the density of supports needs to be increased" (16).

Another SIMRAC study found the CMRR easy to use and robust enough to adequately describe the roof conditions at most South African collieries (17). It took less than four hours for a trained geologist to become competent with the method. The results seemed more reasonable than those obtained from the RMR, which tended to overrate ground conditions by at least one class (20 points) due to its lack of sensitivity to the characteristics of bedded strata. Some improvements were suggested for the CMRR, including adjustments for joint orientation, blasting, and horizontal stress. A follow-on SIMRAC project is currently underway.

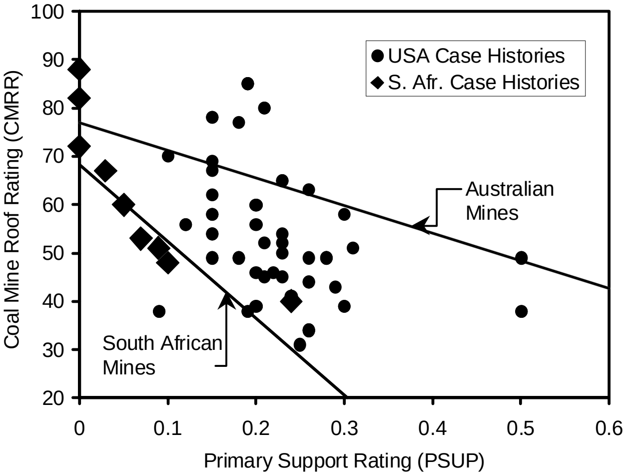

Figure 11. Relationship between the CMRR and roof bolt density in the US, Australia, and South Africa.

Baseline Comparison of Ground Conditions (Canada)

The underground coal industry of Canada is small and geographically dispersed. To assist the mines in maintaining world-class safety standards, CANMET established the Underground Coal Mine Safety Research Consortium. One of the Consortium's first projects was aimed at establishing a "best practice" baseline for conducting geological and geomechanical assessments and applying the findings to geotechnical design.

The CMRR was found to be particularly valuable in the assessment (18). It allowed the Canadian underground mines to be compared with each other and with international benchmarks. Based on the CMRR, many ground control safety technologies developed in the US were found to have direct application to the Canadian mines.

Other Applications

- *Extended cuts* can collapse prematurely in weak roof. Data collected from 36 mines found that when the CMRR was greater than 55, extended cuts were nearly always routine, but when the CMRR was less than 37, they were almost never taken (19).
- *Tailgate support guidelines* incorporating the CMRR have been included in the STOP program (20).
- *Input for numerical models* have been derived from the CMRR (21).
- *Multiple seam mine design guidelines* have been developed that incorporate the CMRR (22).
- *Hazard analysis and mapping* has been based on the CMRR (23).

CONCLUSIONS

Roof geology is central to almost every aspect of ground control. The CMRR makes it possible to quantify roof geology so that it can be included in mine planning decisions. Worldwide experience has shown that the CMRR is a reliable, meaningful, and repeatable measure of roof quality.

A wide variety of design tools that are based on the CMRR have now been developed. They address a broad range of ground control issues, and rely upon large databases of actual mining case histories. Without the CMRR, it would not have been possible to capture this invaluable experience base.

The new core procedures and computer program further expand the potential of the CMRR. It is now possible to routinely collect CMRR data during geologic exploration or from underground mapping, complete the calculations, and integrate the results into mine mapping software. Foreknowledge of conditions means better mine planning and fewer unexpected hazards underground.

REFERENCES

1. Molinda, G. and C. Mark. The Coal Mine Roof Rating (CMRR)–A Practical Rock Mass Classification for Coal Mines. Proceedings, 12th International Conference on Ground Control in Mining, Morgantown, WV, 1993, pp. 92-104.

2. Molinda, G. and C. Mark. The Coal Mine Roof Rating (CMRR)–A Practical Rock Mass Classification for Coal Mines. USBM IC 9387, 1994, 83 pp.

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

4. Hoek, E. Rock Mechanics Laboratory Testing in the Context of a Consulting Engineering Organization. *Int. J. Rock Mech. and Mng. Sci.*, Vol. 22, 1977, pp. 93-101.

5. International Society for Rock Mechanics (ISRM) Commission on Testing Methods. Suggested Method for Determining the Point Load Strength (revised version). *Int. J. Rock Mech. and Mng. Sci.*, Vol. 22, 1985, pp. 51-60.

6. Mark, C. and Molinda, G.M. Rating Coal Mine Roof Strength from Exploratory Drill Core. Proceedings, 15th International Conference on Ground Control, Golden, CO, 1996, pp. 415-428.

7. Vallejo, L.E., Welsh, R.A. and Robinson, M.K. Correlation Between Unconfined Compressive and Point Load Strengths for Appalachian Rocks. Proceedings, 30th U.S. Symposium on Rock Mechanics, 1989, pp. 461-468.

8. Priest, S.D. and Hudson, J.A. Discontinuity Spacings in Rock. Intl. J. Rock Mech. Mng. Sci., Vol 13, 1976, pp. 135-148.

9. Williamson, D. A. United Rock Classification System. Bull. Assoc. Eng. Geol., Vol. 21, No. 3, pp. 345-354.

10. Mark, C., Chase, F. E. and Molinda, G. M. Design of Longwall Gate Entry Systems Using Roof Classification. Paper in New Technology for Longwall Ground Control: Proceedings, USBM Technology Transfer Seminar, USBM SP 94-01, 1994, pp. 5-18.

11 Colwell, M., Frith, R., and Mark C. Calibration of the Analysis of Longwall Pillar Stability (ALPS) for Australian Conditions. Proceedings, 18th International Conference on Ground Control in Mining, Morgantown, WV, 1999, pp. 282-290.

12. Mark, C., Molinda, G.M. and Dolinar, D.R. Analysis of Roof Bolt Systems (ARBS). Proceedings, 20th International Conference on Ground Control in Mining, Morgantown, WV, 2001, pp. 218-225.

13. Molinda, G.M., Mark, C. and Dolinar, D.R. Assessing Coal Mine Roof Stability Through Roof Fall Analysis. Proceedings, New Technology for Coal Mine Roof Support, NIOSH Open Industry Briefing, NIOSH IC 9453, 2000, pp. 53-72.

14. Oyler, D.C., Frith, R., Dolinar, D.R. and Mark, C. International Experience with Longwall Mining into Pre-Driven Rooms. Proceedings 17th International Conference on Ground Control, 1998, pp. 44-53.

15. Mark, C. Ground Control in South African Coal Mines--A U.S. Perspective. Proceedings, 18th International Conference on Ground Control in Mining, Morgantown, WV, 1999, pp. 186-193.

16. Van der Merwe, J.N. In situ Investigation into the Causes of Falls of Roof in South African Collieries. Proceedings, 20th International Conference on Ground Control in Mining, Morgantown, WV, 2001,pp. 105-118.

17. Butcher, R.J. Application of the Coal Mine Roof Rating System in South African Collieries. Proceedings, 20th International Conference on Ground Control in Mining, Morgantown, WV, 2001, pp. 317-321.

18. Forgeron, S., Mark, C. and Forrester, DJ. Standardization of Geological and Geomechanical Assessment at Underground Coal Mines in Canada. CIM Bulletin, July, 2001, pp. 83-90.

19. Mark, C. Application of the Coal Mine Roof Rating (CMRR) to Extended Cuts. *Mining Engineering*, April, 1999, pp. 52-56.

20. Barczak, TM. Optimizing Secondary Roof Support with the NIOSH Support Technology Optimization Program (STOP). Proceedings, New Technology for Coal Mine Roof Support, NIOSH Open Industry Briefing, NIOSH IC 9453, 2000, pp. 151-164.

21. Karabin, G.J. and Evanto, M.A. Experience with the Boundary Element Method of Numerical Modeling to Resolve Complex Ground Control Problems. Proceedings, 2nd International Workshop on Coal Pillar Mechanics and Design, NIOSH IC 9448, 1999, pp. 89-114.

22. Luo, J., Haycocks, C. and Karmis, M. Gate Road Design in Overlying Multiple Seam Mines. SME Preprint 97-107, 1997, 11 pp.

23. Wuest, W., DeMarco, M. J., and Mark, C.. Review of Applications of the Coal Mine Roof Rating (CMRR) for Ground Control Planning and Operations. *Mining Engineering*, July 1996, pp. 49-55.