THE COAL MINE ROOF RATING IN MINING ENGINEERING PRACTICE

Christopher Mark[1] and Gregory M. Molinda [1]

ABSTRACT: The Coal Mine Roof Rating (CMRR) system was developed ten years ago to fill the gap between geologic characterization and engineering design. It combines many years of geologic studies in underground coal mines and worldwide experience with rock mass classification systems. Like other classification systems, the CMRR begins with the premise that the structural competence of mine roof rock is determined primarily by the discontinuities that weaken the rock fabric. Since its introduction, 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. Most recently, a new streamlined process to determine the CMRR from exploratory drill cores has been developed. Just three types of information are now required:

- Fracture spacing Rock Quality Designation (RQD) from a standard geotechnical drill log
- Uniaxial compressive strength from standard lab tests, geophysical downhole logging, or axial point load tests, and;
- Diametral point load testing.

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

Ground 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 the roof of a coal mine is greatly affected by natural weaknesses, including bedding planes, fractures, and small faults. The engineering properties of rock cannot be fully specified in advance, and varies widely from mine to mine and even within individual mines. Moreover, traditional geologic reports contain valuable descriptive information but few quantitative engineering properties. Laboratory tests, on the other hand, are often inadequate because the strength of a small specimen is only indirectly related to the strength of the full-scale rock mass.

Accurate characterization of the strength of the ground is just one problem faced by rock engineers. Another is how to analyze the behavior of the ground. A number of approaches are available, depending on the type of ground:

- For *hard rock*, characterized by high stress and brittle failure, *elastic continuum stress analysis;*
- For *jointed rock,* where most failure is along pre-existing discontinuities, *discrete element* and *keyblock* analyses, and;
- For *very soft rock*, characterized by low stress and shear failure, *soil mechanics.*

Unfortunately, most coal mine ground control problems fall in between these convenient extremes. As a result, the behaviour of a coal mine roof tends to be complex and difficult to predict in advance. If the actual mechanics are to be simulated effectively, highly sophisticated models that include a broad range of potential failure modes are necessary. While such models have been developed (Gale and Tarrant, 1997), they require extensive material properties and validation with field measurements. Rock mass classification schemes were developed to address these concerns. The most widely known systems, including Deere's RQD, Bieniawski's RMR, and Barton's Q, have been used extensively throughout the world. Rock mass classifications have the following attributes:

[1] *NIOSH, Pittsburgh Research Laboratory, USA*

- Provide a methodology for characterizing rock mass strength using simple measurements,
- Allow geologic information to be converted into quantitative engineering data,
- Make it possible to compare ground control experiences between sites, even when the geologic conditions are very different.

This last point highlights an extremely powerful application of rock mass classification systems, which is their use in empirical design methods. Empirical designs base themselves upon mine experience, on the real-world successes and failures of actual ground control designs. By collecting a large number of these "case histories" into a single data base, and subjecting them to statistical analysis, reliable and robust guidelines for design can be developed. A key advantage of empirical techniques is that it is not necessary to obtain a complete understanding of the mechanics to arrive at a reasonable solution. Rock mass classifications play an essential role in empirical design because they allow the overwhelming variety of geologic variables to be reduced to a single, meaningful, and repeatable parameter.

The Coal Mine Roof Rating (CMRR) was developed nearly ten years ago because none of the existing rock mass classification systems adequately provided for the layered geology and geologic structures typical of coal mine roof (Molinda and Mark, 1994 and 1994b). The CMRR integrates years of research into geologic hazards in coal mining with worldwide experience using rock mass classification systems. It employs the familiar format of Bieniawski's roof mass rating (RMR), summing the individual ratings to obtain a final CMRR on a zero to 100 scale. It is also designed so that the CMRR/unsupported span/standup time relationship is roughly comparable to one determined for the RMR. To verify the procedure, field data were collected from nearly 100 mines in every major coalfield in the U.S. In recent years, the CMRR has been successfully used to evaluate ground conditions in many coalfields throughout the world.

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

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

DETERMINATION OF CMRR UNIT RATINGS

The CMRR can be determined from underground exposures such as roof falls and overcasts, or from exploratory drill cores. 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 1994. An underground data sheet is shown in figure 1. Further details on the collection and processing of underground data can also be found in the CMRR program Helpfile.

Procedures to determine Unit Ratings from drill core were originally presented by Mark and Molinda (1996). These have now been streamlined and updated based on recent research. Just three types of information are now required:

- Unconfined Compressive Strength
- Fracture spacing
- Diametral Point Load (an index of bedding plane shear strength)

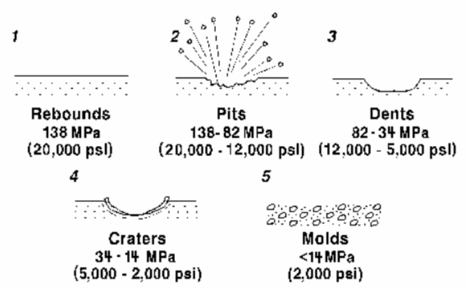
CMRR

DATE__________MINE________________________LOCATION__________________________PAGE_____OF_______ CMRR

TYPE OF EXPOSURE____ NAME

UNIT

Unit No.	Unit Thickness	Strip Log	Description	Strength	Moisture Sensitivity	Disco. I.D.	Description	Cohesion	Roughness	Spacing	Persistence Lateral/Vert
3						A.					
						B.					
						C.					
	CONTACT										
2						A.					
						B.					
						C.					
	CONTACT										
1						A.					
						B.					
						C.					
			1	Rebounds	Not Sensitive		1	Strong (>7)**	Jagged	>1.8 m (6 ft)	0-0.9 m (0-3 ft)
			2	Pits	Slightly Sensitive		2	Moderate (4-7)	Wavy	0.6-1.8 m (2-6 ft)	0.9-3 m (3-10 ft)
			3	Dents	Moderately Sensitive		3	Weak (1-3)	Planar	20-60 cm (8-24 in)	3-9 m (10-30 ft)
			4	Craters	Severely Sensitive		4	Slicken-sided (0)		6-20 cm (2.5-8 in)	>9 m (30 ft)
			5	Molds			5			<6 cm (2.5 in)	



Groundwater (inflow/10 m (33 ft) of entry length) (Circle) L/min (gal/min)				Describe condition in vicinity of fall (circle one)	COMMENTS:
Dry 0	1	Heavy Drip 10-50 (2.7-12.2)	4	1. Good 3. Heavy	
Damp 0-5 (0-1.3)	2	Flowing >50 (13.2)	5	2. Scaly 4. Failed	
Light Drip 5-10 (1.3-2.7)	3				

FIG. 1 - Underground field data sheet.

Unconfined Compressive Strength (UCS) Rating

The UCS can be determined in a number of ways:

- Standard laboratory testing;
- Estimation from Sonic Velocity (V_s) or other geophysical logs, or;
- Estimation from the Point Load Test (PLT) or other index test.

Any of these is acceptable for the CMRR. In the U.S, where laboratory testing is rare and V_s/UCS relationships have not been established, the Point Load Test (PLT) is recommended. The PLT has the advantage that numerous tests can be performed for little cost, because the procedures are simple and minimal sample preparation is required. The apparatus is also inexpensive and portable. The International Society for Rock Mechanics (ISRM) (1985) has developed a standard procedures for testing and data reduction. Another advantage of the PLT is that both *diametral* and *axial* tests can be performed on core.

The axial PLT (figure 2) is used to measure the UCS. The Point Load Index (Is_{50}) is converted to UCS by the following equation:

UCS = K (Is_{50}) Where K is the Conversion Factor. (1)

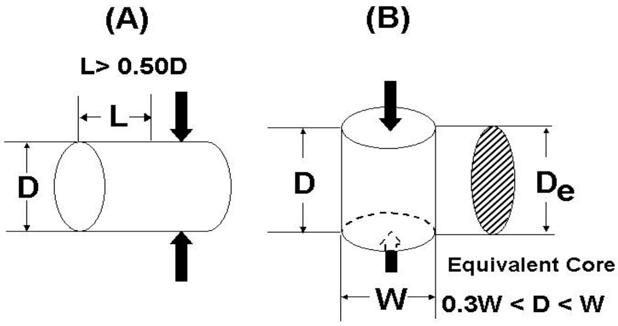


FIG 2 –Diametral and axial point load tests

A comprehensive study involving more than 10,000 tests of coal measure rocks from across the U.S. (Rusnak and Mark, 2000) found that K=21 worked well for the entire range of rock types and geographic regions in the U.S. 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 3 shows the UCS rating scale used in the CMRR program. The rating rises more rapidly when the rock strength is less than 35 MPa, and reaches its maximum value of 30 for rocks stronger than 150 MPa.

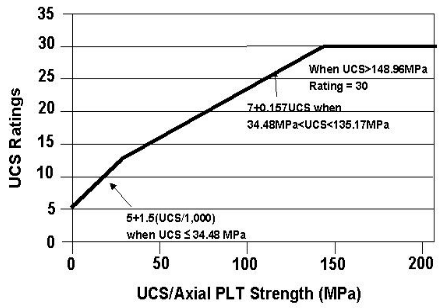


FIG.3- Relationship between axial PLT and UCS tests for shale (Rusnak and Mark, 1999)

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 100 mm in length by the full length of the core run.

Both measures have their advocates in the geotechnical community. Priest and Hudson (1976) suggested that the two can be related by the following formula:

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

Where L=number of discontinuities per metre.

As input, the CMRR uses both the RQD and the fracture spacing. When the fracture spacing is greater than about 0.3 m, 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.

$$DSR = 10.5 \ln (RQD) - 11.6 \text{ or} = 5.64 \ln (\text{fracture spacing (mm)}) + 5.8 \quad (3)$$

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

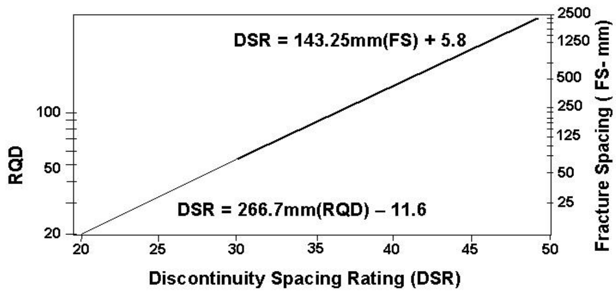


FIG. 4 – CMRR rating scale for axial point load or UCS tests

Diametral PLT Rating

The bedding that is usually present in sedimentary coal measure rocks generally has an important effect on its strength. The problem is particularly acute with soft rocks like shales. Such rocks may be recovered intact, with RQD=100, and may have a respectable UCS, yet their lateral strength may be one-sixth of their axial (Molinda and Mark, 1996). 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 U.S. The diametral PLT is a convenient index test that may be used as a substitute. In a diametral test, the load is applied parallel to bedding (figure 2). 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 (1996), and are shown in Figure 5.

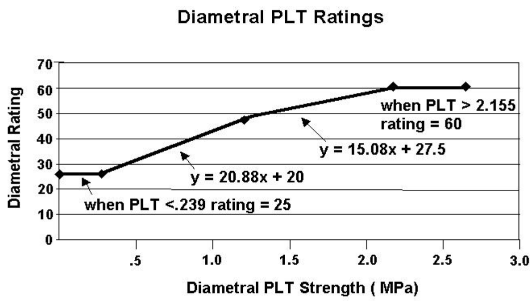


FIG. 5 – CMRR rating scale for fracture sspacing or RQD

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.

The CMRR uses an immersion test to determine moisture sensitivity. A rock specimen is placed in a beaker of water, and given a value of 0 (no effect) to 15 (complete specimen breakdown) depending upon the response. Detailed procedures for conducting immersion tests can be found in the CMRR Helpfile. 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 unit forms the immediate roof or if water is leaking through the bolted interval.

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.

Recently, research was conducted to explore the relationship between the Slake Durability Test (SDT) and the immersion test (Mark et al., 2002). The results are shown in Figure 6. The two tests correlate fairly well, particularly for "not sensitive" and "slightly sensitive" rocks.

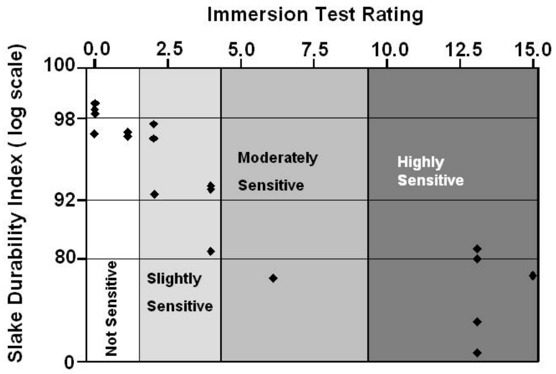


FIG.6 – CMRR rating scale for diametral point load tests

Unit Rating Calculation

An important point is that the fracture spacing (or RQD) is actually a measure of 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. Similarly, 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 CMRR defines the *Discontinuity Rating* as the lower of the Diametral PLT Rating or the Discontinuity Spacing Rating.

The CMRR Unit Rating is simply the Discontinuity Rating plus the UCS Rating, less the Moisture Sensitivity Deduction (when applicable).

DETERMINATION OF THE CMRR

If there is only one rock unit in the roof, then the Unit Rating (plus the Groundwater Adjustment)=CMRR. If there are several units, however, the Unit Ratings must be combined before the adjustments are applied. This is done by determining the "thickness-weighted" average of the Unit Ratings. Only those units that are within the *bolted interval* (up to the height of the bolts) are included in the average.

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 the mine roof. The strong bed adjustment (SBADJ) in the CMRR depends upon:

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

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:

$$SBADJ = [(0.72\ SBD*THSB) - 2.5]\ *\ [1 - (0.33\ (THWR - 0.5))] \tag{4}$$

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 1.2 m, and the allowable range of the THWR is 0.5-2.6 m. The THSB must also be at least 0.3 m, because experience has shown that thinner units cannot be counted on to reinforce the roof.

Other Adjustments

Other adjustments include:

- *Groundwater:* The maximum deduction for a large inflow of groundwater is 10 points. Also, the rock must be at least damp for the moisture sensitivity deduction to be activated.

- *Surcharge:* In most cases, the rock above the bolted interval is approximately the same strength or stronger than the rock within. If the upper rock is weaker, however, it can load the roof beam, and a deduction is made.
- *Number of weak contacts:* Roof failure is often associated with major bedding contacts between rock units. The more of these that are present, the weaker the roof. However, strong or gradational contacts are not considered.

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 7 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 8), 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.

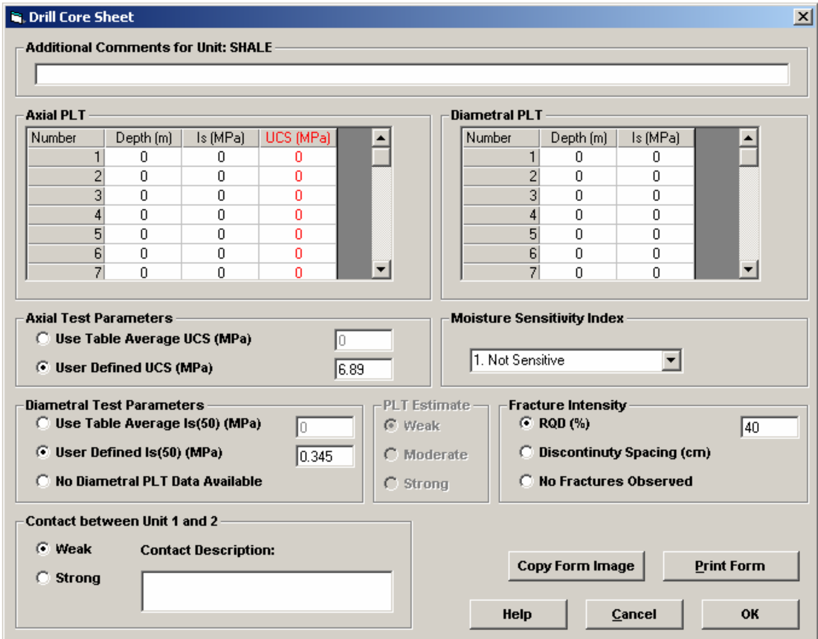


FIG. 7 – Comparison of the slake durability and immersion tests

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.

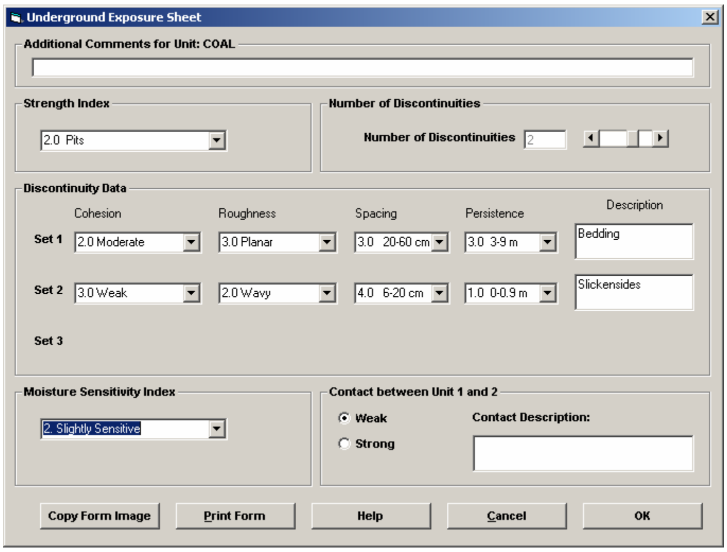


FIG. 8 – underground data entry screen from the CMRR program

RECENT APPLICATIONS OF THE CMRR

During the past eight 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 (Mark et al, 1994). A large database of longwall case histories was collected from throughout the U.S., 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 Safety Factor (SF) might need to be as high as 1.3. It is important to note that while the case histories did not really provide information about whether the pillars were truly "stable" or not, the design guidelines have proved remarkably robust and are very widely used in the U.S. In effect, the statistical approach provided a short cut around the extremely complex mechanics of the interactions between abutment loading, pillar behavior, support response, and entry performance.

Longwall Tailgate Design (Australia)

ALPS was the starting point for an Australian Coal Industry Research Programme (ACARP) project whose goal was to develop an Australian chain pillar design methodology (Colwel, Frith and March, 1999). 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 statistical 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.

Subsequent to the ACARP project, the ALTS case history data base was nearly doubled in size to include virtually all operating Australian longwall mines in year 2000. The final ALTS data base now represents 31 collieries, and extensive statistical analysis resulted in a new design methodology called ALTS II (CGS, 2002). ALTS II can be confidently applied to any Australian longwall where gateroad serviceability is the principle design criterion. It represents a significant leap forward in that chain pillar design and ground support levels (both primary and secondary) can be assessed interactively, rather than independently of one another.

Cut-and-Flit (Extended Cuts)

Cut-and-flit is the standard development method in the U.S. The traditional 6 m cut length was determined by the distance from the cutting head to the operator's compartment. With the advent of remote control continuous miners, "extended cuts" up to 12 m long have become common. However, many mines with extended cut permits only take them when conditions allow. Where the roof is competent, extended cuts are routine. At the other extreme, when the roof is very poor, miners may not be able to complete a traditional 6 m cut before the roof collapses.

To help predict when conditions might be suitable for extended cuts, a study was conducted at thirty six mines throughout the U.S. The study found that when the CMRR was greater than fifty five, extended cuts were nearly always routine, but when the CMRR was less than thirty seven, they were almost never taken (Mark, 1999). The data also showed that extended cuts were less likely to be feasible as the roof span or the depth of cover increased (Figure 9).

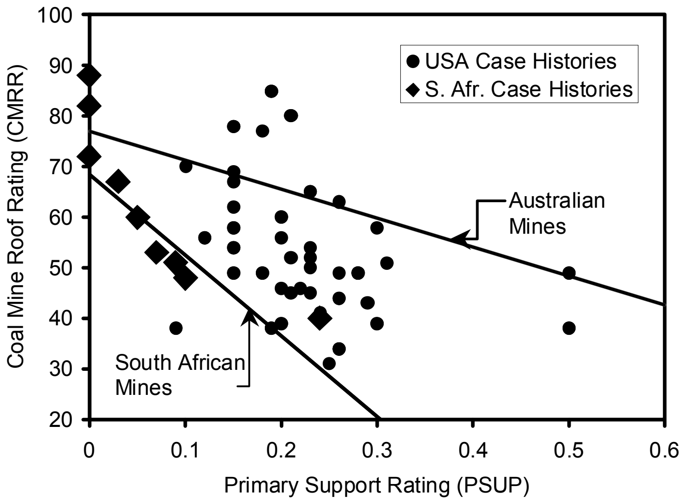


FIG. 9 – Drill core data screen from the CMRR

Roof Bolt Selection

To help develop scientific guidelines for selecting roof bolt systems, NIOSH conducted a study of roof fall rates at thirty seven U.S. mines (Mark et al., 2001; Molinda, Mark and Dolinar, 2000). 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 MSHA-reportable roof falls that occurred per 3000 m of drivage.

The study found that the depth of cover (which correlates with stress) and the roof quality (measured by the 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 appropriate spans, bolt lengths, and bolt capacities 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 (Oyler et al., 1998).

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 fifty five, and when the support density was less than 0.5 MPa. When the CMRR was forty or less, all the successful cases employed a standing support density of at least 1.0 MPa. The study was another example of how the empirical method can result in valuable design guidelines even when the mechanics of the situation are not well understood. In fact, in this instance the empirical analysis clearly pointed to a failure mechanism–overburden shearing in weak rock–that had not been previously identified. In several of the case histories, numerical design techniques had been employed which did not take this mechanism into account, and the results were catastrophic.

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 collected in 10 Australian, 8 South African, and forty U.S. coal mines (Mark, 1998; Mark, 1999) see Figure 10, 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 support needs to be increased" (van der Merwe, 2001).

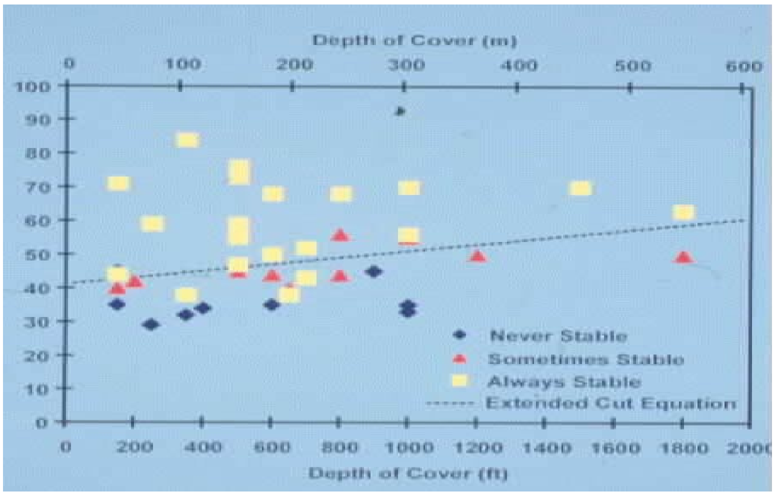


FIG.10 – Relationship between cut depth, CMRR, and depth of cover in U.S. mines

Another SIMRAC study found the CMRR easy to use and robust enough to adequately describe the roof conditions at most South African collieries (Butcher, 2001). 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 (twenty 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.

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 (Forgeron, March & Forrester, 2001). 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 U.S. were found to have direct application to the Canadian mines.

Other Applications

- *Tailgate support guidelines* incorporating the CMRR have been included in the STOP program (Barczak, 2000).
- *Input for numerical models* have been derived from the CMRR (Karabin and Evanto, 1999).
- *Multiple seam mine design guidelines* have been developed that incorporate the CMRR (Luo, Hasycocks and Karmis, 1997).
- *Hazard analysis and mapping* has been based on the CMRR (Wues, DeMario and March, 1996).

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.

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