COAL PILLAR STRENGTH AND PRACTICAL COAL PILLAR DESIGN CONSIDERATIONS

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ABSTRACT

This paper demonstrates that finite-element modeling can be used to predict in situ coal pillar strength, especially under nonideal conditions where interface friction and roof and floor deformation are the primary controlling factors. Despite their differences in approach, empirical, analytical, and numerical pillar design methods have apparently converged on fundamentally similar concepts of coal pillar mechanics. The finite-element model results, however, are not intended to suggest a new pillar design criterion. Rather, they illustrate the site-specific and complex nature of coal pillar design and the value of using modeling procedures to account for such complex site-specific conditions. Because of the site-specific nature of coal pillar design, no single pillar design formula or model can apply in all instances. Understanding and accounting for the site-specific parameters are very important for successful coal pillar design. More work remains before the century-old problems related to pillar design are finally solved. Future research should focus on the cross-linkage of empirical, analytical, and numerical pillar design methods.

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INTRODUCTION

The strength of coal and coal pillars has been the subject of considerable research during the past 40 years. Coal strengths determined in the laboratory typically increase with increasing specimen width-to-height (w/h) ratio and decrease with increasing height and size. Based on the shape and size effect derived from testing of cubical specimens, a number of empirical pillar strength formulas [Gaddy 1956; Holland 1964; Obert and Duvall 1967; Salamon and Munro 1967; Bieniawski 1968] and closed-form analytical solutions for pillar strength [Wilson 1972; Barron 1984] were proposed during the past 4 decades and used by coal operators and regulatory authorities with varying degrees of success. However, empirical formulas may not be extrapolated with confidence beyond the data range from which they were derived, typically from pillars with w/h ratios of #5 [Mark and Iannacchione 1992], and these formulas inherently ignore roof and floor end constraint and subsequent interactions.

The importance of friction and end constraint on laboratory coal strength has been demonstrated by many researchers, including Khair [1968], Brady and Blake [1968], Bieniawski [1981], Salamon and Wagner [1985], Babcock [1990, 1994], and Panek [1994]. Practitioners and researchers alike, including Mark and Bieniawski [1986], Hasenfus and Su [1992], Maleki [1992], and Parker [1993], have noted the significance of roof and floor interactions on in situ pillar strength.

The importance of incorporating fundamental principles of rock material response and failure mechanics into a pillar strength model using a finite-element modeling (FEM) technique has been demonstrated by Su and Hasenfus [1996, 1997]. To accurately assess pillar strength, a model should account not only for the characteristics of the coal, but also for those of the surrounding strata. The frictional end-constraint interaction between the pillar and the surrounding roof and floor has been demonstrated to be one of the most significant factors in the strength of very wide pillars. This paper summarizes the results of a series of FEM cases designed to evaluate the effect on pillar strength of end constraint or confinement over a wide range of pillar w/h ratios, as well as the effects of seam strength, rock partings, and weak floor. The interdependence among pillar design, entry stability, and ventilation efficiency in longwall mining is briefly discussed. Finally, the site-specific nature of coal pillar design is emphasized, and a direction of future research is suggested.

USE OF FINITE-ELEMENT MODELING IN PILLAR DESIGN

In recent years, FEM has been used to predict in situ coal pillar strength, especially under nonideal conditions in which interface friction and roof and floor deformation are the primary controlling factors. Practical coal pillar design considerations that incorporated the results of FEM and field measurements were presented by Su and Hasenfus [1996]. Nonlinear pillar strength curves were first presented to relate pillar strength to w/h ratio under simulated strong mine roof and floor conditions (figure 1). Confinement generated by the frictional effect at coal-rock interfaces was demonstrated to accelerate pillar strength increase beginning at a w/h ratio of about 3. Thereafter, frictional constraint limitations and coal plasticity decelerate pillar strength increases beginning at a w/h of about 6. The simulated pillar strength curve under strong roof and floor compared favorably with measured peak strengths of four failed pillars in two coal mines in southwestern Virginia (figure 2) and is in general agreement with many existing coal pillar design formulas at w/h < 5.

FEM has also been used to evaluate the effect of in-seam and near-seam conditions, such as seam strength, rock partings, and weak floor rock, on pillar strength [Su and Hasenfus 1997]. On a percentage basis, seam strength was found to have a negligible effect on the peak strength for pillars at high w/h ratios (figure 3). For practical coal pillar design, exact determination of intact coal strength thus becomes unnecessary; for wide pillars, an average seam strength of 6.2 to 6.6 MPa may suffice for most U.S. bituminous coal seams. Rock partings within the coal seam, however, were found to have a variable effect on pillar strength, depending on the parting strength. A competent shale parting within the coal seam reduces the effective pillar height, thus increasing the ultimate pillar strength (figure 4). Conversely, a weak claystone parting slightly decreases pillar strength. In addition, weak floor rocks may decrease the ultimate pillar strength by as much as 50% compared to strong floor rock (figure 5). Field observations confirm pillar strength reduction in the presence of weak floor rocks.

Similar to CONSOL's studies, an earlier numerical study by the former U.S. Bureau of Mines employing a finite difference modeling technique concluded that pillar strength was highly dependent on the frictional characteristics of the coal-roof and coal-floor interfaces [Iannacchione 1990].

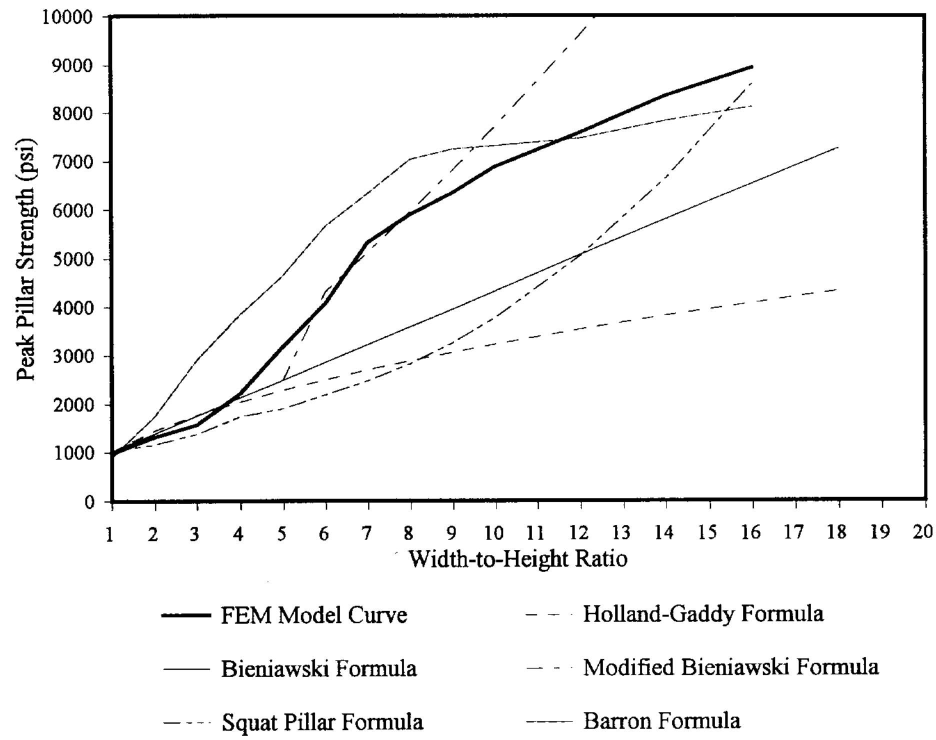

Figure 1.—Pillar strength comparison of FEM model results versus existing empirical formula.

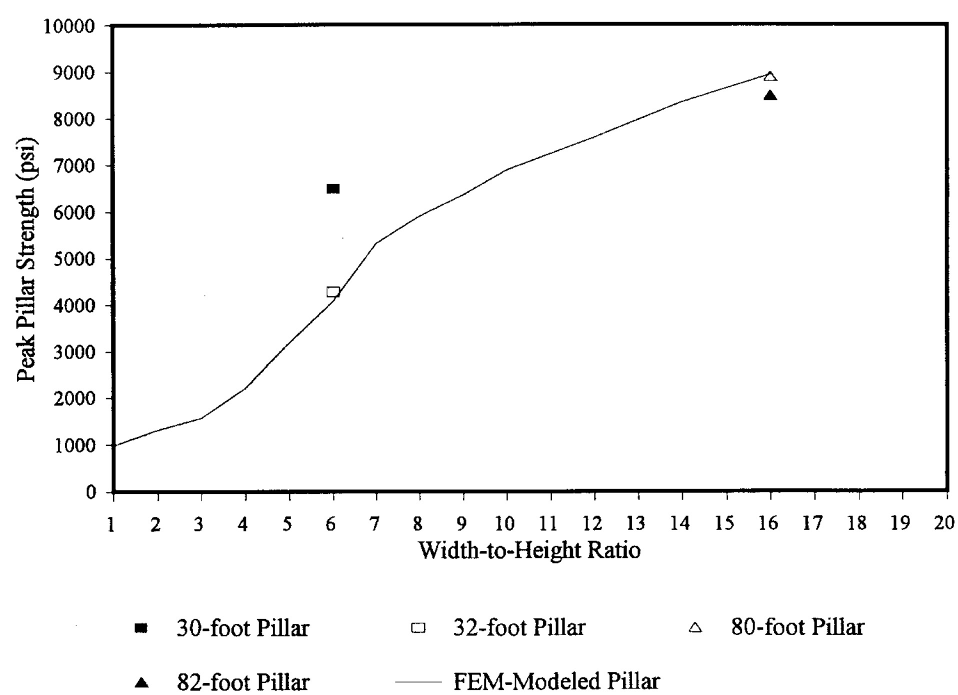

Figure 2.—Comparison of FEM modeled versus field pillar strength data (strong roof and strong floor conditions).

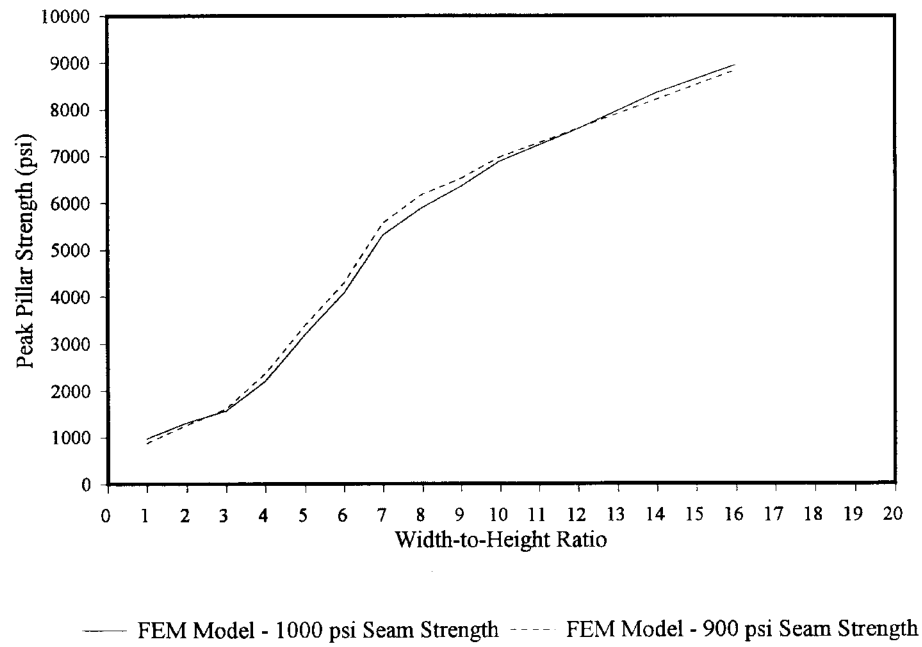

Figure 3.—Effect of seam strength on FEM model results.

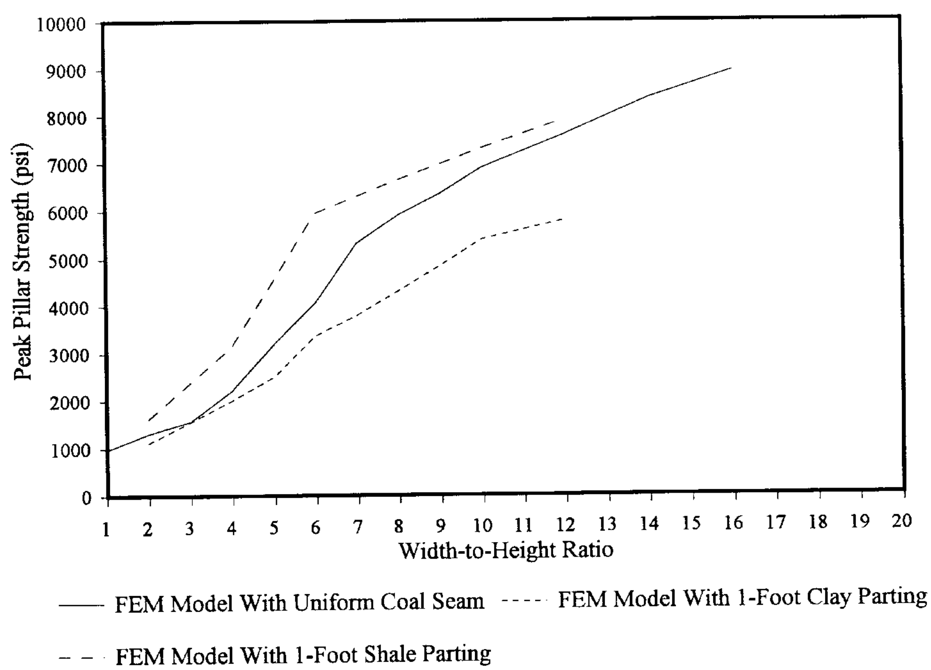

Figure 4.—Effect of claystone and shale parting on FEM model results.

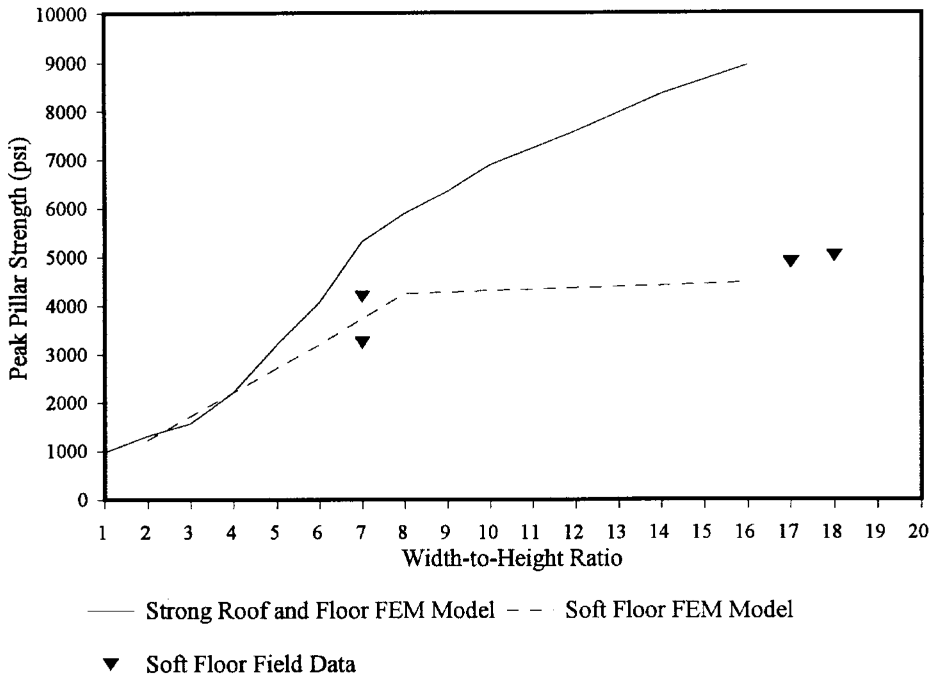

Figure 5.—Effect of weak claystone (soft) floor on pillar strength.

FUTURE PILLAR DESIGN CONSIDERATIONS RELATED TO SITE-SPECIFIC CONDITIONS

Because many coal pillar design formulas are empirical relationships that were developed under limited conditions, application of these formulas may be inappropriate when other factors not specifically addressed in these relationships are encountered. As demonstrated, pillar strength and therefore entry stability are extremely sensitive to the in situ characteristics of not only the coal, but also the adjacent and inclusive rock that comprise the coal pillar system. Unfortunately, a single site-specific empirical formula cannot accurately account for the variations of features that may significantly affect pillar and entry stability within a single coalfield or even a single mine. In addition, it is neither practical nor efficient to develop site-specific empirical formulas for all variations of roof, floor, and pillar characteristics that may occur within a mine.

Over the past decade, the Analysis of Longwall Pillar Stability (ALPS) approach to longwall pillar design has gained wide acceptance for longwall pillar design analysis in U.S. coalfields [Mark and Chase 1993]. Although it has proven to be applicable for use in many mines and mining regions, ALPS, which relies solely on the Bieniawski formula for pillar strength calculation, does not always accurately represent pillar strength at high w/h ratios. For example, for the prevailing strong roof and floor conditions in the Virginia Pocahontas No. 3 Coalfield, ALPS significantly underestimates pillar strength (figure 6). Conversely, under very weak, "soft" conditions, ALPS may significantly overestimate pillar strength (figure 7). Although recent versions of ALPS provide a Coal Mine Roof Rating (CMRR) routine that modifies the safety factor requirement and better accommodates hard roof conditions, this routine does not correct the inherent error in pillar strength calculation, which may be important not only for entry stability and safety, but also for subsidence planning and design.

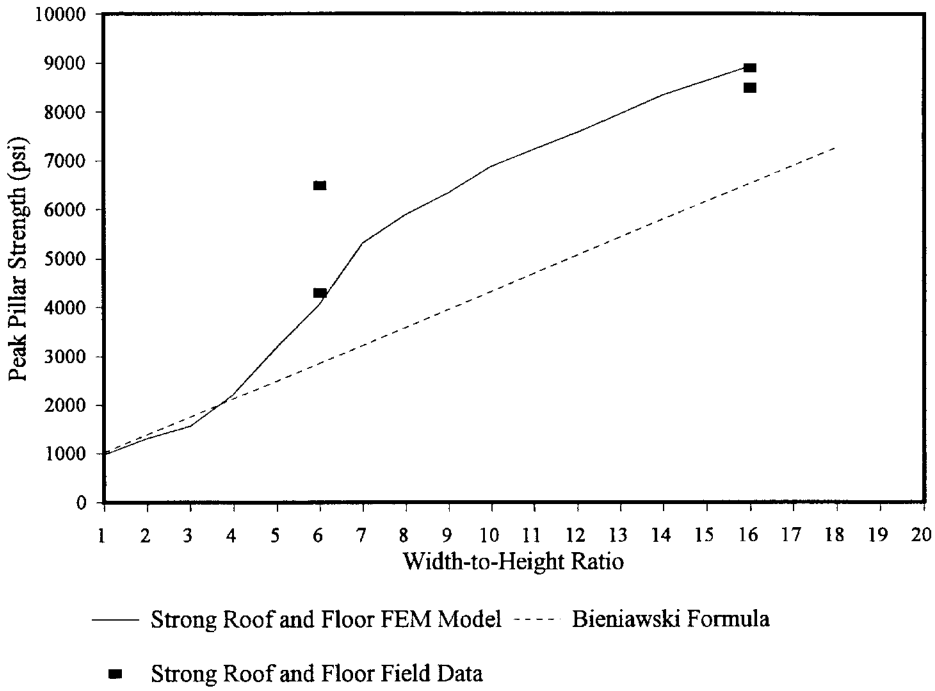

Figure 6.—FEM model and Bieniawski formula comparison with strong roof and floor data.

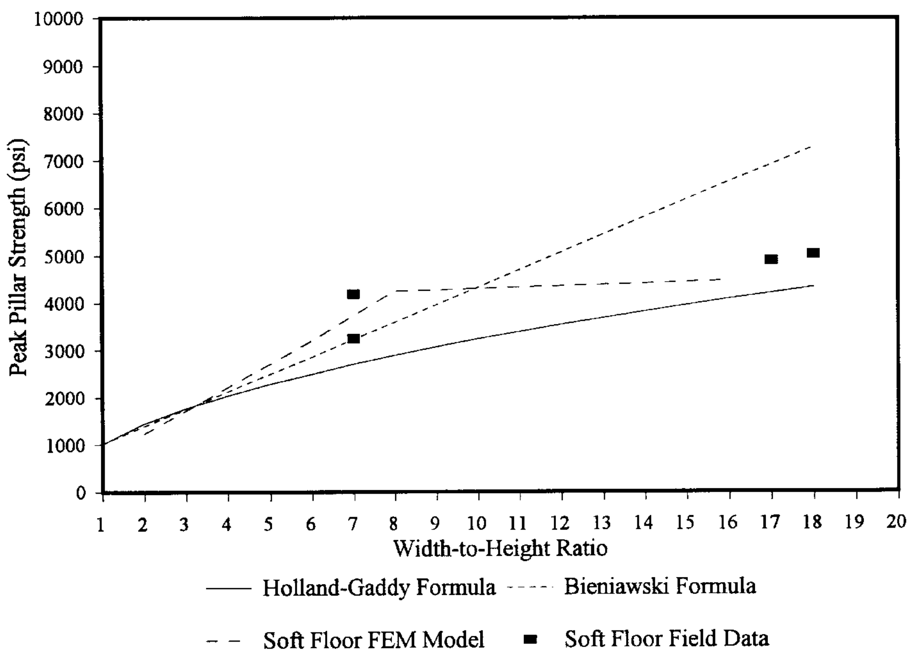

Figure 7.—Empirical pillar strength formula comparison with soft floor field data.

FUTURE PILLAR DESIGN CONSIDERATIONS RELATED TO ENTRY STABILITY AND VENTILATION EFFICIENCY

The ultimate goal of a successful pillar design is to achieve entry stability with optimum support. The classical pillar design approach focuses on determining safety factors from estimates of pillar strength and pillar load. This works well in room-and-pillar operations without second mining and in main entries not subject to abutment pressures. A successful longwall gate road design, on the other hand, requires stable headgate and tailgate entries under the influence of longwall abutment pressures. Headgate or tailgate entry failures, such as a roof fall, severe floor heave, or severe pillar spalling, may pose serious safety hazards and may stop longwall mining for days or weeks. Traditionally, headgate and tailgate stabilities have been correlated with pillar sizes, and many ground control researchers have focused on the design of longwall chain pillars for improving gate road stability. However, gate entry performance is influenced by a number of geotechnical and design factors, including pillar size, pillar loading, roof quality, floor quality, horizontal stresses, entry width, and primary and secondary supports [Mark and Chase 1993]. It suffices to say that pillar size is not the only factor affecting longwall headgate and tailgate stability. Therefore, strength of roof and floor rocks, state of in situ horizontal stresses, entry width, and support methodology are other important factors that should be included in any practical longwall chain pillar design methodology.

In the early 1990s, Mark and Chase [1993] used a back-calculation approach to suggest an ALPS stability factor for longwall pillars and gate entries based on a CMRR. The importance of floor stability and secondary support could not be determined from the data and were not included in the back-calculation. Nevertheless, their effort pioneered pillar design research that included roof rock strength and integrated pillar and entry roof stability. Although the floor strength, roof support, horizontal stresses, and entry width can theoretically be included in a numerical pillar design model, other issues, such as gob formation, load transfer, material properties, and geological variations, may make model formulation difficult. It seems that a hybrid method of the back-calculation and numerical approaches may provide a more effective and versatile pillar design method in the future.

A more rigorous, yet practical pillar design methodology could be developed by incorporating a site-specific pillar strength formula obtained from numerical models or alternative field observations into the ALPS stability factor approach. As an example, for strong roof and floor, the FEM-based pillar strength curve, which incorporates site-specific roof and floor strength, predicts a strength for an 80-ft-wide pillar that closely emulates field results, but is nearly 40% higher than that predicted by the Bieniawski formula (figure 6). In addition, under very weak floor conditions, the Holland-Gaddy formula may better represent pillar strength than the Bieniawski formula (figure 7).

If such a combined approach is adopted, it could be done either on an independent basis or perhaps even as a modification to the overall ALPS design approach. Nevertheless, it is apparent that pillar design methodology could still benefit from a combination of empirical, analytical, and numerical methods to formulate practical pillar design based on site-specific roof, floor, and seam conditions.

An aspect of longwall gate road design that is often overlooked is its impact on ventilation. Specifically, for eastern U.S. coal mines that employ only three or four gate road entries, the ability to provide an effective internal bleeder system in the tailgate behind the face can be quite important. Obviously, effective ventilation area in the tailgate between two gobs is influenced by roof and floor geology, entry width and height, pillar load and pillar strength, and primary and secondary support. Where longwall chain pillar designs must provide an effective internal bleeder system, ground control engineers must account for the aforementioned factors in addition to pillar load and pillar strength.

CONCLUSIONS

With the capability of modeling interface friction and various boundary conditions, a finite-element code can be an effective tool for site-specific evaluation of in situ coal pillar strength that considers the complex failure mechanisms of in situ coal pillars. The modeling technique can be most useful for conditions where interface friction and roof and floor deformation are the primary controlling factors. Nonlinear pillar strength curves relate the increase of pillar strength to the w/h ratio. Confinement generated by frictional effects at the coal-rock interface is shown to increase the pillar strength more rapidly at w/h ratios of about 3. The finite-element modeled in situ pillar strength curve for strong roof and floor conditions compares favorably with the measured peak strengths of five failed pillars in two southwestern Virginia coal mines and is in general agreement with many existing coal pillar design formulas at w/h ratios of <5. However, for wide pillars, modeling predicts a higher in situ coal pillar strength than most accepted formulas. Consequently, use of more conservative empirical formulas may lead to the employment of unnecessarily wide pillars or a lower estimated safety factor.

However, to accurately assess pillar strength, a model or formula should account not only for the characteristics of the coal, but also for those of the surrounding strata. Although seam strength is observed to have some effect on pillar strength, its significance is often overrated. In fact, for coal pillars with large w/h ratios, ultimate pillar strength is more dependent on end constraints than on seam strength. This reduces the significance of laboratory coal compressive strength determination for such conditions. For practical purposes, a uniform seam strength averaging about 6.2 to 6.6 MPa is adequate for most U.S. bituminous coal seams when employing finite-element models to simulate pillars with high w/h ratios.

The finite-element model results presented are not intended to suggest new pillar design relationships with w/h ratios. The primary objective of this paper is to emphasize the site-specific nature of coal pillar design and the value of using modeling procedures to account for such site-specific conditions. Understanding the site-specific parameters is an important ingredient for successful coal pillar design. Due to the variability of in situ properties, no currently available empirical, analytical, or numerical pillar design formula is applicable in all cases. Utilization or imposition of pillar design formulas that do not, or cannot, account for site-specific variations in roof, floor, and parting conditions may lead to incorrect assessments of pillar strength, whether high or low, and incorrect estimates of pillar design safety factors. Empirical, analytical, or numerical design procedures should be validated by site-specific measurements or observational field studies whenever possible.

For longwall mining, pillar design is not the only factor affecting headgate and tailgate stability and ventilation efficiency. Strength of roof and floor rocks, state of in situ stresses, entry width, and support methodology are other important factors affecting longwall gate road stability and should be considered in practical longwall chain pillar design. Certainly, more work remains before the century-old problems related to pillar design are finally solved. Future pillar design methodology could benefit from a cross-linkage of empirical, analytical, and numerical pillar design methods.

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