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Fundamental principles of an effective reinforcing roof bolting strategy in horizontally layered roof strata and areas of potential improvement

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ABSTRACT

It is arguable that the development of reinforcing roof bolting systems has largely stagnated in recent times, primarily due to the prevailing industry view that few, if any, further improvements can be made to what currently exists. However, this paper contends that reinforcing roof bolting systems can be further refined by considering both the specific manner by which horizontally bedded roof strata loses its natural self-supporting ability and the specific means by which reinforcing roof bolts act to promote or retain this natural self-supporting ability. The Australian coal industry has insisted on minimising bolt-hole diameter to maximise load transfer and on targeting full-encapsulation by any means necessary for many years. This has led to a significant, albeit unintended, consequence in terms of overall roof bolting effectiveness, namely increased resin pressures during bolt installation and the associated potential for opening bedding planes that may have, otherwise, remained closed during the bolt installation process. Given that the natural self-supporting ability of roof strata is strongly linked to whether bedding planes are open or closed, logically, minimising resin pressures should be a significant benefit. This paper focuses primarily on three key issues that relate directly to the function of the roof bolting system itself: (1) the importance of proper resin mixing in the context of maximising load transfer strength and stiffness, (2) the importance of minimising resin pressures developed during bolt installation, and (3) the importance of maximising the effectiveness of the available bolt pre-tension. All mine operators should be invested in improving the individual effectiveness of each installed roof bolt, even by relatively small incremental amounts, so this is an important topic for discussion within the mining community.

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1. Introduction

The installation of primary roof bolting as part of the roadway development operation is the most obvious pro-active strata control process that is available to mining operations. The way the primary roof support is installed suitably close to the development face and the extent to which it is geotechnically fit for purpose sets in place the future conditions. The installation of the primary roof support ultimately determines operational outcomes, such as the trigger action response plan (TARP), subsequent roof deterioration or instability, and whether or not expensive, high-density, secondary support measures will be needed. However, in an overall industry context, the effectiveness of primary roof support has received far less attention in more recent times compared to such areas as geotechnical characterisation, geotechnical design, and operational strata management. This paper revisits the subject area by examining several technical areas where substantial improvements can potentially be made based on the published findings of a range of research studies and specific testing data.

The development of reinforcing roof bolting in underground coal mining, which is the mainstay of safe and efficient mining, has reached a point where the design and setup of the bolting system can be further refined by considering the manner by which the roof strata loses its own self-supporting ability. Reinforcement is the promotion or retention of the natural self-supporting ability within the host rock mass. By understanding both the destabilising mechanisms within the roof strata and the various influences that primary roof bolts have on those mechanisms, the setup of each installed roof bolt can be optimised to achieve the highest level of individual roof bolt effectiveness.

Without digressing into a detailed history of roof bolting development over the past 40–50 years, an optimum roof bolting system needs to incorporate measures that address at least eight fundamental principles of roof reinforcement: (1) position of bolt installation with respect to the development face (i.e., cut-out distance), (2) use of an appropriate bolt length and a geotechnically suitable bolt pattern, (3) minimum resin pressure during bolt

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installation to reduce the adverse effects on the roof strata within the bolted interval, (4) proper resin mixing when generating the bond between the bolt and surrounding strata, (5) use of resin system properties that act to promote increased load transfer strength and load transfer stiffness, (6) maximum effectiveness of the bolt pre-tension generated via nut tightening at bolt installation, (7) protection of mine personnel from any roof material that may detach between bolts, and (8) application of an ongoing operational process to both correctly install ground support, as well as manage and control the inherent uncertainties in the stabilisation of a naturally formed engineering material.

Applying these eight fundamental principles leads to various insights as to how a reinforcing roof bolting strategy can be best optimised. This paper considers, in varying detail, several issues that relate directly to the setup of the roof bolting system itself: (1) proper resin mixing in the context of maximising load transfer strength and stiffness, (2) the importance of minimising resin pressures developed during bolt installation, and (3) maximum magnitude and effectiveness of the bolt pre-tension developed at installation.

The discussion around each of these aspects is based on an analysis of how the primary source of self-supporting ability in layered roof strata is retained, how such natural roof stability is lost, and the various interactions between installed roof bolts and the occurrence of de-stabilising mechanisms.

2. Self-supporting ability in layered roof strata

Fig. 1 illustrates a simplified representation of the three fundamental sources of roadway roof stability in a layered and jointed rock mass under the action of some level of horizontal stress [1]. The three stabilising mechanisms are (1) cohesion between bedding planes, (2) horizontal stress acting to prevent shear slip along sub-vertical jointing within the roof strata, and (3) some form of suspension-type support to hold up a roof mass that does not contain the natural stabilising benefits of (1) and (2). Without at least one of these mechanisms in place, a major roadway roof fall is an inevitable consequence.

On the assumption that using a suspension roof control strategy is not a preferred approach in high-production underground coal mining, preventing horizontal separations occurring within the roof strata becomes critically important. First, the opening of bedding planes directly causes the loss of bedding plane cohesion (stabilising mechanism). If closely spaced bedding planes open up, it can lead to the en masse buckling of the roof strata and an associated reduction in horizontal stress levels (stabilising mechanism (2)), as explained in detail in Colwell and Frith [2,3].

A real-world demonstration of the significance of the bedding plane condition to the self-supporting ability of layered roof strata is found in Fig. 2, which is derived from the US extended cut database used to evaluate roadway roof stability without roof bolts installed [4]. The two axes represent the varying compressive

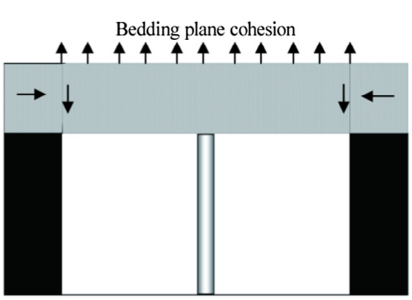

Fig. 1. Schematic representation of the three sources of roadway roof stability [1].

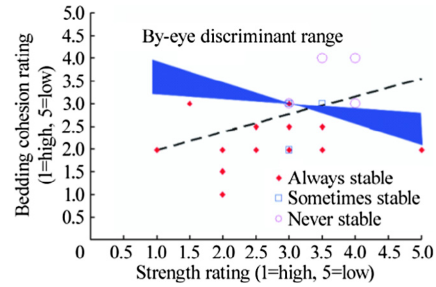

Fig. 2. US extended cut stability database assessed for both UCS and bedding cohesion [4].

strength (UCS) of the roof material (x-axis) and bedding cohesion within the roof (y-axis) for each of the database case histories. The estimation of the latter is part of the underground method for determining the coal mine roof rating (CMRR) as it is used in the Mark study [4].

The key feature of Fig. 2 is the line or boundary that best separates the "always stable" from the "never stable" cases because this provides an indication of the relative importance of the UCS of the roof material, as compared to bedding plane cohesion within the roof, to either the retention or loss of natural roof stability (self-supporting ability).

A "by-eye" discriminant zone (in blue) is shown in Fig. 2, and it is clear that it only discriminates between stable and unstable cases according to varying bedding plane cohesion, i.e., lower cohesion (greater than ≈3) is linked to "never stable" cases, and higher cohesion (less than ≈3) to "always stable" cases. Furthermore, the "always stable" cases cover the full UCS range from low to high, meaning that UCS is not a reliable predictor of natural roof stability [5].

The point of Fig. 2 is that the roof almost certainly loses its natural stability or self-supporting ability in line with the opening of bedding planes, termed "delamination." It logically follows that the higher the level of delamination within the bolted interval, the higher the level of installed roof support required to maintain adequate levels of roof stability (all other factors being equal). Bolted roof reinforcement should, therefore, be primarily focused on preventing bedding planes from opening within the bolted interval. Minimising the degree of bedding separation once they are open should be a secondary, albeit still relevant, consideration.

The setup of a reinforcing roof bolting system is further considered based on the concept that retaining the self-supporting ability of the roof strata prevents the bedding planes from opening within the bolted interval, while accepting that, if they do open, it is beneficial to minimise the level of separation that occurs.

3. Resin mixing and maximising load transfer properties

The entire subject of maximising the load transfer properties of resin-encapsulated roof bolts has been widely researched based largely on both in situ short encapsulation pull-tests and laboratory pull or push tests. The general outcome of this work, in Australia, is that, in order to maximise load-transfer strength and stiffness, the roof bolting system should be fully encapsulated, and the annulus between the bolt and surrounding strata should be as small as possible. When considered in isolation, the logic behind maximising load transfer makes sense and remains the current norm in the Australian coal mining industry.

However, works from New Zealand, published by Campbell and Mould, as well as Pastars and McGregor, find that there is a fundamental problem with the 15:1 ratio (mastic-to-catalyst) resins systems that were almost universally used in the Australian coal

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