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Investigation of the failure mode of shale rocks in biaxial and triaxial compression tests

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ABSTRACT

High horizontal in-situ stress and weak sedimentary laminated roof rock can severely affect underground coal mine roof stability. These sedimentary rocks possess planes of weakness along the horizontal direction in a mine roof and delaminate easily when acted upon by high lateral stresses. Empirical studies have shown that the magnitude of these stresses can be as much as two to three times the local overburden stress. The resulting ground control problems (buckling, cutters, etc.) in such conditions are quite challenging for mining engineers. This paper describes the failure observed in coal mine shale rocks under biaxial and triaxial stress conditions. To carry out the investigation, special platens were fabricated that are capable of applying biaxial compressive stress on a cubic rock specimen when the entire arrangement is used inside a uniaxial compressive loading device. This experimental set-up was further modified to apply a pseudo-triaxial compressive stress. Laminated shale specimens tested under biaxial stress condition showed tensile failure along the laminations at macrolevel. Black shale specimens showed extreme brittle failure. Limestone specimens tested under similar conditions failed violently and it was concluded that failure observed in each rock type tested was unique and not an artifact of the experimental design. The pseudo-triaxial conditions reduced the influence of laminations on the failure mode. Laminated shale specimens were found to fail along multiple shear planes.

1. Introduction

According to the Centers for Disease Control and Prevention (CDC)[3] there are 568 active underground coal mines in the United States. A majority of these mines are located in the eastern part of the country (Fig. 1(a)). Mines in these regions (like Northern Appalachia, Southern Appalachia and the Illinois Basin) are known to have been affected by severe ground control problem (Fig. 1(b)). It is important to note that apart from the high topographic stress (especially in the Appalachian region), other factors like relatively high lateral stress and weak roof have been known to immensely affect the overall stability of underground coal mine openings. A recent study published by Bajpayee et al.[2] analyzed the contributory geologic factors behind roof falls based on well-documented narratives of mine operators involved with 1825 non-injury roof falls between the years 1999 and 2008. The two major factors—namely, the presence of discontinuities in the roof rock and laminated rock surfaces—were determined to be the two prominent contributors in about 60–65% of the roof falls reported. The mechanism underlying typical failures in laminated roof rock has not been researched extensively, and the investigation presented in this paper is an attempt to move in this direction.

An example of failure in laminated roof rock in underground coal mines is the "cutter roof". Hill et al.[7] describe the failure as: "a failure process that initially begins as a fracture plane in the roof rock parallel to, and located at, the roof-rib intersection. The fracture propagates at an angle usually steeper than 60° from the horizontal." A cutter type roof failure could eventually have disastrous consequences, resulting in the collapse of the entire roof of an entry or cross-cut[13]. The entire roof collapse, starting from the initial occurrence of the cutter failure, happens in a step-wise manner (Fig. 2), and can occur over a time period of a few days to a month; and sometimes the intial fracture remains dormant for the rest of the mine panel life.[14] The coal mines in the Appalachian region in the Unites States have been known to be severely affected by this ground control problem,[1,6,14–16] etc. This problem is aggravated in the presence of existing high horizontal in-situ stresses (the maximum horizontal stress in these regions can be two to three times the overburden stress).[4]

The use of numerical modeling has been successful in replicating some of the key aspects of cutter roof failure like step-wise failure, location of failure at the roof rib intersection, and random spatial distribution of cutters within a mine panel. Continuum mechanics-based numerical modeling software has been

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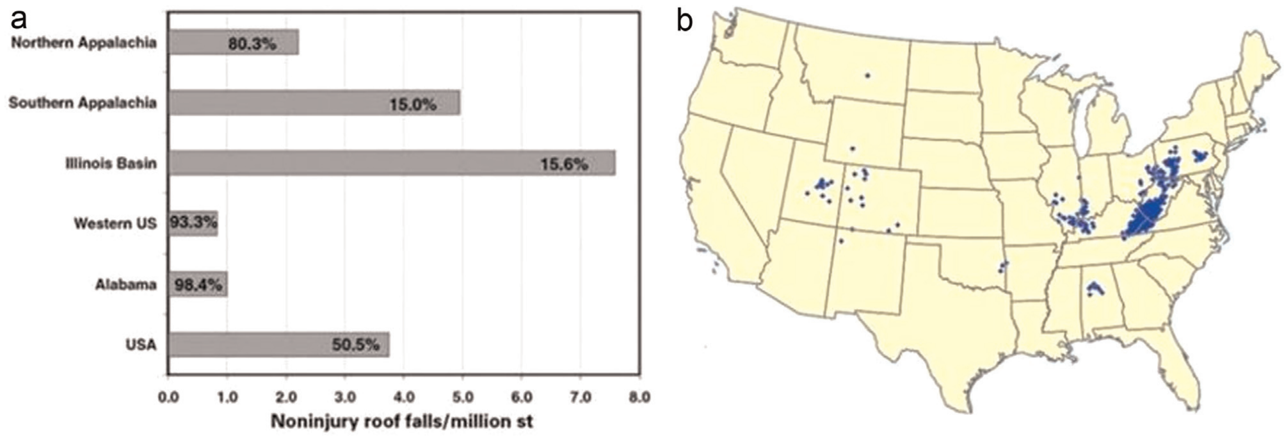

Fig. 1. (a) Roof fall rate in U.S. coalfields from 2005–2006.[11]Note: Percentage in bars indicate the percent of production due to longwall mining method, and (b) location of active underground coal mining operations, 2012.[10]

widely used for this purpose,[1,9,14,16] etc., with strain softening type of rock constitute behavior incorporated into some of the recent modeling attempts.[6,16] However, in this project, discontinuum mechanics-based numerical modeling was deliberately avoided due to the fact that reliable input parameters (pertaining to discontinuity properties) were not readily available.[6] The authors are skeptical about this approach of excluding discontinuum modeling as a pertinent question related to the influence of mechanical properties of laminations (cohesion, friction angle, etc.) on the results of numerical model is raised. Esterhuizen and Bajpayee[5] point out, in this regard, that delamination is common in laminated rock, where the rock separates into thin, weak beams which are then more susceptible to buckling under high lateral stress. Hence, to develop and analyze numerical models simulating failure in laminated rock, it is imperative that we fully understand the failure mechanism in these rocks under varying stress conditions. The research presented in this article is based on this rationale and explores the response of laminated shale specimens from immediate roof rock (rock samples collected from the immediate stratum in the roof of a mine opening) under biaxial and triaxial stress conditions in a laboratory set-up.

2. Approach

As discussed earlier, the magnitude of in-situ horizontal stress in underground coal mines in the eastern United States could be as high as two to three times the overburden stress, and this fact has been identified as a key factor responsible for failure in laminated rock. An analysis of in-situ stress measurements of this region by Mark[10] indicates the presence of a predominant E-NE horizontal stress orientation, which is also biaxial in nature. In an attempt to simulate these in-situ stress conditions at laboratory scale, special platens were designed and fabricated, and these are capable of applying equal biaxial stress on a two inch cubic specimen. Additionally, a pseudo-triaxial stress condition was also simulated using biaxial platens and industrial c-clamp arrangement. Ideally, a true-triaxial equipment would have simulated the in-situ conditions in a more realistic fashion by allowing control over independent triaxial stresses acting on the specimen. However, such equipment was beyond the financial scope of this research project.

3. Experimental design

3.1. Specimen preparation

Samples of irregular shape and size were collected from underground coal mines in West Virginia and Pennsylvania. These samples, consisting of black and laminated shale rocks, were retrieved from mines affected with weak laminated roof (Fig. 3 (a) and (b)). Laminated roof rocks had laminae less than 1 in. The

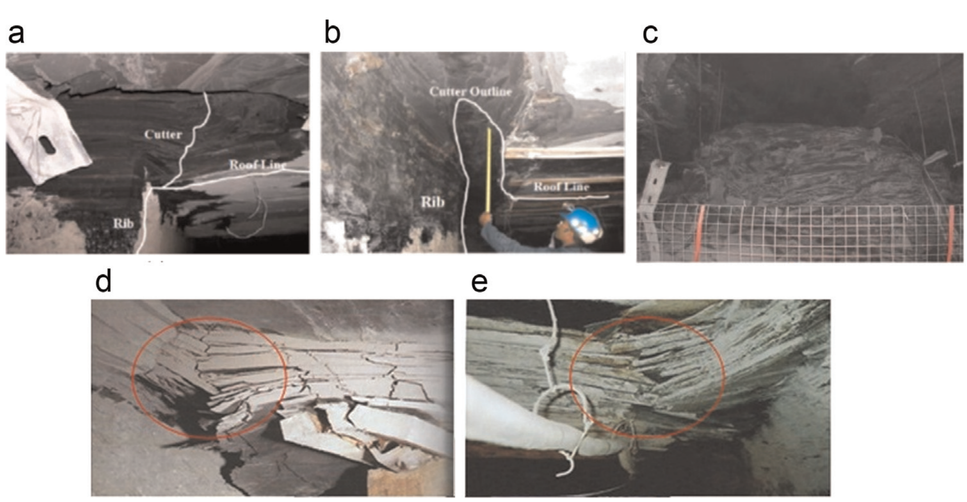

Fig. 2. Stages of "cutter-roof" failure development (a) initial stage of a cutter, (b) small cutter type roof fall at a corner, and (c) roof profile after a massive fall initiated by cutters. Photo credits: Murali Gadde and SS Peng.[6]