Experimental study of coal bursts caused by decrease of local mine stiffness

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ABSTRACT: The crucial role played by local mine stiffness (LMS) in the occurrence of rock strainbursts has been widely acknowledged. To prevent rockbursts, it is essential to comprehend the evolution of LMS during mining operations. Unfortunately, existing studies on this subject are largely limited to theoretical and numerical methods. To address this research gap, we conducted an experimental investigation using an in-house developed equipment. The aim was to generate strainbursts resulting from excavation-induced stress concentration and LMS reduction. In this study, we simulated the excavation process and associated disturbances using real coal blocks in a laboratory setting. The results of our experimental investigation provide a novel approach for producing strainbursts that arise due to the progressive reduction of local mine stiffness during mining operations.

Keywords: strainbursts, local mine stiffness, experimental study, stress concentration.

1 INTRODUCTION

Local mine stiffness (LMS) is a concept that refers to the equivalent stiffness of the roof, coal, and floor strata in various areas of a mine at different stages of mining (Salamon 1970). The impact of mine stiffness on rockbursts is attributed to the comparison of the mine stiffness of the objective rock pillar and the surrounding rocks, which form a loading system. The pillar absorbs energy released from surrounding rocks, but if the amount of energy released from the loading system exceeds the pillar's capacity to absorb it, strainbursts will occur, and the excess energy will convert into kinetic energy, resulting in rock fragment ejection. The crucial role of LMS in rock strainbursts has been widely recognized (Kaiser and Cai 2013; Cai et al. 2021).

The tendency to release kinetic energy increases with a decrease in LMS, which is related to excavation size and other factors such as geology, geometry, and rock mass properties (Iannacchione 1988; Zipf and Mark 1997; Adhikary et al. 2002). Local mine stiffness varies spatially and temporally with excavations and involves continuum and discontinuum interactions at different scales, including mine stiffness versus local rock mass characteristics and properties, pillar-controlled stiffness and influence on skin-controlled failure and energy release (Lachenicht 2001; Maleki 2017). Despite its relative simplicity, evaluating and quantitatively analyzing LMS in both field and laboratory settings is challenging. Numerical simulation software and methods have been developed to calculate LMS under complex geological conditions and provide numerical evidence of LMS stable criteria (Iannacchione 1988; Jaiswal and Shrivastva 2009, 2012; Hauquin et al. 2018). However, limited experimental studies have been conducted to provide direct evidence of strainbursts caused by gradual stress concentration and decreasing LMS during excavation. In this study, an in-house developed loading equipment was employed to produce strainbursts by simulating gradual pillar excavations under high pressures. The excavation process and the resulting disturbances were reproduced using real coal blocks in a laboratory setting.

1.1 Experiment equipment

The testing equipment was developed by the Rock Mechanics Laboratory of the State Key Laboratory of Coal Mining and Clean Utilization at the China Coal Research Institute, as shown in Figure 1. The equipment comprises a loading system for applying loads to the composite samples, an oil hydraulic system that supplies the loading power, and an energy accumulator system.

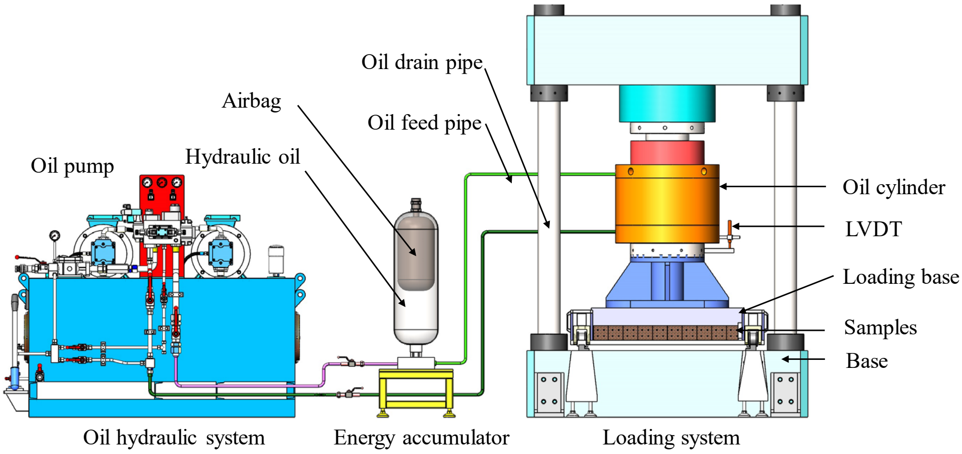


Figure 1. Schematic diagram of the local mine stiffness simulation device.

The energy accumulator system is composed of six accumulators that are connected in parallel, each of which consists of an airbag contained within a 20 L shell. Prior to the application of loading, nitrogen gas is pumped into the airbags until the air pressure reaches a predetermined level. When loading commences, hydraulic oil is introduced through the oil feed pipe into the shell of the accumulators and the loading cylinder. As the oil pressure exceeds the air pressure of the airbag, the airbag is compressed until its pressure equals the oil pressure. Subsequently, as the loading continues, the airbag is further compressed, analogous to the compression of a spring, resulting in the storage of strain energy in the airbag. Upon failure of the specimen, the oil pressure in the loading cylinder decreases, and the cylinder piston rod extends. At this point, the air pressure of the airbag in the accumulator exceeds the oil pressure, and the airbag instantaneously expands, forcing the oil in the shell to expand into the cylinder to complete the energy release process.

1.2 Sample preparation

Cubic coal specimens with an edge length of 100 mm were carefully prepared by cutting large coal blocks obtained from a longwall face at a coal mine in China. The faces of the specimens were precisely ground flat to a tolerance of ±0.1 mm, with tap water used for cooling. A size tolerance of 1% of the edge length was maintained, and the perpendicular tolerance of the opposite surfaces to the axis of the specimen was less than 1°. To gain insight into the behavior of the coal, unconfined compression tests were performed on three randomly selected specimens. The results revealed that the coal blocks exhibit a brittle behavior after the peak stress.

A composite sample was utilized to simulate excavations, as illustrated in Figure 2(a and b). Ideally, the composite sample should have consisted of solely coal blocks; however, due to a shortage of prepared coal blocks, C-S blocks were utilized as a substitute. These blocks consist of

100×100×95 mm concrete blocks using cement C35 and a 100×100×5 mm silicone pad. The soft silicone pad was used to offset the relatively high stiffness of the concrete blocks in comparison to the coal blocks. Compression tests were conducted on the C-S blocks, and the results suggest that the Young's modulus of C-S blocks closely approximates that of coal blocks, making them suitable for representing un-mined coal pillars in the experiment. To represent the coal pillar, relatively intact coal blocks were chosen. Coal blocks were not placed at the front and back of the coal pillar to allow for the placement of monitoring devices.

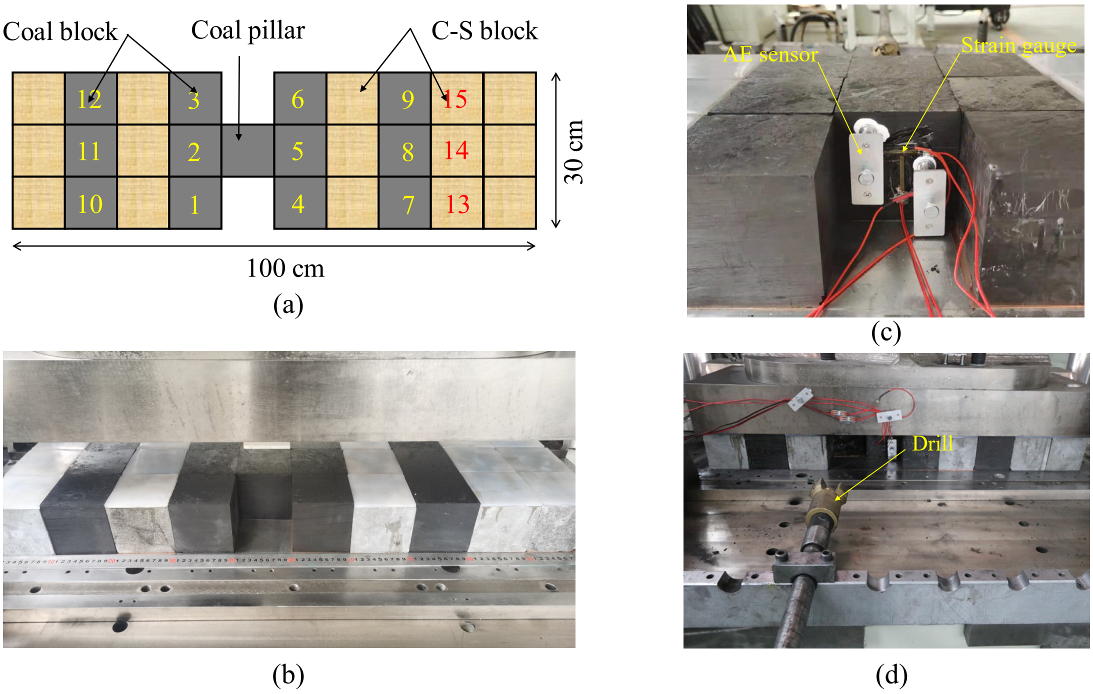


Figure 2. Configuration of the experiments for producing coal bursts in the laboratory. (a) Schematic diagram of composite sample and excavation stages, (b) Photo of the composite sample, (c) Placement of AE sensors and strain gauges, and (d) Pillar excavation.

1.3 Test procedures

The following steps were followed during the test:

(1) Initialization of the energy accumulator: The energy accumulator was initialized by filling the airbags with nitrogen until the initial accumulator pressure reached the target value, after which the nitrogen feed pipe was shut down.

(2) Initial loading: The oil hydraulic system was then activated to apply a monotonic load on the samples under force control with a rate of 2 kN/s until the loading force reached 1900 kN, corresponding to a pre-excavation stress of 6.8 MPa applied to the top of the samples. The oil pressure in the cylinder and the oil chamber of the accumulator was 7.9 MPa, higher than the initial accumulator pressure in the airbag, which led to the compression of the airbag until the pressure in the airbag equaled 7.9 MPa. The oil feed pipe switch was then shut off to maintain the oil volume in the cylinder and the accumulator, and the system was allowed to stabilize for thirty minutes.

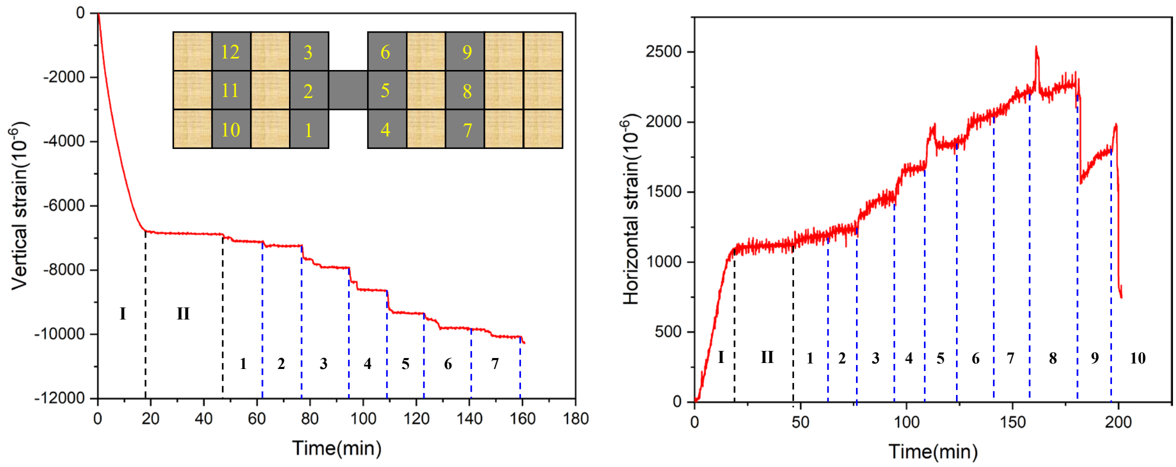
(3) Pillar excavation: The coal blocks were excavated in the sequence shown in Figure 2(a), using an electric drill and an electric hammer as illustrated in Figure 2(d). In each excavation stage, one coal block was removed, and a 10-minute stabilization period was observed before the next excavation. The test was terminated when the coal pillar failed catastrophically.

2 EXPERIMENTAL RESULTS

2.1 Response of the coal pillar with excavation

The deformation response of the coal pillar during the excavation tests is depicted in Figure 3. The results demonstrate that the complete deformation process of the coal pillar during excavation was captured. In the stabilizing stage, there were minimal changes observed in the vertical and horizontal strain, indicating that the system had stabilized and was ready for the subsequent excavation. The experiments revealed that the excavation process caused stress concentration on the coal pillar, resulting in deformation. However, the deformation did not increase linearly with the excavation stages and exhibited distinct features in different stages. The initial three excavation stages (i.e., mining out the left part of the pillar) showed only a slight deformation increase, whereas excavation stages 3-5 (i.e., when the pillar was largely mined out) resulted in significant deformation increase. Interestingly, further excavations (i.e., coal blocks 7-10) also caused a significant increase in deformation, even with the barrier of C-S blocks between the coal pillar and the excavation.

The coal pillar failed catastrophically during the excavation of coal block 10. It might be tempting to conclude that the failure was caused by the disturbance of the electric drill. However, considering that the coal pillar was stable during the excavation of blocks 1-6, when the electric drill was working in close proximity, and there was a C-S block barrier between the excavation and the coal pillar, it is unlikely that the electric drill played a key role in the failure. It is more likely that the excavation caused a sudden loss of the bearing capacity of the excavation block, resulting in further stress concentration on the coal pillar, which exceeded its strength.



(a) (b)

Figure 3. Deformation response of the coal pillar. (a) Changes of the vertical strain, (d) Changes of the horizontal strain. The Roman numerals I and II indicate the loading and stabilizing stage, respectively. The New Roman numerals indicate the excavation stage.

2.2 Failure patterns

The coal pillar of interest displayed a burst failure pattern, which was captured by a high-speed camera. Figure 4 presents snapshots of the bursting failure process, which began with the ejection of small pieces of coal from the skin of the pillar, propagated to other areas, and ultimately led to the catastrophic failure of the coal pillar with the ejection of large fragments from the core. The duration of the bursting failure, defined as the elapsed time from the initial ejection of small pieces from the pillar skin to the final catastrophic failure of the pillar, was 89.940 ms.

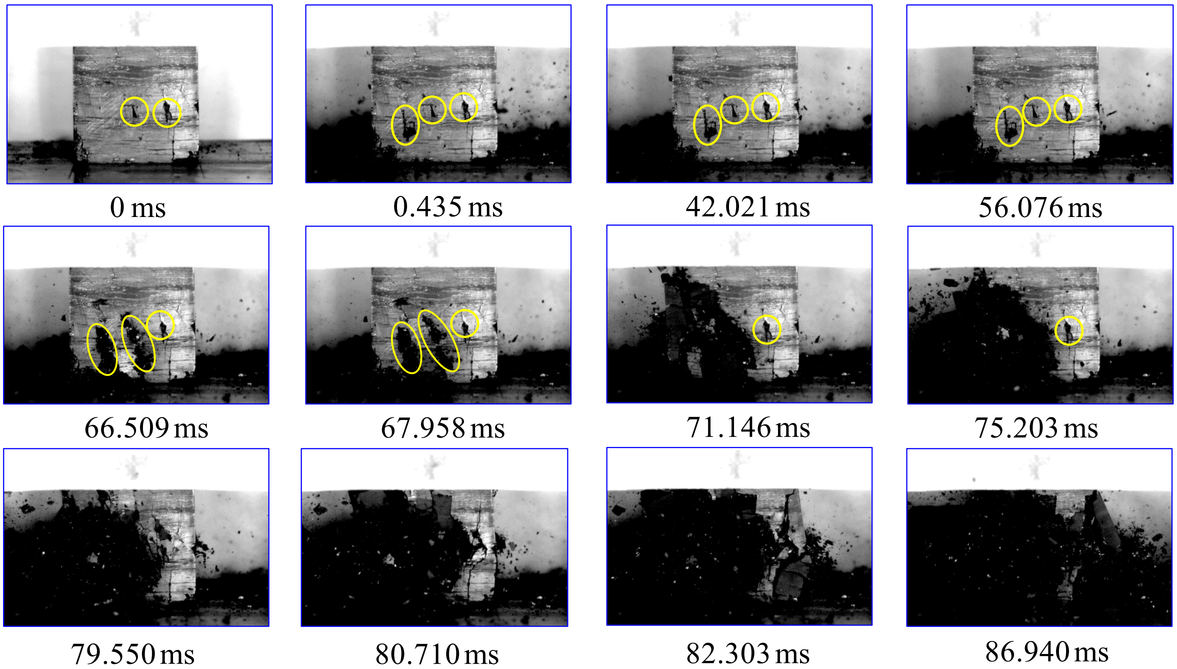


Figure 4. Snapshots showing the strainburst process of the coal pillar under the condition of high accumulator pressure. The time at which the ejection of small fragments initiates is regarded as 0 ms. The yellow ellipses indicate the locations where initial ejection of pieces occurs.

Figure 5 illustrates the post-failure characteristics of the coal pillar following the catastrophic bursting failure. The residual pillar displayed a characteristic "dog bone" profile, with a greater amount of coal ejected from the middle section as compared to its two ends. The pillar experienced a complete loss of its capacity and collapsed immediately upon removal of the top load platen. This observation implies that the bursting failure caused significant damage to the structural integrity of the coal pillar, ultimately leading to its complete failure.

Figure 5. Final failure pattern of the coal pillar after catastrophic bursting failure.

3 CONCLUSION

In this study, an experimental investigation was conducted using custom-built equipment to simulate strainbursts resulting from excavation-induced stress concentration and a decrease in local mine stiffness (LMS). Real coal blocks were used to replicate the process of excavation and its consequential disturbances in a laboratory setting. The proposed experimental approach offers a novel method for producing strainbursts caused by the reduction in LMS as mining progresses.

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