International Journal of Rock Mechanics and Mining Sciences 110 (2018) 140–150

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Mechanical properties and damage constitutive model of coal in coal-rock combined body

X.S. Liu[a,b], Y.L. Tan[a,*], J.G. Ning[a], Y.W. Lu[a], Q.H. Gu[a]

[a] State Key Laboratory of Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China
[b] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou 221116, China

A R T I C L E I N F O

Keywords:
Coal-rock combined sample
Mechanical property
Damage constitutive model
Cascade system
Coal-rock height ratio

A B S T R A C T

Coal and rock mass bear loads together in underground engineering such as coal mining and roadway support, resulting in different mechanical properties from those of pure coal and rock mass. Accurately obtaining the mechanical properties of coal in coal-rock combined body can help to properly understand the deformation and failure characteristics of the underground coal mass. First, an experimental method to obtain the stress and strain of coal in coal-rock combined samples using strain gauges was proposed and validated. Then, tests on thirteen types of coal-rock combined samples were conducted. The results show that the rock experienced a strain recovery and played a loading effect on the failure of coal when coal-rock samples failed. The compressive strength of coal in the sample increased with the rock strength, and decreased with the coal-rock height ratio. Furthermore, two damage constitutive models of coal were established by serially connecting one damage body with one or two Newton body(s), to reveal the influences of rock(s) on the mechanical behavior of coal in coal-rock samples. Finally, test results were fitted using the two models. It was showed that the two models can accurately describe the stress-strain curves of coal in coal-rock samples and reflect the influences of rock(s), coal-rock combination form and coal-rock height ratio. The fitting constants of the two models have clear physical meanings and can be easily obtained, which are expected to be widely used in underground engineering.

1. Introduction

Coal is a complex fractured geological medium containing numerous randomly distributed micro holes and cracks. Its mechanical properties are important essential parameters for the mining design, roadway support and some other underground coal engineering.[1–4] Experiments have been conducted to study the mechanical behaviors of coal subjected to different types of loads, e. g. uniaxial loading, cyclic loading and triaxial loading, and it is showed that they can accurately accord with the deformation and failure evolution law of pure coal mass.[5–9] However, the coal and rock mass bear loads together in underground engineering, which results in that the mechanical behavior of underground coal mass is greatly different from that of pure coal samples.[10–15] In other words, there would be significant errors to reveal the deformation and failure characteristics of the underground coal mass on the basis of experimental results of pure coal samples. Therefore, researchers proposed to build a kind of coal-rock combined sample and use its mechanical properties as foundation to forecast the deformation and failure of the underground coal mass, as shown in Fig. 1.[16–25]

In recent years, experiments on the mechanical properties of coal-rock combined samples subjected to different loads have been conducted, and the failure precursor information was obtained by means of acoustic-electric effect and/or seismic spectrum analysis.[23–39] Petukhov and Linkov[16] discussed the stability of two-body combined samples composed of coal and roof or floor rock. Dou et al.[25–27] and Tan et al.[28–30] tested the impact tendency of coal–rock combined samples and obtained the influences of rock strength and coal-rock height ratio. Zhao et al.[31–33] and Guo et al.[34] studied the effect of contact angle on the strength and failure evolution of coal-rock combined samples under uniaxial and tri-axial loadings. Zhang et al.[35] and Zhao et al.[36] studied the differences of two-body and three-body coal-rock combined samples in strength and failure behavior. Huang and Liu[37] tested the effect of loading rate on the mechanical behavior of coal-rock combined samples. Zuo et al.[38] studied the rupture evolution behavior of coal-rock combined samples under cyclic loadings using acoustic emission system. Wang et al.[39] and Li et al.[40] did a research on the sliding characteristics and shear strength of coal-rock structure. Some other

* Correspondence to: Shandong University of Science and Technology, 579 Qianwangang Road, Economic & Technical Developing Zone, Qingdao, Shandong Province 266590, China.
E-mail addresses: xuesheng1134@163.com, yunliangtan@163.com (Y.L. Tan).

https://doi.org/10.1016/j.ijrmms.2018.07.020
Received 4 December 2017; Received in revised form 7 May 2018; Accepted 31 July 2018

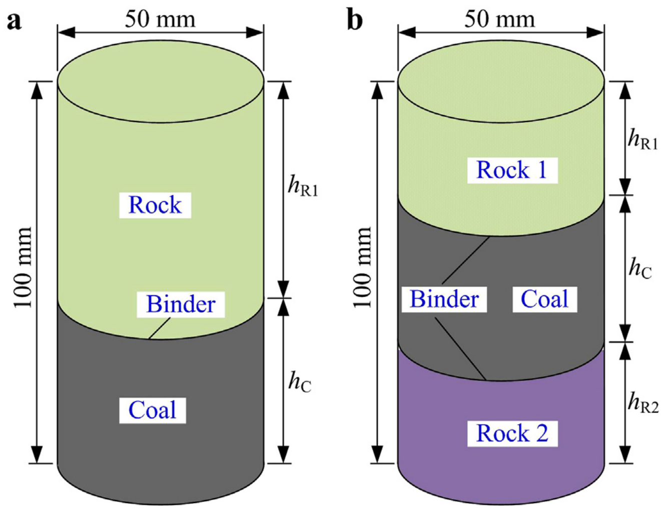

Fig. 1. Coal-rock combined bodies. (a) two-body combination form; (b) three-body combination form.

researchers[23,24,41–43] studied the electromagnetic radiation characteristics of the combined sample subjected to different loadings.

Except for experimental studies, Gao et al.[44] and Pan et al.[45] established a cusp catastrophe model for the two-body system and used it to analyze the unstable failure process of coal pillars. Zhao et al.[46] derived the compression–shear strength criterion of coal–rock combined bodies considering interface effect based on the strain energy equivalency principle. Liu et al.[47] analyzed the failure criterion and energy evolution of coal-rock combined samples under static-dynamic loadings. Both the testing results and theoretical analysis showed that the mechanical properties of coal-rock combined samples were quite different from these of pure coal samples and they were much closer to the true behavior of coal mass in underground engineering. And the mechanical properties were greatly influenced by rock properties, coal-rock height ratio and combination form, contact angle, loading mode, etc.

However, existing researches mainly focused on the mechanical behavior of the whole combined body, while the deformation and failure evolution of coal section in the combined body have not been seen in literature. As the mechanical behavior of coal in the combined body is different from that of the whole combined body, obtaining the mechanical properties of coal in the combined body can provide a basis for the design and assessment of the underground coal engineering. This paper first proposed a test method to obtain the stress and strain of coal in coal-rock combined samples and introduced a validation method for this test method. Then uniaxial loading tests were conducted on thirteen types of coal-rock combined samples and the mechanical properties of the coal sections were analyzed. Finally, two damage constitutive models were established to describe the deformation and failure evolution of coals in the combined samples. Additionally, the comparison between the fitted results from the models and the experimental results was conducted.

2. Test method and results

2.1. Sample preparation

There were three kinds of rock samples (sandy conglomerate, siltstone and medium sandstone) and one kind of coal sample: the sandy conglomerate and siltstone samples were taken from the roof of no. 3–5 coal seam, Tongxin Mine, Shanxi Province, China; the coal and medium sandstone samples were respectively taken from no. 2–2 coal seam and its roof, Gaojialiang Mine, Inner Mongolia, China. The natural samples obtained on site were sealed with plastic film to prevent the change of water content and maintain their original state. The sandy conglomerate and siltstone were even-textured and compact with a brittle property and a high strength. The medium sandstone was well cemented with a plastic property. The coal was simple in structure with a low strength. These materials were processed into cylinders with the diameter of 50 mm, and the heights of the cylinders ranged from 25 mm to 100 mm. According to the ISRM Suggested Methods for Rock Characterization, Testing and Monitoring, the samples were ground to make both ends of the cylinders parallel and smooth. According to Fig. 1, one coal sample and one or two rock sample(s) were glued together using Deli 502 super glue to make a 100 mm high coal-rock combined sample. As the Deli 502 super glue is very thinning, the width of adhesive substances on the interface between rock and coal sample is very small and can be neglected. There were three types of pure rock samples, one type of pure coal samples and thirteen types of coal-rock combined samples in total, and each type had at least three samples. The sample labels, combination forms and coal-rock height ratios were listed in Table 1.

Table 1
The lithology combinations and coal-rock height ratios of the samples.

Sample label	Lithology	Rock-coal-rock height ratio	Density /(kg/m^3)
SCR	Sandy conglomerate	1–0–0	2636.64
SR	Siltstone	1–0–0	2455.45
MSR	Medium sandstone	1–0–0	2254.33
CM	Coal	0–1–0	1328.85
SCRM	Sandy conglomerate–Coal	1–1–0	–
SRM1	Siltstone–Coal	1–1–0	–
MSRM	Medium sandstone–Coal	1–1–0	–
SRM2	Siltstone–Coal	3–1–0	–
SRM3	Siltstone–Coal	2–1–0	–
SRM4	Siltstone–Coal	1–1.5–0	–
SRM5	Siltstone–Coal	1–2–0	–
SCR2M	Sandy conglomerate–Coal–Sandy conglomerate	1–1–1	–
SR2M	Siltstone–Coal–Siltstone	1–1–1	–
MSR2M	Medium sandstone–Coal–Medium sandstone	1–1–1	–
SCRMS	Sandy conglomerate–Coal–Siltstone	1–1–1	–
SCRMM	Sandy conglomerate–Coal–Medium sandstone	1–1–1	–
SRMM	Siltstone–Coal–Medium sandstone	1–1–1	–

2.2. Test method and validation

2.2.1. Test method

As shown in Fig. 1, the coal and rock in coal-rock combined samples are connected as designed. When the combined sample subjected to static loading, the stresses in the coal section, rock section(s) and the whole combined sample are equal during the loading process, as follows:

$$\sigma_M = \sigma_{Ri} = \sigma_w \tag{1}$$

where σ_M is the stress in the coal section; σ_{Ri} is the stress in the i-th rock section; σ_w is the stress of the whole combined sample.

The axial deformation of the combined sample is equal to the sum of the axial deformations of the coal and rock sections, as follows:

$$\Delta H = \Delta h_M + \sum \Delta h_{Ri} \tag{2}$$

where $\triangle H$ is the axial deformation of the combined sample; $\triangle h_M$ is the axial deformation of the coal section; $\triangle h_{Ri}$ is the axial deformation of the i-th rock section.

When a coal-rock combined sample is loaded on a test equipment (e.g., rock servo-controlled testing machine, Shimadzu precision universal tester, and rheological testing machine), the stress and axial deformation of the combined sample, σ_w and $\triangle H$, could be acquired