8. Karin, M., How NF-kappaB is activated: the role of the IkappaB kinase (IKK) complex. *Oncogene*, 1999, **18**, 6867–6874; doi: 10.1038/sj.onc.1203219.
9. Rayet, B. and Gelinas, C., Aberrant *rel*/*nfkb* genes and activity in human cancer. *Oncogene*, 1999, **18**, 6938–6947; doi:10.1038/sj.onc.1203221.
10. Barakat, A. F., Elson, C. J. and Westacott, C. I., Susceptibility to physiological concentrations of IL-1beta varies in cartilage at different anatomical locations on human osteoarthritic knee joints. *Osteoarthritis Cartilage*, 2002, **10**, 264–269; doi:10.1053/joca.2002.0515.
11. Rasmussen, M. K. *et al.*, IL-8 and p53 are inversely regulated through JNK, p38 and NF-kappaB p65 in HepG2 cells during an inflammatory response. *Inflamm. Research: Off. J. Eur. Histamine Res. Soc.*, 2008, **57**, 329–339; doi:10.1007/s00011-007-7220-1.
12. Moynagh, P. N., Williams, D. C. and O'Neill, L. A., Interleukin-1 activates transcription factor NF kappa B in glial cells. *Biochem. J.*, 1993, **294**(Pt 2), 343–347.
13. Li, W., Tan, D., Zenali, M. J. and Brown, R. E., Constitutive activation of nuclear factor-kappa B (NF-kB) signaling pathway in fibrolamellar hepatocellular carcinoma. *Int. J. Clin. Exp. Pathol.*, 2009, **3**, 238–243.
14. Nagel, D., Vincendeau, M., Eitelhuber, A. C. and Krappmann, D., Mechanisms and consequences of constitutive NF-kappaB activation in B-cell lymphoid malignancies. *Oncogene*, 2014, **33**, 5655–5665; doi:10.1038/onc.2013.565.
15. Neil, J. R. and Schiemann, W. P., Altered TAB1 : I kappaB kinase interaction promotes transforming growth factor beta-mediated nuclear factor-kappaB activation during breast cancer progression. *Cancer Res.*, 2008, **68**, 1462–1470; doi:10.1158/0008-5472.CAN-07-3094.
16. Lu, M. *et al.*, XIAP induces NF-kappaB activation via the BIR1/TAB1 interaction and BIR1 dimerization. *Mol. Cell*, 2007, **26**, 689–702; doi:10.1016/j.molcel.2007.05.006.
17. Tak, P. P. and Firestein, G. S., NF-kappaB: a key role in inflammatory diseases. *J. Clin. Invest.*, 2001, **107**, 7–11; doi:10.1172/JCI11830.
18. Baker, R. G., Hayden, M. S. and Ghosh, S., NF-kappaB, inflammation, and metabolic disease. *Cell Metab.*, 2011, **13**, 11–22; doi:10.1016/j.cmet.2010.12.008.
19. O'Sullivan, B., Thompson, A. and Thomas, R., NF-kappa B as a therapeutic target in autoimmune disease. *Expert Opin. Therap. Targets*, 2007, **11**, 111–122; doi:10.1517/14728222.11.2.111.
20. Karin, M., NF-kappaB as a critical link between inflammation and cancer. *Cold Spring Harbor Perspect. Biol.*, 2009, **1**, a000141; doi:10.1101/cshperspect.a000141.
21. Wu, B. Y., Woffendin, C., Duckett, C. S., Ohno, T. and Nabel, G. J., Regulation of human retroviral latency by the NF-kappa B/I kappa B family: inhibition of human immunodeficiency virus replication by I kappa B through a Rev-dependent mechanism. *Proc. Natl. Acad. Sci. USA*, 1995, **92**, 1480–1484.
22. Zhao, Y., Krishnamurthy, B., Mollah, Z. U., Kay, T. W. and Thomas, H. E., NF-kappaB in type 1 diabetes. *Inflamm. Allergy Drug Targets*, 2011, **10**, 208–217.

ACKNOWLEDGEMENT. This work was supported by the Indian Institute of Technology Kanpur grant IITK/CHE/20090282 to RS.

Received 26 December 2016; revised accepted 7 July 2017

doi: 10.18520/cs/v113/i11/2168-2174

Experimental analysis of the ratio of similar materials by similarity model test on raw coal

Fan Zhang[1,*], Geng Ma[1–3], Xiao Liu[1], Yunqi Tao[1–3], Rui Li[4] and Dan Feng[5]

[1]School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454003, China
[2]Research Institute of Henan Energy Resource and Chemical Industry Group Co, Ltd, Zhengzhou, Henan 450046, China
[3]Henan Engineering Research Center of Simultaneous Extraction of Coal and Gas with Low Permeability and Outburst Coal Seam, Zhengzhou 450046, China
[4]Applied Technical College, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China
[5]State Key Laboratory for Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China

Similarity model test is an effective approach to study the mechanism of hydraulic fracture propagation in coalbed methane reservoirs as well as theoretical analysis and numerical simulation. The efficiency of the similarity model test result is closely related to the selection and ratio of similar materials. Similar material ratio test was conducted to simulate the mechanical parameters of raw coal using orthogonal method and an appropriate similarity model for hydraulic fracturing experiment was developed in this study. Results show that it is suitable to select cement, gypsum as binder and apply pulverized coal as aggregate through the analysis of experimental data. The mechanical parameters of similar materials, including uniaxial compressive strength, elastic modulus, Poisson ratio and firmness coefficient are tested using laboratory tests. The impact of diverse ratios of similar materials on the mechanical parameters is analysed. A proper ratio is selected to make the mechanical parameters of raw coal close to the ones of similar material, in order to meet the demand of the similarity model test based on raw coal. The results can provide theoretical basis and technical support for the selection of similar materials to carry out hydraulic fracturing experiments.

Keywords: Experimental investigation, hydraulic fracturing, raw coal, similar materials, mechanical parameters.

COALBED methane (CBM) reserves are abundant in China, ranking third in the world, but have the characteristics of low permeability, saturation and porosity, which make it difficult to realize commercial development of CBM[1]. Hydraulic fracturing technology can effectively improve coal reservoir permeability, and prevent coal and gas outburst[2–5]. Hydraulic fractures are the main channel for CBM; the efficiency of hydraulic fracturing depends

*For correspondence. (e-mail: CZzhangfan0210@126.com)

on not only the geometric size of the fracture, but also its conductivity. High conductivity of hydraulic fracture is one of the main factors affecting the high and stable yield of CBM. However, the study of hydraulic fracture morphology and propagation is not sufficient. At the same time, there is no perfect device to observe the initiation and propagation of hydraulic fractures in coal and rock seam[6]. So it is necessary to conduct simulation experiments for exploring the generation, morphological characteristics and expansion law of hydraulic fracture[7–9].

However, the collection, transportation and processing of raw coal from coal mines are difficult and expensive. Similar simulation has gradually become an important method to study specific engineering problems in mining and rock engineering. Several books and papers, especially on hydraulic fracturing experiments[10–12] have been published[13–15]. Thus physical simulation experiment of hydraulic fracturing has been adopted by a majority of scholars[16,17]. Nevertheless, the choice of similar materials and ratio is the main factor influencing experimental results. Right selection of similar materials not only plays a decisive role in the accuracy of experimental research, but is also important in the simulation of engineering problems.

In this communication, the uniqueness of the experiment is highlighted as follows. First, the selection of similar materials applied in hydraulic fracturing simulation experiment was analysed after a series of comparisons based on similarity principle. Secondly, a ratio plan with three factors and five levels was designed. Finally, the mechanical properties of different ratios of similar materials were tested using different devices. The research findings can provide theoretical basis and technical support for the selection of similar materials to replace raw coal.

The standard principle of similarity model test indicates that the model has good agreement with the prototype in geometric shape, mechanical properties and deformation characteristics, which can help reproduce the physical characteristics of the prototype. The similarity scale C is the ratio of the physical quantities of the same dimension between the prototype and the model. The similarity between the prototype and the model can be deduced according to the dimensional method.

$$C_\varepsilon = C_\varphi = C_{k_d}, \quad (1)$$

$$C_\delta = C_\varepsilon C_l, \quad (2)$$

$$C_\sigma = C_\gamma C_l = C_E C_\varepsilon, \quad (3)$$

$$C_\sigma = C_E = C_{\sigma_c} = C_{\sigma_t} = C_c, \quad (4)$$

$$C_k = C_t = (C_l/C_\gamma)^{1/2}, \quad (5)$$

where C_ε, C_φ, C_{k_d}, C_δ, C_l, C_σ, C_γ, C_E, C_c, C_{σ_c}, C_{σ_t}, C_k, C_t are the similarity coefficients of the strain, internal friction angle, softening coefficient, displacement, geometric size, stress, severe, elastic modulus, cohesion, compressive strength, tensile strength, permeability coefficient and time respectively. In this study, the similarity ratio of elastic modulus is one, so the five parameters are all one deduced from eq. (4).

The raw coal simulated here is selected from no. 4 coal seam of Yonggui Energy Xintian Coal Mine of Henan Energy and Chemical Industry Group Co Ltd, China. Hydraulic fracturing can only be carried out in hard coal seam. The mechanical parameters of structural coal in the coal seam are measured; its uniaxial compressive strength is 8.53 MPa, tensile strength is 0.63 MPa, elastic modulus is 0.82 GPa, Poisson ratio is 0.28 and firmness coefficient is 0.80. Sedimentary rocks are usually composed of aggregates and cements; so it is approximate to simulate sedimentary rocks with aggregates and cements. The aggregate materials include sand, iron powder, barite powder, aluminum powder and pumice powder. The cement materials contain gypsum, lime, cement, kaolin, paraffin and water glass[18,19]. The mechanical properties of binder influence the ones of similar materials greatly.

Whether similar simulation experiment can be conducted successfully depends on whether the mechanical properties of similar materials and the ones of raw coal are close. Most of the characteristics of similar materials should be close to raw coal. Therefore, the selection of similar materials and the ratio has a significant influence on the physical mechanical properties of the sample, which is the most important factor for successful similar simulation experiments. When it comes to selecting similar materials, the following rules should be obeyed. First, the main mechanical properties of similar materials are similar to those of raw coal. Secondly, the mechanical parameters greatly change to facilitate the selection and differentiation after changing the proportion. Finally, the solidification time is short and the price is low.

Gypsum has a significant influence on the strength of similar materials, the range of elastic modulus and compressive strength vary for different gypsum contents; so it is one of the most widely applied plastic materials. Cement has high strength and can quickly improve the strength of similar materials. Pulverized coal is more capable of simulating the deformation and failure characteristics of raw coal, and the strength of the sample is linearly negatively correlated to the amount of pulverized coal. Thus in this study, cement and gypsum are selected as binder while pulverized coal is applied as aggregate.

In order to make the mechanical parameters of raw coal close to the ones of similar materials, the mechanical parameters of similar materials were studied based on the experimental programme compared with the quoting references (Table 1).

Based on Table 1, different kinds of similar materials were made into samples of dimensions 200 mm × 200 mm × 200 mm. First, pulverized coal, cement and gypsum were measured using electronic scale. Then, the similar materials were mixed thoroughly in case the distribution of components in every part of the sample was not uniform; this may affect the mechanical parameters of similar materials. Secondly, water was poured into the mould and stirred well so as to remove bubbles from the mixture. Finally, after maintenance of 30 days, the samples were made into different specifications to meet the requirements of mechanical experiments, including the process of coring, cutting, grinding, etc. (Figure 1).

Similar materials should follow certain similarity with the mechanical parameters of raw coal to ensure accuracy of the experiment. However, the geological structure varies in coal seam, and the movement and deformation of raw coal are complex. Measuring the influences of individual geological parameters like existing fractures, cleats, grain boundary, etc. is not possible for all the similar materials. The key indexes of deformation, movement and destruction of overlying strata are compressive strength and tensile pressure. The basic failure modes are shear and pull-out. The deformation of raw coal is correlated to elastic modulus and Poisson ratio. Therefore, the main strength parameters are compressive strength and firmness coefficient, while the main deformation indexes are elastic modulus and Poisson ratio.

Figure 2 shows the device for uniaxial compression experiment (AGI 250 Electronic Precision Materials Testing Machine). In the process of testing uniaxial compression, the axial and radial deformation of the samples were tested using a stress plate. Poisson ratio was calculated in the elastic stage using strain gauge which was

Table 1. Proportion of similar materials

	Similar materials		
Sample group	Cement	Gypsum	Pulverized coal
A	1.0	1.0	1.0
B	1.0	1.0	1.5
C	1.5	1.0	1.0
D	1.0	2.0	1.0
E	2.0	1.0	1.0

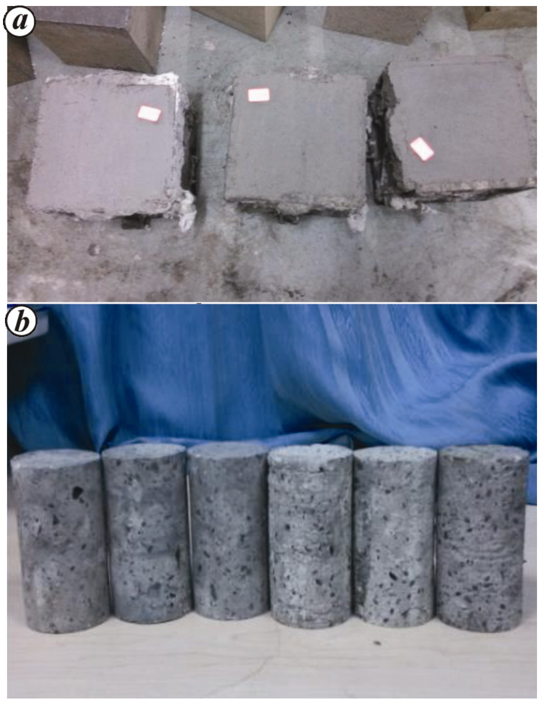

Figure 1. Samples for uniaxial compression test. ***a***, Cube samples made of similar materials; ***b***, Standard experimental samples.

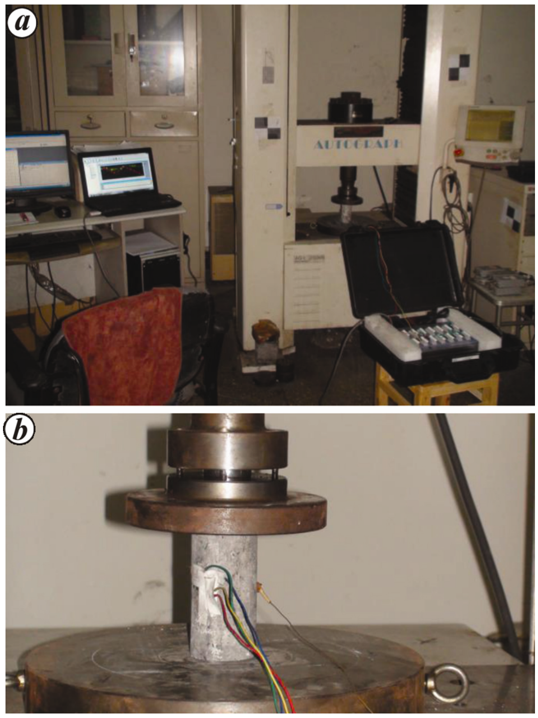

Figure 2. Uniaxial compression test device. ***a***, Test system; ***b***, Device for stress loading.

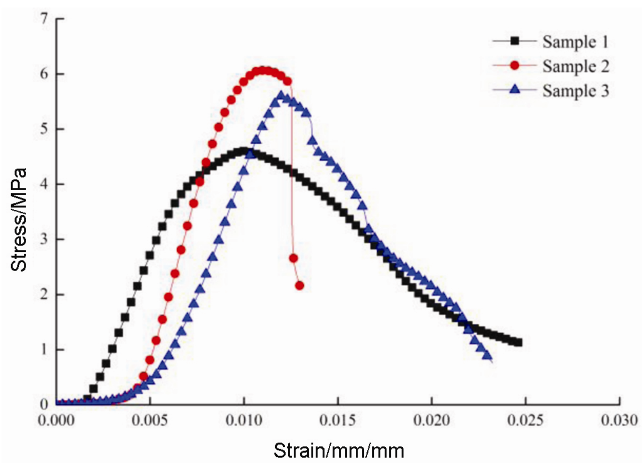

Figure 3. Stress–strain curves of samples.

Table 2. Mechanical parameters of similar materials and raw coal

Samples		σ_c (MPa)		E (GPa)		μ	
Group	Number	Single	Average	Single	Average	Single	Average
A	1#	2.93	3.01	0.45	0.55	0.22	0.22
	2#	3.05		0.46		0.23	
	3#	3.04		0.74		0.21	
B	1#	5.44	5.41	0.75	0.75	0.18	0.17
	2#	5.01		0.65		0.17	
	3#	5.77		0.85		0.17	
C	1#	6.32	5.47	0.83	0.65	0.36	0.35
	2#	4.98		0.50		0.35	
	3#	5.12		0.63		0.33	
D	1#	3.21	3.13	0.63	0.66	0.25	0.28
	2#	3.18		0.79		0.27	
	3#	2.99		0.56		0.33	
E	1#	5.98	5.36	1.13	0.95	0.26	0.25
	2#	4.59		0.84		0.25	
	3#	5.51		0.88		0.24	
Raw coal		8.53			0.82	0.28	

Figure 4. Failure morphology of samples.

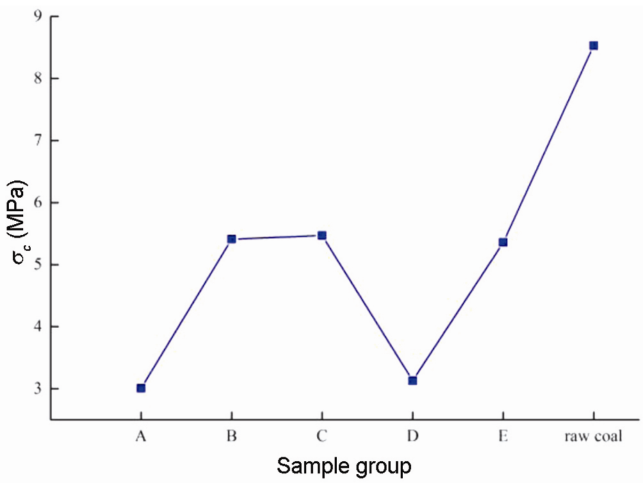

Figure 5. Uniaxial compressive strength of similar materials and raw coal.

T form. Then the compressive strength (σ_c), elastic modulus (E) and Poisson ratio (μ) of different similar materials were tested. The uniaxial compression experiment was controlled by displacement, the rate was 0.05 mm/min and the size of sample was 50 mm in diameter and 100 mm in height. Figure 3 shows the stress–strain curve of the sample while Figure 4 shows its failure mode. Table 2 provides the experimental results of similar materials.

Firmness coefficient (f) was tested by counter balance, measuring cylinder, sieve, a small hammer, funnel and other devices. The steps for testing were as follows: First, a small hammer was used to make samples of 20–30 mm weighting 50 g. Secondly, firmness coefficient was tested by drop hammer three times and similar materials of five groups were placed in a 0.5 mm diameter sieve for sieving. Finally, the sieved powder was put in a measuring cylinder, tapping gently to make it dense and the height of the powder was read from the measuring cylinder.

The firmness coefficient can be obtained by

$$f = \frac{2n}{L}, \tag{6}$$

where n is the number of shocks and L is the height of the powder read from the measuring cylinder. Table 3 shows results of firmness coefficient of similar materials.

The uniaxial compressive strength, elastic modulus, Poisson ratio and firmness coefficient of similar materials under different matching conditions were tested by carrying out a large number of comparisons. The influence of each component on the mechanical parameters was analysed (Table 4).

Figure 5 shows the uniaxial compressive strength of similar materials and raw coal, while Figure 6 shows their elastic modulus, Poisson ratio and firmness coefficient.

Table 3. Firmness coefficient of similar materials and raw coal

Group	Samples: Ratio cement : gypsum : pulverized coal	Samples: Number	*f*: Single	*f*: Average
A	1 : 1 : 1	1#	0.51	0.61
		2#	0.72	
		3#	0.59	
B	1 : 1 : 1.5	1#	0.62	0.64
		2#	0.66	
		3#	0.64	
C	1 : 0.67 : 0.67	1#	0.69	0.65
		2#	0.49	
		3#	0.78	
D	1 : 2 : 1	1#	0.60	0.58
		2#	0.59	
		3#	0.56	
E	1 : 0.5 : 0.5	1#	0.90	0.82
		2#	0.81	
		3#	0.75	
	Raw coal		0.80	

Table 4. Ratio of components and mechanical properties

Group	Ratio	σ_c	*E*	μ	*f*	Cement (%)	Gypsum (%)	Cement + gypsum (%)	Pulverized coal (%)
A	1 : 1 : 1	3.01	0.55	0.22	0.61	0.33	0.33	0.66	0.33
B	1 : 1 : 1.5	5.41	0.75	0.17	0.64	0.29	0.29	0.57	0.43
C	1.5 : 1 : 1	5.47	0.65	0.35	0.65	0.43	0.29	0.71	0.29
D	1 : 2 : 1	3.13	0.66	0.28	0.58	0.25	0.50	0.75	0.25
E	2 : 1 : 1	5.36	0.95	0.25	0.82	0.50	0.25	0.75	0.25
Raw coal	–	8.53	0.82	0.28	0.80	–	–	–	–

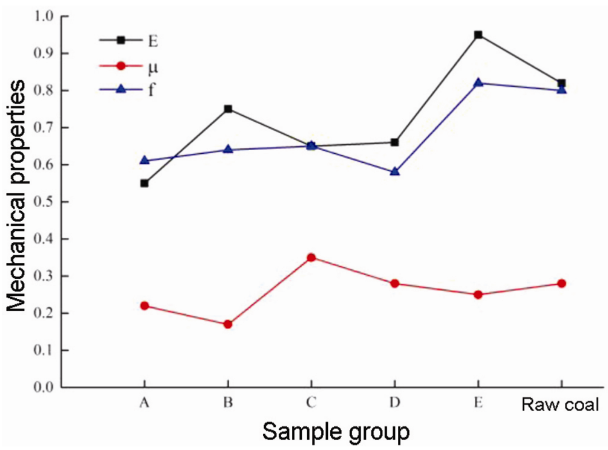

Figure 6. Mechanical properties of similar materials and raw coal.

It can be seen that the uniaxial compressive strength, elastic modulus and firmness coefficient of groups B, C and E are larger than those of group A (Table 4), while the relationship between Poisson ratio and cement content is not obvious. Based on the percentage of cement in group A, it is found that the mechanical properties of similar materials vary with changing cement content. The results show that the uniaxial compressive strength and firmness coefficient increase with the increase in cement percentage; thus cement can significantly increase the strength of similar materials.

According to the percentage of gypsum in the ratio of group A, it can be seen that the relationship of similar materials and raw coal is not obvious in terms of uniaxial compressive strength, elastic modulus, Poisson ratio and firmness coefficient. The results show that the change in gypsum content in cementing agent leads to a wide range of mechanical properties of similar materials.

It can be seen that the uniaxial compressive strength and elastic modulus of groups B–E are larger than those of group A, while the relationship of similar materials and the percentage of cement and gypsum in the terms of Poisson ratio is not obvious, as shown in Table 4. Comparing with the percentage of cement and gypsum in group A, the mechanical properties change with the cement and gypsum content. Thus cement and gypsum content have obvious effects on the mechanical properties of similar materials.

It can be seen from Table 4 that although the percentage of pulverized coal in groups C–E is smaller than that in group A, the uniaxial compressive strength, elastic modulus and Poisson ratio are larger and the firmness coefficient is smaller than those of group A. While pulverized coal in group B is more than that in group A, uniaxial compressive strength and elastic modulus are larger than those of group A; Poisson ratio of group B is smaller than that of group A. The results show that with the increase of aggregate, Poisson ratio decreases and there is a negative correlation between them.

Comparison of the five groups indicates that the uniaxial compressive strengths of similar materials of groups B, C and E are close to 5.55 MPa. The uniaxial compressive strengths of groups A and D are close to 3.10 MPa. Based on the uniaxial compressive strength of these similar materials, the ratio of groups B, C and E is selected, which is similar to the mechanical properties of raw coal. In addition, the firmness coefficients of groups A, C and D are similar. Among groups A, C and E, the firmness coefficient of group E is the largest, which is very close to the one of raw coal. Therefore, from the point of firmness coefficient, the ratio E is selected. The elastic modulus and Poisson ratio of group E are similar to those of raw coal.

Thus from the above discussions, the ratio of cement, gypsum and pulverized coal is selected to form samples for hydraulic fracturing simulation experiment.

Due to the difficulties in collecting and processing of raw coal from coal mines, three kinds of materials were selected as similar materials through experimental analysis. According to the ratio of similar materials, a series of experiments were carried out. Poisson ratio and firmness coefficient were similar to the mechanical properties of raw coal. The experimental results are as follows.

(a) Based on a large number of papers and a series of experiments, similar materials for the raw coal model were developed. Among them, cement and gypsum were selected as cementing agents, which had obvious influence on the mechanical properties for different contents. The pulverized coal was applied to the aggregate, which represented the destruction and mechanical properties of raw coal.

(b) The strength of similar materials was significantly affected by the content of cementing agent. The increase in cement content resulted in an increase in firmness coefficient. The change in gypsum content induced a wide range of the mechanical properties of similar materials. While Poisson ratio of similar materials decreased with the increase in the content of pulverized coal.

(c) The experimental results indicate that the mechanical properties of similar materials are similar to those of raw coal, when the proportion of cement, gypsum, and pulverized coal is 2 : 1 : 1. Thus, this ratio of similar materials could replace raw coal in engineering applications.

1. Shikuo, C., Tianhong, Y., Ranjith, P. G. and Chenhui, W., Mechanism of the two-phase flow model for water and gas based on adsorption and desorption in fractured coal and rock. *Rock Mech. Rock Eng.*, 2017, **50**, 571–586.
2. Dehghan, A. N., Goshtasbi, K., Ahangari, K., Jin, Y. and Bahmani, A., 3D numerical modeling of the propagation of hydraulic fracture at its intersection with natural (pre-existing) fracture. *Rock Mech. Rock Eng.*, 2017, **50**, 367–386.
3. Tiankui, G., Zhang, S., Zhanqing, Q., Tong, Z., Yongshun, X. and Jun, G., Experimental study of hydraulic fracturing for shale by stimulated reservoir volume. *Fuel*, 2014, **128**, 373–380.
4. He, Q., Suorineni, F. T. and Oh, J., Review of hydraulic fracturing for preconditioning in cave mining. *Rock Mech. Rock Eng.*, 2016, **49**(12), 4893–4910.
5. Shangyu, Y., Xingru, W., Lihong, H., Jianjun, W. and Yaorong, F., Migration of variable density proppant particles in hydraulic fracture in coal-bed methane reservoir. *J. Nat. Gas Sci. Eng.*, 2016, **36**, 662–668.
6. Yiyu, L., Liang, C., Zhaolong, G., Binwei, X., Qian, L. and Jiufu, C., Analysis on the initial cracking parameters of cross-measure hydraulic fracture in underground coal mines. *Energies*, 2015, **8**(7), 6977–6994.
7. Bingxiang, H., Changyou, L., Junhui, F. and Hui, G., Hydraulic fracturing after water pressure control blasting for increased fracturing. *Int. J. Rock Mech. Min. Sci.*, 2011, **48**, 976–983.
8. Wang, Y., Li, X. and Zhang, B., Analysis of fracturing network evolution behaviors in random naturally fractured rock blocks. *Rock Mech. Rock Eng.*, 2016, **49**, 4339–4347.
9. Jian, Z., Mian, C., Yan, J. and Guangqing, Z., Analysis of fracture propagation behavior and fracture geometry using a tri-axial fracturing system in naturally fractured reservoirs. *Int. J. Rock Mech. Min, Sci.*, 2008, **45**, 1143–1152.
10. Guo, C. H., Xu, J. C., Wei, M. Z. and Jiang, R. Z., Experimental study and numerical simulation of hydraulic fracturing tight sandstone reservoirs. *Fuel*, 2015, **159**, 334–344.
11. Estrada, J. M. and Rao, B., A review of the issues and treatment options for wastewater from shale gas extraction by hydraulic fracturing. *Fuel*, 2016, **182**, 292–303.
12. Jianpeng, Z., Weizhong, C., Jingqiang, Y., Diansen, Y. and Jianping, Y., 3-D numerical simulation of hydraulic fracturing in a CBM reservoir. *J. Nat. Gas Sci. Eng.*, 2017, **37**, 386–396.
13. Kui, L., Deli, G., Yanbin, W. and Yuanchao, Y., Effect of local loads on shale gas well integrity during hydraulic fracturing process. *J. Nat. Gas Sci. Eng.*, 2017, **37**, 291–302.
14. Xie, L. M., Min, K.-B. and Shen, B. T., Simulation of hydraulic fracturing and its interactions with a preexisting fracture using displacement discontinuity method. *J. Nat. Gas Sci. Eng.*, 2016, **36**, 1284–1294.
15. Zhipeng, X., Zhiye, Z., Jianping, S. and Ming, L., Determination of hydraulic conductivity of fractured rock masses: a case study for a rock cavern project in Singapore. *J. Rock Mech. Geotech. Eng.*, 2015, **7**, 178–184.
16. Dazhao, S., Zhentang, L., Enyuan, W., Limin, Q., Qinqing, G. and Zhaoyong, X., Evaluation of coal seam hydraulic fracturing using the direct current method. *Int. J. Rock Mech. Min. Sci.*, 2015, **78**, 230–239.
17. Huiying, T., Winterfeld Philip, H., Yushu, W., Zhaoqin, H., Yuan, D., Zhengfu, P. and Juncheng, Z., Integrated simulation of multi-stage hydraulic fracturing in unconventional reservoirs. *J. Nat. Gas Sci. Eng.*, 2016, **36**, 875–892.
18. Xiao, L., Haixiao, L. and Fan, Z., Study on ratio of similar materials based on coal mass strength. *Comput. Modell. New Technol.*, 2014, **18**(12), 336–340.
19. Wenyan, Z., Mohamed, Z. and Yukio, H., Influence of aggregate materials characteristics on the drying shrinkage properties of mortar and concrete. *Const. Build. Mater.*, 2013, **49**, 500–510.

ACKNOWLEDGEMENTS. This work was supported by the Innovative Talent Team Construction Project of Science and Technology of Henan Province (No. 164100510024); Science and Technology Research Project of Henan Province in 2015 (No. 152102310095); Major work on Innovation Methods of the Ministry of Science and Technology of China in 2016 (No. 2016IM010400) and National Natural Foundation of China (No. 71472171).

Received 5 April 2017; revised accepted 8 July 2017

doi: 10.18520/cs/v113/i11/2174-2179