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Application of simulation material for water-resisting soil layer in mining physical simulation[1]

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Abstract. In order to study the failure mechanism of water-resisting soil layer under both coal excavation and seepage effect, a new kind of experimental material for fluid-solid physical simulation (FPS) has been established. The material adopts river sand and clay as the aggregates, besides engine oil and low-temperature grease are used as the gelatinizing agents. According to relevant property testing on the experimental material, the mechanical parameters and seepage parameters of the material totally match the parameters of the soil layer, and meets the requirements of the fluid-solid coupling experiment. A FPS model has been constructed to simulate coal excavation under water-bearing strata with the specific material. The results indicated that movement and failure mechanism of the water-resisting soil layer agree with the in-situ monitoring results. In addition, revolution law of mining-induced crack also matched the actual data. The mechanism of submarine seepage and its parameters on the material and the prototype are similar. Meanwhile, the model demonstrates that selection of the material and coupling parameters are effective and correct.

Key words. Water-resisting soil layer, physical simulation, fluid-solid coupling, simulation material, mining-induced destroy.

1. Introduction

Physical simulation, as an experimental methodology combining simulation theory and dimensional analysis, was introduced to solve mining problems [1]. As we know that fluid-solid coupling is interaction between fluid (water) and solid (rock and soil) in geotechnical engineering [2]. The coupling effect contains deformation and failure of the rock and soil and flow characteristics from the fluid [3]. So we mainly study evolution mechanism of mechanical behavior and seepage trait after rock and soil failure with fluid flowing [4]. Many field of engineering technology would relate

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the fluid-solid problems like mining engineering, petroleum engineering, hydraulic and hydro-Power engineering and so on [5]. An accurate mechanism on fluid-solid coupling can control failure of water-resisting soil layer by mining excavation [6]. We studied the mechanism on fluid-solid coupling by theoretical analysis and numerical simulation. Now fluid-solid physical simulation is a new way. In the way, we can determine experimental settings such as single factor or multi-factor. Particularly, in the fluid-solid physical simulation with multi-factor, we need design fluid feature into the research course but not general simulation by only solid material.

Simulation principle of fluid-solid coupling needs determine simulation coefficients of elastics mechanics and hydromechanics of fluid-solid media desperately in the same settings with fluid-solid coupling theoretical model for continuous medium. When we determine the simulation coefficients, simulation constants in the hydromechanics should be replaced with simulation constants in the elastics mechanics, which can achieve fluid-solid coupling simulation.

$$\begin{cases} [T]\left\{H\right\}+[S]\left\{\frac{\partial H}{\partial t}\right\}+\left\{I\right\}=0, \\ \left\{R\right\}[B]\left\{\Delta\delta\right\}_{\epsilon}=\frac{n\gamma}{E_{\mathrm{w}}}\Delta H, \\ \left\{F_{\mathrm{w}}\right\}+\left\{\Delta F_{\mathrm{w}}\right\}=[K]\cdot\left[\left\{\delta\right\}_{\epsilon}+\left\{\Delta\delta\right\}_{\epsilon}\right], \end{cases} \tag{1}$$

where $[T]$, $[S]$ and $\{M\}$ are transmission matrix, storage matrix and converge column matrix, respectively. Symbols $\{R\}$, $[B]$ and δ_{ϵ} are unit vector, unit stain vector and unit displacement vector, respectively. Symbols n, γ and H are crack rate of rock-masses, water unit weight and underwater head, respectively. Symbols $\{F_{\mathrm{w}}\}$ and $\{\Delta F_{\mathrm{w}}\}$ are equivalent nodal force by body force from water seepage and relevant equivalent node force increment. Finally, $[K]$ is the global stiffness matrix for the simulation model.

According to simulation theory in elastics mechanics, $C_{\mathrm{G}}=C_{\mathrm{E}}=C_{\lambda}$. Besides, geometry, stress and inertia force simulation settings are $C_{\mathrm{u}}=C_{\mathrm{l}}$, $C_{\mathrm{G}}=C_{\mathrm{E}}=C_{\gamma}C_{\mathrm{l}}$ and $C_{\mathrm{t}}=\sqrt{C_{\mathrm{l}}}$ apart.

According to simulation theory in hydromechanics, converge column, seepage coefficient and storage rate simulation settings are, respectively

$$C_{\mathrm{I}}=\frac{1}{C_{\mathrm{t}}}=\frac{1}{\sqrt{C_{\mathrm{l}}}},\ C_{\mathrm{KX}}=C_{\mathrm{KY}}=C_{\mathrm{KZ}}=\sqrt{\frac{C_{\mathrm{l}}}{C_{\gamma}}},\ C_{\mathrm{S}}=\frac{C_{\mathrm{t}}C_{\mathrm{I}}}{C_{\mathrm{H}}}=\frac{1}{C_{\gamma}C_{\mathrm{l}}}\,.$$

The main ingredients of red clay aquiclude are red-brown clay, loam, mineral composition is mainly based chlorite, 11 % sand, 51 % silt, 38 % clay, void ratio is 0.6∼0.89, it is silty clay, compact structure, is in hard plastic state, and it has the high strength and low compressibility. The results of physical and mechanical parameters of soil samples are shown in Table 1.

In order to test the seepage deformation characteristics of soil under seepage flow, through the water head pressure applied, to Measure the hydraulic pressure on the soil. Main completed the clay try, grain size analysis, fluid density and water content, plastic limit and penetration test. Step by step under the set seepage water pressure on the upper load to stable. In the seepage water pressure for 10 kPa, 20 kPa, 30 kPa, 40 KPa cases of head seepage deformation test showed that the basic seepage deformation were positively correlated, stronger water-resisting layer. The experimental results are shown in Table 2.

Table 1. Physical and mechanical parameters on red clay

Physical properties				Mechanical properties			
Water content W (%)	Void ratio e	Porosity n (%)	Cohesive force c (kPa)	Internal friction angle φ (°)	Coefficient of compressibility (MPa^{-1})	Modulus of compression Es (MPa)	Unconfined compressive strength qn (kPa)
11.3∼17	0.6∼0.89	38∼46.1	42∼98	27.8∼33	0.1∼0.25	8∼21	110∼151

Table 2. Water-physical property of red clay

Lithology	Liquid limit W_1 (%)	Plastic limit (Wp) (%)	Permeability coefficient K (mm/h)	Saturability Sr (%)	Coefficient of collapsibility δ (s)	Flee welling ratio δct (%)
Red clay	25.1∼31.5	16.6∼18.3	10.24∼26.25	40.2∼65.5	0∼0.005	1∼18

In the physical simulation experiment, proper material selection would be crucial for the experiment. With relevant simulation theory, simulation material should satisfy the simulation principle for fluid-solid coupling and other basic properties. Specially, the simulation material for the fluid-solid coupling need be non-hydrophilic, low permeability and plastics deformation. Moreover, non-hydrophilic material is similar with the prototype in the mechanics characteristics aspect. We have finished related simulation material on rock-water two-phase experiment and confirmed low fusibility high quality paraffin (42 °–54 °) as the gelatinizing agents [7]. Simultaneously, simulation material should meet sealing, which do not influence the movement mechanism of rock and soil layer. In the end, we need simulate failure mechanism of the rock and soil layer and crack evolution characteristics. The crack would emerge by the mining excavation rather than artificial water seepage channel and water seepage through the crack should be visual.

In general, we made specimens with various matching on the aggregate and gelatinizing agent and obtained related mechanical and seepage parameters. We determine the aggregate by the prototype composition, property and experimental purpose. According to former research results, river sand and clay can get low strength simulation material. River sand mainly offers strength and brittleness. With the same relative density, internal friction angle of the river sand is larger due to larger superficial roughness of sand particle. When sand particle is oversize, permeability of the simulation material would increase remarkably. On the contrary, fine sand which has larger surface area, would integrate with the gelatinizing agent better. Material made by various particle size sand would reduce the void rate and when Cu>5, seepage rate of the material would decrease obviously. So the material should choose the river sand with good psephicity and small particle size.

Clay mainly represents plastics trait. According to geological investigation in coal mine restrict, north part of Shaanxi Province, China, stone loess is comprised by loam and sub-sand. Hipparion red soil is consist by clay, sandy clay with compact structure. Considering high content of mineral in the water-resisting clay, crack be induced by the coal excavation would be close promptly, so we should choose the clay with low permeability and solid deformation behavior .

Engine oil and low-temperature grease were chosen as the gelatinizing agents. Engine oil, which is the machine oil addicting thickening agent and lubricant additive presenting semi-solid state mechanical parts lubricant, was applied for controlling non-hydrophilia of the material. Besides, low-temperature grease called mineral grease, which was white or faint yellow cream, provided large plastic deformation. The grease had good stickiness, lipophilicity, high density and good waterproofness.

2. Materials and methods

2.1. Strength and water-physical property test

Strength and water-physical property test of the material would be crucial in the simulation material experiment. We adopted the technical geotechnical facilities to make the material specimens. Particularly, the gelatinizing agents, which has obvious influence on the material strength. We employed high precision physical balance to weigh up related indigents. Based on experimental matching, the aggregates and gelatinizing agents would be blended evenly with automatic agitator kettle. Simultaneously, we heated and stirred the mixture for two reasons: in one hand, the aggregates can mix with the gelatinizing agents after fusion; on the other hand, the mixture would be heated evenly. In order to ensure the specimens quality and take apart the specimen, we would smear lubricant on the internal surface of specimen mould before manufacturing the specimens, which can guarantee the specimen quality. The heated experimental materials were easy to bond the mould, so we used bi-partition mould to make cylinder specimens. The mixture would pour into the mould, and we tamped it tightly. When the experimental materials have been cooled, we took apart the relative mould. The specimens needed to be conserved due to low strength after taking apart the moulds. Each group with various matching has triple specimens being numbered for subsequent testing. We set ratio sand (S) with soil (T) 1:1 as initial value and obtained the mechanics and water-physical properties being influenced by the engine oil and low-temperature grease. Next, we altered the matching of the aggregates to obtain relevant impact on the properties. Fig. 1 to Fig. 2 indicated the relevant experiments. The results were shown that the specimen would disintegrate after 48 hour soaking. The experimental material was non-hydrophilia obviously. When the specimens were compressed, dilatation was clear in the center of specimens, which was similar with failure behavior of the water-resisting layer. Moreover, liquid limit moisture content of the material is 34.01 %, plastic limit moisture content is 25.21 %. Plastic index (IP) is 8.8 and liquidity index is ranged from 0.25 to 0.75 with good plasticity.

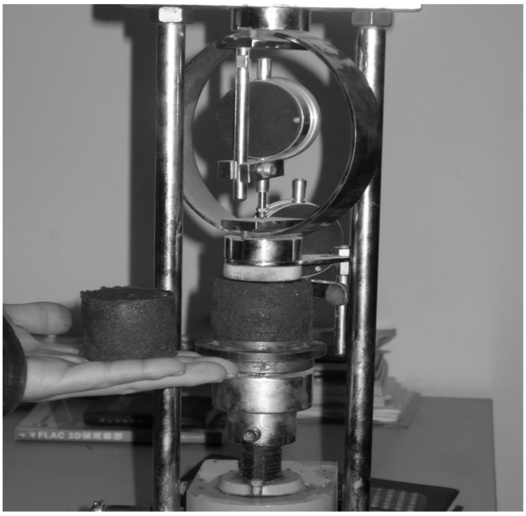

Fig. 1. Compressive strength testing

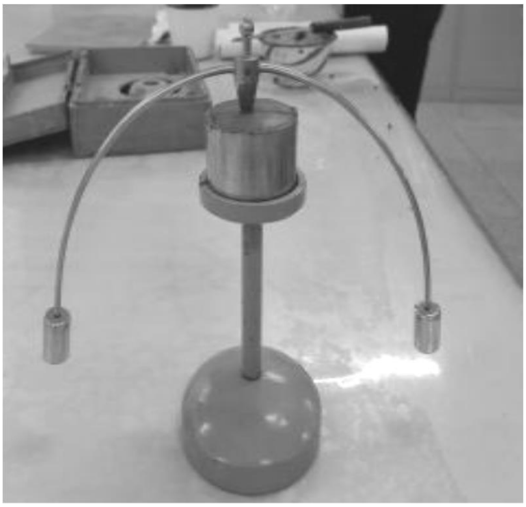

Fig. 2. Liquid and plastic limit testing

2.2. Material experiment analysis

Based on former abundant testing results, we have known the mechanics and water-physical properties of the materials basically. We schemed the various matching of sand and soil including 2:1, 1:1, 1:2, 1:3 and 1:5. Simultaneously, the gelatinizing agent ratio adopted 4:1, 6:1, 8:1 and 10:1. The relative results are shown below.

Material strength influence by the ratio between sand and soil. When the gelatinizing agent ratio was constant, sand as the aggregate had large impact on the material mechanics characteristics. Values of material strength and elastic modulus would increase to specific value and then decrease remarkably with the ratio decreasing. When the ratio was 2:1, the specimen strength was lower due to inadequate cement of the aggregates. When the ratio was 3:1, curve tendency after peak value was similar. When the gelatinizing agent ratio increased from 6:1 to 10:1, the gelatinizing agent had huge effect on deformation behavior of the materials. Fig. 3 shows stress-strain curve with various the ratio between sand and soil, when the gelatinizing agent ratio were 6:1 and 10:1, respectively.

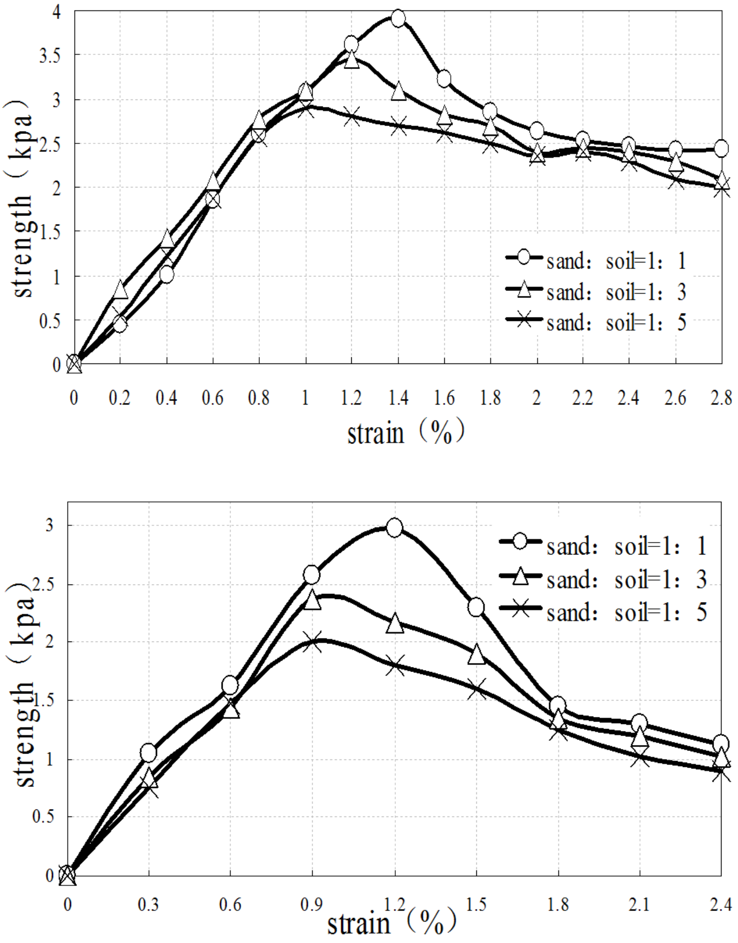

Fig. 3. Stress-strain curve in various ratios between sand and soil: up–gelatinizing agent ratio 10:1, bottom–gelatinizing agent ratio 6:1

Material strength influence by engine oil and low-temperature grease. Here, the influence was mainly performance on the plasticity of the material by engine oil, and low-temperature grease has large effect on the permeability behavior of the material. When we just use single kind of the gelatinizing agent, material strength always decreased with ratio between the aggregate and the gelatinizing agent decreasing. However, we adopted both gelatinizing agents for the simulation materials, which was better for the permeability experiment. Fig. 4 indicates stress-strain value on grease ratio with ratio between sand and soil 1:3 and 1:5.

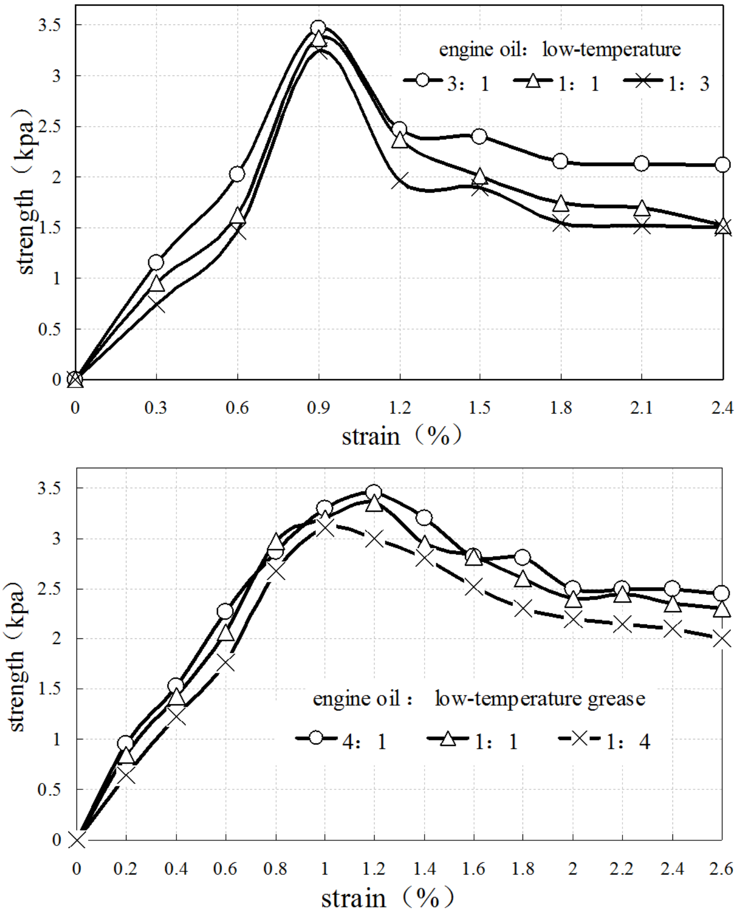

Fig. 4. Ratio between sand and soil 1:3: up–ratio between sand and soil 1:3, bottom–ratio between sand and soil 1:5

Material strength influence by ratio between the aggregate and the gelatinizing agent. In each specimen, the ratio between engine oil and low-temperature grease was 1:1 generally. With the same ratio between sand and soil, the strength of material would decrease obviously with ratio between the aggregate and the gelatinizing agent. Specially, ratio between sand and soil was down to 1:3, the curve kept steady remarkably. When the ratio continued to decrease, post-peak value decrease quickly with distinct plasticity. Fig. 5 depicts stress-strain curve with ratio between sand and soil 1:1 and 1:3.

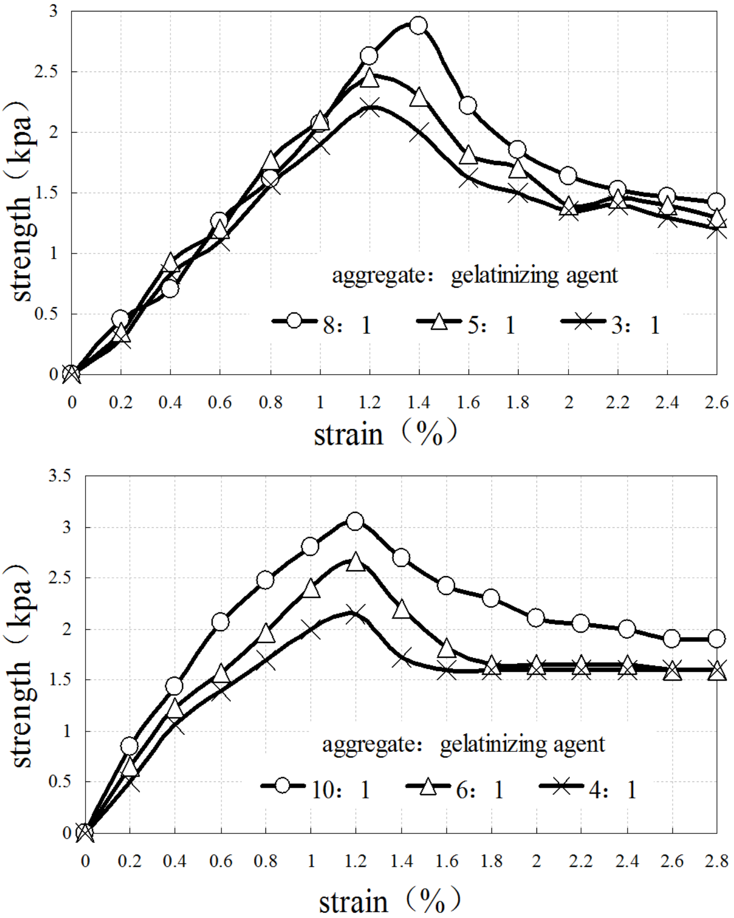

Fig. 5. Stress-strain curve in various ratios between the aggregate and gelatinizing agent: up–ratio between sand and soil 1:1, bottom–ratio between sand and soil 1:3

Proper analysis on material matching. In general, the strength of the material would decrease with increment of the ratio between sand and soil, between the aggregate and the gelatinizing agent. Stress-strain curves with various matching were totally similar with the curve from the prototype, which can satisfy the experiment settings well. With multi-target orthogonal experiment, the experiment should meet two index requirements. Firstly, proportion between engine oil and low-temperature grease should be equal, because that the grease ratio has few impact on the mechanics property of materials. From the above analysis, the specimens with ratio between sand and soil 1:5, whose mechanics property were similar with the property of soil furthest. So, we finally decided the reasonable matching, which is ratio between sand and soil 1:5, the grease ratio 1:1. However, ratio between the aggregate and the gelatinizing agent should be conformed further by the permeability testing.

2.3. Material permeability testing

Material permeability testing mainly ensured the ratio between the aggregate and the gelatinizing agent. According to Darcy law, we adopted hydraulic conductivity methodology to measure permeability coefficient of the material. The relative formula for permeability coefficient is

$$K = \frac{QL}{t_n S(h+L)}\,. \tag{2}$$

Here, K is the permeability coefficient (mm/h), L is the thickness of experimental material (mm), h is the thickness of the water layer (mm) and t_n is time interval (hours). Symbol Q can be calculated by the formula

$$Q = \frac{Q_1 + Q_2 + Q_3 + \cdots + Q_n}{n}\,, \tag{3}$$

where Q is the average amount of water (mm^3). $Q_1, Q_2, Q_3, \cdots, Q_n$ are amounts of water in each permeability (mm^3). Symbol S means the cross-section area (mm^2). After 48 hours uf soaking, we started the testing and use water drum to gather the permeable water. The model needed 1 hour to achieve steady status and then we launched timer and read the data each one hour the values of Q_1, Q_2,$\cdots$, Q_n. Table 1 contains permeability coefficients in eight groups with various gelatinizing agent amount, ordered from large to small. We can conclude that the smaller proportion of the gelatinizing agent, the larger permeability coefficient, which indicates that the more loose the material, the larger permeability coefficient. Combining indigent and structure analysis on the soil group, we can conclude that the more compact structure of the soil group, the more weak permeability coefficient.

Permeability coefficient value of field soil is 10.24–26.25 mm/h by the testing . Geometry simulation constant is 100 and weight simulation constant is 1.56 in the experiment. Considering fluid-solid coupling simulation principle, permeability coefficient simulation constant is 6.4. So we can calculate permeability coefficient of the simulation material is 1.62–4.10 mm/h. Analyzing the data in the Table 3, the experimental material satisfies requirements in the simulation experiment and is similar with the soil.

3. Results

3.1. Investigation on geological settings and model schemes

Destruction of geological environment by coal excavation is more and more serious in Shenfu coal district. Particularly, we focus on the destruction of water resource. When height of excavated coal is about 2 m and water-resisting l layer is weak clay strata, actual operation could achieve water protection mining, if the water-resisting layer would recover water-resisting performance after slight failure. So, we studied evolution mechanism of water flowing cracks in the soil layer and analyzed the cracks effect on water-resisting property. Next, protection measurement on water-resisting layer has been proposed finally after mastering relation between soil layer failure and overlying water body. The measurement can promote substantial and rational development of regional economics, and have important theoretical significance and application value . We set No. 2–2 working face as research area. Here, average angle of the coal seam is 1.5 degrees and excavated height is 2.0 m. Overlying strata is loose layer and 15 m hipparion red soil in tertiary. The soil in the research area has a tight structure and is medium hard. Void ratio of the soil is 0.70–0.83 and relevant permeability coefficient is 0.0058–0.6300 m/d. Besides, phreatic layer lies above the loose layer . Main mechanical parameter for overburden strata is in Table 4.

Table 3. Permeability coefficient of each experimental material

Ratio between aggregate and gelatinizing agent		4:1	5:1	6:1	7:1	8:1	9:1	10:1	11:1
Permeability coefficient (mm/h)	Specimen 1	1.25	1.48	1.69	2.31	2.85	3.63	3.91	4.32
	Specimen 2	1.21	1.41	1.61	2.29	2.86	3.50	3.89	4.28
	Specimen 3	1.19	1.46	1.68	2.33	2.89	3.58	3.85	4.31
	Average	1.22	1.45	1.66	2.31	2.87	3.57	3.88	4.30

Table 4. Mechanical parameters of overlying strata above working face

Serial number	Lithology	Thickness (m)	Density (10^3 kg/m3)	Tensile strength (MPa)	Elastic modulus (GPa)
8	Loose phreatic aquifer	20.0	1.6	-	2.0
7	Red soil layer	15.0	2.3	1.84	6.0
6	Medium sandstone	6.0	2.4	4.89	18.0
5	Siltstone with medium and fine sandstone	10.0	2.3	4.84	13.0
4	Medium sandstone	6.0	2.4	4.89	18.0
3	Siltstone	4.0	2.5	3.90	8.0
2	CityplaceSandy mudstone	4.0	2.5	3.62	7.0
1	Siltstone	2.0	2.4	3.90	6.0
0	Coal seam	2.0	1.3	0.70	1.5

We have established the fluid-solid coupling physical simulation model with geometry scale 1:100. The specific excavation method simulated actual longwall mining and the excavated height of coal seam was 2.0 m. We set 30 m boundary coal pillars which lied both in left and right sides of the model. Fig. 6 indicates model situation before and after the model excavation.

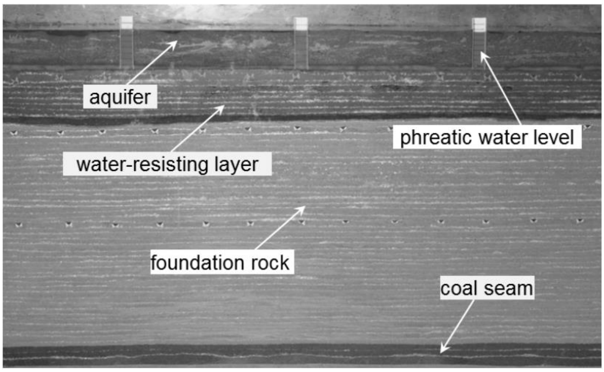

Fig. 6. Actual physical simulation model

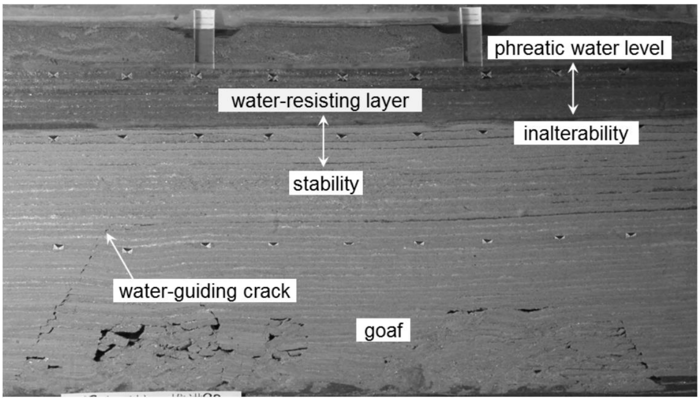

Fig. 7. Model status after coal seam excavation

3.2. Model result analysis

The experiment results indicated that coal roofs emerge a large-scale collapse when the working face advances 7 m and the collapse height reaches up to 15 m or so. With the working face advancing increasingly, periodical collapse of the coal roof is presented and mining-induced cracks gradually develop upward until the working face advances 150 m. Generally speak, final height of caving zone is about 20 m and the height of fissure zone can be up to 36 m. In particular, few small cracks has been developed into bottom of the water-resisting layer. Remarkable submerge has happened in the soil layer, however, cracks never connect the soil layer. In whole experiment, phreatic water level kept steady.

4. Conclusion

This paper developed a new physical material for fluid-solid coupled experiment based on fluid-solid coupling theories. We selected relevant materials for aggregates and gelatinizing agents. Moreover, the matching testing was also attempted and analyzed mechanical and water-physical properties. Finally, we adopted valid simulation materials and related matching. Main conclusions are following as:

Deduced simulation settings for elastic mechanics of rock mass and hydromechanics of water with fluid-solid coupling mathematics model. The theoretical basis for fluid-solid coupling is ensured with related simulation principle.

According to mechanical property and material matching testing, we offer relevant experimental materials, which are non-hydrophilia well and stable deformation performance. Considering coupling test data, the experimental materials can satisfy requirements for fluid-solid coupled model.

Built up the simulation model setting 2–2 coal seam as research area. Water-resisting layer is still steady with coal seam excavation. Water inrush and leakage seldom happened in the working face. The experimental results showed that movement and failure of overlying strata and crack evolution mechanism by the model coincided with the actual situation. Also, permeability laws and its parameters were also similar with in-situ monitoring results.

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