Physical modeling of rocks on the basis of rock–gas–moisture composites

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Abstract. The issues of obtaining and investigating composites consisting of coal and rock solid particles, gases (methane, hydrogen) and moisture, as well as approaches to mechanisms initiating catastrophic dynamic phenomena in mining are discussed. On the samples of different materials (coal, limestone, graphite, etc.) using the developed test bench, the dependences of physico-mechanical properties of cores on pressure are established. For longflame coal of various size, the features are shown for changing the temperature of briquette mass in increasing pressure up to 200 MPa. The composites imitating natural coal and other rocks are created.

1. Introduction
Attempts to introduce more advanced mining equipment for intensification of coal deposits development often activate gas-dynamic phenomena, thereby dramatically increasing the risk of fire and explosive situations at mines. Ever since coal mining began to develop, the mass media regularly report coal mine accidents and deaths as a result of explosions of combustible gases both in Russia and abroad.

Early in mining history their picture was far more dreadful: thus, among others, the explosion which occurred in England on May 25, 1812 at one of the coal mines claimed the lives of 92 people. The Sunderland Society for Preventing Accidents in Coal Mines established in the wake of this disaster invited Sir Humphrey Davy and other scientists to carry out systematic research on the causes of ignition of firedamp/air mixtures.

Coal represents a complex dispersed system, which is primary a mixture of three major macro-components: organic mass, moisture, and mineral components. Each of them is equally important for characterization of coal properties [1]. The role of the gas phase is accentuated by the presence of methane, hydrogen, and other gases entering the mine as a result of the disturbance created by the mining operation, and demands its detailed consideration [2].

One of the main tasks of coal science consists in the study of variations in physical and chemical properties of coal along with revealing structural parameters to provide for their accurate description. This problem solution will allow robust coal rank and quality indicators and predict its worthiness for particular technological applications, on the basis of the inferred physicochemical and structural characteristics.

Despite the extensive research conducted worldwide since the 1950s [3] and numerous publications on this issue there has still not been found a satisfactory solution. Besides, it is very unfortunate that
most of these papers, instead focus on specific problems that are limited to establishing correlations of black box type, without involving physical modeling.

Therefore, one of the critical aspects in physical modeling of the geological environment is to provide an adequate foundation, which is primarily represented by a three-phase solid–gas–moisture composite, where the solid phase is coal which contains organic mass and mineral components, i.e. constitutes a matrix filled with liquid and gases; the gas phase is methane which forms during metamorphism of the coal substance and is partially retained within the coal matrix. The coalbed methane (CBM) occurs in several states described as: (i) free gaseous state in the system of closed and open pores; (ii) adsorbed gas in minor amounts on the inner surface of pores and micropores, whose size is comparable to the molecule size; (iii) partly incorporated into solid coal substance as dissolved gas in water which is present within coal. However, the sorption and solubility laws [4, 5] applicable to describing gas content and its emissions, have failed to provide a comprehensive elucidation on the natural phenomena inherent in methane during underground coal mining. Among the examples provided in [4, 6, 7–11], the most illustrative are the avalanche-like decomposition of methane in coal seams in the case of sudden emissions of coal and gas (outburst events), as well as abnormally low gas flow into the drilled degassing wells [12, 13].

The works [14–17] have shown that there is no explicable mechanism of the formation of an outburst-prone environment, however, there are several theories emphasizing the involvement of the stress-strain state of the coal massif (and its physical-mechanical and physical-chemical properties) into coal and gas outbursts.

This paper sets out to find a new approach to physical modeling of rocks on the basis of the rock–gas–moisture composite, whose qualitative and quantitative composition and creation of coal model has long been one of the principal lines of research at the Chinakal Institute of Mining SB RAS (Siberian A special hydraulic test bench was designed and manufactured to create various composite models (Figure 1). The experiment results have largely contributed to understanding of the influence of its physical parameters (moisture, fractional and mineral compositions of the solid phase, temperature, pressure, etc.) on the formation of artificial samples of composites, including their mechanical and structural properties.

2. The composition of the test bench and results
The test bench consists of a hydraulic power cylinder 1 and high-pressure chambers 2 connected by pins 3. The high-pressure chamber 2 contains a punch 4 driven by a rod of the hydraulic power cylinder. The composite mass is placed into the working cavity of chamber 2 and locked with a removable flange 5. During the working stroke of the power cylinder rod, the composite matrix forms a briquette (composite briquette) 6. A removable flange 5 enables the briquette 6 expulsion.

At the first stage of the experiment, we studied the temperature effect on the carbon matrix formation by the static pressing. The temperature was measured on the test bench which was additionally equipped with a temperature controller and a vacuum pump. The initial material of a certain grain-size, moisture, and temperature was loaded into a high-pressure chamber 2, where its bulk compression was developing. The values of the briquette sample deformation and temperature in its middle part were recorded as the compacting pressure increased.

The temperature was measured with the RTK-02 temperature control. The temperature sensor is mounted in a pressure shell with rated pressure of 250 MPa and connected to the temperature controller via a duct. The necessary pressure in chamber 2 (low vacuum, atmospheric or higher pressure) was maintained with a vacuum pump.
Figure 1. Element of the hydraulic test bench developed for obtaining and study of the coal–gas–moisture composite: 1—power hydraulic cylinder; 2—high-pressure chamber; 3—connecting pins; 4—punch; 5—removable flange; 6—composite briquette.

Figure 2 provides a general layout of the test bench designed to study the influence of the composite’s qualitative and quantitative composition on the coal model properties. In the foreground, one can see a coal briquette obtained by the static pressing on the test bench.

Figure 2. Test bench designed to study properties of the qualitative and quantitative composition of the composite.

Figure 3 shows the established relationships between the sample temperature variations and the compacting pressure for longflame coal of various sizes. Its temperature was measured under atmospheric pressure and low-vacuum conditions. The deformation patterns of the briquette mass were experimentally identified for this coal.
**Figure 3.** Dependences of the temperature of longflame coal sample of different particle size (1 — ≤ 1 mm; 2 — ≤ 2 mm; 3 — ≤ 5 mm) under vacuum conditions (a) and atmospheric pressure (b) on the compacting pressure.

The dependencies for coal with a particle size < 1.0 mm are shown in Figure 4. The summarized research results on the example of different materials are given in the Table 1. Further use of the test bench for the study of the rock–gas–moisture composites would be focused on better understanding the mechanism of formation of an outburst-prone medium, its detonation and dynamic failure in the zones of metastable state of the coal massif and develop its physical model.

**Figure 4.** Dependencies of the punch displacements (a) (1—under low vacuum conditions; 2—under atmospheric conditions), density of the briquette mass (b) on the compacting pressure, and the compression work of the briquette mass on the punch displacements (c) for longflame coal of fraction ≤ 1.0 mm under atmospheric conditions.

**Table 1.** Summarized research results on the influence of the composite’s qualitative and quantitative composition on the briquettes properties

| Material, size, mm | $\Delta T_{\text{max}}, ^{\circ}\text{C under conditions}$ | Punch displacement under deformation, max, mm | Density, kg/m$^3$ | Compression work, kJ |
|-------------------|----------------------|------------------------------------------|------------------|---------------------|
| Coal, ≤ 1.0       | atmospheric: 11      | low-vacuum: 7                           | 106              | 1260                | 25.05               |
| Coal, ≤ 2         | 9                    | 7                                       | 112              | 1140                | 20.29               |
| Coal, ≤ 5.0       | 9                    | 7                                       | 113              | 1140                | 20.29               |
| Limestone, ≤ 1.0  | 6                    | 7                                       | 106              | 2410                | 21.20               |
| Limestone, ≤ 2.5  | 6                    | 4                                       | 107              | 2460                | 21.60               |
| Limestone, ≤ 5.0  | 11                   | 4                                       | 114              | 2510                | 21.40               |
| Graphite, ≤ 1.0   | 6                    | 6                                       | 139              | 1680                | 31.28               |
| Deashing product, ≤ 1.0 | 11                 | 12                                      | 137              | 1570                | 25.98               |
| Sawdust           | 6                    | 6                                       | 183              | 1730                | 13.34               |

Temperature variations of the longflame coal samples of different particle sizes during the compression process (Figure 3) show that under increasing pressure, the briquette temperature rises maximum by 14 $^{\circ}$C at atmospheric pressure and by 10 $^{\circ}$C in vacuum. As it was observed in [18], the temperature was $\Delta T \geq 3$ $^{\circ}$C in coal samples sized 40×60 mm under a pressure of up to 5 MPa.

The summarized results (see Table 1) of the influence of the composite’s qualitative and quantitative composition on the briquettes properties, indicate their temperature rise. The maximum temperature values 11$^{\circ}$C (under atmospheric conditions) and 12$^{\circ}$C (in a vacuum) are reported for briquettes manufactured on the base on deashing product with a particle size of ≤ 1.0 mm.
Analysis of the measurements of deformation (Figure 4a) and density of the coal briquettes shows that they differ slightly. Note that the maximum deformation is reported for sawdust, and the maximum compression work (31.28 kJ)—for graphite with a particle size of ≤ 1.0 mm.

Laboratory experiments on the hydraulic test bench enabled creation of the coal–gas–moisture composite models and physical modeling of rocks taking into account their material composition, and effects of the physical parameters (fractional and mineral composition of the solid phase, temperature and pressure conditions) on the formation of artificial samples of composites. Numerical values of physical characteristics of different composite briquette samples (temperature, density, deformation, compression work) correspond to real rocks [19–23].

A linear dependence of the deformation of various coal brands on the increase in pressure is provided in [20]. The stepwise behavior of the experimental dependences of coal deformation and density on pressure (Figures 4a and 4b) is associated with the formation of a new state of coal. Cyclic loading of the samples coupled with the concomitantly increasing pressure produces foliated structure of coal thereby ensuring its stable physical condition. Given that compression work (Figure 4c) is controlled by pressure and deformation, the experiments revealed its stepwise character. Density of different coal ranks varies in the range from 1150 to 1800 kg/m³ with varying ash content and occurrence depth. The results on the properties of briquettes are generally consistent with the data [21] on the densities established for longflame coal (1200 kg/m³) and for limestone (from 2370 to 2510 kg/m³), depending on their occurrence depth and the effective pressure.

3. Conclusions
The study presents a specially designed test bench for obtaining rock–gas–moisture composites (briquettes) using coal, limestone, graphite, sawdust, ash as initial materials corresponding to real rocks, which allows physical modeling with account of the material, fractional and mineral compositions, temperature and pressure. Dependences of temperature changes, deformation and density of the briquette mass on the compacting pressure, as well as the compression work on the samples deformation were obtained for different rocks. On the example of longflame coal of different grain sizes, variations in temperature, deformation, and density of the briquette mass were estimated in the case when the pressure increased to 200 MPa, which showed that the coal sample temperature increases maximum by 14°C under the atmospheric conditions and by 10°C, in a vacuum.

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