Analysis of rock strength properties in Kuznetsk Basin coal-bearing formations

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Abstract. The formation features and rock strength properties in Kuzbas coal-bearing basin have been described. The influence of granulometric, mineralogical and chemical composition on rock strength has been determined. The change of rock strength property has been identified at different stages of lithogenetic alterations.

1. Introduction
Determining the rock strength properties in Kuznetsk Basin (Kuzbass Basin) is of profound importance in evaluating the geotechnical conditions for coal strip mining. Pit wall stability, in most cases, depends on the specific physico-mechanical properties developed during lithogenesis and their further forecasting [1-3, 6-8].

Kuzbass Basin embraces well-developed coal formations from Balakhonian (C2.3 б), Kolchugino (P2) and Tarbagansky (I1.2) stages, which, in its turn, include sandstones, aleurolites and agrillites. Identifying the rock strength properties in Kuzbass coal-bearing formations is of great importance because of the necessity to evaluate the geotechnical conditions for coal strip mining and determine the pit wall stability of these massive coal formation intervals. This, in itself, urges the analysis of the rock composition and its physico-mechanical properties within Balakhonsky and Kolchugino series during different diagenetic transformation stages [4, 5].

2. Influence of granulometric rock compositions on their strength in Balakhonian and Kolchugino coal-bearing formations
Granulometric composition indicates the sedimentation conditions and, in many cases within Kuzbass coal-bearing formations, these conditions vary depending on different geologic-genetic rock complexes. According to the granulometric composition analysis, the rock granulometric composition of one and the same lithologically formed rock type, involved in identical transformation stages and formed in similar geotectonic zones, practically does not affect the rock strength properties. Only early-catagenetic Kolchugino aleurolites and adjacent coal beds (open burning and parabituminous coals) under conditions of increasing aleurolite concentration revealed a decreasing tendency of tensile strength in uniaxial compression and shearing resistance angle, whereas adhesion insignificantly changed. And, conversely, the increase in arenaceous concentration results in the increasing shearing resistance angle and limited adhesion decrease. As diagenetic transformation continues the granulometric composition influence on rock strength sharply decreases. The research results indicated that there is no correlation between tensile strength in uniaxial compression and the concentration percentage of varied-size clastic particles. This could be explained by the fact that during diagenetic
transformation new rock structural bonds were formed as a result of the replacement of feldspar clastics and volcanic rocks by carbonates and / or clay matter by carbonate cement. Simultaneously, the dissolution of quartz fragments could have been observed followed by the re-sedimentation of the latter, resulting in regeneration nodes and rims. At the same time, conformed-generation granoblastic and micro-stylolitic structures were formed. As the transformation stages progress, the more intensive the involved processes are. In consequence of newly-formed structures and structure bonds, the tensile strength in uniaxial compression differences of rocks are balanced due to the difference in the granulometric composition.

3. Influence of clastic composition on rock strength
The research determined that during the early transformation stages of Kolchugino aleurolites, volcanic rock fragments and sedimentary clastics significantly influence the strength properties; whereas their increase sensibly decreases the tensile strength in uniaxial compression and adhesion. It is conversely in the mid diagenetic transformation stage which embraces bituminous coal in Balakhonian sandstones being located within the intensive linear Prisalaire folded zone. These rocks show an intensive replacement of feldspar clastics by carbonates, corrosive quartz grains, formed generation nodes on quartz fragments and replacement of clay cement by carbonate matter. The more intensive the processes are, the greater is the extent that diagenetic carbonates form as clastics replacement. Simultaneously, new highly strong structure bonds between rock clastic particles and cement are formed. As a result, the concentration of pseudomorphous carbonates in the rocks could be indicators of intensive diagenetic processes and the further formation of highly strong structure bonds. The high concentration of well-preserved quartz and feldspar clastics in the rocks indicates the fact that the diagenetic processes are decelerated resulting in a strength decrease. An excellent example could be the composition of Balakhonian sandstones hosting coking and bituminous coals. According to the research data, it should be noted that sandstones with a high quartz and feldspar concentration have the lowest tensile strength in uniaxial compression and adhesion values. If the latter decreases and carbonate clastics content increases, the strength properties intensify.

4. Influence of chemical composition on rock strength
The influence of rock chemical composition on structure bond strength involved a detailed examination of the chemical composition and %-content determination of SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MgO, CaO, K$_2$O, Na$_2$O in lithologically different rock types from Kuzbass Basin. These rocks formed during various catagenesis stages and were pervasive throughout different geotectonic zones. The strength indicators ($\sigma_c$, $\sigma_p$) were defined and the interrelation between these indicators and the chemical composition characteristics were also identified. The analysis data showed that various oxide concentrations in rocks differently affect the rock strength. It should be noted that more than 200 correlation relationship pairs (bonds) were investigated, and, only in 4 cases, there existed a strong correlation relationship (bond), where the correlation coefficient exceeded 0.75. Kolchugino aleurolites, associated to gas coals, revealed a positive $\sigma_c$ increase and increasing Fe$_2$O$_3$ content in the rocks during the transformation stage; however there appeared to be a reversed pattern $\sigma_c$ decreased to an increase of Na$_2$O. This could be explained by the fact that during early diagenesis and catagenesis siderite was formed within Kuzbass rocks. Na$_2$O content could indicate insignificant changes of plagioclase itself during these early stages, whereas, it could have been replaced by carbonate matter in the later formation stages.

5. Influence of cement content on the chemical-mechanical rock properties
Kolchugino rocks include well-formed argillaceous, argillaceous-carbonate, and carbonate cement. It was established that the composition and percentage content of above-mentioned cement types significantly depends on the conditions (i.e. stages) and intensity of diagenetic transformation itself. Argillaceous cement in early transformation rocks (open burning coals) was predominately kaolinite clay, but sometimes, montmorillonite or hydromica. During the late transformation stages secondary
hydromica (hydromuscovite) was formed resulting in the subsequent vanishing of kaolinite clay and montmorillonite, which, in its turn, was not involved in the formation stages of semi-anthracite and anthracite coals. Such secondary minerals as sericite and chlorite could be found in the cement matter.

Clay strength cementing of clastic particles was the lowest under identical transformation conditions in regard to parabituminous coals. Although rock strength increases proportionally to the transformation stages, it does not exceed the strength factor of rocks with carbonate cement.

Carbonate cement is predominately dolomite, rarely calcite. Well-formed rocks also could include siderite cement. Originally, carbonate cement is catagenetic, especially during the late rock transformation stages. The strength factor of rocks with carbonate cement under identical conditions is the highest. Moreover, the strength factor within this or that transformation stage and within different geotectonic zones is governed by one and the same behavior patterns as those of rocks with argillaceous cement. However, the latter strength factor is lower than the former one. The rocks with argillaceous-carbonate and carbonate clay cement reveal intermediate strength factors resulting from clay cementing matter being replaced by carbonate cement.

As a result of catagenesis processes the content of cemented clastic Balakhonian rocks significantly changes. However, as in the case of Kolchugino rocks, there are three main cement types: argillaceous, argillaceous-carbonate and carbonate. Comparable to Kolchugino rocks, the cement content in Balakhonian rocks is predominately hydromica (hydromuscovite) and sericate, as well as chlorite, and no kaolinite or montmorillonite. The latter could be explained by the significant secondary alterations of Balakhonian rocks during catagenesis. Carbonate cement includes catagenetic minerals, in most cases, dolomite, rarely calcite and/or siderite. The most coherent clastic cemented rocks are those with carbonate cement, while the less coherent are those rocks with argillaceous cement.

Based on above-mentioned factors, it could be stated that the cement content itself significantly influences the structure bond strength of rocks from Kuznetsk Basin. In this regard, to determine the rigidity of rocks on the open-pit walls, the rocks (i.e. rocks from Kuznetsk Basin) classification should include the rock cement content factor.

6. Changes of rock strength properties affected by catagenesis and regressive lithogenesis

Catagenetically, Kuzbass rocks alter as a result of high pressure, temperature and/or the intensive involvement of pore solutions and ground waters. Ground waters play a significant role in the diagenetic transformation of rocks. It is the composition of groundwaters and pore solutions that defines the plagioclase replacement intensity and formation of secondary clay minerals and carbonates. As a result, not only the content and behavior of rock structure bonds change, but also it initiates the formation of hydrocarbonate-sodium groundwaters in Kuzbass coal deposits. Carbonate clastics could be an important source of carbonate matter, whereas, interacting with $CO_2$, this carbonate dissolves and passes into the groundwaters. Besides early catagenetic transformation of rocks and free pore-filling carbonate crystallization, the intensive corrosion of clastic matter occurs. Recrystallization of carbonates under significant pressure occurs in Kuzbass rocks during late catagenesis, resulting in clay matter replaced by carbonate cement and further formation of monocrystal carbonates. Simultaneously, plagioclase, volcanic rock clastics and shale are replaced by carbonate matter. In response to high pressure new structure bond types as micro-stilolites are formed, resulting in significant changes of rock strength (Table 1).

It was established that cemented clastic Balakhonian rocks, especially sandstones with carbonate cement, have the highest strength factor in Kuzbass coal-bearing formations. Significant tectonic activity within the intensive linear Prisalaire folded zone (Kuzbass) during the post-inversion period notably decreased the structure bond strength, but did not have a strong effect on the rock properties. Thus, it can be stated that Balakhonian rocks, being abundant in this zone and formed during late catagenesis, have a rather low strength factor comparable to the rocks hosting coking coals. However, these Balakhonian rocks are found in Prigornoshor zone, Kuzbass monocline.
Table 1. Changes of physico-mechanical rock properties during different lithogenesis stages.

| Lithogenesis stages | Rock types  | Density, gr/cm$^3$ | Porosity, % | Resistance of uniaxial compression, MPa | Shearing resistance angle, ° | Cohesion, MPa |
|---------------------|-------------|---------------------|-------------|----------------------------------------|-----------------------------|--------------|
| Late diagenesis     | Sandstones  | 2.01                | 36.0        | 0.16                                   | 21                          | 0.05         |
|                     | Aleurolites | 2.10                | 33.6        | 0.13                                   | 29                          | 0.04         |
| Catagenesis         | Sandstones  | 2.36                | 14.0        | 3.13                                   | 41                          |              |
|                     | Aleurolites | 2.38                | 13.2        | 3.16                                   | 41                          |              |
|                     | Sandstones  | 2.47                | 8.2         | 4.91                                   | 41                          |              |
|                     | Aleurolites | 2.47                | 9.5         | 4.05                                   | 39                          |              |
| Late                | Sandstones  | 2.53                | 6.2         | 7.57                                   | 38                          |              |
|                     | Aleurolites | 2.49                | 5.3         | 6.54                                   | 38                          |              |
| Metagenesis         | Sandstones  | 2.56                | 4.8         | 5.26                                   | 35                          | 1.34         |
|                     | Aleurolites | 2.50                | 5.0         | 5.08                                   | 36                          | 1.08         |

7. Conclusion

Research data results have been used in determining the rock stability on the open-pit walls within Kuznetsk Basin. According to the calculations the highest rock stability level was established in Prigornoshor monocline zone, while the lowest- in intensive linear Prisalaire folded zone (Kuzbass).

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