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Permeability and seepage stability of coal-reject and clay mix

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Abstract

This paper presents an experimental investigation into the permeability and seepage stability of the granular coal-reject mixed with clay, which is affected by clay content, axial pressure, and the use of geotextile. Laboratory seepage tests were performed to determine the coefficients of permeability under both Darcy's and non-Darcy's flow conditions. The critical hydraulic gradients of coal-reject with different percentages of clay, axial pressures and geotextile were also tested. The results indicate that the coefficients of permeability, k, and global permeability, K, decrease while the critical hydraulic gradient increases with increasing clay content and axial pressure. The permeability and the critical hydraulic gradient start their radical changes when the clay content exceeds 10% of the total dry weight of the sample. The placing of a layer of geotextile on the bottom of specimen can decrease the permeability and significantly improve the seepage stability of the coal-reject and clay mixture.

Keywords: coal-reject; non-Darcy's flow; permeability; seepage stability

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1. Introduction

Coal-reject is now regarded as a resource instead of a "waste" material, which is a by-product of coal mining and processing, and also known as refuse, coal gangue, course discard, culm, spoil, etc. The increasing activity of the coal mining industry all over the world is associated with the increasing disposals of coal wastes. Many tons of mine wastes have been used in Germany, the United Kingdom, the USA, France, Belgium, Netherlands and Poland in the construction of road and railroad banks, river embankments, dykes and dams [1]. In China, there are more than 1500 coal-reject heaps in the state owned mines, with a total accumulation of 3 billion tons of coal-rejects, which accounts for over 40% of total industry solid wastes in the country. It is predicted that the utilization of coal-reject will reach 0.4 billion tons by the year 2010, which consumes 70% of the annual production [2]. The majority of coal-reject in China has been used as a replacement of construction materials for highway, railway, dam, embankment, reclamation of land, and backfill of underground mined-out area, etc. [3-6].

The geological and geotechnical properties of coal-reject have attracted the interests of many researchers in both the laboratory and the field investigations. The laboratory tests include gradation, particle shape, specific gravity,

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moisture content, unit weight, Atterberg limits, slaking, permeability, shear strength, compaction; while the field tests include in-place density, permeability, weathering, fires, vegetation, hydrogeological characteristics, etc. Skarzynska presented a characterization of the geotechnical properties of mine stones from different sources, which includes the environmental consequences of coal mining, the origin of by-products, and classification of materials [7]. Okogbue and Ezeajugh studied the engineering properties of Nigeria coal-reject and its potential for use in engineering construction. They found that the coal-reject was suitable for highway fills, embankments and subbases, but not for base course and structural fills, unless improved [8]. Ulusay et al. studied the geomechanical characteristics of the spoil material as the basis of his analysis of spoil pile instabilities in Turkey [9]. Okagbue and Ochulor improved the engineering properties of coal-reject with the addition of Portland cement [10]. He et al. studied the mechanical properties of coal-reject mixed with clay and the filling techniques [3].

Among the geotechnical properties of coal-reject, the permeability and seepage stability are the particular concern when it is used for dam embankments, road construction, and reclamation purposes. The permeability of coal-reject is significantly influenced by its related geotechnical properties, such as grain size distribution, density, void ratio and mineral composition.

Skarzynska gave a summary about the permeability of mine stones from several countries based on laboratory or in-situ tests (Table 1) [7]. Ulusay et al. conducted laboratory falling head permeability tests on three samples and yielded coefficients of permeability from 8.4×10^{-3} to 8.7×10^{-3} cm/s, and deduced an in-situ permeability in the range of 10^{-4}~10^{-5} cm/s [9]. Jiang et al. experimentally measured the coefficients of permeability to be 7.43×10^{-2}, 1.25×10^{-2} cm/s and 8.16×10^{-3} cm/s for coal-reject, coal-reject with 20% clay, and 20% fly ash [4]. Liu et al. investigated the relationship between the coefficient of permeability and coarse grain content, indicating that the coefficient of permeability increased from 10^{-6} to 10^{-3} cm/s with the increase of coarse grain content from 30 % to 60 %. They also found that the coefficient of permeability decreased with increasing dry unit weight of coal-reject [6]. Miao et al. reported their experimental results on seepage properties of non-Darcy's flow in granular coal-rejects and concluded that the permeability K decreased with the decrease of porosity, while the absolute value of non-Darcy's flow coefficient β, which varied between positive or negative values, increased [11].

The permeability of coal-reject in field shows some different characteristics from that in the laboratory. Holubec predicted the range of the in-situ coefficient of permeability might be from 10^{-8} to 10^{-1} cm/s for coarse coal wastes with different density and weathering, while the coefficients of permeability varying from 10^{-6} to 10^{-4} cm/s for samples with the same densities from his laboratory tests [12]. Leventhal and Ambrosis back-calculated the coefficient of permeability to be 5.6×10^{-3} cm/s in a coal-reject embankment from piezometer and seepage measurements [13].

Table 1. Permeability values of mine stone from various sources (after Skarzynska) [7]

Country	Mine stone	Coef. of permeability k (cm/s)
Czecho-Slovakia	Loose	10^{-1}
	Compacted	10^{-5}
Germany		10^{-1}-10^{-6}
Polan	Loose	10^{-1}-10^{-4}
	Compacted	10^{-3}-10^{-6}
Spain	From tips	10^{-4}
	Compacted	10^{-6}
UK	Coarse	10^{-2}-10^{-6}
	Compacted	10^{-2}-10^{-9}
USA	Coarse	10^{-4}
	Fine	10^{-4}-10^{-5}
	Compacted	10^{-3}-10^{-5}

There are few systematic researches on the permeability and seepage stability of the mixed coal-reject and clay to date. This paper focuses on the permeability and seepage stability of coal-reject mixed with clay, investigates the efficiency of the addition of clay in reducing the coefficient of permeability and improving the seepage stability

2. Test procedure and samples

A series of tests have been conducted to examine the permeability and the seepage stability of coal-reject with different clay contents and geotextile. The tests have been carried out on the samples placed in a steel cylindrical seepage device with a 30 cm inner diameter and a 70 cm height (Fig. 1(a)). The O ring seals were installed to seal off the leakage between the cover and the piston, the container. Two entrances were set up on the upper position of the container; one was for water supply, the other was for connecting a water pressure transducer. The water pressure was automatically recorded by a computer using the C-DAS software [14]. The axial pressure was applied through the piston by a lever mechanism.

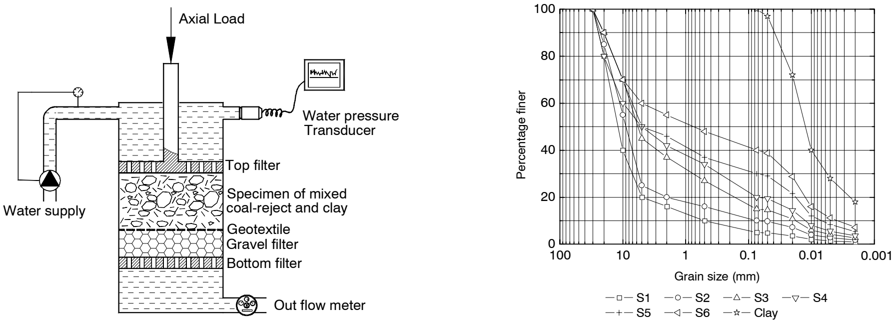

Fig. 1. (a) Schematic set-up for permeability tests; (b) Grain size distribution of coal-reject and clay mix

The coal-reject used in the tests was collected from a coal-reject heap at Xuzhou Mining Corporation in Xuzhou, China. It was composed of slightly or medium weathered sand stone and mudstone. The clay used in the tests was sampled from the Quaternary System within the same city with a content of 28% of clay particle (here refers to particle size less than 0.005 mm), and an average coefficient of permeability of 5.25×10^{-7} cm/s based on falling head permeability tests. Table 2 summarizes the samples used in the tests, which were composed of coal-reject with different grain sizes and different contents of clay. Fig. 1(b) shows the grain size distributions of other samples used in the tests. The geotextile used in the tests was a kind of woven polypropylene geotextile, with a thickness of 1.2 mm and a coefficient of permeability of 0.2 cm/s normal to the geotextile plane with no surcharge.

The procedure for the permeability test was as follows: First, to place and compact the filter gravel with a particle size of 30~50 mm, a height of 20 cm, then place a layer of filter on the gravel; Second, place and compact a well mixed coal-reject and clay specimen with a specific water content and density in the mould; Third, allow water to filtrate gradually through the system and specimen from the bottom, allowing for sufficient time to ensure that no air remained in the system and the specimen; Fourth, connect axial load, water supply, water pressure transducer and water flow meter; Fifth, fill the mould with water; Sixth, apply the desired load through the piston; Seventh, apply a steady water pressure using a regulator pressure panel to generate a vertical downward flow through the specimen; Eighth, record the flux, water pressure difference between the top and bottom of the specimen, time and settlement of piston when the seepage reached steady state; Last, replace the specimen and repeat the same procedures for the next test. All results calculated included a temperature adjustment to 20 °C.

The specimen installation and system arrangement for the seepage stability test was the same as the permeability test. The supplied water pressure was gradually increased until seepage erosion failure in the specimen occurred, which was identified by a sudden drop of the water pressure measured by a transducer and a visual muddy outflow due to clay particle erosion. The critical hydraulic gradient was calculated based on the pressure difference at the moment of the seepage failure.

Table 2. Grain composition of samples of granular coal-reject mixed with clay

Specimens	A1	A2	A3	A4	B1	B2	B3	B4	B5	C1	C2	C3	C4
Granular size (mm)	30-20				20-10					10-5			
Clay content (%)	30	40	50	60	30	40	50	60	70	30	40	60	70

3. Results and discussion

The well known Darcy's law is valid under the condition of a laminar flow. In the case of turbulent flow, the relationship between the velocity and the hydraulic gradient is no longer linear. Reynolds number is generally used to identify the transition between the laminar and turbulent flow. The experimental results showed that Darcy's law was valid before a certain seepage velocity was reached, generally before the erosion of the clay in the voids of granular coal-rejects occurred.

Fig. 2 shows the coefficient of permeability, k, calculated from Darcy's law for the samples in Table 2. There was an appreciable drop of k when the clay content was more than 40%. The seepage and the erosion become difficult when the clay content reaches this value due to the fact that the voids between granular coal-reject are permeated with clay. While the clay content is less that this threshold, clay cannot fill the voids and make close contact between the skeletons of coal-reject. Therefore, the clay particles are easily eroded by the seepage force.

Fig. 3(a) shows the relationship between k and the axial pressure applied to the specimen, which indicates a close relation between k and the density of different specimens. This was due to the fact that the increase of vertical pressure reduces the void ratio in the sample and makes the seepage more difficult. The relationship can be expressed in an exponential equation

$$k = ae^{b\sigma_v} \tag{1}$$

where k is the coefficient of permeability; σ_v the axial pressure; a and b are experimental factors.

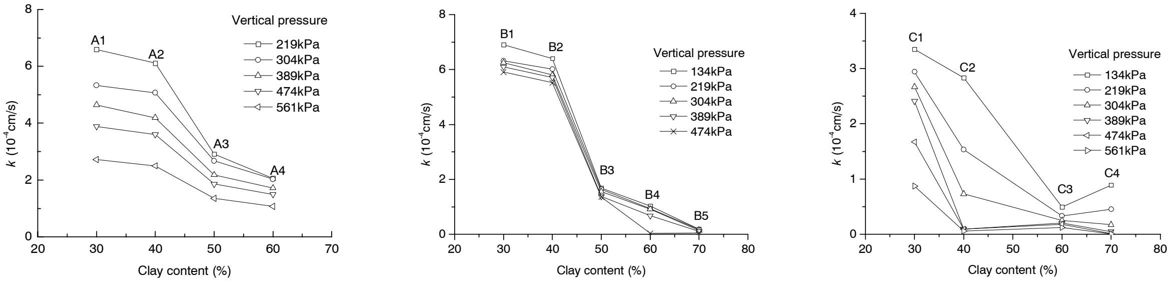

Fig. 2. The coefficients of permeability of coal-reject with clay

When the Reynolds number increases to a certain value, the relationship between the velocity and hydraulic gradient is no longer linear. Izbansh's and Forchheimer's equations are the most widely used nonlinear velocity-hydraulic gradient relationships (v-i) among those kinds of equations proposed by the various researchers.

Izbansh's equation [14-15] takes the form of

$$v = Mi^n \tag{2}$$

where M and n are the coefficients determined by experiments.

Table 3 lists the values of M and n for different specimens. The value of M decreases, while n increases with increasing clay content. The placement of a layer of geotextile dramatically decreases the value of M, as shown in Fig. 3(b). For example, a dramatic difference in the velocity was measured between two specimens with geotextile (S4G) and without geotextile (S4).

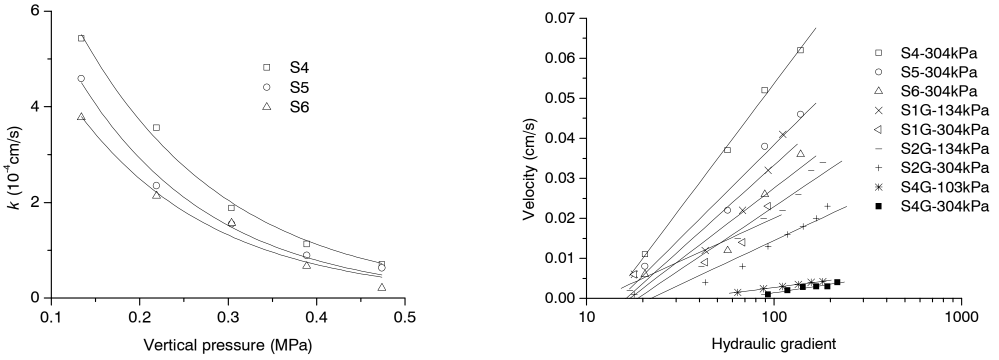

Fig. 3. (a) relationships between permeability and vertical pressure; (b) Relationship between seepage velocity and hydraulic gradient

Table 3. Values of M and n in Izbansh's equation for different specimens

Specimen No.	Axial pressure (kPa)	M (cm/s)	n	R^2
S4	304	7×10^{-4}	0.93	0.96
S5	304	5×10^{-4}	0.95	0.99
S6	304	3×10^{-4}	0.96	0.97
S1G	134	6×10^{-4}	0.78	0.93
	304	3×10^{-4}	1.06	0.99
S2G	134	9×10^{-5}	1.17	0.97
	304	5×10^{-5}	1.21	0.99
S4G	134	3×10^{-5}	0.98	0.97
	304	1×10^{-6}	1.52	0.92

Note: Where G means a layer of geotextile placed at the bottom of the sample, the same notation for Table 4 and Fig. 5.

The velocity of seepage increases with increasing percentage of coarse grains in coal-reject under the same axial pressure and hydraulic gradient conditions. While it decreases with increasing axial pressure at the same hydraulic gradient.

Forchheimer's equation [16-22] can be expressed as

$$i = -\frac{dH}{dL} = \frac{\mu}{k} v + \beta\rho v^2 \qquad (3)$$

where K is the global or specific permeability (m^2); β is non-Darcy's flow coefficient (m-1); μ is the dynamic viscosity of fluid (Pa·s), β is the density of material (kg/m^3).

Table 4 lists the values of K and β. The value of K decreases with increasing clay content, axial pressure and the presence of geotextile. The value of β can be positive or negative, and the absolute value of β decreases with increasing clay content and axial pressure.

Fig. 4 shows that the critical hydraulic gradient increases with increasing clay content and the axial pressure when other conditions remain the same. The critical hydraulic gradient has a range of 2.9 to 67.2 when the clay content changes from 5% to 40%. When the clay content is larger than 10%, the increase in critical hydraulic gradient becomes remarkable, which indicates that the cohesion between coal-reject particles enhances the integrity of the specimen. The relationship between the critical gradient, i, and the clay content, x, can be expressed as equation (4) at an axial pressure of 134 kPa, and (5) at 304 kPa:

Table 4. Values of K andβ for different specimens

Specimen No.	Axial pressure (kPa)	K (m^2)	β (m-1)	R2
S4	304	1.41×10^{-12}	8.0×108	0.97
S5	304	5.0×10^{-12}	8.0×108	0.97
S6	304	2.5×10^{-13}	-2.0×108	0.97
S1G	134	2.0×10^{-13}	-1.2×109	0.95
	304	2.5×10^{-13}	-8.0×108	0.99
S2G	134	1.4×10^{-13}	1.6×109	0.98
	304	2.5×10^{-13}	1.2×109	0.99
S4G	134	1.4×10^{-14}	-1.6×1011	0.89
	304	3.3×10^{-14}	8×1010	0.97

$$i(x) = -0.0030x^3 + 0.22x^2 - 2.55x + 10.56$$

$$i(x) = -0.0038x^3 + 0.27x^2 - 3.54x + 5.73$$

The results also indicated that the presence of geotextile increases the critical hydraulic gradient dramatically. For example, the critical hydraulic gradients of specimen S1, S2 and S3 are 2.6, 4.1 and 13.3 under an axial pressure of 134 kPa, these values increase to greater than 125 when a layer of geotextile was placed at the bottom of the specimens under the same pressure. This indicates that the widely used woven geotextile in geotechnical engineering can be used to prevent the seepage failure of coal-reject and clay mixture.

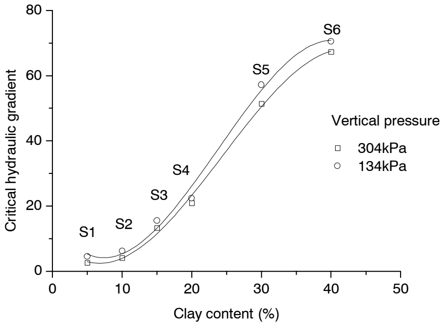

Fig. 4. Relationship between hydraulic gradient and clay content

4. Conclusions

Coal-rejects exhibit different geotechnical properties due to their different origins, compositions, structures, weathering conditions, etc. The permeability is one of the most important properties of coal-rejects for their applications in road and railroad banks, river embankments, dykes, and dams. This paper presents an experimental investigation on the permeability and seepage stability of coal-reject mixed with clay. The main conclusions of this research are summarized as follows:

1) The relationship between the velocity and the hydraulic gradient changes from linear to nonlinear with increasing Reynolds number. The coefficient of permeability decreases with increasing clay content. It also decreases with increasing axial pressure on the specimen.

2) Izbansh's and Forchheimer's equations are applicable for coal-reject and clay mix when there is a non-Darcy's flow. For Izbansh's equation, the value of *M* decreases and *n* increases with increasing clay content and axial pressure. For Forchheimer's equation, the value of *K* decreases with increasing clay content and axial pressure; the

value of β varied between positive and negative values, and the absolute value of β decreases with increasing clay content and axial pressure.

3) The critical hydraulic gradient increases with the increasing clay content and axial pressure. The change becomes remarkable when the clay content is over 10 %.

4) A layer of woven geotextile placed at the bottom of the specimen can reduce the permeability and significantly improve the seepage stability. This phenomenon indicates the potential applications of geotextile to improve the geotechnical properties of coal-reject. Further research is being undertaken for multiple layers of geotextile within the specimen.

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