Research Article

Formation Mechanism of “Large-Area Sweating” Water Seepage from Deep Mine Sandstone Pores

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The groundwater in nonkarst areas can be divided into two categories: pore water and fracture water. Unlike fracture seepage, sandstone pore seepage in deep mines manifests as a large area of “sweating,” rather than an area of local “spray,” and is difficult to plug via conventional grouting methods. This study focused on pore seepage in deep mine sandstone to improve the grouting effect. Taking the deep mine sandstone in the southwest Shandong coalfield, where “large-area sweating” seepage occurs, as the study object, this study examined the pore structure, petrological characteristics, physical properties, and grain sizes of the sandstone by analyzing experimental data from thin sections and scanning electron microscopy samples. The formation mechanism of the “large-area sweating” seepage was then analyzed. The range of permeability in which “large-area sweating” seepage may occur in the sandstone was discussed. The results indicate that the process of “large-area sweating” seepage in deep mine sandstone can be divided into a matrix softening stage, a matrix erosion stage, and a “large-area sweating” water seepage formation stage. According to the case analysis on the “large-area sweating” seepage in the Tangkou coal mine of the Southwest Shandong coalfield, the lower limit of permeability of the “large-area sweating” sandstone is approximately 0.25 mD. Thus, this type of seepage can occur in deep mine sandstone with a permeability of greater than 0.25 mD and affect typical mining production. The results of this study provide information about the formation mechanism of “large-area sweating” water seepage from sandstone pores and can theoretically inform the development of a new permeation grouting technique.

1. Introduction

Over the last two decades, due to a large number of deep underground engineering projects, the impacts of groundwater seepage through pores cannot be ignored [1]. For example, coal is an important form of energy and an industrial raw material that is used worldwide. Developing deep underground coal resources is inevitable because long-term mining is gradually reducing shallow coal resources [2]. Most of the strata that are crossed by deep mining shafts are sedimentary sandstones with abundant water and developed pores [3]. The phenomena of water seeping and gushing from shaft walls often occur during shaft construction. Years of grouting sandstone aquifers to plug water seepage in deep mining shafts show that even when cementing and chemical grouting are carried out in the rock mass behind the wall and the main water inflow channels caused by fractures in the rock mass are effectively blocked, residual water still extrudes through sandstone pores on the shaft wall. Such extrusion cannot be ignored because the total water leakage exceeds the upper limit of the accepted specification (≤10 m³/h) [4, 5]. Therefore, the difficulty of grouting sandstone pores has become a bottleneck that restricts the rapid excavation and typical handover of shafts [3, 6].
To date, numerous scholars have studied the pore structure and the groundwater seepage, including the pore structure of materials, the pore structure of petroleum and gas reservoirs, the groundwater seepage of rock fractures, and pore seepage of Quaternary sandy soil. For example, some scholars have studied the influence of porosity on the properties of various materials [7, 8]; a large number of scholars have studied the pore structure in oil and gas reservoirs to understand its impact on the quality, migration, and accumulation of oil and gas [9–13]. Many scholars have studied the seepage characteristics of rock fractures and their impacts on engineering construction because such fractures usually have a good hydraulic conductivity [14–17]. Quaternary sandy soil has a loose structure and abundant pore water, which is a primary concern for hydrogeology and civil engineering projects [18–21]. Rudakov and Westermann presented and validated an analytical model of water inflow and rising level in a flooded mine by comprehensively considering various voids and the heterogeneities of rocks [22]. The results of the above studies inform the continued study of pore seepage in sandstone. However, because the small area of “sweating” in shallow sandstone generally produces a small seepage discharge, the prevention and control of pore water in shallow sandstone are often ignored. To date, the formation mechanism of “sweating” water seepage from sandstone pores has not been investigated, and the cause, process, and conditions of such seepage are unclear. In fact, as mentioned above, with the deepening of coal mines and the increasing area of sandstone pore seepage, the pore seepage discharge from deep mine sandstone has increased significantly, and this issue requires immediate attention. Therefore, this study focused on the pore seepage from deep sandstone, proposed the concept of “sweating” seepage based on the characteristics of the pore seepage, and assessed the formation mechanism and conditions of “large-area sweating” water seepage from deep sandstone pores. The aim of this study was to provide technical support for the prevention and control of “large-area sweating” water seepage from deep sandstone pores in underground engineering projects.

2. Samples and Methods

2.1. Structural Logistics Scheme of This Study. An overview of the flow of this study is shown in Figure 1. Taking the deep mine sandstone in the Southwest Shandong coalfield as an example, samples were collected, and appropriate experimental methods were determined. Next, the pore structure, petrological characteristics, physical properties, and grain sizes of the sandstone were carefully studied by analyzing experimental data from casting thin sections and scanning electron microscopy (SEM) samples. The formation mechanism of “large-area sweating” water seepage from deep mine sandstone pores was analyzed, and the formation conditions for this type of seepage were discussed by taking the ventilating shaft of the Tangkou coal mine, where “large-area sweating” water seepage once occurred, as an example.

2.2. Sample Collection. All deep mine sandstone samples in this study were collected from typical sections with three layers of sandstone aquifers in the deep coal mines in the Southwest Shandong coalfield, as shown in Figure 2 in orange. The strata in the Southwest Shandong coalfield are part of the West Shandong stratigraphic subprovince, which is part of the North China stratigraphic province. From old to new, Ordovician, Carboniferous, Permian, Jurassic, Paleogene, Neogene, and Quaternary strata are present [23, 24]. The three most widespread layers of sandstone aquifers are Permian Shanxi Formation sandstone, Permian Shihezi Formation sandstone, and Jurassic sandstone, which are widely distributed in the Southwest Shandong coalfield and have an important impact on coal mining [25]. In this study, more than 800 m of drilling cores from the 28 wells of the Anju, Tangkou, Xiezhuang, Huafeng, and Longyun coal mine was logged, and about 310 core samples were collected.

2.3. Experimental Methods. All samples were transported to the laboratory without disturbance; the samples were sealed to retain moisture and held under pressure. The original samples were divided into four groups to carry out various laboratory tests (see Figure 3). The group (a) samples were used to test the porosity and permeability with STY-2 gas permeability and porosity meters according to the specifications of the Core Analysis Method (GBT 29172-2012) [26] and the China Petroleum and Natural Gas Industries Standard (SY/T 5815-2016) [27]. Additionally, to observe the composition and texture of the grains and the pore structure of the sandstone, a Zeiss Imaging-2M polarizing microscope and a Nova Nano Sem450 SEM were used with the group (b) and group (c) samples. Furthermore, the grain size of the sandstone was analyzed using a Mastersizer 3000E laser grain size analyzer with the group (d) samples. The experimental sample sizes are shown in Figure 3.

3. Results and Analysis

3.1. Petrological Characteristics. The petrological characteristics of the deep mine sandstone are shown in Table 1. According to the casting thin section and SEM observations, the primary clastic grains of the deep mine sandstone in the study area are quartz, feldspar, and various kinds of rock debris. Nevertheless, the proportion of clastic grains in different sandstones varies. The Jurassic sandstone is mainly purplish red lithic arkosic sandstone with a relatively low clay matrix content, mostly 2%-5% and rarely 5%-12%. The Shihezi Formation sandstone is mainly gray lithic feldspathic quartz sandstone with a high clay matrix content, generally 5%-12%. The Shanxi Formation sandstone is mainly gray–white feldspathic lithic sandstone with a high clay matrix content, typically 5%-12%.

3.2. Pore Structure. According to the experimental data and considering the occurrence and genesis of pores, the pore types of the deep mine sandstone in the Southwest Shandong coalfield are divided into intergranular pores, intragranular pores, intercrystalline pores, and microfractures. The contents of the three main pore types are shown in Table 2.
Engineering problems: In 2001, “large-area sweating” water seepage occurred during the excavation of the ventilation shaft of the Tangkou coal mine. This seepage affected the normal handover of the shaft because the total amount of seepage exceeded the upper limit of the accepted specification.

Research object: Three layers of sandstone crossed by the ventilation shaft and distributed widely in the southwest Shandong coal field.

Methods

Experimental methods
- Optical casting thin section observations
- SEM observations
- Grain size analysis
- Porosity and permeability tests

Theoretical analysis methods
- Theory of sedimentary petrology
- Theory of multivariate statistical analysis
- Linear (radial) vadose theory

Conclusions

Understanding the formation mechanism of “large-area sweating” water seepage from the pores of deep mine sandstone

Discussion

Formation condition: In what types of deep mine sandstone does “large-area sweating” water seepage occur?

Figure 1: A general overview of the flow of this study.

Figure 2: Distribution of samples into groups for laboratory research: (a) Jurassic sandstone; (b) Permian Shihezi Formation sandstone; and (c) Permian Shanxi Formation sandstone.
Intergranular pores are a vital pore type that affects the permeability of deep mine sandstone. This pore type can be divided further into primary intergranular pores and secondary intergranular pores. The contents of all kinds of intergranular pores are shown in Table 3.

The original primary intergranular pores most affected the permeability of the studied sandstone (see red arrows in Figure 4(a)); these pores are largely preserved in the Jurassic sandstone and comprise 2.5-9.0% of the visual sandstone area, as shown in the bold green numbers in Table 3.

### Table 1: The petrological characteristics of deep mine sandstone.

<table>
<thead>
<tr>
<th>Petrological characteristics</th>
<th>Jurassic sandstone</th>
<th>Shihezi sandstone</th>
<th>Shanxi sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main rock type</td>
<td>Lithic arkosic sandstone</td>
<td>Feldspathic quartz sandstone</td>
<td>Feldspathic lithic sandstone</td>
</tr>
<tr>
<td>Clay matrix (%)</td>
<td>Mostly 2-5, rarely 5-12</td>
<td>5-12</td>
<td>5-12</td>
</tr>
<tr>
<td>Cement</td>
<td>Siliceous, calcareous</td>
<td>Siliceous, calcareous</td>
<td>Siliceous</td>
</tr>
<tr>
<td>Compositional maturity</td>
<td>Low</td>
<td>Relatively low</td>
<td>Low</td>
</tr>
<tr>
<td>Sorting coefficient ($S_o$)</td>
<td>Well (1.15-1.37)</td>
<td>Medium-well (1.47-1.60)</td>
<td>Medium-well (1.16-1.93)</td>
</tr>
<tr>
<td>Grain shape</td>
<td>Medium psephicity, subrounded-subangular</td>
<td>Medium psephicity, subrounded-subangular</td>
<td>Medium psephicity, subrounded-subangular</td>
</tr>
<tr>
<td>Cement type</td>
<td>Porous</td>
<td>Porous, contact</td>
<td>Porous, contact</td>
</tr>
<tr>
<td>Textural maturity</td>
<td>Secondary immature</td>
<td>Immature</td>
<td>Immature</td>
</tr>
</tbody>
</table>

### Table 2: Contents of the three main pore types in deep mine sandstone*.

<table>
<thead>
<tr>
<th>Sandstone type</th>
<th>Intergranular pores (%)</th>
<th>Intragranular pores (%)</th>
<th>Intercrystalline pores (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic sandstone</td>
<td>3.2-10.1</td>
<td>0.7-1.7</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Shihezi sandstone</td>
<td>0.8-5.0</td>
<td>0.8-3.5</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>Shanxi sandstone</td>
<td>0.5-6.1</td>
<td>0.4-2.9</td>
<td>0.1-0.3</td>
</tr>
</tbody>
</table>

*The contents in this table indicate the visual area percentage of the sandstone samples.

### Table 3: Types and contents of intergranular pores in deep mine sandstone*.

<table>
<thead>
<tr>
<th>Sandstone types</th>
<th>Primary pores (%)</th>
<th>Secondary pores (%)</th>
<th>Matrix pores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Residual</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Jurassic sandstone</td>
<td>2.5-9.0</td>
<td>0.1</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>Shihezi sandstone</td>
<td>0.2</td>
<td>0.3-2.0</td>
<td>0.2-1.3</td>
</tr>
<tr>
<td>Shanxi sandstone</td>
<td>0.1-3.5</td>
<td>0.2-1.5</td>
<td>0.1-0.8</td>
</tr>
</tbody>
</table>

*The contents in this table indicate the visual area percentage of the sandstone samples.
Figure 4: Continued.
However, the other types of intergranular pores are rare in Jurassic sandstone, and they comprise less than 0.5% of the visual area of the samples.

The original primary intergranular pores in the Permian sandstone are much lower in number (see red arrows in Figure 4(b)). These pores comprise 0.1-3.5% of the visual area of the samples and have a large distribution deviation. However, the other intergranular pores, including residual intergranular pores (see red rectangles in Figure 4(c)), secondary intergranular pores (see red arrows in Figure 4(c)), and matrix intergranular pores (see red rectangle in Figure 4(d)), are relatively developed and comprise 0.1-2.0% of the visual area of the samples, as shown in Table 3.

Intragranular pores are more developed in Permian sandstone than in Jurassic sandstone, as shown in Table 4. The most developed intragranular pores in the three layers of sandstone are feldspar dissolved intraparticle pores (see red arrows in Figure 4(e)), rock debris dissolved intraparticle pores (see red arrows in Figure 4(d)), and feldspar cleavage pores (see red arrows in Figure 4(e)). Only a small number of moldic (see red arrow in Figure 4(g)) and broken grain pores (see red arrow in Figure 4(f)) are present.

Intercrystalline pores formed during diagenesis. They are primarily found in the intercrystalline areas of calcareous cement and authigenic clay cement in the three layers of sandstone (see red arrows in Figure 4(h)); they are generally micropores with diameters less than 0.5 μm and are identified only under SEM. Because they are too small to grout, they are not the main object of this study.

Microfractures include bedding microfractures caused by sedimentation (see red arrow in Figure 4(i)) and structural microfractures caused by tectonism (see red arrows in Figure 4(j)) in the three layers of sandstone. Along the strike direction of bedding microfractures and structural microfractures, the permeability of the sandstone is improved significantly due to good pore connectivity [28, 29].

3.3. Analysis of the Formation Process of "Large-Area Sweating" Seepage. As mentioned in Section 2.1, the three most widespread layers of sandstone aquifers distributed widely in the Southwest Shandong coalfield are Permian Shanxi Formation sandstone, Permian Shihezi Formation sandstone, and Jurassic sandstone [25]. The hydrogeological features of these sandstone aquifers are shown in Table 5.

The levels of water abundance for these sandstone aquifers are usually weak to moderate except when coupled with faults or folds. The so-called sweating seepage reported by many coal miners is an underground water seepage feature of these kinds of sandstone, i.e., water seepage through sandstone pores is manifested as large areas of "sweating" rather than as a permeable state of "local spray," and the water inflow rate is usually low (see Table 5). However, when a deep shaft passes through a large area of such sandstone, the amount of total seepage flow in the deep environment will become an engineering problem that cannot be ignored.

According to the petrological characteristics of the sandstone mentioned in Section 3.1, the deep mine sandstones in the Southwest Shandong coal mine have three prominent petrological characteristics (see Table 1). First, the compositional maturity is low to relatively low, which manifests as high contents of feldspar and rock debris in the sandstone. Second, the textural maturity is immature to secondarily immature, which manifests as a high matrix content in the sandstone (generally 5%-12%), and SEM shows that the main components of the matrix are kaolinite (see Figures 5(b)-5(d)), illite, chlorite, and other clay minerals. Third, many calcareous cement types are present in the

![Figure 4: Pore types in the deep mine sandstone.](image)

<table>
<thead>
<tr>
<th>Sandstone Type</th>
<th>Feldspar (%)</th>
<th>Rock Debris (%)</th>
<th>Cleavage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic sandstone</td>
<td>0.5-2.5</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Shihezi sandstone</td>
<td>0.5-2.5</td>
<td>0.2-0.5</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>Shanxi sandstone</td>
<td>0.2-1.5</td>
<td>0.1-0.2</td>
<td>0.1-0.2</td>
</tr>
</tbody>
</table>

*The contents in this table indicate the visual area percentage of sandstone samples.*
interstitial materials (see red arrows in Figures 5(e) and 5(f)). The above petrological characteristics laid an internal material foundation for various late diagenetic changes in the deep mine sandstone pore structure.

In contrast, compared with shallow environmental conditions, the deep mining environment is characterized by high water pressures, high temperatures, high pH values, and high carbon dioxide concentrations. Due to these conditions, unstable minerals, rock debris grains, and matrix and calcareous cements in the pores of deep mine sandstone can be damaged by various physical, chemical, and metasomatic effects.

Moreover, various deep mine sandstone intergranular pores initiate "large-area sweating" water seepage. As mentioned in Section 3.2, many primary and secondary intergranular pores are present in the deep mine sandstone in the Southwest Shandong coal mine. In particular, original intergranular pores are common in the Jurassic sandstone, with good connectivity and 100% probability of appearance (see red arrows in Figure 5(a)). The original intergranular pores of Permian sandstone are much lower in number (see red arrows in Figure 5(b)) (see Table 3). Nevertheless, the other types of intergranular pores, such as residual intergranular pores and secondary intergranular pores, are relatively developed.

Based on the above understanding, the process of "large-area sweating" seepage in sandstone on the ventilating shaft wall in the Tangkou coal mine was analyzed. This process can be divided into three stages: a matrix softening stage, a matrix erosion stage, and a "large-area sweating" water seepage formation stage.

In the matrix softening stage, with the deepening of the shaft excavation, the hydrostatic pressure in the sandstone on the shaft wall increases, and some coarse-grained sandstone with developed intergranular pores begin to seep locally under the action of hydrostatic pressure at depth. Additionally, under the influence of deep environmental factors, such as high temperature, high acidity and alkalinity, and carbon dioxide concentration, feldspar, rock debris, and calcareous cement in sandstone begin to dissolve gradually, resulting in the increase and enlargement of various dissolution pores in sandstone (see red arrows in Figure 5(g)). Thus, the matrix interstitial fillers in the sandstone intergranular pores begin to make contact with the groundwater and are soaked for a long time, thereby softening and loosening. The main characteristic of this stage is that although the matrix is softened and loosened, it is still present in sandstone pores (see red arrows in Figure 5(h)).

In the matrix eroding stage, under increasing hydrostatic pressure at depth, a large number of softened and loosened nanosized matrix interstitial fillers were first removed, and then the micron-sized matrix interstitial fillers resulted in increased permeability, increased intergranular pore diameter, and improved pore connectivity. The main characteristic of this stage is that under the action of the pore water seepage pressure in the deep shaft, the nano- to micron-sized matrix in the sandstone pores is gradually eroded by the seepage water (see red arrows in Figures 5(i) and 5(j)).

In the "large-area sweating" seepage formation stage, with the increasing dissolution and erosion occurring in the deep mining environment, a large number of calcareous cement types are dissolved, and an increasing amount of the matrix erodes. Thus, the pore sizes of the deep mine sandstone are enlarged (see red arrows in Figure 5(k)), the pore connectivity greatly improves (see red arrows in Figure 5(l)), the groundwater seepage significantly accelerates, "large-area sweating" seepage begins, and the flow volume becomes large enough to affect the normal shaft construction. The main characteristics of this stage are that the seepage is obviously accelerated, and "large-area sweating" seepage begins.

<table>
<thead>
<tr>
<th>Aquifer features</th>
<th>Jurassic sandstone</th>
<th>Shihezi sandstone</th>
<th>Shanxi sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size</td>
<td>Medium, fine, and coarse sandstone and conglomerate</td>
<td>Medium and fine sandstone and a small amount of coarse sandstone</td>
<td>Medium and fine sandstone and a small amount of coarse sandstone</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>Single layer of 2.50-35.40; total thickness of 176.20-460.65</td>
<td>Single layer of 2.70-30.25; total thickness of 34.50-270.80</td>
<td>Single layer of 4.10-20.30; total thickness of 4.10-52.80</td>
</tr>
<tr>
<td>Types of groundwater</td>
<td>Confined pore water and fracture water</td>
<td>Confined pore water and fracture water</td>
<td>Confined pore water and fracture water</td>
</tr>
<tr>
<td>Pore permeability</td>
<td>Medium-low</td>
<td>Low-ultralow</td>
<td>Low-ultralow</td>
</tr>
<tr>
<td>Fracture numbers</td>
<td>A small amount, developed locally near faults and folds</td>
<td>A small amount, developed locally near faults and folds</td>
<td>A small amount, developed locally near faults and folds</td>
</tr>
<tr>
<td>Main hydrochemical types</td>
<td>HCO₃⁻SO₄²⁻Na⁺</td>
<td>SO₄²⁻Na⁺</td>
<td>HCO₃⁻SO₄²⁻Na⁺</td>
</tr>
<tr>
<td>Reservoir pressures (MPa)</td>
<td>3.16-14.69</td>
<td>5.08-17.74</td>
<td>6.55-19.21</td>
</tr>
<tr>
<td>Unit water inflow (L/s m)</td>
<td>0.0471-0.1550</td>
<td>0.0039-0.0400</td>
<td>0.0020-0.0415</td>
</tr>
<tr>
<td>Water abundance</td>
<td>Weak-moderate</td>
<td>Weak</td>
<td>Weak</td>
</tr>
</tbody>
</table>
Clay matrices in the pores

Fig. 5c

Kaolinite

Ca

Ca

Ca

Ca

Ca

Ca

100 μm

Fig. 5d

Kaolinite

Ca

Ca

Ca

Ca

Ca

Ca

50 μm

(Figure 5: Continued.)

Small pore sizes

Feldspar
4. Discussion

4.1. Permeability Analysis of “Large-Area Sweating” Sandstone. Before grouting in deep mine sandstone pores, we need to understand the permeability of “large-area sweating” sandstone and in which kinds of sandstone “large-area sweating” seepage may occur. This discussion will analyze and estimate the range of values of the permeability of “large-area sweating” sandstone. Because different stratigraphic structures or sandstone pore structures have different permeabilities, the estimated permeability of “large-area sweating” sandstone is different. Here, as a case study [30], permeability analysis and estimation are carried out by taking the sandstone seepage on the ventilating shaft wall of the Tangkou coal mine where “large-area sweating” seepage has occurred.

According to the geological observations obtained from the construction of the ventilating shaft in the Tangkou coal mine [30], the diameter of the shaft is 6 m, the wellhead elevation of the shaft is +39 m, and the vertical depth of the shaft is 1044 m. The strata that are crossed by the ventilating shaft from top to bottom include Quaternary, Jurassic, and Permian systems. The aquifers through which the ventilating shaft passes are mainly Jurassic sandstone aquifers and Permian sandstone aquifers. These sandstone aquifers are mainly pore aquifers with small numbers of microfractures. No water seepage outlet point became visible during the excavation. The seepage water is in the form of “large-area sweating” and is large in volume. A total of 6 main sandstone seepage sections occur in the bedrock below a 284 m wellhead with a total thickness of 559.4 m (see Table 6). In the construction process, conventional grouting was carried out in the rock mass behind the wall of the ventilating shaft (see Figure 6(b)). Two kinds of slurry materials were used in the construction process: (a) portland cement slurry: the water cement ratio was 0.6-2.0 and (b) portland cement slurry with sodium silicate (SiO$_2$/Na$_2$O = 2.3 – 2.8): the water cement ratio of the portland cement slurry was

<table>
<thead>
<tr>
<th>Strata</th>
<th>Thickness (m)</th>
<th>Lithological characteristics</th>
<th>Hydrogeological feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary system</td>
<td>217</td>
<td>Coarse, medium, and fine sandstone, clay, and sandy clay</td>
<td>Lacks an important sandstone seepage section</td>
</tr>
<tr>
<td>Jurassic system</td>
<td>516</td>
<td>Fine sandstone, siltstone, and magmatic rock</td>
<td>Contains 3 main sandstone seepage sections</td>
</tr>
<tr>
<td>Permian system</td>
<td>311</td>
<td>Coarse, medium, and fine sandstone, siltstone, mudstone, and sandy clay</td>
<td>Contains 3 main sandstone seepage sections</td>
</tr>
</tbody>
</table>

Figure 5: Microscopic changes in the pore structures occurring during the formation process of “large-area sweating” seepage in deep mine sandstones.
1.25:1, and the volume ratio of portland cement and sodium silicate was 1:0.8-1:0.4. However, the water plugging effect was not ideal and failed to meet the requirements of the acceptance specification.

According to the code for the acceptance of shaft sinking and drifting of the coal mine (GB50213-2010) [4], the total water inflow of the shafts exceeding 600 m depth shall not be more than 10 m$^3$/h.

The following is the permeability analysis and estimation process of the "large-area sweating" sandstone on the ventilating shaft wall of the Tangkou coal mine. To simplify the calculation, the "large-area sweating" sandstone is calculated as a whole without interlayers, and the "large-area sweating" seepage is in the form of radial flow, as shown in Figure 6(a). Thus, the permeability of sandstone can be calculated according to the Darcy formula of plane radial flow proposed by Amyx in 1960 [31], as shown in the following formula.

$$K = \frac{Q \mu \ln \left( \frac{R_e}{R_w} \right)}{2\pi h(P_e - P_w)}$$  \hspace{1cm} (1)

where $K$ is the permeability of sandstone, $Q$ is the seepage amount, $\mu$ is the water viscosity, $R_e/R_w$ is the ratio of the outer diameter to the inner diameter, $h$ is the thickness of "large-area sweating" sandstone, and $(P_e - P_w)$ is the water pressure difference between the outer and inner sides of the ventilating shaft.

According to the geological data of the main shaft and the ventilating shaft of the Tangkou coal mine, the calculation parameters in the above formula are estimated as follows:

(i) Regarding the water pressure difference $(P_e - P_w)$, according to the People's Republic of China petroleum natural gas professional standard (SY/T5815-2016) [27], the water pressure difference of the shaft wall at 1 kilometer is estimated to be 11.3 MPa and equal in different directions. Because the actual water pressure difference increases with increasing depth from top to bottom, to simplify the estimation, the water pressure difference is estimated to be the water pressure difference at half a kilometer, i.e., 5.65 MPa

(ii) Regarding the seepage amount $(Q)$, according to the code for the acceptance of shaft sinking and drifting of coal mines (GB50213-2010) [4] and assuming conditions at the limit, the seepage amount is estimated at the maximum allowable water seepage value $Q_{\text{max}}$ of the 1-kilometer shaft, i.e., 10 m$^3$/h

(iii) Regarding the ratio of the outer diameter to the inner diameter $(R_e/R_w)$, according to the conventional back wall grouting scheme of the main shaft and ventilating shaft of the Tangkou coal mine [32], the distance between the water stop and shaft wall is generally 2 m, and the inner radius of the shaft is 3 m; accordingly, the outer diameter is 5 m, as shown in Figure 6(a), and thus, the logarithm of the ratio of internal and external diameters is 0.51

(iv) The water viscosity $(\mu)$ is $1.005 \times 10^{-9}$ MPa$\text{s}$

(v) Regarding the thickness of "large-area sweating" sandstone $(h)$, considering that 6 main sandstone seepage sections of the ventilating shaft have a total thickness of 559.4 m, and only a certain proportion of the total thickness is "large-area sweating" sandstone, to simplify the estimation, the thicknesses of "large-area sweating" sandstone are assumed to be 50%, 40%, 30%, 20%, and 10% of the total thickness, respectively, i.e., 279.70 m, 223.76 m, 167.82 m, 111.88 m, and 55.94 m, respectively

By substituting the above estimation parameters into Equation (1), the permeability of "large-area sweating" sandstone can be calculated.
sandstone (K) can be calculated as 0.15 mD, 0.18 mD, 0.24 mD, 0.36 mD, and 0.73 mD.

According to the survey and mining data of the Southwest Shandong coalfield, the average thickness of the deep mine sandstone in the Shanxi Formation accounts for approximately 31% of the total thickness [33]. Therefore, it is estimated that the minimum lower permeability limit of the "large-area sweating" sandstone in the Tangkou coal mine of the Southwest Shandong coalfield is approximately 0.25 mD.

According to the permeability distributions of the three layers of deep mine sandstone (see Figure 7), the permeability of Jurassic sandstone is more significant than 0.25 mD (minimum 0.7 mD), so all of the Jurassic sandstone is medium- to low-permeability "large-area sweating" sandstone. The average permeability of the Permian Shihezi and Shanxi Formation sandstones is smaller than 0.25 mD. Nevertheless, the maximum value is more significant than 0.25 mD, so only a small portion of Permian sandstone is low-permeability "large-area sweating" sandstone.

4.2. Sandstone Pores Coupled with Microfractures. In Section 4.1, the lower permeability limit of "large-area sweating" sandstone refers to the matrix permeability of sandstone without fractures. Nevertheless, mining data from the Southwest Shandong coal mine show that deep mine sandstone often contains several fractures. For example, during the construction period of the Longyun coal mine, because the auxiliary shaft station is located in the Shihezi Formation, many microfractures occur in the deep mine sandstone, and the water inrush phenomenon of pore sandstone frequently occurs, so the second-phase sinking and driving engineering of the mine needs the support of curtain grouting, which has slowed the progress of the project. In addition, studies have shown that the development of bedding fractures [28] and structural fractures [29] can significantly improve the connectivity of the pore structure of sandstone and increase the permeability. Therefore, when different numbers of microfractures are coupled with pores in deep mine sandstone, the lower permeability limit of “large-area sweating” sandstone can be less than 0.25 mD.

4.3. Recommendations for the Prevention of “Large-Area Sweating” Water Seepage. The efficiency and safety of underground mining is very important. If “large-area sweating” seepage of sandstone pores is not effectively controlled in a timely manner, normal coal mine production will be stopped, the shaft will even be scrapped, and the economic loss will be very severe. Based on our understanding of its formation mechanism, "large-area sweating" seepage from deep mine sandstone pores can be prevented effectively by paying considerable attention to the following three aspects of the work done during construction and rapid production expansions of deep coal mines.

4.3.1. Prediction of “Large Area Sweating” Seepage from Sandstone Pores. In the process of tunneling in deep shaft coal mines, it is possible to predict the occurrence of "large-area sweating" water seepage from sandstone pores by identifying the following four conditions, namely, (a) sandstone located in deep mining environments, (b) large numbers of intergranular pores in the sandstone, (c) sandstone permeability greater than 0.25 mD (it can even be less than 0.25 mD if the sandstone is accompanied by microcracks), and (d) a large area of sandstone exposed by excavations of main shafts or roadways. "Large area sweating" water seepage from sandstone pores will occur if all the above conditions are met. This is the conclusion of this study based on case analyses for many deep shaft coal mines in Southwest Shandong Province where "large-area sweating" seepage has occurred through sandstone pores many times.
4.3.2. Prevent “Large Area Sweating” Seepage from Deep Sandstone Pores. If it is predicted that “large-area sweating” water seepage may occur in a certain layer of deep shaft sandstone by the analysis of geological data, the ground pregrouting can be carried out behind the shaft wall to reduce the pore pressure in the sandstone by the grouting curtain, so as to prevent “large-area sweating” seepage from the sandstone.

4.3.3. Stop the “Large-Area Sweating” Seepage from Deep Sandstone Pores. If “large-area sweating” seepage has occurred through some sandstone pores in the shaft or roadway, high-pressure pore grouting can be carried out in the areas where the seepage is obvious, because at the formation stage of “large-area sweating” seepage, the pore connectivity is greatly improved, and pore grouting is possible. Based on the experience gained from sandstone pore grouting in Southwest Shandong coal mines, it is suggested that three kinds of slurry should be selected: (a) single cement slurry, (b) cement and water glass slurry, and (c) PM-21 chemical slurry with a ratio for toluene diisocyanate : polyether (N330) : dibutyl ester : acetone : blowing agent : triethylamine equal to 2 : 1 : 0.4 : 0.4 : 0.05 : 0.03. The slurry is used as follows: first inject the single cement slurry. If sandstone pore grouting is difficult, then the cement and water glass slurry can be injected. If it is still difficult to carry out sandstone pore grouting with the cement and water glass slurries, then the PM-21 chemical slurry can be injected.

The above recommendations are based on prevention and control experience with “large-area sweating” leakage of sandstone pores in deep coal mines in Southwest Shandong, China, and they can be used as an important reference for prevention and control of “large-area sweating” water seepage in areas with similar stratigraphic conditions. However, in areas with very different stratigraphic conditions, these recommendations should be used in combination with strategies developed for the local stratigraphic characteristics.

5. Summary and Conclusions

Taking the deep mine sandstone in the southwest Shandong coal field, where “large-area sweating” seepage has occurred, as an example, this study analyzed the formation mechanism of “large-area sweating” water seepage based on the pore structure and petrological characteristics of the sandstone. In addition, the permeability ranges of sandstone in which “large-area sweating” seepage may occur was discussed. The main findings of this study are as follows:

(1) The deep mine sandstone in the Southwest Shandong coal mine has three prominent petrological characteristics. First, the compositional maturity is low to relatively low, which manifests as high contents of feldspar and rock debris grains in the sandstone. Second, the textural maturity is immature to secondarily immature, which manifests as a high matrix content in the sandstone (generally 5%~12%). Third, many calcareous cement types are present in the interstitial materials, except for the matrix. The above petrological characteristics laid an internal material foundation for various late diagenetic changes in the deep mine sandstone pore structure.

(2) Compared with the shallow environment, the deep mining environment has high water pressures, high temperatures, and high pH values and carbon dioxide concentrations, thereby reducing the difficulty of dissolving many minerals. In particular, many unstable minerals, rock debris grains, and a large number of matrix and calcareous cement types fill the deep mine sandstone pores and are easily damaged by various physical, chemical and metasomatic effects. These environmental differences provide the necessary external environmental conditions for various late diagenetic changes in deep mine sandstone pore structures.

(3) Various intergranular pores in deep mine sandstone initiate “large-area sweating” water seepage. Many primary intergranular pores and secondary intergranular pores are present in the deep mine sandstone in the Southwest Shandong coal mine. In particular, original primary intergranular pores are common in the Jurassic sandstone, with good connectivity and a 100% appearance probability. The original primary intergranular pores in the Permian sandstone are much lower in number, and the other types of intergranular pores, such as residual intergranular pores and secondary intergranular pores, are still relatively developed.

(4) The process of “large-area sweating” water seepage in deep mine sandstone can be divided into the matrix softening stage, the matrix erosion stage, and the “large-area sweating” water seepage formation stage. In the matrix softening stage, although the matrix is softened and loosened, it is still present in the sandstone pores. In the matrix eroding stage, under the action of the pore water seepage pressure in the deep shaft, the nano- to micron-sized matrix in the sandstone pores is gradually eroded by the seepage water. In the “large-area sweating” seepage formation stage, the pore connectivity of the deep mine sandstone significantly improves with increasing erosion, the groundwater seepage significantly accelerates, and “large-area sweating” seepage forms.

(5) According to the permeability analysis of the “large-area sweating” sandstone in the Tangkou coal mine in the Southwest Shandong coalfield, the lower limit of permeability of the “large-area sweating” sandstone is approximately 0.25 mD. All of the Jurassic sandstone is medium- to low-permeability “large-area sweating” sandstone; only a small portion of the Permian sandstone is low-permeability “large-area sweating” sandstone. However, when different numbers of microfractures are coupled with pores
in deep mine sandstone, the lower permeability limit of "large-area sweating" sandstone can be less than 0.25 mD.

(6) This study proposed the concept of "sweating" water seepage in sandstone pores, analyzed the formation mechanism of "large-area sweating" water seepage in sandstone under deep shaft environmental conditions, and discussed the permeability range of sandstone in which "large-area sweating" seepage may occur. These findings contribute to a better understanding of the formation mechanism of "large-area sweating" seepage from deep mine sandstone pores, so that it is possible to predict, prevent, and stop the formation of "large-area sweating" water seepage from deep mine sandstone pores.

Abbreviations

\( Q \): Quaternary system  
\( J_1 \): Jurassic system  
\( P_2 \): Permian Shihezi Formation  
\( P_1 \): Permian Shanxi Formation  
3A: 3A coal layer  
\( K \): Sandstone permeability (mD)  
\( Q_{\text{max}} \): The maximum allowable water seepage value (m³/h)  
\( h \): The thickness of "large-area sweating" sandstone (m)  
\( \mu \): The water viscosity (MPa.s)  
\( R_e \): The outer diameter of the ventilating shaft (m)  
\( R_\text{i} \): Inner diameter of the ventilating shaft (m)  
\( P_e \): Water pressure at outer side of the ventilating shaft (MPa)  
\( P_i \): Water pressure at inner side of the ventilating shaft (MPa)

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declared that they have no conflicts of interest to this work.

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