

EXPERIMENTAL STUDY ON MULTI-SCALE MIGRATION CHARACTERISTICS OF CAPILLARY WATER IN TAILINGS

by

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The increase of water content in tailings is the key cause of various diseases. In order to study the microscopical mechanism of tailings capillary water transport, an online monitoring capillary water rise test system was developed by itself, which mainly includes distortionless high definition digital microscope, 3-D mobile microscopic observation frame, CAMERA/VIEW PLAY CAP wireless acquisition system and computer. The system is used to carry out the dynamic real-time observation experiment of the capillary water rising process of tailings, analyze the movement trajectory and migration characteristics of the capillary water; and clarify the evolution law of the unsaturated tailings micro-structure under the hydraulic path. The results show that: There is a power exponential relationship between the rising height of capillary water and time, and the rising process can be divided into pure inertia stage, viscosity-inertia stage and pure viscosity stage. Capillary absorption is a process of non-uniform water absorption, the water content of the capillary zone decreases with the increase of the height, and its relationship curve shows an inverse "S" shape, the water content varies from 4.15% to 21.3%. Capillary water migration is a dynamic process in both vertical and lateral directions and the most obvious change in the microscopic structure of tailings is the occurrence of water in pores, with the change of the saturation from low to high, the occurrence shows the shape of pendulum, ring cord, capillary and serous liquid bridge. The capillarity of tailings follows the order of macropores, mesopores and micropores to absorb water; most of which occurs in mesopores, the mechanism of 'in the macropores and mesopores, capillary water increased preferentially' in tailings granular materials is proposed. The research results revealed the internal correlation mechanism of macro and micro capillary mechanics of tailings, clarified the evolution model of the micro-structure of tailings during the rise of capillary water, and further clarified the reasons for the macroscopic damage phenomenon of granular materials caused by the development process of tailings particle drying to humidification.

Key words: *tailing, capillary water rising height, moisture content, mesoscopic structure, particle characteristics*

Introduction

Tailings have the characteristics of water sensitivity, which is extremely unfavorable to the stability of the dam [1, 2]. The steady-state flow of the tailings pond after the closure can

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continue for decades. Under the action of the rainstorm, the capillary action makes the infiltration-line position quickly rise to a certain height. Therefore, the stability of the tailings dam largely depends on the capillary phenomenon of the tailings, and the long-term accumulation effect of the capillary action is macroscopic and extremely harmful. Utilizing tailings resources is an essential approach towards establishing a *waste-free mine* and fostering a *green mine* [3, 4]. The influence of capillary action on tailings materials is caused by long-term cumulative effect [5, 6]. Therefore, the evolution mechanism of hydration meso-structure of tailings materials is a key scientific question to be answered in the study of tailings dam.

While domestic and foreign scholars have extensively explored soil capillarity [6-9], research on tailings capillarity remains relatively scarce, particularly in terms of understanding the alterations in tailings micro-structure induced by capillary action. In recent years, the extensive development of lean ore has led to a substantial increase in the content of fine tailings [10], thereby highlighting the prominence of tailings capillarity. Zandarin *et al.* [11] initially posited that capillarity may significantly reduce the stability of the dam body. Subsequently, Zhang *et al.* [12] studied the macro migration characteristics of tailings capillary water, and obtained that the rise height 0.28 days before the test accounted for 30% of the total height. Zhang *et al.* [13] took into consideration the influence of temperature, air pressure, and other factors on the surface tension during the rising process of tailings capillary water. The effect of temperature on the rise of capillary water is greater than that of air pressure. In the early stage of the rise of capillary water, the effect of temperature and air pressure on the rise of capillary water is little, but in the later stage of the rise, the effect is gradually obvious. Yin *et al.* [14] used the self-developed tailings micromechanics and deformation observation experimental device to study the migration characteristics of pore water in the process of water filling and drainage of tailings. The settlement displacement of tailings particles in each layer under load is significantly greater than that of particles in the same position under the condition of no water filling. The settlement displacement and micro-structure of tailings particles are less affected by drainage, and their changes are mainly in the early stage of drainage. Zhang *et al.* [15] studied the capillary water absorption characteristics and pore structure changes of tailings filling materials, indicating that increasing the amount of fly ash and cement can reduce the surface capillary water absorption of bulk filling materials, and the effect of fly ash is more significant. Scholars have carried out a series of researches on capillarity, which is of great practical significance for in-depth exploration of water induced tailings dam disaster mechanism and stability evaluation. The aforementioned research primarily centers on the influence of factors such as particle size gradation, particle size, water content, *etc.*, on the macroscopic rise pattern of capillary water. The development process of tailings particles from drying to wetting is the inducing factor of disasters such as piping, soil flow and marsh on dam slope [16]. In order to explore the cause of macro damage, it is necessary to start from the relative position, contact state, size and shape of pores between tailings particles [17, 18] meso structure to study the meso mechanism of water and soil interaction associated with it. The existing researches on the meso structure of tailings mostly focus on the observation of the micro structure section or tangent plane [19, 20], and the scope and vision of the research have certain limitations. The evolution mechanism of the meso structure of tailings capillarity needs further research.

At present, in order to observe the whole process of the rise of capillary water in tailings, neither SEM nor ESEM can satisfy the long-term experiment of the mine tailing capillarity process. The nuclear magnetic resonance test cannot meet the scale requirements of the capillarity test. The CT scan is difficult to carry out and its equipment is expensive [21]. On this basis, an on-line monitoring test device for capillary water rise was developed independently, and mesoscopic tests were conducted on the process of capillary water rise in tail-

ings. Combined with meso-images of tailings at different water absorption times and different rising heights, the evolution mechanism of the meso-structure of unsaturated tailings under the hydraulic path was expounded and aims to make the meso-mechanism of tailings capillary water transport.

Experiment

Experimental principle

At the interface between water and tailings, there is a thin layer of liquid whose thickness is approximately the molecular radius, which, macroscopically speaking, is referred to as an *adhesive layer* [22]. When the cohesive force is greater than the adhesive force, the resultant direction of the cohesive and adhesive forces of the liquid interface layer points towards the liquid interior, and the molecules in the interface layer tend to be squeezed into the liquid, causing the liquid interface layer to tend towards spontaneous contraction, resulting in a convex surface and obtuse contact angle. At this time, the solid phase cannot be wetted by the liquid phase. When the cohesive force is less than the adhesive force, the resultant direction of the cohesive and adhesive forces of the liquid phase interface layer is outward of the liquid, molecules in the liquid phase tend to be dragged into the liquid interface layer, and at the same time, the liquid phase interface layer has a tendency towards spontaneous expansion, resulting in a concave surface and acute contact angle, that is, the solid phase is wettable by the liquid phase. Therefore, the root cause of wetting phenomenon is that adhesive force is greater than cohesive force, as shown in fig. 1.

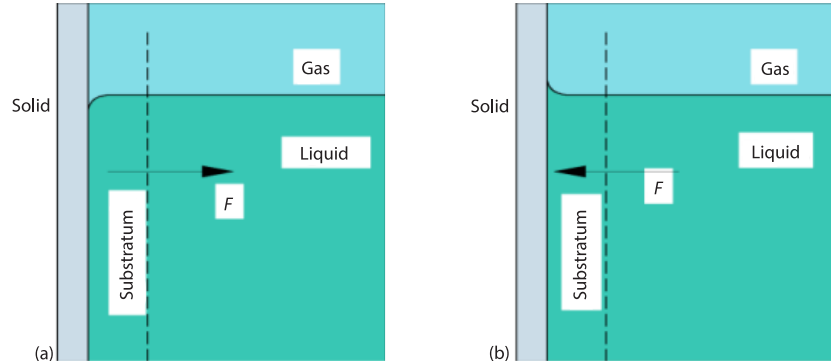


Figure 1. The wetting phenomenon; (a) wetting and (b) non-wetting

The interaction between adjacent liquid levels is manifested as tension. Young eq. (1) is the basic equation for the wetting of solid surface, also known as the wetting equation [23]:

$$\gamma_{sg} = \gamma_{sl} + \gamma_{gl} \cos \theta \quad (1)$$

where γ_{sg} , γ_{sl} , and γ_{gl} [Nm^{-1}], respectively, represent the interfacial tension of solid-gas, solid-liquid and liquid-gas and θ [$^\circ$] – the contact angle.

Material properties

The tailings were obtained from a copper mine tailings pond located in Shaanxi province, with particle sizes ranging from 0.5-350 μm , with the majority falling within the range of 100-200 μm . The uniformity coefficient Cu value of 6.69 and curvature coefficient Cc value of 1.86 indicate that the particle size distribution range of the tailings is broad and well graded. Figure 2 shows the grain grading curves of the tailings. Quartz is the main mineral component

in the copper tailings, accounting for 79.51%. The average pore size is 10.739 μm , and the porosity is 4.91%. The pores are mainly mesoporous and have good connectivity. Figure 3 shows the results of pore distribution characteristics. Table 1 presents the grain composition and main physical property indexes.

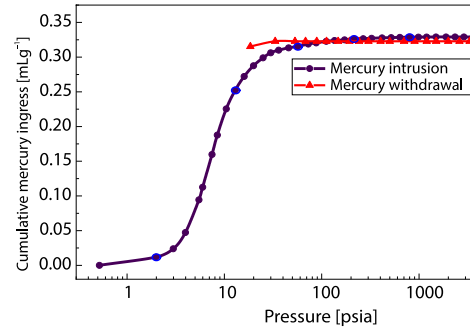
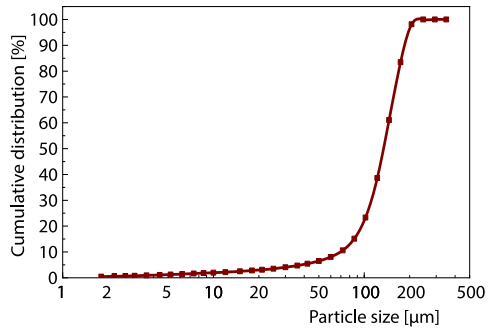


Figure 2. Particle size distribution of tailings Figure 3. Pressure-cumulative mercury ingress curve

Table 1. Particle size distribution and index of main physical properties of the sample

Name	Grain composition indexes					Physical property indexes							
	Effective grain size, d_{10} [μm]	Middle grain size, d_{50} [μm]	Constrained grain size, d_{60} [μm]	Uniformity coefficient, C_u	Curvature coefficient, C_c	Relative density [gcm^{-3}]	Dry density [gcm^{-3}]	Void ratio	Porosity [%]	Initial moisture content [wt.%]	Plastic limit [%]	Liquid limit, [%]	Plastic index
Copper tailings	21.22	114.31	142.12	6.69	1.86	2.90	1.77	0.985	49.6	4.01	18.8	24.9	6.1

Experimental device

The testing device is the self-developed online monitoring capillary water rise visual testing system (abbreviated as OM-CRT system). The main component is composed of six sections: capillary water absorption-water release test column group, online water-content monitoring system, data and image acquisition system, mesoscopic observation system, water supply system and drainage system, fig. 4.

- *Capillary water absorption – water release test column group.* The test system consists of two transparent organic glass columns, with the glass column including the upper sample loading structure and the lower supporting structure. The sample structure was designed with an inner diameter of 110 mm, a height of 480 mm, and a wall thickness of 5 mm. The lower support structure is 100 mm high, so as to avoid the influence of the arc of the plexiglass column on the observation effect and meet the requirements of the sample size. The wall thickness and an inner diameter are consistent with the upper sample structure, and the side 50 mm high is provided with a water inlet hole. The upper sample loading structure and the lower supporting structure are separated by a porous disk, with rubber gaskets in the middle interval to achieve the sealing effect. The disc is filled with holes, each of which

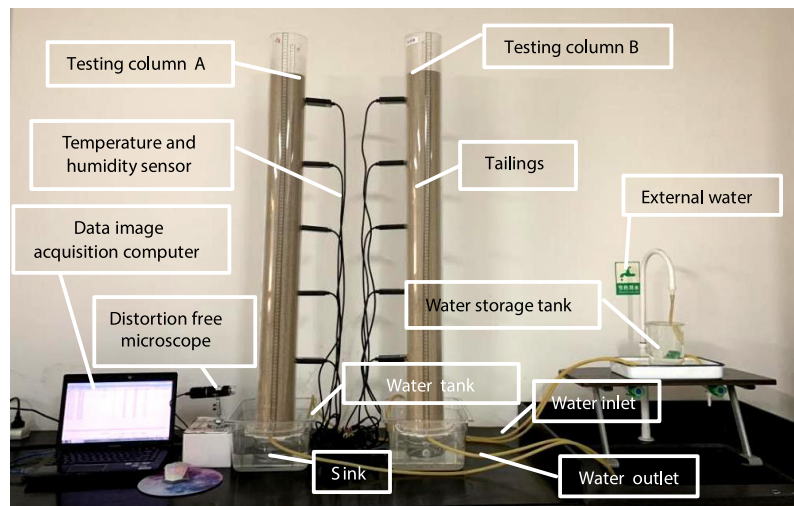


Figure 4. On-line monitoring capillary water rise test device

has a diameter of 3 mm and a thickness of 10 mm, in order to ensure water accessibility to the tailings. It is covered with geotextile with a diameter of 110 mm to prevent leakage of tailings particles. On each side of symmetry, there is one used to provide a reference for recording the height of the wetting front and the saturation front. The height of the top surface of the porous disk is zero, and the minimum scale is 1 mm. The groups A and B is to serve as control experiments to verify the experimental process and results.

- *On-line water-content monitoring system.* The system is primarily composed of a SM3001B temperature and humidity sensor, a SU9101B RS485 converter, and a SV3010 data acquisition system.
- *Data and image acquisition system.* It contain a computer and SV3010 data acquisition system.
- *Meso-observation system.* The system includes a microscope system and an image analyzer system. The microscope observation system, as depicted in fig. 5, consists primarily of a high definition digital microscope devoid of distortion, a 3-D mobile microscope observation frame, a CAMERA/VIEW PLAY CAP wireless acquisition system, and a computer. With the assistance of the WIFI function, the microscope is capable of transmitting the continuous tone analog images to the computer or mobile phone device through sampling and quantization. During the observation process, images can be adjusted, received, transmitted, and stored by a computer, realizing online monitoring and information processing automation. The microscope overcomes the shortcoming of the narrow focal surface of traditional microscopes, and can meet the needs of long-term experiments. It can be considered as an ideal instrument for observing meso-scale structures during capillary rise processes. The image analyzer observation system, as shown in fig. 6, is primarily composed of an X61 image analyzer and a computer, and is employed to observe the capillary aquifer state of the tailings within the cylinder.
- *Water supply system.* The water supply source is provided by the water source of the laboratory water pipe, and the water storage tank is then diverted to the water tank using the principle of siphon. The water tank is equipped with a drainage pipe to ensure that the liquid level in the water tank remains constant.

- *Drainage system.* The system is mainly composed of water tank and drainage pipe. The water tank is equipped with a drainage hose to keep the liquid level at 12.5 cm.

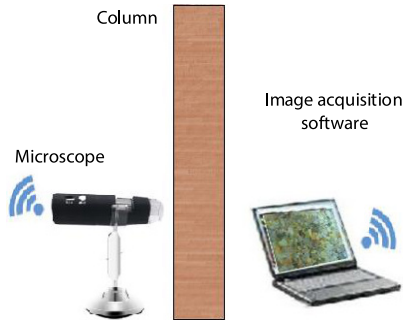


Figure 5. Microscopic observation test system



Figure 6. The image analyzer

Experimental program

Through the whole process of the capillary water absorption, the characteristics of capillary water transport and the changes of particle meso-structure were observed. During the experiment, the temperature was kept constant at 25 °C and the pressure was standard atmosphere. The specific test steps are:

- *Prepare and load tailings samples.* After cleaning, drying, and screening the tailings samples, perform stratified sample loading and seismic compaction every 5 cm to ensure uniform sample loading, and maintain a certain dry density of the scale and filling mass calculations. Keep the loaded tailings specimen in place for 24 hours for testing.
- *Adjust and install equipment.* Install and debug the constant liquid level water supply device, install the moisture content online monitoring sensor in the reserved hole of the plexiglass column, seal it with glass glue, and check to ensure the sensor circuit is in good working condition. Install an orthoscopic microscopic and adjust the lens so that the microscope can accurately observe the particles. After the installation and commissioning are completed, the initial tailings meso-structure collection is conducted.
- *Capillary-water absorption test.* Moving the plexiglass column into the fixed water supply device. Open the control valve of the injection device to allow the solution enter the tank, and control the velocity of water flow to ensure the water just touches the bottom of the tailings. Meanwhile, use the principle of siphon ensure that the water level in the flume is constant.

Results and analysis

Changes in the rising height of capillary water

Figure 7 show the relationship between the wetting front of tailings with time in the first 500 minutes and 11000 minutes. The height of the wetting front increases exponentially with time and shows the characteristics of a rapid rise in the early stage, slow rise in the middle stage and steady rise in the later stage.

According to the changing characteristics of capillary rising speed, the capillary rising process can be divided into three-stages: rapid rising stage, slow rising stage and stable rising stage. From the perspective of mechanics, the capillary rising process is affected by a combination of capillary force, inertia force, viscous resistance and its gravity, and the predominant forces acting on the process vary depending on the stage [24].

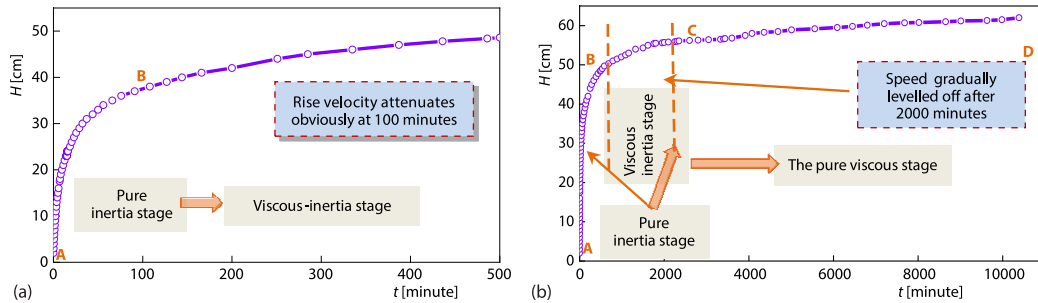


Figure 7. Relationship between height and time; (a) the first 500 minutes and (b) the first 11000 minutes

The first stage (AB) is the initial stage of capillary rise, the stage is characterized by the rapid rise of the wetting front, which reaches 37.8 cm in the first 100 minutes with an average rise rate of 17.76 cm per hour. In the initial stage, the amount of water is very small, and the viscous resistance which is related to the amount of liquid and its own gravity effect can be ignored, the capillary pressure independent of the volume of liquid and the inertia force which is related to the rate of change in liquid volume liquid together support the rise of capillary water. Therefore, this initial rapid rise stage is also called the pure inertia stage of tailing capillary rise. The second stage (BC) (100-2000 minutes) is the middle stage of capillary rising. In this stage, the capillary rising rate is relatively slow, and the amount of liquid in the capillary gradually increases with time. The related viscous resistance, self-gravity, inertia force and capillary driving pressure all support the capillary water flow. Thus, this stage is the viscous-inertia stage of tailing capillary rising. The third stage (CD) is the later stage of capillary rising. The driving force of capillary pressure is closer and closer to the action of viscous force and its gravity resistance, and the driving force and resistance can cancel each other. The increasing acceleration of capillary water is gradually smaller, the inertia effect is weaker, and the fluid-flow tends to be stable Poiseuille flow. The only forces that are left to dominate are the viscous and capillary forces, and this stage is the pure viscous stage of the capillary rise of the tailings.

Moisture content change during water absorption

The relation between water content and height is shown in fig. 8. It can be seen that the relation between water content and rising height of capillary water is similar to the water-soil characteristic curve showing an inverse S-shape. The water content varied from 4.15% to 21.3%, with an average value of 12.725% and a change value of 17.15%. With the increase of capillary water rising height, the water content decreases gradually, and the closer to the bottom, the more obvious the change of water content. The water content at the bottom of the sample is 21.3%, which is nearly saturated.

When the water and soil potential of each point in the tailings column reaches the equilibrium state, the total soil water potential value is 0:

$$\psi = \psi_m + z \quad (2)$$

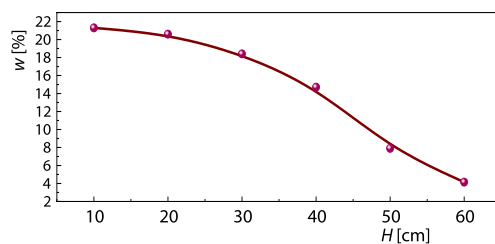


Figure 8. The relation between moisture content and height

$$\psi_m = -z \quad (3)$$

where ψ is the total soil and water potential, ψ_m – the matrix potential, and z – the gravity potential. With the increase of the rising height of capillary water, the gravity potential increases, the matrix potential decreases, and the water content decreases, thus, the moisture content in the tailing pillar shows a decreasing trend from bottom to top. By analyzing the change of matrix suction in the tailings pillar, it can be seen that the matrix suction decreases with the extension of time, and the initial decline rate is fast, while the later decline rate gradually slows down. This changing relationship is consistent with the negative correlation between matric suction and volume moisture content, that the process of capillary water absorption is an uneven process.

Water transport characteristics and meso-structure of tailings capillaries

Figure 9 shows the meso-structure images of the tailings at 18.1 cm (a scale with the top surface height of the porous disc at 0 points is carved on the bottom of the plexiglass column, 18.1 cm is measured from the bottom to the top), after the initial water absorption and after the water absorption at not bibulous, 0.02*d* (30 minutes), 0.0625*d* (90 minutes), 2*d*, 4*d*, and 7*d*. Figure 9(a) shows the situation of the tailings without water absorption. It can be seen that the tailings have a single particle structure with uniform particle size. The color is clear and the shape is close to a sphere, it is similar to soil particles. The contact between tailings particles is close, and the contact mode is mainly vertical, so that the parallel vertical columnar structure between tailings particles and pores is formed. The pores are small and evenly distributed, fig. 9(a), A represents tailings particles, and B represents pores). After absorbing water for 0.02*d*, the contour of 50% of the tailings particles becomes blurred, as shown in the left part of fig. 9(b), the color becomes dark, and the contour of the particles cannot be clearly identified, water film C appears between the particles, fig. 9(b). This is primarily due to the fact that the micro-structure of tailings facilitate the formation of capillary tubes, which causes capillary water to rise rapidly under the influence of water surface tension. In the case of low saturation, short-range adsorption forms a very thin water film on the surface of tailings particles. After absorbing water for 0.0625*d*, part of the pores are filled with water, the overall color of the image became darker compared with the initial image fig. 9(a), the undischarged gas D, fig. 9(c), can be seen between the large pores, which is in the form of discontinuous gas bub-

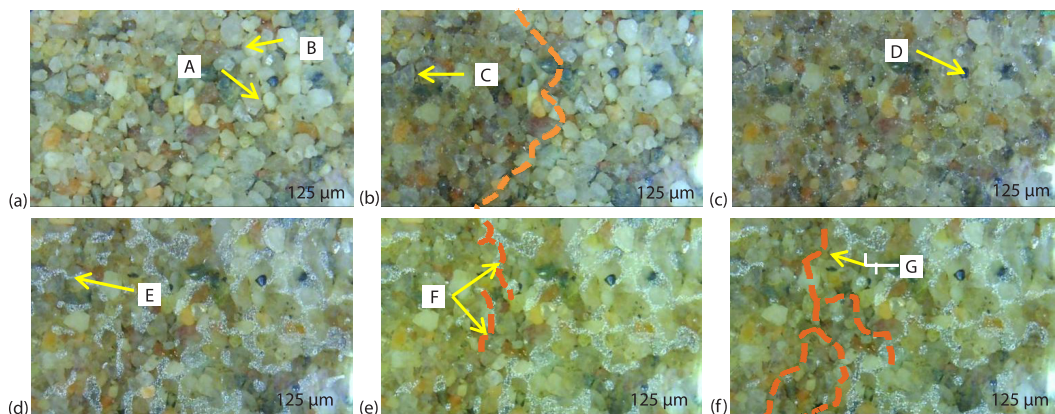


Figure 9. The tailings micro-structure; (a) not bibulous, (b) 0.02*d*, (c) 0.0625*d*, (d) 2*d*; (e) 4*d*, and (f) after 7*d*

bles, therefore, the complex three phases of solid, liquid and gas are formed. After absorbing water for $2d$, large bubbles are interconnected to form a continuous *dendritic* bubble band, fig. 9(d), which is pale white and occupies the majority of the pore region. Meanwhile, capillary water continues to migrate upward. After absorbing water for $4d$, the left part of fig. 9(e) is almost completely filled with water. Compared with fig. 9(d), the capillary water connected area is larger, but there is still a small part of capillary disconnection phenomenon, F , which is caused by the fact that the bubble band forms a closed loop and creates blind pores that hinder the migration of capillary water. After absorbing water for $7d$, fig. 9(f), the bubble zone is darker and more obvious and occupies a smaller proportion of the whole region than the former. As the capillary action time increases, the capillary connectivity, fig. 9(f), Region G increases, but there is still undischarged gas.

As can be seen from figs. 9(a)-9(f), the color of tailings and the number of bubble zones show that the migration of capillary water is a dynamic process in both vertical and lateral directions.

Figure 10 is the image collected 1 hour after the experiment, it is the mesoscopic image of the capillary at different heights. It can be seen that with the increase of capillary water rising height, the water between particles gradually decreases, and the state of particles is from wet to non-wet, which also reflects the law of moisture content gradually decreasing.

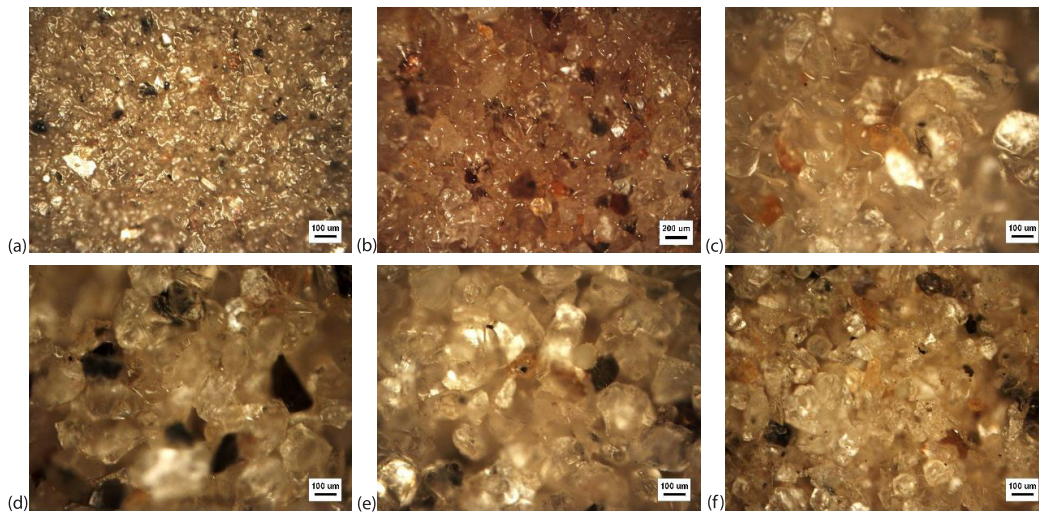


Figure 10. The micrograph of tailings at different heights ($\times 50$ times); (a) 10 cm, (b) 20 cm, (c) 30 cm, (d) 40 cm, (e) 50 cm, and (f) 60 cm

Therefore, during the capillary rise process, the micro-structure of the tailings is also undergoing changes, with the most significant alteration being the moisture content distribution within the pores. As the capillary water migrates upward from the smaller pores, it removes some of the gas, after the meso-structure of tailings is stabilized, there is still gas in the tailings, finally, a complex solid-liquid-gas three-phase system is formed.

Meso-mechanism of tailing capillary water transport

The pore structure plays a decisive role in the physical and mechanical properties of saturated and unsaturated tailings, especially unsaturated tailings. According to the pore size, pores can be divided into micropores, mesopores and macropores [25]. Micropore refers to the

pore diameter less than $0.1 \mu\text{m}$, the water in the pore is mainly adsorption water. Mesopore refers to the pore diameter between $0.1\text{-}1000 \mu\text{m}$, the water in the pore is mainly capillary water, and there is also some gravity water in the pores close to the macropore. Macropore refers to the pore size greater than $1000 \mu\text{m}$, the water in the pore is mainly gravity water, its migration process follows Darcy's law [26, 27]. In addition, almost all mineral particle surfaces have water films that bind to them, and those close to the surface of mineral particles are strongly bound water. With the weakening of its binding force of water, it gradually becomes weakly bound water and finally becomes free water [28]. That is shown in fig. 11.

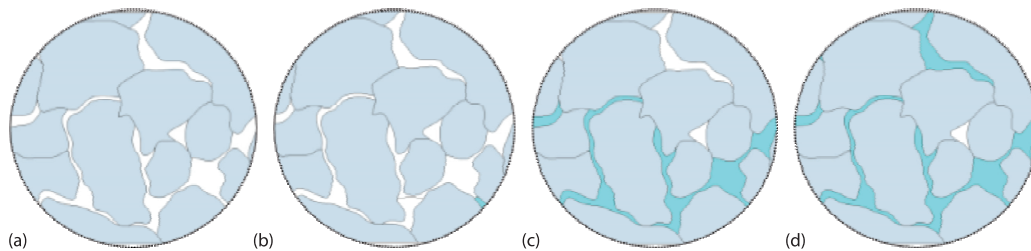


Figure 11. The capillary water absorption process of tailings: (a) initial state, (b) initiation of water absorption, (c) macropore and mesoporous water absorption, and (d) micropore water absorption

After water absorption, the main driving force of water migration the tailings is the capillary force. Since most of the air inside the tailings is discharged during the process of stratified compaction, the initial capillary water rises faster and can rise to 9 cm in the first 60 seconds. At the early stage of water absorption, the macropores and mesoporous pores are quickly filled with water, mainly the mesoporous pores. As saturation slowly increases, water gradually enters the micropores .

The capillary action is very microscopic, and its mechanism belongs to the action of intermolecular forces, and the molecules are only at the size of 0.1 nm , and the molecular spacing is only at the size of 0.1 nm , so the origin of its action is microscopic. The thickness of the bonded water film is very thin and the proportion of the total water content is very small, but it has an important influence on the physical and mechanical properties of soil [29, 30].

Continuous capillary water absorption tests show that the meso-structure of tailings with different moisture content is obviously different. Figure 12 is the liquid bridge shape change after the capillary rise of tailings is completed. Once the moisture content is less than the plastic limit of tailings (such as 8%), among the grains, there are mainly pendulum-like and cable-like liquid bridges, figs. 12(a) and 12(b). The liquid bridge is slender and the pores are mainly composed of particle point contact. The pores are mainly composed of particle point contacts, and the tailings show solid and semi-solid states. When the moisture content is greater than the plastic limit (such as 18.8%), the liquid bridge between the particles gradually changes from the annular shape to the capillary shape, fig. 12(c). As some particles become filled with water, the proportion of liquid-filled interparticle pores increases, and the tailings exist around the contact points in a viscous state. It can be seen that the color of the image collected by the microscope begins to become dark, the structure of single tailings particles becomes fuzzy, the adhesion force between particles becomes larger, and the structure gradually transforms into a small structure formed by water cohesive particles. When the moisture content is greater than the liquid limit (such as 21%), the pores between particles are filled with free water, and the liquid bridge is mainly capillary. A single particle can no longer be clearly observed, and some particles are in the form of grout, fig. 12(d), the pore is mainly a cohesive block structure gap.

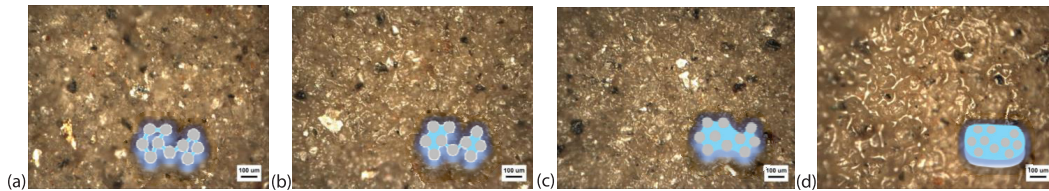


Figure 12. The shape of tailings liquid bridge (gray represents tailings particles, blue represents liquid in pores); (a) ring-shaped liquid bridge, (b) pendulous bridge, (c) capillary bridge, and (d) serous bridge

Conclusions

- The rising process of tailing capillary water shows an obvious three-stage decreasing trend according to the change of velocity, which can be divided into the early rapid rising stage, the middle slow rising stage and the late stable rising stage. In the first 100 minutes of the experiment, the rising height reached 37.8 cm, accounting for 58% of the total rising height, and the average rising speed was 17.76 cm per hour.
- Capillary water absorption is a process of non-uniform water absorption. With the increase of capillary water rising height, the moisture content decreased gradually, its change curve showed an inverse S-shape, and the change range of moisture content was 4.15%-21.3%. Besides, the closer to the bottom, the more obvious the change of moisture content.
- The meso-structure of tailings with different moisture content has obvious differences in particle profile, particle linking mode, pore state and liquid bridge form, and the most obvious change is the occurrence form of water in the pores.
- The capillary action of tailings follows the order of macropore → mesopore → micropore to absorb water, which mostly occurs in the mesopore. The variation of saturation from low to high results in the different occurrence states of water between particles, showing the liquid bridge shape of the pendulum, loop, capillary and serous.

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