Wang et al. Int J Concr Struct Mater (2024) 18:65
https://doi.org/10.1186/s40069-024-00704-w

International Journal of Concrete Structures and Materials

RESEARCH

Open Access

Study on the Diffusion Mechanism of Infiltration Grouting in Fault Fracture Zone Considering the Time-Varying Characteristics of Slurry Viscosity Under Seawater Environment

Hongbo Wang[1*], Yunchang Yu[1], Peiyuan Zhang[2], Chunyu Yang[1], Hao Wen[1], Fansheng Zhang[1] and Sanlin Du[3]

Abstract

Fault fracture zones are rock formations commonly encountered in submarine tunnels, and the diffusion mechanism of slurry in fault fracture zones has a crucial impact on submarine tunnel reinforcement. Based on the seepage equation of Bingham fluid, the tortuosity parameter, fractal theory, and variable viscosity equation are introduced to establish a spherical permeation grouting model of Bingham fluid considering the slurry diffusion path and viscosity time variability. The viscosity variation law with time of sulfur aluminate cement slurry under different seawater admixture conditions was tested, and the time-varying equation of viscosity of sulfur aluminate cement slurry was obtained by fitting. A set of fault fracture zone permeation grouting test system was developed, and a fault fracture zone grouting simulation test was carried out. The study shows that the diffusion distance calculated without considering the influence of slurry diffusion path and seawater is 1.63–1.91 times of the test value, which obviously overestimates the diffusion distance; the diffusion distance calculated with considering the influence of diffusion path and seawater is 1.06–1.35 times of the test value, which is in good agreement with the test value. The research results can provide some theoretical support for the design of grouting in seawater environment.

Keywords Seawater environment, Fault fracture zone, Permeation grouting, Diffusion path, Sulfur aluminate cement

1 Introduction

In the submarine tunnel construction project, fault fracture zone is a common engineering geology, which often induces sudden water and mud disasters. At present, grouting method is generally used at home and abroad to reinforce the fractured rock body, and grouting refers to injecting the slurry that can gel and solidify into the stratum or rock gap through a certain pressure to achieve the purpose of reinforcing the stratum or preventing seepage (Kuang et al., 2001; Zhang et al., 2019; Xu, 2022; Li, 2017). Fault fracture zone rocks are more fragmented, the pore size is generally larger, and the diffusion of slurry is mostly in the form of osmotic diffusion (Zhang et al., 2019). As early as 1938, Maag derived the equation for the permeation diffusion of Newtonian fluids in sand layers(Kuang et al., 2001), and with the development of the theory of permeation grouting, scholars at home and abroad have carried out a lot of research on the time-varying characteristics of the viscosity of grouting materials and the diffusion mechanism of slurry in porous media.

Kim & Whittle, 2009; Zhang, 2011 studied several grout diffusion mechanisms after assuming and simplifying some of some limited known conditions such as

Journal information: ISSN 1976-0485 / eISSN 2234-1315.

*Correspondence:
Hongbo Wang
hongbo_wangsdu@163.com
[1] College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China
[2] Qingdao West Coast Rail Transit Co., Ltd, Qingdao 266427, China
[3] Huaneng Tibet Hydropower Safety Engineering Technology Research Center, Sichuan 610041, China

geological conditions and construction process parameters, which can be divided into two categories: grout diffusion mechanisms without considering fluid time variability and grout diffusion mechanisms considering fluid time variability. At present, in terms of the time-varying properties of slurry viscosity not considered, Yang et al., 2005; Yu & Li, 2001 derived the formulae for the penetration diffusion radius of Bingham and power-law type slurries in geotechnical soils based on the generalized Darcy's law and spherical diffusion theory model, and analyzed the influence of slurry performance parameters on the grouting pressure and diffusion radius; Baker, 1974 derived the maximum diffusion radius of Bingham and Newtonian fluids for grouting in fractures of rock bodies. Bouchelaghem & Vulliet, 2001 studied the flow–solid coupling phenomenon and filtration effect of saturated porous media during the injection of mixed-phase slurry and established a corresponding theoretical model; Zhu et al., 2020 used the particle deposition probability model to establish a column permeation grouting model considering the percolation effect; Tekin & Akbas, 2010 established a model that can be used to estimate the percolation effect considering the slurry Saada et al., 2005, 2006 conducted an indoor test to analyze the diffusion and reinforcement mechanism of ultrafine cement slurry in sandy soil layer with the variation parameters of compactness, grouting pressure, water–cement ratio, slurry solidification degree and grouting rate; Zhang et al., 2011 developed the Herschel–Bulkley slurry diffusion and reinforcement model. Bulkley slurry diffusion model, and explored the influence of parameters such as grouting time, grouting pressure, rheological index and fracture dip angle on slurry diffusion radius.

In considering the time-varying viscosity characteristics of slurry, Ruan, 2005 proved the existence of time-varying viscosity of cement-based slurry through a large number of experiments and established a stable slurry injection diffusion model for rock fractures; Yang et al., 2011, 2021 established corresponding spherical and columnar infiltration diffusion models based on the rheological equations of power-law fluid and Bingham fluid with time-varying viscosity equations, respectively; Zhang et al., 2017, 2022a, b established a one-dimensional permeation grouting diffusion model under constant grouting rate conditions based on the viscosity time-varying Bingham fluid constitutive model, taking into account the inhomogeneity of the spatial distribution of slurry viscosity. The above scholars have not considered the influence of the tortuosity of the injected medium on the slurry diffusion path when studying the permeation–diffusion mechanism of grouting. With the further development of permeation grouting theories, some scholars have carried out a lot of research in considering the diffusion path of slurry in porous media, and Zhou et al., 2016 derived the tortuosity effect equation of the pore channel based on fractal theory and derived the slurry diffusion model considering the pore through the power-law fluid constitutive equation. Pisani, 2016 studied the dependence of tortuosity on the geometrical structure of a porous medium is studied. Geometrical expressions for the tortuosity as a function of the porosity, of shape factors characterizing the geometry of the solid objects and of the orientation of the flow with respect to the object axes are derived. Lala, 2020 Development of a new model for sample tortuosity using micromechanics theory and then the model with a sand-pack flow laboratory experiment was verified to obtain tortuosity variation with porosity indicates an inverse relationship or a negative power-law regression approximation. Zhang et al., 2018 established a model of permeation grouting in porous media considering the diffusion path of slurry by analyzing the diffusion path of slurry infiltration in porous media based on the equation of motion of seepage of Newtonian fluid. These studies promoted the further development of permeation grouting theory.

For coastal areas, if the use of seawater mixing to prepare cement slurry can greatly reduce the project cost, relevant scholars have carried out research on this. Zheng, 2023 studied the effect of seawater mixing on the mechanical strength of different types of cement, and the results showed that seawater mixing increased the generation of ettringite during sulfoaluminate salting, thus improving the late compressive strength of sulfoaluminate cement mortar, but had no effect on the flexural strength. Meanwhile, seawater mixing reduced the mechanical strength of Portland cement. Li, 2023 studied the effect of seawater mixing on the working performance of ordinary Portland cement, and the research showed that seawater mixing would accelerate the early hydration of ordinary Portland cement, shorten the setting time of cement, but reduce the mechanical strength of cement. Yu et al., 2023 studied the influence of different water mixing on the working performance of sulfoaluminate cement and added nanomaterials into the cement system for modification. The results showed that the compressive strength of sulfoaluminate cement paste after adding seawater was higher than that of sulfoaluminate cement paste mixed with fresh water, and the addition of nanomaterials would further improve the mechanical properties of cement. Zhang et al., 2022a, 2022b found through the test that seawater mixing would prolong the hydration time of magnesium phosphate cement grouting material, improve the early viscosity of the slurry, but reduce its spillability in the sand layer.

In summary, scholars at home and abroad have made abundant research results on the diffusion law and mechanism of permeation grouting, but most of the results are established based on the viscosity characteristics of slurry in freshwater environment, however, in practical engineering, seawater will have certain influence on the viscosity of slurry, and then affect the diffusion of slurry. Therefore, this paper takes sulfoaluminate cement slurry as the research object and establishes a theoretical model of grout diffusion considering seawater environment, to provide some theoretical support for the actual grouting project.

2 Theoretical Model of Viscosity Time-Varying Fluid Permeation Grouting Considering Diffusion Path

2.1 Analysis of the Diffusion Mechanism of Slurry in Porous Media

To study the diffusion mechanism of slurry in porous media, the following hypothesis was made:

(1) The slurry is homogeneous, incompressible, and gravity is ignored during the grouting process;
(2) The slurry is Bingham fluid and the flow pattern remains constant in the grouting process, and the slurry is laminar in the diffusion process;
(3) Ignore the percolation effect of slurry in the process of permeation and diffusion in porous media, and the flow process does not produce precipitation;
(4) The slurry is spherical diffusion with the end of the grouting pipeline as the point source(Fu et al., 2019; Liu et al., 2021);
(5) The porous medium is homogeneous and isotropic.

The slurry does not flow forward in a straight line when flowing in porous media formations, the complexity of the pore channels causes the slurry to form a tortuous flow path.Fig. 1 shows a schematic diagram of slurry flow in porous media, the actual length of the porous media pore channel is recorded as l_t, and the straight length of the pore channel is recorded as l.

The tortuosity of pore channels in porous media can be expressed as (Dai et al., 2021):

$$\xi = \sqrt{(1-\phi)m} + \frac{1-\phi}{2} + \frac{\sqrt{\frac{1-\phi}{m}} - 1 + \phi}{2\cos[(1-\phi)^2 \times \alpha]} + (1 - 0.5 \times \sqrt{\frac{1-\phi}{m}}) \times \sqrt{[1-\sqrt{(1-\phi)m}]^2 + \tan^2[(1-\phi)^2 \times \alpha]}, \tag{1a}$$

where ϕ is the porosity;α is the hindrance parameter with values between 0 and arctan(1/2); m is the anisotropy parameter with values greater than 0; m and α can be determined by sampling analysis methods.

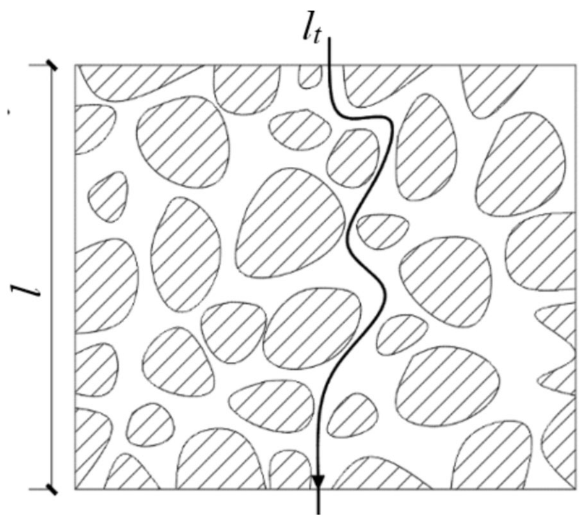

Fig. 1 Schematic diagram of slurry flow in porous media

In the case where the porous medium is isotropic, $m = 1, \alpha = 0$, then Eq. (1a) can be simplified as:

$$\xi = \frac{l_t}{l} = \frac{3-\phi}{2}. \tag{1b}$$

According to the fractal theory (Yu & Li, 2001), the porosity of porous media can be expressed as:

$$\phi = \left(\frac{r_{\min}}{r_{\max}}\right)^{2-D_f}, \tag{2}$$

where $r_{\max}$ and $r_{\min}$ are the maximum and minimum radii of the pore channels in porous media, respectively; D_f is the fractal dimension of the pore channel size.

Meanwhile, according to the research results of Yu, 2004, the relationship between the porosity of porous media and $r_{\min}/r_{\max}$ can be expressed by the following equation:

$$\frac{r_{\min}}{r_{\max}} = \frac{\sqrt{2}}{\mathrm{d}^+}\sqrt{\frac{1-\phi}{1-0.342\phi}}, \tag{3}$$

where d^+ is generally taken as 24.

Combining Eq. (2a) and Eq. (3), the fractal dimension D_f, which represents the size of the pore channel, can be expressed as:

$$D_f = 2 - \frac{\text{In}\phi}{\text{In}\frac{\sqrt{2}}{\text{d}^+}\sqrt{\frac{1-\phi}{1-0.342\phi}}}. \tag{4}$$

The pore channel tortuous curvature fractal dimension D_t can be expressed as (Xu & Yu, 2008):

$$D_t = 1 + \frac{\ln \xi}{\ln \eta}, \tag{5}$$

where η is the length ratio of pore channels of porous media,$\eta = l/r$.

According to the literature (Xu & Yu, 2008; Yu, 2004; Yu & Li, 2001), the length ratio of pore channels in porous media can be obtained as:

$$\eta = \frac{D_f - 1}{\sqrt{D_f}}\sqrt{\left[\frac{1-\phi}{\phi}\cdot\frac{\pi}{4(2-D_f)}\right]\frac{r_{\max}}{r_{\min}}}. \tag{6}$$

2.2 Fractal Theory of Porous Medium Time-varying Viscosity Slurry Seepage Equation Considering Diffusion Path

The equation for the flow velocity of a Bingham fluid in a single pipe can be expressed as (Kong, 1999; Yang et al., 2004):

$$v = \frac{K}{\mu_p}\left(-\frac{\mathrm{d}p}{\mathrm{d}l_t}\right)\left[1 - \frac{4}{3}\left(\frac{\lambda}{-\mathrm{d}p/\mathrm{d}l_t}\right) + \frac{1}{3}\left(\frac{\lambda}{-\mathrm{d}p/\mathrm{d}l_t}\right)^4\right], \tag{7a}$$

$$K = \frac{\phi r^2}{8}, \tag{7b}$$

where v is the fluid percolation velocity in the pore channel;K is the permeability of the porous medium; μ_p is the viscosity of the slurry;$-dp/dl_0$ is the pressure gradient in the direction of slurry percolation;λ is the initiation pressure gradient of the slurry ($\lambda = 2\tau_0/r$,τ_0 is the yield stress of Bingham fluid).

The process of viscosity change in viscous time-varying slurries follows the following pattern (Cai et al., 2006; Ruan, 2005; Ye et al., 2013):

$$\mu_p(t) = ae^{bt}, \tag{8}$$

where μ_p is the viscosity of the slurry; a,b is the constant to be determined; t is the time after the slurry is mixed.

Substituting Eq. (8) into Eq. (7a):

$$v = \left(\frac{K}{\mu_p(t)}\right)\left(-\frac{\mathrm{d}p}{\mathrm{d}l_t}\right)\left[1 - \frac{4}{3}\left(\frac{\lambda}{-\mathrm{d}p/\mathrm{d}l_t}\right) + \frac{1}{3}\left(\frac{\lambda}{-\mathrm{d}p/\mathrm{d}l_t}\right)^4\right]. \tag{9}$$

The above formula is the seepage movement equation of viscosity time-varying slurry.

During the grouting process, the grouting pressure is much higher than the slurry starting pressure, and the quartic term of Eq. (9) can be ignored:

$$v = \left(\frac{K}{\mu_p(t)}\right)\left(-\frac{\mathrm{d}p}{\mathrm{d}l_t}\right)\left[1 - \frac{4}{3}\left(\frac{\lambda}{-\mathrm{d}p/\mathrm{d}l_t}\right)\right]. \tag{10}$$

The total volume flow of fluid through a given cell can be expressed as:

$$q = vA \tag{11}$$

where A is the slurry diffusion cross-sectional area.

Combining Eqs. (10) and (11) yields:

$$q = \left(\frac{AK}{\mu_p(t)}\right)\left(-\frac{\mathrm{d}p}{\mathrm{d}l_t}\right)\left[1 - \frac{4}{3}\left(\frac{\lambda}{-\mathrm{d}p/\mathrm{d}l_t}\right)\right]. \tag{12}$$

Separating the variables for Eq. (12) yields:

$$\mathrm{d}p = -\left(\frac{4\lambda}{3} + \frac{q\mu_p(t)}{AK}\right)\mathrm{d}l_t. \tag{13}$$

For spherical permeation grouting: $A = 4\pi l^2$,combining $\eta = l/r$,$\lambda = 2\tau_0/r$ and Eqs. (1b) and (13) yields:

$$\mathrm{d}p = -\xi\left(\frac{\tau_0\phi l}{3K\eta} + \frac{q\mu_p(t)}{4\pi l^2 K}\right)\mathrm{d}l. \tag{14}$$

Integrating Eq. (14) yields:

$$p = \xi\left(\frac{q\mu_p(t)}{4\pi lK} - \frac{\tau_0\phi l^2}{6K\eta}\right) + C. \tag{15}$$

From the boundary conditions at the time of grouting $l = l_0$,$p = p_1$;$l = l_1$,$p = p_0$ substituting into Eq. (15) yields:

$$\Delta p = p_1 - p_0 = \xi\left[\frac{q\mu_p(t)}{4\pi K}\left(\frac{1}{l_0} - \frac{1}{l_1}\right) - \frac{\tau_0\phi}{6K\eta}\left(l_0^2 - l_1^2\right)\right], \tag{16}$$

where l_0 is the radius of the grouting pipe,l_1 is the slurry diffusion radius,p_0 is the groundwater pressure, and p_1 is the grouting pressure.

Due to grouting volume $Q = qt = \frac{4}{3}\phi\pi l_1^3$,,substituting it into Eq. (16) yields:

$$\Delta p = \xi\left[\frac{\phi l_1^3\mu_p(t)}{3tK}\left(\frac{1}{l_0} - \frac{1}{l_1}\right) - \frac{\tau_0\phi}{6K\eta}\left(l_0^2 - l_1^2\right)\right], \tag{17}$$

where t is the grouting time required for the slurry to diffuse to l_1.

In the actual grouting project, the $l_1 \gg l_0$,then $1/l_0 - 1/l_1 \approx 1/l_0$, then Eq. (17) can be simplified as:

$$\Delta p = \xi\left[\frac{\phi l_1^3\mu_p(t)}{3tl_0K} - \frac{\tau_0\phi}{6K\eta}\left(l_0^2 - l_1^2\right)\right]. \tag{18}$$

Equation (18) is the theoretical model of viscous time-varying slurry permeation grouting considering the diffusion path.

When the slurry diffusion path and viscous time-varying are not considered, the spherical osmotic diffusion equation of the slurry is:

$$\Delta p = \frac{\phi l_1^3\mu_{p0}}{3tl_0k} + \frac{4}{3}\lambda(l_1 - l_0), \tag{19}$$

where μ_{p0} is the plastic viscosity value of the fluid, that is, the initial viscosity value of the viscous time-varying fluid.

2.3 Formula Application Scope

Equations (18) and (19) are derived on the basis of the assumption that the slurry flow regime is laminar and are not applicable to slurries where the fluid flow regime is turbulent. The Reynolds number R_e is the main basis for discriminating the slurry flow state, and according to the literature (Li & Yuan, 2008), $R_e = 2000$ is the critical value for the transition of the flow state of Bingham fluid from laminar to turbulent flow, and when $R_e < 2000$, the permeable diffusive flow pattern of Bingham fluid in porous media belongs to the laminar flow state.

The generalized Reynolds number R_e is determined using the following method:

$$R_e = \frac{\rho v d}{\mu_p}, \tag{20}$$

where ρ is the density of the fluid; v is the flow velocity of the fluid; d is a characteristic length (in this paper is the diameter of the pore channel of porous media); μ_p is the viscosity of the fluid.

The flow rate of slurry is the key to determine the fluid Reynolds number, but the flow rate of slurry in the formation is not easy to determine, and it is difficult to determine the slurry flow state by the above method. According to the study of Liu et al., 2008, the slurry belongs to laminar flow state when it diffuses by permeation in the formation, and it may change to turbulent flow only when splitting diffusion occurs. Therefore, it can be assumed that the slurry flow pattern is laminar during the permeation and diffusion of sulfur aluminate cement slurry.

3 Fault Fracture Permeation Grouting Simulation Test

3.1 Viscosity Test of Sulfur Aluminate Cement Slurry Under Seawater Environment

(1)Test Materials, Programs, and Equipment

The viscosity of sulfur aluminate cement as a common grouting material for submarine tunnel fault fracture zone is influenced by chloride ions. By reviewing the data, we learned that the salinity of natural seawater varies with the region, season and water depth, and artificial seawater with 35% salinity was prepared by dissolving sea salt in tap water. The sulfur aluminate cement used in the test is 42.5R ordinary sulfur aluminate cement produced by Shandong Zibo Yunhe Color Cement Company, and the quality of the cement conforms to "sulfur aluminate cement" (GB/T 20472-2006).

Configure the sulfur aluminate cement slurry with water–cement ratio of 0.8:1, 1:1 and 1.25:1 under complete seawater, 50% seawater and complete freshwater environment respectively, and choose NDJ-5S rotary viscometer (see Fig. 2) to test the viscosity of sulfur aluminate cement slurry, the specific testing scheme is shown in Table 1, the range of viscometer is from 10 to 100,000 mPa · *s*.

The viscosity variation data of the designed proportion of sulfur aluminate cement slurry under the conditions of complete seawater, 50% seawater, and freshwater were measured, respectively, and the test data were fitted and analyzed as shown in Fig. 3.

As can be seen from Fig. 3, the viscosity of sulfur aluminate cement slurry grows nonlinearly with time, and its viscosity growth rate is also increasing; the viscosity of sulfur aluminate cement slurry is negatively correlated with the water–cement ratio, and the smaller the water–cement ratio, the greater the viscosity; the influence of

Fig. 2 NDJ-5S rotational viscometer

Table 1 Viscosity testing scheme for sulfur aluminate cement slurry

Test number	Water to ash ratio	Seawater environment
A1	0.8:1	Complete seawater
A2		50% seawater
A3		Complete fresh water
B1	1:1	Complete seawater
B2		50% seawater
B3		Complete fresh water
C1	1.25:1	Complete seawater
C2		50% seawater
C3		Complete fresh water

seawater environment on the viscosity of sulfur aluminate cement slurry is more obvious, and the viscosity of sulfur aluminate cement slurry changes relatively slowly under the seawater environment, and seawater inhibits the viscosity growth of sulfur aluminate cement.

According to the experimental data, the viscosity variation curve of sulfur aluminate cement slurry with time is consistent with the characteristics of exponential function, so $\mu(t) = Ae^{t/B} + C$ is used for fitting, and the time-varying equations of viscosity of sulfur aluminate cement slurry with representative ratios in different water environments are fitted separately in Table 2, and the fitted curves are shown in Fig. 3b.

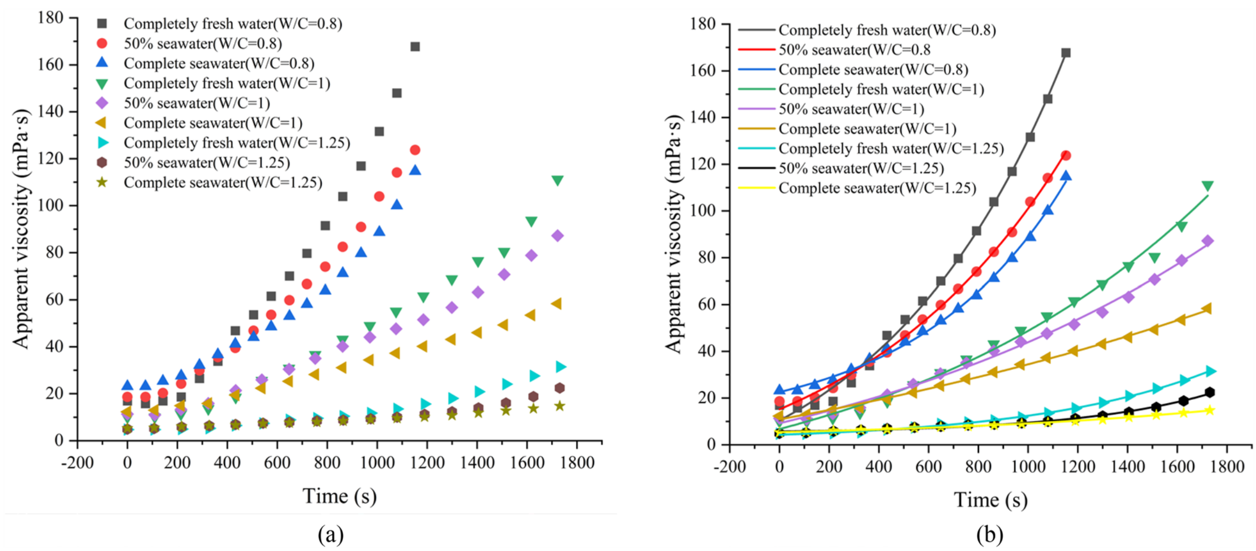

Fig. 3 Viscosity test data and fitting curve of sulfate aluminate cement slurry. **a** Test data; **b** Fitting the curve

Table 2 Time variation equation of viscosity of sulfate aluminate cement slurry

Water–cement ratio	Seawater environment	Fitting equation	R^2
0.8:1	Complete seawater	$\mu(t) = 15.38e^{t/599.44} + 7.23$	0.99776
	50% seawater	$\mu(t) = 38.24e^{t/850.67} - 22.90$	0.99844
	Complete fresh water	$\mu(t) = 42.62e^{t/746.86} - 32.13$	0.99639
1:1	Complete seawater	$\mu(t) = 52.06e^{t/2659.98} - 41.14$	0.99714
	50% seawater	$\mu(t) = 44.27e^{t/1726.55} - 35.05$	0.99285
	Complete fresh water	$\mu(t) = 37.14e^{t/1325.20} - 30.42$	0.99004
1.25:1	Complete seawater	$\mu(t) = 2.55e^{t/1167.86} + 4.94$	0.99812
	50% seawater	$\mu(t) = 0.70e^{t/555.02} + 7.07$	0.99074
	Complete fresh water	$\mu(t) = 2.50e^{t/717.93} + 3.99$	0.99852

where $\mu(t)$ is the apparent viscosity of the slurry, unit mPa·s

3.2 Fault Fracture Zone Permeability Simulation Test

(1) Test Equipment

The fault fracture zone permeation grouting simulation test system mainly includes slurry making device, pressure stabilization grouting device and visualization stratigraphic simulation device.

EWS200 air compressor is used to provide power for the grouting system. The air supply volume of the air compressor is 0.3m^3/min, air pressure:0.5 ± 0.02 MPa, and the rotational speed is 1400 revolutions per minute. The slurry making device is composed of mixer, mixing barrel and pneumatic grouting pump. The mixer adopts TJ3 pneumatic mixer, the rotation speed is 50 ~ 400 rpm; the volume of mixing barrel is 200 L; the pneumatic grouting pump adopts ZBQ-2771.5 coal mine pneumatic grouting pump, the grouting volume is 0–30 L/min, the maximum grouting pressure is 3 MPa; the maximum withstand pressure of high-pressure grouting pipe is 20 MPa, the inner diameter is 12.5 mm.

The pressure stabilization grouting device consists of slurry storage tank, liquid level indicator, air pressure regulator and pressure gauge. The maximum withstand pressure of slurry storage tank is 1.5 MPa, and the pressure gauge range is 0.3 MPa. AR4000-04 air pressure regulator is used, and the pressure adjustment range is 0.05–0.85 MPa, which can pressurize or depressurize the pressure stabilization grouting device.

The visualized stratigraphic simulation device is composed of Plexiglas panels and supporting steel fixtures, with filling size of 1000 mm × 800 mm × 800 mm. The steel fixtures are bolted together for easy disassembly and installation. To restore the stratigraphic conditions more realistically, the simulation device is filled with sandstone of different grain sizes as the injected medium, and the two ends are fixed with fixing devices, and a grouting hole is set at the top of the device.

The schematic diagram of the fault fracture zone permeation grouting test setup is shown in Fig. 4.

(2) Test Program

In this test, sulfur aluminate cement was selected as the grouting material, and a total of five groups of test schemes were designed, and the specific grouting test schemes are shown in Table 3.

When conducting the test, the rock samples are first sieved and combined, and the high-pressure grouting pipes, air compressors, and grouting pumps are connected. Then, the formation simulation device is assembled and filled, before filling, grease is applied to the inner wall of the model to ensure the sealing of the model, and the permeability coefficient and porosity of

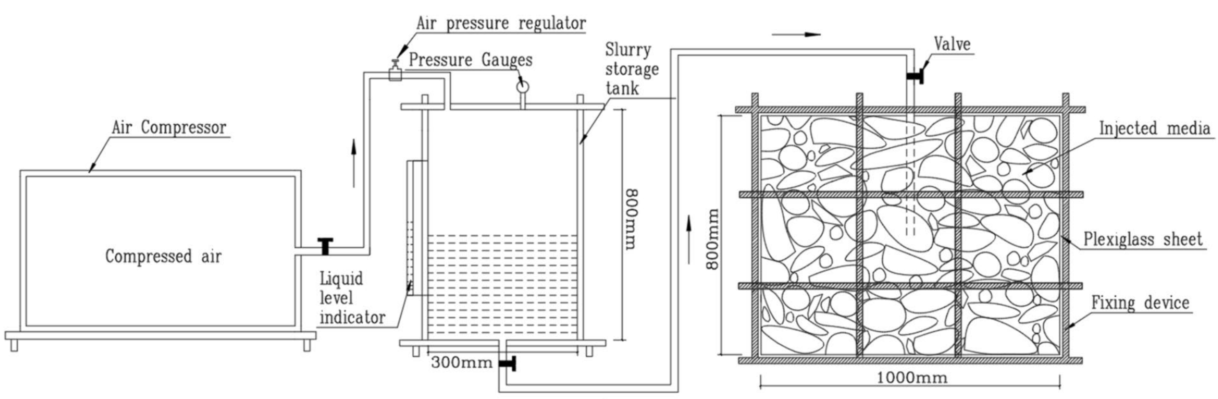

Fig. 4 Schematic diagram of the permeation grouting test device for fault fracture zone

Table 3 Permeation grouting simulation test scheme

Test number	Seawater environment	Water–cement ratio	Grouting pressure/MPa	Porous media porosity	Permeability coefficient of porous media (cm/s)
1	Complete seawater	1	0.06	49.96%	8.25
2	Complete seawater	0.8	0.06	49.96%	8.25
3	Complete seawater	1.25	0.06	49.96%	8.25
4	50% seawater	1	0.06	49.96%	8.25
5	Complete fresh water	1	0.06	49.96%	8.25

the rock samples inside the model are tested after the filling is completed. The sulfur aluminate cement slurry is prepared in the mixing barrel according to the design ratio, and then pumped into the storage tank through the pneumatic grouting pump, and through the air pressure regulator to make the grouting pressure to the test design pressure, and the permeation grouting is started after the pressure is stabilized.

After the initial setting of the slurry, the formation simulation device was opened and excavated to observe the slurry diffusion, which was basically spherical in shape and was measured. The test results of fault fracture zone permeation grouting test are shown in Table 4.

4 Analysis of Test Results and Comparison of Experimental and Theoretical Models

The theoretical model considering the slurry diffusion path and viscosity time-varying, and the theoretical model without considering the slurry diffusion path and viscosity time-varying are compared and analyzed with the test results, respectively, to verify the theoretical model proposed in this paper. The calculated parameters of the theoretical model (see Table 5) with Eq. (18) and Eq. (19) lead to the curve of the slurry diffusion radius with time (as shown in Fig. 5).

According to Fig. 5, with the increase of grouting time, the slurry diffusion radius of the theoretical model considering slurry diffusion path and Viscosity time-varying and that without considering slurry diffusion path and Viscosity time-varying both show nonlinear growth, and the growth rate of slurry diffusion radius is decreasing with time; the theory without considering slurry diffusion path and viscosity time-varying is larger than the diffusion distance considering slurry diffusion path and viscosity time-varying theory, and the difference between them is increasing with time.

Water–cement ratio and slurry diffusion radius are positively correlated, with the increase of water–cement ratio, the diffusion radius of slurry increases; seawater admixture and slurry diffusion radius are negatively correlated, with the increase of seawater admixture, the diffusion distance of slurry tends to decrease.

When the grouting pressure is 0.06 MPa, the diffusion distance calculated without considering the slurry diffusion path and viscosity time variability is 1.63–1.91 times of the experimental value, and the diffusion distance calculated with considering the slurry diffusion path and viscosity time variability is 1.06–1.35 times of the experimental value, which is obviously closer to the experimental value. Therefore, the Bingham fluid permeation grouting mechanism considering diffusion path and slurry viscosity time variability better reflects the diffusion pattern and law of Bingham fluid permeation grouting in porous media than the spherical diffusion mechanism of Bingham fluid permeation grouting without considering diffusion path and slurry viscosity time variability.

The main reasons for considering the theoretical value of slurry diffusion path and viscous time variability greater than the test value are as follows: (1) the slurry in the porous media pore channel during the injection process may occur precipitation, blockage and other percolation effects; (2) there are problems such as pressure loss in the grouting pipeline, and the performance index of the cement slurry prepared in the test is unstable, and the precipitation rate often exceeds the standard, while the theoretical formula uses the stability slurry performance index, which leads to large results of the theoretical calculation of the diffusion radius; (3) the size and shape of the particles of the crushed rock block selected to be injected into the medium are difficult to be completely

Table 4 Results of permeation grouting simulation test

Test number	Grouting pressure p/MPa	Grouting time t/s	Measured value of diffusion radius/cm
1	0.06	26.8	20.6
2	0.06	22.5	16.5
3	0.06	30.5	27.9
4	0.06	27.6	22.5
5	0.06	29.8	24.8

Table 5 Calculated parameters of the theoretical model

Test number	Grouting pressure (MPa)	Initial viscosity of slurry μ_{p0} (mPa ● s)	Slurry yield stress τ_0 (Pa)	Porous media porosity	Permeability coefficient of porous media (cm/s)	Pore channel length ratio η
1	0.06	10.92	1.397	49.96%	8.25	24.15
2		22.61	2.635			
3		7.49	0.764			
4		9.22	1.023			
5		6.72	0.953			

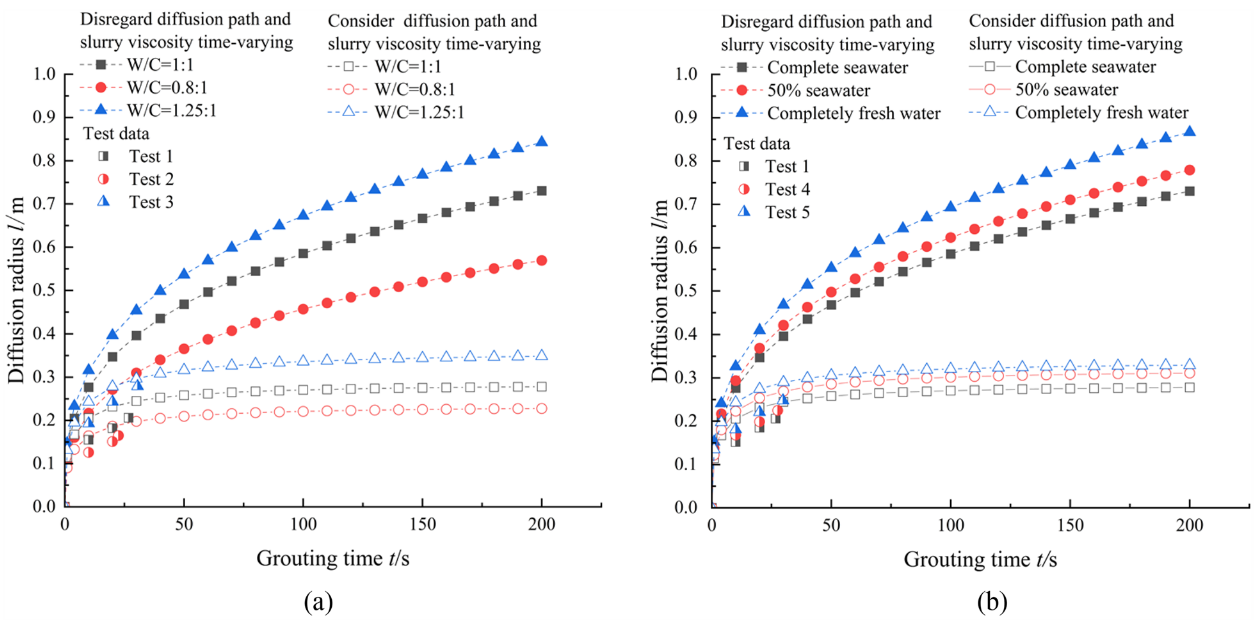

Fig. 5 Variation curve of slurry diffusion radius with time. **a** The effect of water–cement ratio on the diffusion distance; **b** The effect of seawater admixture on the diffusion distance

uniform, and cannot fully meet the assumption of isotropy; and (4) the test results are also affected by the test environment (such as: temperature factors, gravity factors, etc.), test personnel operation, and many other factors, resulting in small test results.

5 Conclusion

(1) Based on the seepage equation of Bingham fluid, the tortuosity parameter of porous media, the fractal theory and the time-varying viscosity of slurry, a spherical permeation grouting model of Bingham fluid considering the diffusion path of slurry and the time-varying viscosity is established.
(2) The viscosity of sulfur aluminate cement slurry under seawater environment was tested, and the equation of its viscosity variation with time was obtained, and the seawater environment showed an obvious inhibitory effect on the viscosity of sulfur aluminate cement slurry. A fault fracture zone permeation grouting test system was developed, and sulfur aluminate cement was used for fault fracture zone grouting simulation tests.
(3) The diffusion distance calculated without considering the influence of slurry diffusion path and seawater is 1.63–1.91 times of the experimental value, and the diffusion distance calculated with considering the influence of slurry diffusion path and seawater is 1.06–1.35 times of the experimental value; the theoretical model considering the influence of diffusion path and seawater can better describe the dynamic process of slurry diffusion.

Acknowledgements
The authors wish to express their gratitude to the Natural Science Foundation of China with the research number 52109131 and the Natural Science Foundation of Shandong Province with research number ZR2020QE290.

Author contributions
HW is mainly responsible for the overall writing of the full text. YY and PZ are responsible for data processing and analysis. CY and HW. is responsible for the innovative ideas of the article. FZ and SD are responsible for the test operation. All authors have read and agreed to the published version of the manuscript.

Funding
This work was supported by the National Natural Science. Foundation of China (Grant No. 52109131); the Natural Science. Foundation of Shandong Province (Grant No. ZR2020QE290).

Availability of data and materials
The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 13 October 2023 Accepted: 23 June 2024
Published online: 06 September 2024

References

Baker, C. (1974). Seepage problems in rock mechanics. *Geophysics Journal International, 54*(2), 465–469.

Bouchelaghem, F., & Vulliet, L. (2001). Mathematical and numerical filtration–advection–dispersion model of miscible grout propagation in saturated porous media. *International Journal for Numerical and Analytical Methods in Geomechanics, 25*(12), 1195–1227.

Cai, S., Huang, Z., & Dong, J. (2006). *Grouting method* (1st ed., pp. 38–51). China Water & Power Press.

Dai, S., Tong, C., Yan, H., Teng, J., & Zhang, S. (2021). Calculation of soil tortuosity based on sampling reliability. *Rock Soil Mech, 42*(03), 855–862.

Fu, Y., Wang, X., Zhang, S., & Yang, Y. (2019). Modelling of permeation grouting considering grout self-gravity effect: Theoretical and experimental study. *Advances in Materials Science and Engineering., 2019*, 16.

Kim, Y. S., & Whittle, A. J. (2009). Particle network model for simulating the filtration of a micro fine cement grout in sand. *Journal of Geotechnical and Geoenvironmental Engineering, 135*(2), 224–236.

Kong, X. (1999). *Advanced mechanics of fluid in porous media* (3rd ed., pp. 422–427). University of Science and Technology of China Press.

Kuang, J., Zan, Y., Wang, J., et al. (2001). *Theory and project example of grout in geotechnical engineering* (1st ed., pp. 1–5). Science Press.

Lala, A. M. S. (2020). A novel model for reservoir rock tortuosity estimation. *Journal of Petroleum Science and Engineering, 192*, 107331.

Li, Y. (2017).Key Technology Study On Qingdao Jiaozhou Bay Subsea Tunnel Crossing Seabed Fault Zone. PhD Thesis,Beijing Jiaotong University, Beijing.

Li, X. (2023). Experimental study on workability and physical properties of seawater concrete. *Tech Superv Water Resour, 10*, 168–171188.

Li, Y., & Yuan, M. (2008). *Fluid mechanics* (2nd ed., pp. 118–123). Higher Education Press.

Liu, J., Zhang, X., Li, M., Lan, X., & Hao, P. (2021). Research on permeation grouting mechanism considering gravity in the treatment of mud inrush disaster. *Polish Journal of Environmental Studies., 30*(1), 751–762.

Liu, W., Wang, X., & Feng, C. (2008). *Grouting materials and construction technology* (1st ed., pp. 56–64). China Building Material Industry Press.

Pisani, L. (2016). A geometrical study of the tortuosity of anisotropic porous media. *Transport in Porous Media, 114*(1), 201–211.

Ruan, W. (2005). Spreading model of grouting in rock mass fissures based on time-dependent behavior of viscosity of cement-based grouts. *Chinese Journal of Rock Mechanics and Engineering, 15*, 2709–2714.

Saada, Z., Canou, J., Dormieux, L., & Dupla, J. C. (2006). Evaluation of elementary filtration properties of a cement grout injected in a sand. *Canadian Geotechnical Journal, 43*(12), 1273–1289.

Saada, Z., Canou, J., Dormieux, L., Dupla, J. C., & Maghous, S. (2005). Modelling of cement suspension flow in granular porous media. *International Journal for Numerical and Analytical Methods in Geomechanics, 29*(7), 691–711.

Tekin, E., & Akbas, S. O. (2010). Artificial neural networks approach for estimating the groutability of granular soils with cement-based grouts. *Bulletin of Engineering Geology and the Environment., 70*(1), 153–161.

Xu, P., & Yu, B. (2008). Developing a new form of permeability and Kozeny-Carman constant for homogeneous porous media by means of fractal geometry. *Advances in Water Resources, 31*(1), 74–81.

Xu, S. (2022). Research on the key construction technology of Qingdao metro line 8 undersea tunnel over faulted fracture zone. *Int Ar Chn, 04*, 126–128.

Yang, X., Lei, J., Xia, L., & Wang, X. (2005). Study on grouting diffusion radius of exponential fluids. *Rock Soil Mech, 26*(11), 112–115.

Yang, X., Wang, X., & Lei, J. (2004). Study on grouting diffusion radius of Bingham fluids. *Journal of Hydraulic Engineering Division of the American Society of Civil Engineers, 6*, 75–79.

Yang, Z., Hou, K., Guo, T., & Ma, Q. (2011). Study of column-hemispherical penetration grouting mechanism based on Bingham fluid of time-dependent behavior of viscosity. *Rock Soil Mech, 32*(09), 2697–2703.

Yang, Z., Lu, J., Wang, Y., Zhang, Z., Yang, Y., Zhu, Y., Zhang, J., Guo, Y., & Chen, X. (2021). Column penetration grouting mechanism for power-law fluids considering tortuosity effect of porous media. *Chinese Journal of Rock Mechanics and Engineering, 40*(02), 410–418.

Ye, F., Gou, C., Chen, Z., Liu, Y., & Zhang, J. (2013). Back-filled grouts diffusion model of shield tunnel considering its viscosity degeneration. *China Journal of Highway and Transport, 26*(01), 127–134.

Yu, B. (2004). Fractal character for tortuous streamtubes in porous media. *Chinese Physics Letters, 22*(1), 158–160.

Yu, B., & Li, J. (2001). Some fractal characters of porous media. *Fractals, 9*(3), 365–372.

Yu, X., Song, L., Zhong, Q., et al. (2023). Study on Mechanical properties and carbonization resistance of nano-modified sea sand sulfoaluminate concrete. *Shihezi Science Technology, 02*, 29–31.

Zhang, X. (2011). Study on mechanism of slurry diffusion and sealing at the process of underground engineering moving water grouting and its application. PhD Thesis, Shandong University, Jinan.

Zhang, D., Sun, Z., & Chen, T. (2019). Composite grouting technology for subsea tunnels and its engineering application. *Chinese Journal of Rock Mechanics and Engineering, 38*(06), 1102–1116.

Zhang, L., Zhang, Q., Liu, R., Li, S., Wang, H., Li, W., Zhang, S., & Zhu, G. (2017). Penetration grouting mechanism of quick setting slurry considering spatiotemporal variation of viscosity. *Rock Soil Mech, 38*(02), 443–452.

Zhang, L., Yu, R., Zhang, Q., Liu, R., Feng, H., & Chu, Y. (2022a). Permeation grouting diffusion mechanism of quick setting grout. *Tunnelling and Underground Space Technology, 124*, 104449.

Zhang, M., Zhang, Q., Pei, Y., et al. (2022b). Injectability analysis of seawater-mixed magnesium phosphate cement slurry applied to a sand layer. *Construction and Building Materials, 359*, 129538.

Zhang, M., Wang, X., & Wang, Y. (2011). Diffusion of Herschel-Bulkley slurry in fractures. *Chinese Journal of Geotechnical Engineering., 33*(5), 815–820.

Zhang, Q., Wang, H., Liu, R., Li, S., Zhang, L., Zhu, G., & Zhang, L. (2018). Infiltration grouting mechanism of porous media considering diffusion paths of grout. *Chinese Journal of Geotechnical Engineering, 40*(05), 918–924.

Zheng, J. (2023). Effect of seawater on mechanical properties of new sulphoaluminate cement and its mechanism. M. Thesis, Hebei University of Technology,Tianjin.

Zhou, Z., Du, X., Chen, Z., Zhao, Y., & Chen, L. (2016). Grout dispersion considering effect of pore tortuosity. *The Chinese Journal of Nonferrous Metals., 26*(08), 1721–1727.

Zhu, G., Zhang, Q., Feng, X., Liu, R., Zhang, L., Liu, S., & Zhang, J. (2020). Study on the filtration mechanism in permeation grouting using the particle deposition probability model. *Advanced Engineering Sciences, 52*(5), 125–135.

Publisher's Note

Hongbo Wang Associate Professor, College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China

Yunchang Yu Master student, College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China

Peiyuan Zhang Senior engineer, Qingdao West Coast Rail Transit Co., Qingdao 266427, China

Chunyu Yang Master student, College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China

Hao Wen Master student, College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao, China

Fansheng Zhang Master student, College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266,590, China

Sanlin Du Senior engineer, Huaneng Tibet Hydropower Safety Engineering Technology Research Center, Sichuan 610,041, China