Study on Time-dependent Viscosity of Slurry and Its Diffusion Model

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Study on Time-dependent Viscosity of Slurry and Its Diffusion Model

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Abstract. Floor water disasters have occurred frequently, which can be treated by grouting and reinforcement of floor. The purpose of this paper is to study on time-dependent viscosity of slurry and its diffusion model for guiding grouting and reinforcement engineering by observing of the change of slurry viscosity with time in laboratory. The result showed that the slurry viscosity had an exponential trend with time. A slurry diffusion model based on the time-dependent viscosity of slurry is derived, according to the diffusion model of grouting in horizontal single fracture under hydrostatic condition. These results will provide theoretical basis for grouting process adjustment and regional grouting transformation.

1. Introduction

Coal is an important energy source in China. Coal production is related to the people's livelihood and the sustainable development of economy and society in China. North China coalfield is an important and one of the most serious threatened by groundwater coalfield in China. Floor water hazards are the main types of water hazards in North China coalfields [1].

At present, grouting reinforcement and modification of floor aquifer are commonly used to control groundwater [2]. Clarifying the law of slurry diffusion plays a very important role in grouting reform and reinforcement. The law of slurry diffusion is very complicated, and the time-dependent of slurry should be considered. However, previous studies were relatively few.

In this paper, the time-dependent test of slurry diffusion was carried out to study the law of slurry diffusion and obtain the change equation of slurry viscosity. These results will provide theoretical basis for grouting process adjustment and regional grouting transformation.

2. Flow pattern and time -dependent behavior of viscosity of grout

Judgment of the flow pattern of grout is the preconditions for building grout diffusion model. In the paper, system test was carried out for fly ash-based grout during burdening test of grouting materials, after the function fitting of the rheological curve was made, the time-dependent function was obtained.

2.1 Flow pattern of grout.

According to the difference in the relationship between shear stress and shearing rate (rheological equation), grout is divided into different flow patterns. On the basis of whether the rheological equation has influence of time effect, it is divided into time-dependent grout and non-time-dependent grout. Previous research has shown that with different water cement ratio, the flow patterns of pure cement grout are of three different flow patterns: power law fluid for grout with low water cement ratio(W/C=0.5～0.7); Bingham fluid for grout with W/C=0.8～1.0;while with the increase of water cement ration(W/C＞1.0), cement grout approximates Newtonian fluid. Hereby it arrives at that the critical water cement ratio for conversion of cement grout from power law fluid to Bingham fluid was 0.7, that from Bingham fluid to Newtonian fluid was 1.0[3].

From the existing research results, cement-based grout such as cement clay grout, cement composite grout, polymer cement grout is generally Bingham plastic fluid, but when the polymer has big viscosity and bigger dosage results in bigger viscosity of grout, the grout is power law fluid.

In addition, the present grout diffusion theory all assumes that the flow patterns during grouting does not vary with time. Through great number of researches, predecessors have found: the viscosity of grout increases before gelation, while the flow patterns keep constant, thus verifying the assumption, providing basis for building diffusion model of grout [4].

2.2 Time -dependent behavior of grout viscosity.

During the study of the law of grout diffusion and migration, the time-dependent behavior of grout decides at certain extent the factors such as the diffusion distance, pressure dissipation and velocity distribution of grout, therefore it is necessary to consider the influence of time-dependent behavior on grout diffusion. Great amount of studies made by predecessors showed:grout viscosity is time-dependent[3,5,6]. But the concrete law of time -dependent behavior of the grout used in the paper needs further study through experiments.

In the present burdening test of grout materials, systematic test of the selected proportion of fly ash-based cement grout (water solid ratio 1:1, proportion of fly ash 70%, water glass proportion 3%) was conducted, three sets of viscosity variation of grout were obtained（Fig.1）,function fitting was made for time-dependent curve of the mean viscosity of three sets of grout, the results are shown in figure 2.

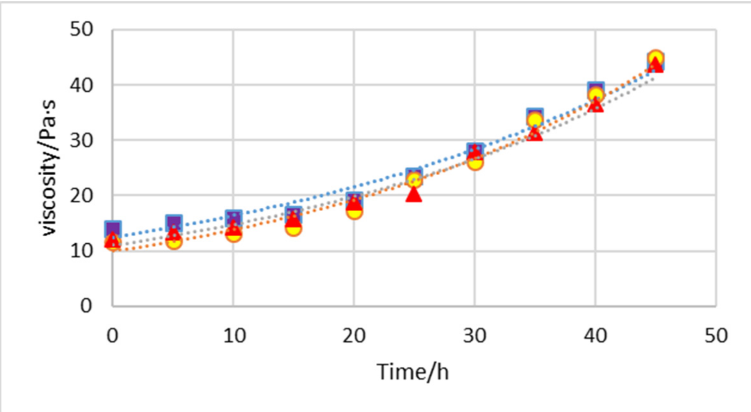

Fig.1 Result of time-dependent behavior test of grout viscosity

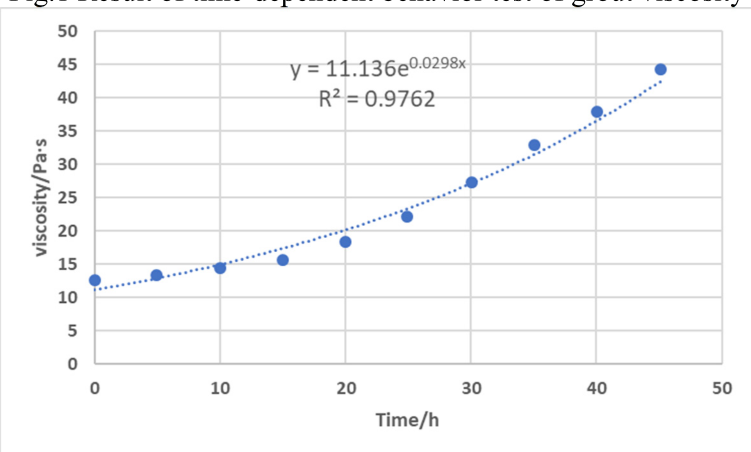

Fig. 2 Time-dependent function fitting curve of grout viscosity

In the paper, the time-dependent equation of viscosity of fly ash-based cement grout（water solid ratio 1:1, fly ash proportion 70%, water glass proportion3%）is:

$$\mu(t) = 11.136e^{0.0298t} \tag{1}$$

3. Grout diffusion model of single horizontal fracture under hydrostatic condition

Aiming at Bingham plastic fluid, the paper built the grout diffusion models of fractures. The preconditions and the basic assumption for build-up of the models are:

(1) the grout was homogeneous incompressible isotropic fluid;

(2) the aperture of fractures was not big, the grout velocity was smaller, except for the turbulent state of the flow regime in local area around grouting borehole, the rest was all laminar flow;

(3) when grout flowed in fractures, there was non- slipping in the fracture wall, i.e., the velocity of grout on the upper and lower surfaces was zero;

(4) fracture wall surface was impermeable, i.e., the moisture of the grout did not infiltrate to rock mass;

(5) flow patterns were invariant during grouting;

(6) the grout viscosity was time-dependent（grout viscosity increased with time）, the variation was of exponential function, while the dynamic shear of Bingham fluid kept basically unchanged during grout flow.

Moreover, the present paper aimed at fly ash-based cement grout(water solid ratio 1:1, fly ash proportion 70%, water glass proportion 3%) in grout burdening test, the flow pattern was set as Bingham plastic fluid.

It is can be known that, all the physical quantities of grout movement were axisymmetric, all forces met also axisymmetric relation, therefore it could be simplified as one dimension problem to study.

The continuity and motion equations are as follow:

Continuity equation:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \tag{2}$$

Motion equation:

$$\frac{\partial v_x}{\partial t} = \frac{1}{\rho}\frac{\partial P_{xx}}{\partial x} + f_x + \frac{1}{\rho}\frac{\partial P_{yx}}{\partial y} \tag{3}$$

$$\frac{\partial v_y}{\partial t} = \frac{1}{\rho}\frac{\partial \rho}{\partial y} + f_y + \frac{1}{\rho}\frac{\partial \tau_{xy}}{\partial x} \tag{4}$$

Because grout is incompressible,during grout injection, the flow velocity of grout along flow line at any moment is the same, obviously, $v_y = 0$, therefore $\frac{\partial v_x}{\partial x} = \frac{\partial v_y}{\partial y} = 0$, thus $v_x = v$,and v is only the function of y and t, i.e., $v = v(y,\ t)$, substituting the above relation into the motion equation gives:

$$\frac{\partial \tau}{\partial y} = \frac{\partial P}{\partial x} - F_x, \quad F_x = \rho f_x \tag{5}$$

$$\frac{\partial \tau}{\partial x} = \frac{\partial P}{\partial y} - F_y + \frac{\partial \tau_{yy}}{\partial y}, \quad F_y = \rho f_y \tag{6}$$

4. Grout diffusion model based on the time-dependent behaviour of grout viscosity

In formula (5), $\frac{\partial P}{\partial x}$ is the variation of grouting pressure in direction x, according to formula (6), $\frac{\partial P}{\partial y}$ is only related to the component of gravity in direction y. Because the fracture aperture b relative to the distance of grout distance may be negligible, and the speed of grout movement in direction y is zero, thus $\frac{\partial P}{\partial y}$ is neglected, i.e., $\frac{\partial P}{\partial y} = 0$. So it does not influence the study on grout diffusion law（$x = 0$）along fractures, thus we can obtain:

$$\frac{dP}{dx} - F_x = A \tag{7}$$

Its shear stress is:

$$\tau = Ay + C \tag{8}$$

Because the velocity distribution is symmetric in regard to y =0, then when y =0, $\frac{dv}{dy}$ =0, i.e., at the place y =0, τ =0. From formula (8) it can be known that the shear stress on the fracture wall surface $\tau_w = Ab$.

In the interior of fluid there exists a flow core where the regional shear stress is zero, called Bingham fluid（assume its height is $2h_0$）. The fluid in the flow core move along with the fluid at two sides in the way similar to sliding of rigid body. The stress distribution in the cross section is:

$$\tau = \begin{cases} 0 & (-h_0 < y < h_0) \\ \tau_0 & (y = h_0) \\ Ay & (-h_0 > y > -b,\quad h_0 < y < b) \\ Ab & (y = b) \end{cases} \tag{9}$$

According to the constitutive equation of Bingham fluid:

$$\tau = \tau_0 + \mu(t)\gamma_1 = \tau_0 + \mu(t)\frac{dv}{dy} \tag{10}$$

$$\tau = \lambda(\gamma_1) = \lambda\left(\frac{dv}{dy}\right) \tag{11}$$

Therefore,

$$\gamma_1 = \frac{dv}{dy} = f(\tau) = \frac{\tau - \tau_0}{\mu(t)} \tag{12}$$

According to formula (8), $\tau = Ay$, $\tau_0 = Ah_0$,

$$\tau = Ay = \tau_0 + \mu(t)\frac{dv}{dy} \tag{13}$$

$$\frac{dv}{dy} = -\frac{1}{\mu(t)}(\tau_0 - Ay) \tag{14}$$

$$v = -\left[\frac{1}{\mu(t)}\left(\tau_0 y - \frac{1}{2}Ay^2\right) + C\right] \tag{15}$$

Substitute the boundary conditions（$y = b, v = 0$）,

$$C = \frac{1}{\mu(t)}\left(\frac{1}{2}Ab^2 - \tau_0 b\right) \tag{16}$$

$$v = -\frac{A}{\mu(t)}\left(\tau_0 y - \frac{1}{2}y^2\right) - \frac{1}{\mu(t)}\left(\frac{1}{2}b^2 - \tau_0 b\right) \tag{17}$$

The velocity distribution of fluid is:

$$v = \begin{cases} -\frac{1}{\mu(t)}\left[\frac{1}{2}A\left(b^2 - {h_0}^2\right) - \tau_0(b - h_0)\right] & (-h_0 \leq y \leq h_0) \\ -\frac{1}{\mu(t)}\left[\frac{1}{2}A(b^2 - y^2) - \tau_0(b - y)\right] & (-h_0 > y > -b,\ h_0 < y < b) \end{cases} \quad (18)$$

Suppose that the injected flow of grout at the moment is q:

$$\bar{v} = -\frac{A}{b\mu(t)}\left\{\int_0^{h_0}\left[\frac{1}{2}A\left(b^2 - {h_0}^2\right) - \tau_0(b - h_0)\right]dy + \int_{h_0}^{b}\left[\frac{1}{2}A(b^2 - y^2) - \tau_0(b - y)\right]dy\right\} \quad (19)$$

$$\bar{v} = -A\frac{b^2}{\mu(t)}\left(\frac{1}{3} - \frac{h_0}{2b} + \frac{h_0^3}{6b^3}\right) \quad (20)$$

Where $\tau_0 = Ah_0$.

Because during grout injection A is generally much bigger than τ_0, b is much bigger than h_0, thus the minor term of high order $\frac{h_0^3}{6b^3}$ is omitted, therefore,

$$\bar{v} = -\frac{b^2}{3\mu(t)}\left(1 - \frac{3h_0}{2b}\right)A \quad (\tau_0 = Ah_0) \quad (21)$$

$$q = \bar{v}(2b \times 2\pi x) = -\frac{4\pi x b^3}{3\mu(t)}\left(1 - \frac{3h_0}{2b}\right)A \quad (22)$$

$\frac{3q\mu(t)}{4\pi x b^3} = -A + \frac{3\tau_0}{2}$, $\tau_0 = Ah_0$, substituting $\frac{dP}{dx} - F_x = A$, for $B = \frac{3q\mu(t)}{4\pi x b^3}$:

$$\frac{dP}{dx} = \left(\frac{3}{2b}\tau_0 + F_x\right) - \frac{B}{x} \quad (23)$$

$$P = \left(\frac{3}{2b}\tau_0 + F_x\right)x - \frac{3q\mu(t)}{4\pi b^3}\ln x + C \quad (24)$$

Substitute the initial conditions, $t = 0$, $x = r_C$（radius of grouting borehole）, $P = P_C - P_0$（P_C is the pressure in grouting borehole, P_0 is the hydrostatic pressure）, the solution is:

$$P = P_C - P_0 + \left(\frac{3}{2b}\tau_0 + F_x\right)(x - r_C) - \frac{3q\mu(t)}{4\pi b^3}\ln\frac{x}{r_C} \quad (25)$$

In formula (25), the direction of the yield shear force of Bingham fluid is negative direction x, for clear expression, τ_0 in the formula is rewrited as $-|\tau_0|$.

F_x is body force, here the gravity is only considered, then:

$$F_x = \rho g \sin\alpha \cos\beta \quad (26)$$

α,β express respectively the dip and the azimuth of fracture. Then :

$$P = P_C - P_0 + \left(-\frac{3}{2b}|\tau_0| + \rho g \sin\alpha \cos\beta\right)(x - r_C) - \frac{3q\mu(t)}{4\pi b^3}\ln\frac{x}{r_C} \quad (27)$$

This equation is the grout diffusion equation based on the time-dependent behavior of grout viscosity.

Where: P-grout pressure at any moment and any position,Pa; P_C-pressure in grouting borehole,Pa;τ_0-yield shear force of Bingham fluid,Pa;ρ- grout density,kg/m^3;α-fracture dip,(°);x-grout diffusion distance, m.

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5. Conclusion

Judgment of the flow pattern of grout is the preconditions for building grout diffusion model. With the increase of water cement ratio, the flow pattern of cement slurry will eventually become Newtonian fluid. In addition, great amount of studies made by predecessors showed that grout viscosity is time-dependent. In this paper, according to the experiment, the change law of three groups of slurry viscosity was obtained, the curve fitting was carried out, and the change equation of slurry viscosity was obtained. The diffusion model of grouting is derived based on the time-varying viscosity of grout, according to the diffusion model of grouting in horizontal single fracture under hydrostatic condition. These results will provide theoretical basis for grouting process adjustment and regional grouting transformation.

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