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On the deformability and mobility of clay-cement grout

As a low-cost grouting material, clay-cement grout has been increasingly applied to grouting construction and other aspects. The current research on its properties is, however, limited to physical mechanical properties such as the compressive strength of its hardened body, permeation coefficient, setting time and stability. As a comparison, there are few studies of the deformability and mobility of grouting materials. To enrich this research area, we used NXS-11A rotational viscometer to gauge the relationship between the change of intermolecular shear force and the change of intermolecular shear rate as our test method. The corresponding results show that the clay-cement grout can be regarded as a type of viscoplastic fluid because its' deformability and mobility curves resemble the viscoplastic fluid counterparts to a large extent.

Keywords: *Grouting material, property, deformability and mobility curve.*

1. Introduction

Grouting technology is an indispensable part of underground engineering construction with its role in stratum reinforcement, leaking stoppage, etc. Grouting materials are the pillar of the grouting technology, its properties exerting direct effect on project quality.

Clay cement grouting material is prepared from the main agent of clay as well as the additives of structural agents (ordinary Portland cement) and other auxiliary materials. As a frequently-used anti-seepage material, clay cement grout has the following advantages [1]: water-repellent, high deformability and mobility, earthquake-resistant, high hardening rate, good sealing, anti-erosion, quick setting, and low cost. As a result, clay-cement grout is widely used in anti-seepage engineering construction sites such as deep foundation pit, landfill, subway, karst embankment and tunnel, and its performance has been widely studied. However, the major research focus of its performance lies on parameters of compressive strength of its hardened body, permeation coefficient, setting time and stability, whereas there are a few studies of the deformability and mobility of grouting materials [2], [3]. To enrich this research area, we conducted an in-depth theoretical research on this characteristic. Our research results are aimed at providing references and service for engineering technicians.

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2. Rheology foundation

Rheological properties reflect the mutual resistance generated between slurry particles or between the slurry and void walls, and describe deformation and motion of slurries. The rheological equations and rheological curves are generally used to describe rheological properties, on whose basis the effect of slurry deformation and motion on slurry parameters is considered. Mobility is a property of slurry flow in stratums under external force. It reflects the flow law of slurries at the presence of external force, and is in essence dependent on the rheological property of slurries. The stronger the mobility is, the smaller the head loss is, and the longer distance the fluid travels when diffusing in the stratum; and the inverse is true [4], [5], [6] and [7].

According to rheological properties, the commonly-seen slurries can be divided into three classes: viscous fluid (Newtonian fluid), plastic fluid (Bingham fluid) and viscoplastic fluid.

Newtonian fluid is a typical viscous fluid whose rheological curve is a straight line passing through the origin of the coordinate, as is shown in Fig.1.

The rheological equation can be expressed as:

$$\eta = \frac{\tau}{\gamma} \quad \text{... (1)}$$

where η is the Newtonian viscosity (parameter) (mPa.s), τ is the shear force (the internal friction per unit area, Pa), γ is the shear rate or velocity gradient (s^{-1}). Newtonian fluid is a single-phase homogeneous system, whose members include water, a majority of chemical slurries and dilute grouts. It begins to flow immediately under shear force (by figure the rheological curve passes through the coordinate origin), with speed gradient positively proportional to shear stress.

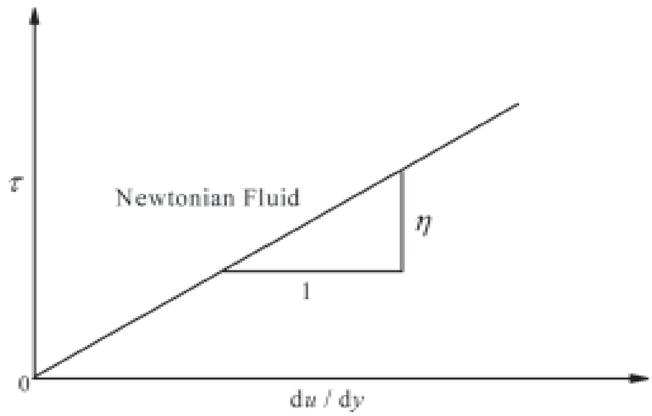


Fig.1 The rheological curve of Newtonian fluids

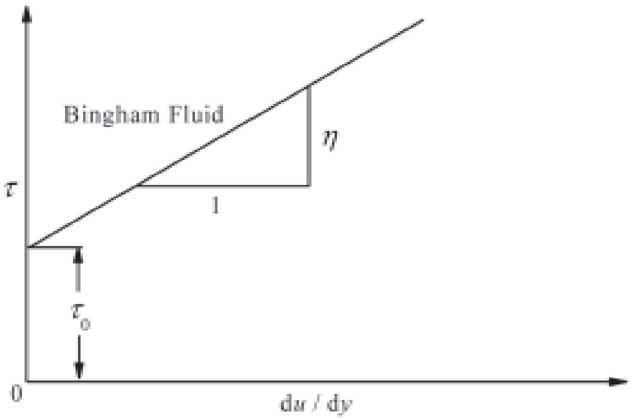


Fig.2 The rheological curve of Bingham fluid

Bingham fluid is a typical plastic fluid, whose rheological curve does not pass through the origin of the coordinate system, as is shown in Fig.2.

The physical reason for this behaviour is that Bingham fluid contains particles which create an inter-particle association structure. When the external shear stress is small, the slurry exhibits only elasticity similar to that of solids. When the external shear stress is strong enough to destroy its structure (the external shear stress is greater than the cohesion of the slurry), the slurry will flow similar to the Newtonian fluid, which is called plasticity. The rheological equation can be expressed as follows:

$$\tau = C + \eta\gamma \quad \text{... (2)}$$

where C is cohesion (Pa).

Due to the heterogeneity of solid-phase particles, viscoplastic fluid tends to form structure under the action of surface attraction and repulsion. At low shear rates, the shape of rheological curves is always curved. It will continue deviating from the straight line until the shear rate increases to the laminar flow stage. The rheological curve is shown in Fig.3.

Several important parameters describing the rheological properties of viscoplastic fluid slurries are plastic viscosity,

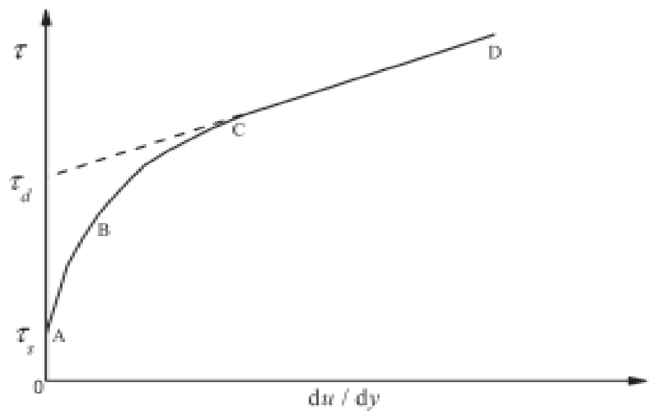


Fig.3 The rheology curve of viscoplastic fluids

yield value, and static shear force. As can be seen from Fig. 3, the viscosity of the viscoplastic fluid varies in the process. When the shear stress exerted on the slurry is actually smaller than τ_s, the slurry has a certain strength due to the internal formation of the network structure, and thus will not flow.

τ_s is the critical value of the externally applied shear stress that can cause the slurry to flow.

$$\tau_s = \frac{M\varphi_1}{2} \quad \text{... (3)}$$

where M is the viscometer's torsion index, and φ_1 is the viscometer's reading of the first-gear revolving speed.

3. Clay material selection

In the light of the geology of Yunnan area as well as clay mineralogy knowledge [8], [9] and [10], we selected the following three materials as the research object: white clay, red clay, and lake mud. The disintegration and dissolution test was used to determine which grouting material is suitable [11], [12]. The samples are air-dried and partly sifted through 2mm filter. The three-phase ratio of the filtered samples is shown in Table 1.

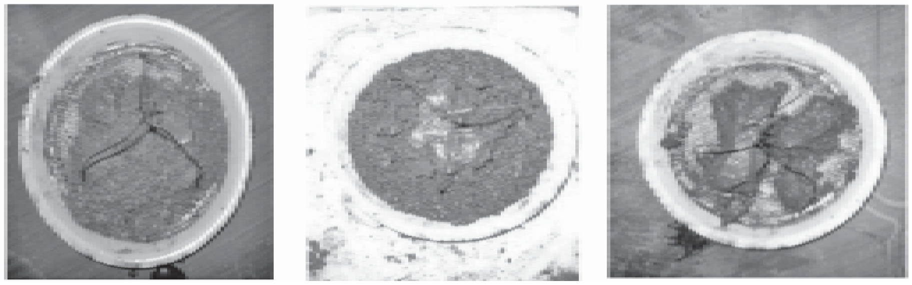
TABLE 1: THE THREE-PHASE RATIO OF THE SAMPLE SOIL (ALL SAMPLES ARE AIR-DRIED SAMPLES)

Property / Soil type	Moisture content	Gravity	Dry density /g·cm^{-3}
White clay	1.6	2.77	0.995
Red clay	5	2.76	1.105
Lake clay	4.5	2.78	0.810
Property / Soil type	Saturated density /g·cm^{-3}	Void ratio	Porosity /%
White clay	1.8	1.18	54
Red clay	1.7	1.49	60
Lake clay	1.5	2.43	71
Property / Soil type	Effective density /g·cm^{-3}	Saturation /%	Organic content /%
White clay	0.8	4	0
Red clay	0.7	9	0
Lake clay	0.5	5	1.1

The disintegration amount is calculated with this formula:

$$A_t = \frac{R_t - R_0}{100 - R_0} \times 100\% \quad ... \quad (4)$$

where A_t is the amount of disintegrated samples at the moment t; R_t is the reading of the sample at the moment t when the pontoon reaches the water surface; R_0 is the instantaneous steady reading at the very beginning of the experiment when the pontoon reaches the water surface. The experiment results are shown in Table 2.



(a) The disintegrated white clay (b) The disintegrated white clay (c) The disintegrated white clay

Fig.4 The disintegrated soil

TABLE 2: THE RESULT OF THE DISINTEGRATION TEST

Time /min	Pontoon readings		
	White clay	Red clay	Lake clay
3	149	148	147
10	144	142	140
30	138	136	135
60	130	127	125
120	120	114	112
240	115	110	110
360	113	109	107
600	112	108	107
Time /min	Pontoon reading difference		
	White clay	Red clay	Lake clay
3	149	148	147
10	144	142	140
30	138	136	135
60	130	127	125
120	120	114	112
240	115	110	110
360	113	109	107
600	112	108	107
Time /min	Disintegration amount /%		
	White clay	Red clay	Lake clay
3	149	148	147
10	144	142	140
30	138	136	135
60	130	127	125
120	120	114	112
240	115	110	110
360	113	109	107
600	112	108	107

When the disintegration stops, the residues of the white clay is granular, a minority of red clay is blocky, and a majority of lake mud is blocky. The picture of the disintegrated sample is shown in Fig.4.

Fig.5 shows the relationship between the disintegration amount and time, where the disintegration amount is the ordinate and the time is the abscissa. It can be seen that the disintegration is unapparent during the first 3 minutes, remarkable during 10-120 min, becomes slow during 240-600 min, and then nearly stops. The results show that the amount of white clay is 76%, red clay is 84% and lake mud is 86%. The amount of white clay is the smallest, and the amount of lake mud is the largest.

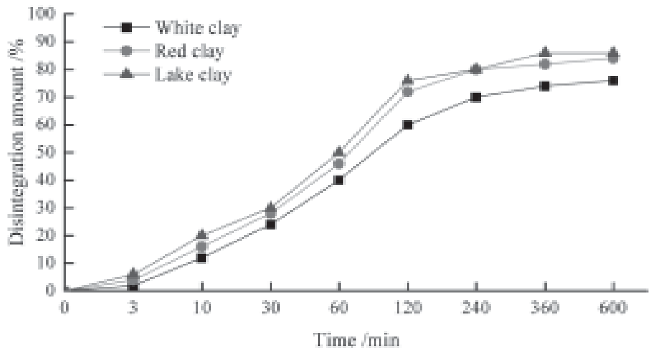


Fig.5 The relationship between the disintegration amount and time

To satisfy the requirements of raw material selection in the grouting and anti-seepage engineering project [13], we selected white clay as the major raw material of the slurry sample.

4. Experimental test

Through the three indexes of plastic viscosity, yield value and static shear force, the internal flow regime of the fluid can be determined. The differences between Bingham fluid and Newtonian fluid and between viscoplastic fluid and Newtonian fluid are that Binghan fluid and viscoplastic fluid can only flow when the shear force reaches a certain value, and that their diffusion distance is limited in the case of a fixed pressure. Therefore, the viscosity is the main parameter.

The three indicators of the slurry were tested by using NXS-11A rotational viscometer. All test parameters should satisfy the following equations:

$$\eta = \frac{\tau}{\mathrm{d}r / \mathrm{d}t} \quad ... \quad (5)$$

$$\tau = \frac{m}{4\pi r^2 h} \quad ... \quad (6)$$

$$\mathrm{d}r/\mathrm{d}t = \frac{2R_2^2}{R_1^1 - R_2^2} \quad \cdots \quad (7)$$

where η is viscosity; τ is shear stress; dr/dt is shear rate; *m* is the moment of force; R_1 is the radius of the outer cylinder; R_2 is the radius of the inner cylinder; *h* is the working height of the inner cylinder.

Under the guidance of the test procedures and equipment appendix, we selected the measurement system according to the estimated material viscosity [14], installed the inner cylinder, and added an approximate amount of materials in the external cylinder. After installing the measurement system, we checked the corresponding system rotational angle constant and shear rate, and used the formula "Shear Stress = System Rotational Angle×Grid Number" to calculate the shear stress at different rotate speed. Then, we dotted the rheological curves in the coordinate system so that obtaining the rheological parameter of different materials.

5. Study on the slurry's rheological properties

The factors influencing the rheological properties of the slurry are the undisturbed slurry's viscosity and the cement's addition amount [7]. In this paper, several clay samples with representative ratio were selected for rheological experiments [1], [2], and [15]. The experimental results are shown in Tables 3-5.

The rheological curves are drawn according to the above experiment results:

It can be seen from Figs.8-10 that the rheological curve of the clay cement grout is similar to the rheological curve of the viscoplastic fluid and can be considered as viscoplastic. The fact is, for a long period of time, people have regarded clay cement grout as a type of Bingham fluid. In the strict sense, the rheological properties of the clay cement grout do not conform to the rheological properties of the Bingham fluid. Only when the shear rate is greater than 50 S^{-1} can the shear stress and

TABLE 3: SLURRY RHEOLOGICAL EXPERIMENT (B SYSTEM) RESULTS

Speed setting	Readings /grid	dr/dt /S^{-1}	τ
1	44	3.178	24.97
2	46	4.313	26.11
3	47	5.675	26.67
4	49	7.378	27.81
5	53	10.22	30.07
6	55	15.89	31.21
7	56	21.57	31.78
8	59	28.38	33.48
9	62	36.89	35.18
10	64	51.08	36.32
11	67	63.56	38.02
12	71	86.28	40.29
13	72	113.5	40.86
14	75	147.6	42.56
15	83	204.3	47.1
	Water-cement ratio	1:1	
	Cement addition amount	15%	
	Accelerator addition amount	7%	

Fig.6 The photo of the viscometer

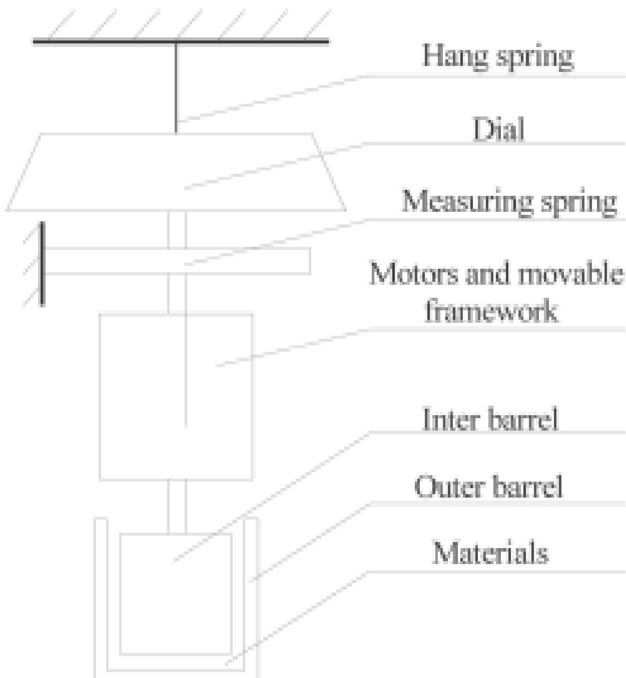


Fig.7 The schematic diagram of the viscometer

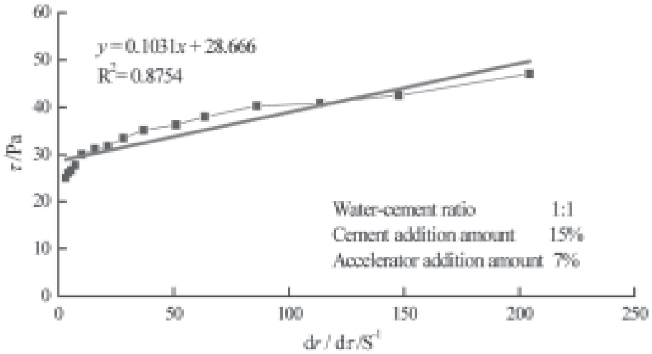


Fig.8 The rheological curve diagram of clay-cement grout

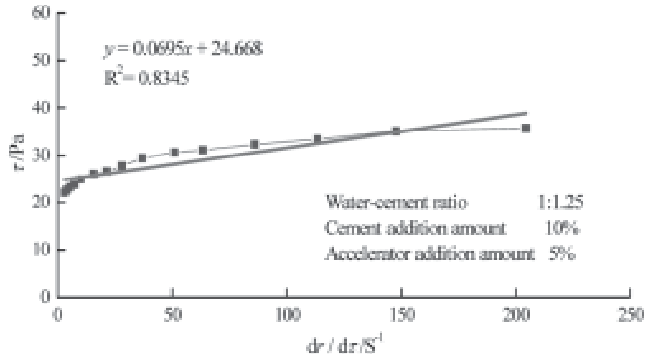


Fig.9 The rheological curve diagram of clay-cement grout

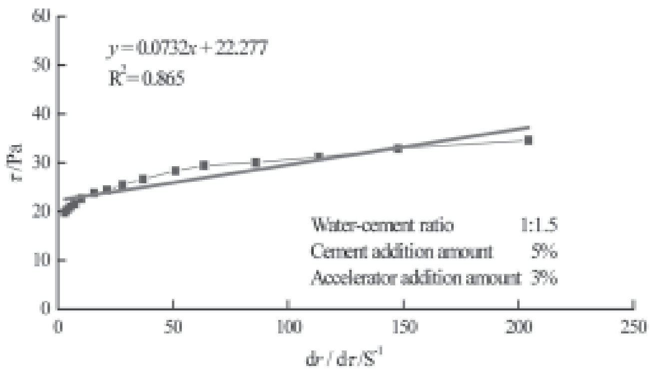


Fig.10 The rheological curve diagram of clay-cement grout

shear rate are linearly related. Only when the shear rate is lower than 50 S^{-1} can the rheological curve be curve-like.

As the diffusion distance of the clay cement grout is enlarged, the resistance to flow increases, the flow amount decreases gradually and the diffusion is slowed down. The grout stops diffusing when the resistance to diffusion is equal to the pump pressure. It can be seen from Fig.3 that in the 0-A section, due to $\tau < \tau_s$, the slurry does not flow, which means that when the shear rate approaches zero, $\tau = \tau_s$, i.e. the moment when the slurry stops diffusing in the stratum, the resistance to diffusion is dependent on nothing but the static shear force τ_s. In the A-B section, the grout begins to overcome the resistance to flow along the pipe wall, and the network structure of the grout begins to be destroyed, displaying the characteristics of plug flow; in the B-C section, as the shear stress τ increases, the plug flow disappears gradually and the grout flow is almost fully driven. In the C-D section, the velocity gradient of the slurry flow is close to parabola, showing the total flow of the slurry in the cross section part. Thus, the slurry will only flow when the shear force exerted on the slurry exceeds τ_s. Afterwards, as the shear stress τ increases, the slurry flow continues to accelerate until transiting gradually to the state that the ratio of shear stress to velocity gradient is a constant (the time when the rheological curve is in the form of a straight line).

TABLE 4: SLURRY RHEOLOGICAL EXPERIMENT (B SYSTEM) RESULTS

Speed setting	Readings /grid	dr/dt /S^{-1}	t
1	39	3.178	22.13
2	40	4.313	22.7
3	41	5.675	23.26
4	42	7.378	23.83
5	44	10.22	24.97
6	46	15.89	26.11
7	47	21.57	26.67
8	49	28.38	27.81
9	52	36.89	29.51
10	54	51.08	30.65
11	55	63.56	31.21
12	57	86.28	32.35
13	59	113.5	33.48
14	62	147.6	35.18
15	63	204.3	35.75
	Water-cement ratio	1:1.25	
	Cement addition amount	10%	
	Accelerator addition amount	5%	

TABLE 5: SLURRY RHEOLOGICAL EXPERIMENT (B SYSTEM) RESULTS

Speed setting	Readings /grid	dr/dt /S^{-1}	t
1	35	3.178	19.86
2	36	4.313	20.43
3	37	5.675	20.99
4	38	7.378	21.57
5	40	10.22	22.7
6	42	15.89	23.84
7	43	21.57	24.4
8	45	28.38	25.54
9	47	36.89	26.67
10	50	51.08	28.37
11	52	63.56	29.51
12	53	86.28	30.07
13	55	113.5	31.21
14	58	147.6	32.92
15	61	204.3	34.62
	Water-cement ratio	1:1.5	
	Cement addition amount	5%	
	Accelerator addition amount	3%	

Faster diffusion speed and shear rate means larger resistance to flow and shear force. Therefore, the plastic viscosity of the slurry determines the rate at which the slurry diffuses from the grouting hole in a stratum with fixed void ratio and at a certain grouting pressure. Nevertheless, the determinant of the maximum radius of slurry diffusion is static shear force. Since the static shear force of the slurry blocks the slurry from diffusing, only when the pump pressure is larger than the static shear force in the inner part of the slurry can the slurry flows in the stratum. The static shear force increases with the grouting time. The grouting behaviour should end when the static shear force exceeds pump pressure, which set constraints on the diffusion distance. Therefore, in the grouting process, the change of static shear force decides the slurry radius. The smaller the static shear force is, the easier the grout be grouted, and the larger the slurry radius is. However, when the static force of the slurry is overly small, the slurry may become unstable and enlarge its diffusion radius as a result. More importantly, when the static shear force is lower than the groundwater hydrodynamic pressure, it will cause the slurry to be washed away by groundwater; when the static force of the slurry is oversized, the further the diffused slurry is from the grouting pump, the smaller the pump pressure exerted on it is. The slurry will stop diffusing when the static shear force is equal to the pump pressure. The plastic viscosity of the slurry also varies with the grouting time, influencing grout time to a certain extent. Therefore, the plastic viscosity value should be reduced as much as possible.

6. Conclusion

(1) Depending on the rheological properties of the slurry, the commonly-used grouting slurry can be divided into three classes-viscous fluid (Newtonian fluid), plastic fluid (Bingham fluid) and viscoplastic fluid. According to time effect, slurries can be divided into time-dependent slurries and time-independent. The former one is also known as time-varying viscous fluids which include thixotropic fluids and condensed fluids.

(2) The rheological properties of the clay cement grout are largely comparable to the rheological properties of the viscoplastic fluid, and thus can be considered viscoplastic. Only when the shear rate is greater than 50 S^{-1} can the shear stress and shear rate are linearly related. Only when the shear rate is lower than 50 S^{-1} can the rheological curve be curve-like.

(3) The size of the static shear force determines the maximum diffusion radius of the slurry. The smaller the static force is, the easier it is grouted into the fluid, and the larger the grount radius is. However, when the static force of the slurry is overly small, the slurry may become unstable and enlarge its diffusion radius as a result. More importantly, when the static shear force is lower than the groundwater hydrodynamic pressure, it will cause the slurry to be washed away by ground water; When the static force of the slurry is oversized, the further the diffused slurry is from the grouting pump, the smaller the pump pressure exerted on it is.

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