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Rheological Characteristics of Power-law Cement Grouts Based on Time-dependent Behavior of Viscosity

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Grouting technology is playing an increasingly important role in engineering construction, but the theoretical research lags behind the engineering practice of the grouting technology in need. At present, the research on the laws of the grouts rheological properties and grout diffusion are important contents of scientific research workers. This paper researches grouts time-dependent behavior of viscosity, and verifies the engineering commonly used water-cement ratio (W/C) 0.5, 0.6, 0.7 cement grout obey the power-law fluid properties. Different water cement ratio grouts viscosity increases with the increase of gelation time. Experimental results show that quantitative relationship between W/C and consistency coefficient and apparent viscosity of power-law cement grouts may be all expressed by exponential function of taking e as base number, in addition their fitting effect are very good. The theoretical values of these parameters calculated by quantitative relationship are greater than those of actual measurement values in the verification experiments, moreover their difference are all distributed in the range 5%. Both consistency coefficient and apparent viscosity of power-law cement grouts have rapidly increased over time, but rheological index is little variation over time. So the consistency coefficient and apparent viscosity belong to time-dependent rheological parameters. Considering the time-dependent behavior of power-law grouts, its rheological equation can be expressed as $\tau=c_0e^{kt}\gamma^n$, and these research results could provide reasonable scientific guidance to practical engineering.

1. Introduction

Prepare certain materials into grouts, then pour the grouts into layer or gaps with air compressor for its extension, gel or solidification, which further achieve the goal of solidifying layer or leakage prevention, this process can be called grouting. Cement is presently widely used for grouting projects, among which ordinary Portland cement is widely applied to geotechnical engineering because of its rich resource, convenient grout preparing, easy construction, and high consolidating strength (Zeng et al., 1999; Wang et al., 2016).
Based on the water cement ration (W/C), cement grouts usually may be divided into three categories: Power-law fluid, Bingham fluid and Newtonian fluid (Zenit et al., 2001). With the increasing progress of technical skill, power-fluid has extensive application in many practical engineering in the countries of the world, such as, metallurgy, construction, railways, water-power engineering and mining and so on. Nowadays, a lot of studies or rheological theory of power-law fluid has been done by scholars in the worldwide. Wu (Xu, 1993) and Wang (Wang et al., 1996) analyse the applicability of the power-law fluid in geotechnical reinforcement technique. Hou (2002) discusses the test method on rheological properties of power-law fluid. Ruan (Ruan, 2005) points out lower water cement ration (W/C 0.5~0.7) grouts belong to typical power-law fluid. Based on the generalized Darcy's Law and theory for spherical diffusion model, Yang (Yang et al., 2005) deduces a formula for calculating the effective diffusion radius of Power-fluid injected into homogeneous sandy stratum in grouting, and analyses grouting pressure difference change with rheological parameter *c* by linearity rule and with parameter *n* by nonlinearity rule. Diffusion radius of hemispheroid and diffusion length belong to cylinder of column-hemispherical penetration grouting mechanism based on power-law fluid are deduced (Yang et al., 2014). Yang (Yang et al., 2015) establishes rheological and seepage equation for power-law cement grouts with time-dependent rheological parameters through theoretical analysis and experiments, and analyses the applicability of seepage equation and the method to determine the parameters.

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Although many scholars conduct in-depth research on the rheological properties and strengthening mechanism of power-law cement grouts, these studies are ill-considered on time-dependent behavior of grouts. The rheological properties of cement grout have very significant changed with timehistory. However, for present grouting mechanism of power-fluid, their rheological parameters are constant in the whole grouting process, thus calculated theoretical values by them are much larger than the actual measurement values from practical engineering. So, carrying out experiment researches and numerical analysis on time-dependent behavior of power-law cement grouts will play a reference guiding role for design and construction of grouting engineering.

2. Rheological experiment of cement grouts

During the grouting, the cement grouts are in liquid status, thus, confirming its flow pattern and property is the precondition of grouting diffusion model. Therefore, experimental research on the law of pure grout's viscosity changes with time is conducted in this paper.

2.1 Experimental materials and equipment

Test materials select P.O 42.5 ordinary Portland cement labelled #4.25MPa and water. Test equipment: NXS-11B rotational viscometer is shown in Figure 1. It is driven by a stepping motor. By adopting the concentric cylinder's upper rotary system as operating principle, when the outer cylinder is fixed, the inner cylinder will rotates (There are five metering systems including A, B, C, D and E). Then measured materials will be filled between the inner and outer cylinders as shown in Figure 2. When the motor driven inner cylinder rotates, measured materials act on the surface of inner cylinder, and then rotors of the motor and inner cylinder rotate at the same time. Meanwhile, torques that are equal and opposite in direction act on rotors and movable frame, then the frame is deflected until that the moment of twisting force is equal with the referred torques. At this moment, the angel value of deflection shown on division circle is in proportion to viscosity.

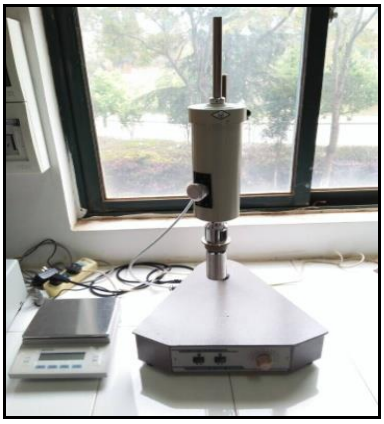


Figure 1: NXS-11B rotational viscometer

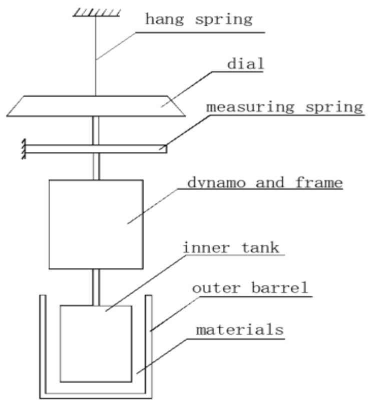


Figure 2: Working principle of rotational viscometer

2.2 Experimental design and process

According to national standards, the initial setting time of common Portland cement shall be not less than 45min. Thus, we are mainly testing on the viscosity changes of grout in the first 40min after the mixing is finished. The setting cement water ratios are 0.5, 0.55, 0.6, 0.65 and 0.7. The experimental process shall be as follows: (1) measuring the cement with electronic balance; (2) measuring and taking some water from incubator with a graduate; (3) pouring cement and measured water into the stirrer, then mixing it slowly and fast for 1 min respectively. After that, pour the grout into experiment container. (4) adjusting the speed of rotational viscometer from low to high to obtain flow curves of different grouts with different proportions; (5) measuring its viscosity in every 10min.

2.3 Experimental condition

In order to ensure the accuracy of experimental results during these experimental, the following two aspects must be satisfied: (1) both indoor environment temperature and temperature of water should be constant in the process of experimental; (2) least 3 experiments are carried out under the same experimental conditions for the same sample, to ensure that their standard deviation is controlled in the range of 5%.

3. Experimental analysis and discussion

3.1 Verification the equation of power-law cement grouts

The viscosity of cement grouts with W/C 0.5, 0.6 and 0.7 are measured by NXS-11B rotational viscometer, and the experimental results are shown in Table 1.

Table 1: Rheological characteristics of power-law cement grouts

Rheological characteristics	W/C=0.5	W/C=0.6	W/C=0.7
consistency coefficient *c*	6.475	3.246	1.569
rheological index *n*	0.324	0.330	0.308
apparent viscosity η_a(*Pa. S*)	0.134	0.072	0.028
rheological equation	$\tau=6.475\gamma^{0.324}$	$\tau=3.246\gamma^{0.330}$	$\tau=1.569\gamma^{0.303}$

From table 1,we may see that rheological equations of power-law cement grouts of W/C0.5,0.6 and 0.7 are consistent with the basic rheological equation of power-law fluid shown in Eq(1)

$$\tau = c\gamma^{n} \tag{1}$$

In this formula, τ-shear stress/Pa; *c*-consistency coefficient; γ-shear velocity/s^{-1}; *n*-rheological index, when n<1, fluid is fake plastic fluid, while it is dilatant fluid as n>1.

3.2 Relationship between W/C and rheological parameters of grouts

According to the results of Table 1, the relationships between W/C and rheological parameters of power-law grouts are analyzed. The relationship curves between consistency coefficient *c*, apparent viscosity η_a and W/C are respectively shown in Figure 3 and Figure 4. By data fitting, the quantitative relationship between rheological parameters of power-law cement grouts and W/C are established, as show in Table2.

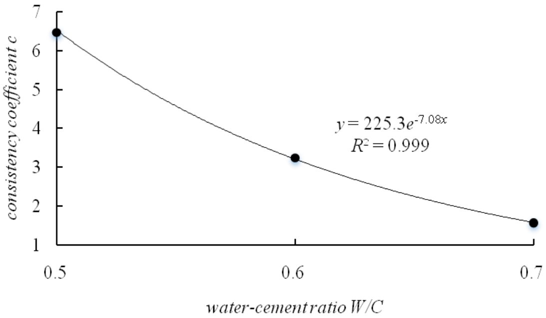


Figure 3: Relationship between W/C and c

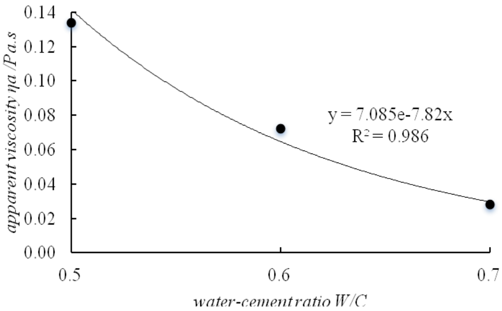


Figure 4: Relationship between W/C and η_a

Table 2: Quantitative relationship between rheological parameters and W/C

Rheological parameters	Quantitative equation	Correlationcoefficient
Consistency coefficient *c*	$C=225.38e^{-7.087w}$	R^2=99.98%
Apparent viscosity η_a(*Pa·S*)	$\eta_\alpha=7.06e^{-7.828w}$	R^2=99.60%

According to Table 2, correlation coefficient R^2 of quantitative relationships between water-cement ratio and consistency coefficient and apparent viscosity of Power-law cement grouts are all very high, even close 1. So they indicate that fitting effect between water-cement ratio and rheological characteristics of power-law cement grouts are very good.

From above numerical analysis results, it can be found following conclusions: (1) consistency coefficient and apparent viscosity of Power-law cement grouts show reverse change with their water-cement ratio; (2) quantitative relationship between water-cement ratio and consistency coefficient and apparent viscosity of power-law cement grouts may be all expressed by exponential function of taking e as base number, in addition their fitting effect are very good.

In order to verify the applicability of quantitative relationships in the Table 2, two verification experiments can be designed in the paper. Cement grouts of W/C 0.55 and 0.65 are respectively configured with ordinary Portland cements labeled #4.25MPa and carried out their rheological experiments. Actual measurement values (ACV) of consistency coefficient and apparent viscosity from verification experiments and theoretical values (TV) calculated by their corresponding quantitative relationships (seen in the Table 2) may be shown in Table 3.

Table 3: Error analysis between theoretical calculation and actual measured values

W/C	Consistency coefficient c			Apparent viscosity $\eta_a(Pa\cdot S)$		
	ACV	TV	error analysis	ACV	TV	error analysis
0.55	4.7360	4.5719	3.465%	0.0980	0.0953	2.755%
0.65	2.3290	2.2507	3.362%	0.0450	0.0436	3.211%

Table 3 shows that theoretical values of rheological parameters calculated by their corresponding quantitative relationship are greater than actual measurement values, but their difference are all distributed in the range of 5%. It can be seen that quantitative relationship between W/C and rheological parameters of power-law cement grouts are correct.

3.3 Analysis of time-dependent behavior of rheological parameters

The rheological properties of grouts vary largely over time, and common Portland cement's initial setting time shall not be less than 45min. Thus, we are mainly testing on the viscosity changes of grout in the first 40min after mixing. Then choose the grouts whose W/C is respectively 0.5, 0.6 and 0.7 and divide every grout into 4 groups, and then respectively test their viscosity after 0min, 10min, 20 min and 30min. Because of space limitation, this paper only list shear stress and apparent viscosity values of W/C 0.6 grouts at 0min, 10mints, 20mints and 30mints, as show in Table4 and Table 5.

Table 4: Time-dependent behavior of viscosity experimental results (W/C 0.6)

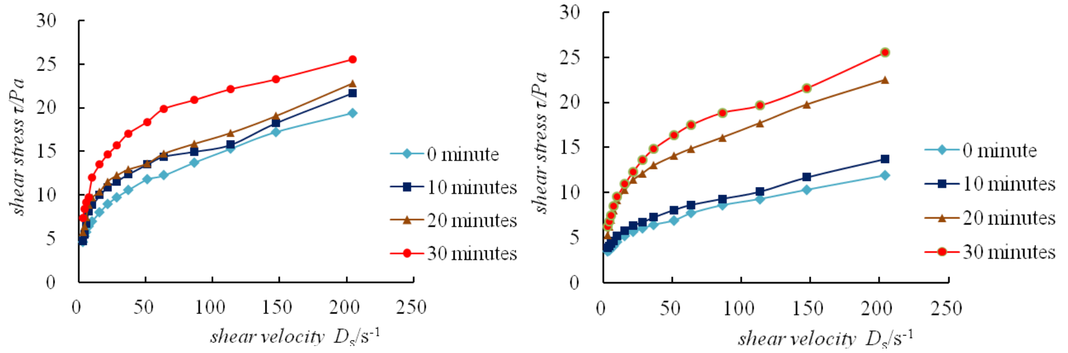
Shear rate D_s/s^{-1}	Shear stress τ / *Pa*			
	0 minute	10 minute	20 minute	30 minute
3.178	4.654	4.767	5.789	7.378
4.313	5.335	5.448	6.470	8.399
5.675	5.789	6.697	7.491	9.194
7.378	6.413	8.115	8.853	9.761
10.220	7.037	8.853	9.761	12.031
15.890	8.059	9.988	10.442	13.507
21.570	8.967	10.896	11.577	14.642
28.380	9.761	11.577	12.258	15.663
36.890	10.556	12.372	12.939	17.025
51.080	11.804	13.507	13.620	18.387
63.560	12.258	14.415	14.755	19.863
86.280	13.734	14.982	15.890	20.884
113.50	15.323	15.777	17.139	22.133
147.60	17.252	18.274	19.102	23.268
204.30	19.409	21.679	22.814	25.538

Table 5: Time-dependent behaviour of rheological parameters calculated results (W/C 0.6)

Rheological parameters	Time t			
	0 *minute*	10 *minutes*	20 *minutes*	30 *minutes*
consistency coefficient c	3.2456	3.8039	4.5061	5.6440
rheological index n	0.3296	0.3214	0.2928	0.2945
apparent viscosity $\eta_a(Pa\cdot S)$	0.0718	0.0739	0.0756	0.0864

According to the experimental results of time-dependent behaviour of cement grouts (W/C 0.5,0.6 and 0.7), the rheological curves of cement grouts with different time are drew as shown in figure 5 (because of space limitation, Figure 5 only list rheological curves of cement grouts with W/C 0.6 and 0.7).

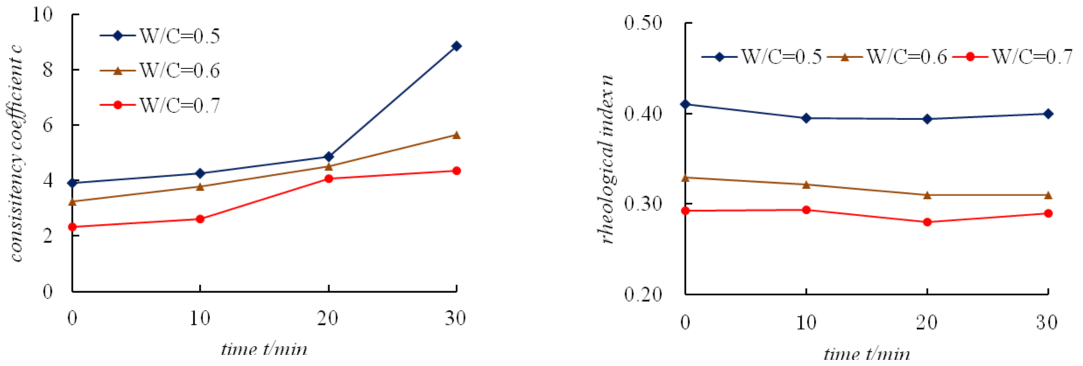
Figure 5 shows that the rheological curves of cement grouts with time-dependent behavior accord with typical power-law fluid. The longer the gel time is, the larger the corresponding shearing stress corresponding to equal shear rate will be, with large viscosity. The larger the water cement ratio is, the smaller the shearing stress, which corresponds to the equal shear rate, will be.



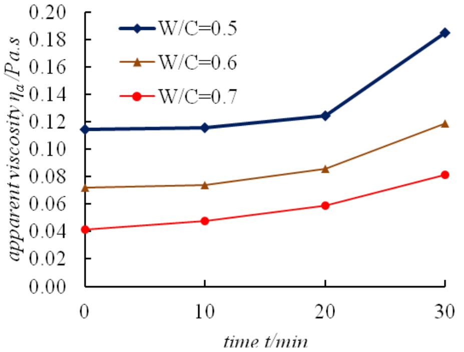
(*a*) W/C 0.6 (*b*) W/C 0.7

Figure 5: Rheological curves of 3 cement grouts at 4 different times

According to the above analytic results, time-dependent behavior characteristics of power-law cement grouts are obtained, as shown in Figure 6.



(a) Time-dependent behavior of consistency coefficient (b) Time-dependent behavior of rheological index



(c) Time-dependent behaviour of apparent viscosity

Figure 6: Time-dependent behaviour of rheological parameters

Analysis of time-dependent behavior of rheological parameters, it can be found following conclusions. (1) Both consistency coefficient and apparent viscosity of power-law cement grouts have rapidly increased over time. So they belong to time-dependent rheological parameters. (2) Rheological index of power-law cement grouts is little variation with time. Therefore, rheological index can be deemed a constant over time.

3.4 Rheological equation of power-law cement grouts

The power-law grout's consistency coefficient is in exponential relationship with time and it has the characteristic of time varying. While the rheological index varies little with time, so it is not time varying. Thus, the time varying rule of power-law grout's rheological parameter is given under:

$$c(t) = c_0 e^{kt} \quad (2)$$

$$n \approx n(t) \quad (3)$$

Comprehensive analysis equation from (1) to (4), we can establish the rheological equation of time varying power-law grout as follows:

$$\tau = c_0 e^{kt} \gamma^n \quad (4)$$

Where τ is shear stress; c is consistency coefficient; c_0 is initial consistency coefficient; $c(t)$ is t moment's consistency coefficient. n is rheological index; $n(t)$ is t moment's rheological index, and it is the same to n in formula 2. γ is shearing rate, $\gamma = dv/dr$; t is grouting time. k is time-varying coefficients, and it can be obtained by experiment.

4. Conclusion

(1) Cement grouts of W/C 0.5, 0.6 and 0.7 is typical power-law fluid, and they belong to fake plastic fluid. Consistency coefficient and apparent viscosity of power-law cement grouts show reverse with water-cement ratio.
(2) Empirical equation between water-cement ratio and consistency coefficient and apparent viscosity of power-law cement grouts could be expressed by exponential function of taking e as base number. The error is all distributed in the range of 5% between theoretical values with empirical equation and actual measurement values by verification experiment.
(3) Consistency coefficient and apparent viscosity of power-law cement grouts belong to time-dependent rheological parameters, and rheological index is constant over time.
(4) Considering the rheological law of time-dependent behavior of power-law grouts, its rheological equation with time-dependent is established as: $\tau = c_0 e^{kt} \gamma^n$.

Acknowledgements

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