Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 5781753, 10 pages
https://doi.org/10.1155/2021/5781753

Research Article

Influence of Coupling Effects of Time and Water-to-Cement Ratio on Rheological Properties of Bingham Cement Grouts

Zhiquan Yang,[1,2,3] Mao Chen,[1,3] Yi Ding,[2,3] Yi Yang,[2,3] Yingyan Zhu,[2,3,4] Yanhui Guo,[2,3] Renchao Wang,[5] Bihua Zhang,[6] Yingchao Fang,[7] Dongliang Yu,[7] Yapeng Mi,[8] Jiankung Su,[9] Liu Hao,[9] Jie Zhang,[10] Yongfa Guo,[11] Zhihou Li,[12] Junzhi Chen,[13] and Wanzhong Xu[13]

[1]*Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, Yunnan, Kunming, China*
[2]*Faculty of Public Safety and Emergency Management, Kunming University of Science and Technology, Yunnan, Kunming, China*
[3]*Key Laboratory of Early Rapid Identi-Fication, Prevention and Control of Geological Diseases in Traffic Corridor of High Intensity Earthquake Mount-ainous Area of Yunnan Province, Kunming University of Science and Technology, Yunnan, Kunming, China*
[4]*Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610041, China*
[5]*School of Computer Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*
[6]*Beijing Fibote Photoelectric Technology Co.,Ltd, Beijing 100083, China*
[7]*PipeChina SouthWest Pipeline Company, Chengdu, Sichuan 610041, China*
[8]*The Third Engineering Co.,Ltd. of China Railway Seventh Bureau Group Corporation, Xi'an 710026, China*
[9]*Yunnan Aerospace Engineering Geophysical Detecting Co.,Ltd., Kunming 650217, China*
[10]*Yunnan Institute of Geological Environment Monitoring, Kunming, Yunnan 650216, China*
[11]*Kunming Survey, Design and Research Institute Co.,Ltd. of CREEC, Kunming, Yunnan 650200, China*
[12]*Broadvision Engineering Consultants, Kunming 650041, China*
[13]*Faculty of Land Resource Engineering, Kunming University of Science and Technology, Yunnan, Kunming, China*

Correspondence should be addressed to Mao Chen; zgm543@163.com

Received 10 June 2021; Revised 5 September 2021; Accepted 5 October 2021; Published 23 October 2021

Academic Editor: José António Fonseca de Oliveira Correia

Time and water-to-cement ratio have significant influences on rheology of cement grouts. In order to study effects of time and water-to-cement ratio on rheology of Bingham cement grouts, taking Bingham cement grouts widely used in practical engineering (cement grouts with water-to-cement ratio of 0.75–1.25) as research object, some rheological experiments of five cement grouts with water-to-cement ratio of 0.8, 0.9, 1.0, 1.1, and 1.25 were carried out at six moments of 0, 5, 10, 20, 30, and 60 minutes, respectively. Combining theoretical discussion with numerical analysis, influence of coupling effects of time and water-to-cement ratio on rheological properties of Bingham cement grouts was discussed. Results show that at the level of $\alpha = 0.05$, time has a significant influence on plastic viscosity but has no significant influence on the yield stress of Bingham cement grouts. Water-to-cement ratio has a significant influence on both plastic viscosity and yield stress. Exponential models obtained by comprehensive analysis from statistical theory, practical applicability, and accuracy are the optimal models to describe quantitative change in the relationship of coupling effects of time and water-to-cement ratio on plastic viscosity and yield stress of Bingham cement grouts. The rheological equation considering coupling effects of time and water-to-cement ratio of Bingham cement grouts is constructed. Research achievements not only have certain theoretical significance to the development and improvement of fluid mechanics and theoretical system of penetration grouting but also provide theoretical support and technical reference for practical grouting engineering and also have certain practical significance for solving or improving the practical engineering problems.

1. Introduction

Engineering practice shows that cement, an inorganic cementitious material with low cost and good performance, is widely used in many engineering fields, such as roads, tunnels, slopes, foundations, railways, buildings, mines, and water conservancy. The rheology of cement grouts has a significant influence on its migration and diffusion and the engineering effects on rock and soil. Therefore, the study of the rheology of cement grouts can not only provide a theoretical basis for the study of its migration and diffusion mechanism but also provide technical support for practical engineering design [1–3].

The rheology of cement grouts is influenced by its composition, water-to-cement ratio, temperature, and time. The rheology under these factors has been studied deeply. Ruan et al. [4–9] studied the change of cement grouts rheology with time. Sahmaran et al. [10–15] explored the effect of composition and particle size on rheological properties. Manisha et al. [16] analyzed the relationship between filler and the rheological properties of cement grouts. Li et al. [17] explored the effect of nano-SiO_2 on the rheology of ultrafine cement grouts by conducting an experiment. Costas considered the effect of different superplasticizer on the rheological properties of cement grouts [18]. In terms of the effects of water-to-cement ratio on the rheology of cement grouts, Mirza et al. [19] investigated the rheological properties of fly ash-cement grouts at different ratios. Yang et al. [20–25] studied the effect of water-to-cement ratio on the rheology of cement grouts. Liu et al. [21, 26–31] considered the characteristics of temperature change on the fluidity of cement grouts.

In conclusion, the results have been studied from the point of view of the influence of single factor on the rheology of cement grouts, whereas the influence of the coupling effect of these factors on rheology has not yet been well grasped. For example, the application values of rheological parameters such as shear stress and yield stress of Bingham cement grouts under the combined effects of time and water-to-cement ratio cannot be reasonably and scientifically determined in the engineering practice. For this reason, Bingham cement grouts, which are widely used in practical projects (cement grout is a typical Bingham fluid under the condition of a water-to-cement ratio in the range of 0.75–1.25 [4, 24]), such as seepage prevention and plugging of tunnel projects, foundation reinforcement of buildings, and support of underground engineering [32], were taken as the research object in this study. Combining experimental research, theoretical discussion, and numerical analysis, the effects of time and water-to-cement ratio on the rheological parameters of Bingham cement grouts were analyzed. The quantitative change model of the coupling effects of time and water-to-cement ratio on the plastic viscosity and yield stress of Bingham cement grouts was explored. On this basis, the rheological equation of Bingham cement grouts with the coupling effects of time and water-to-cement ratio was constructed. The research results not only have certain theoretical significance for the development and improvement of the theoretical system of fluid mechanics and infiltration grouting, ut also can provide technical support for practical grouting projects and have certain practical significance for solving or improving difficult problems in actual projects.

2. Materials and Methods

2.1. Experimental Material. The experimental material is #32.5 ordinary Portland cement produced by Kunming cement plant, which is widely used in current practical engineering. The basic physical properties of the cement are shown in Table 1 with reference to the specification "Test methods for water requirement of normal consistency, setting time, and soundness of the Portland cement". The chemical compositions of the cement are shown in Table 2.

The water used for the experiments was pure drinking water.

2.2. Experimental Equipment. A NXS-11A rotary viscometer from Chengdu instrument plant was used for the experiments. The apparatus is driven by a stepper motor to rotate the inner cylinder, and the outer cylinder is fixed. By controlling the speed of the inner cylinder, the shearing motion of the cement grouts between the inner and outer cylinders with different shear speeds is generated, and the corresponding shear stress is measured. Rheological curve of the cement grouts is then plotted in the shear speed-shear stress coordinates.

2.3. Experimental Design. As indicated by Ruan and Yang [4, 24], cement grout is a typical Bingham fluid under the condition of water-to-cement ratio in the range of 0.75–1.25. Therefore, some rheological experiments of five cement grouts with water-to-cement ratio (ω) of 0.80, 0.90, 1.00, 1.10, and 1.25 were carried out at six moments of 0 (the moment that grout configuration is completed), 5, 10, 20, 30, and 60 minutes, respectively. The indoor ambient temperature for the rheological experiments and the water temperature for the cement grouts were designed to be kept within the range of $25 \pm 2^{\circ}C$.

2.4. Test Methods. Preparation method of cement grout sample [35]: firstly, weigh 500 g of pure drinking water and pour it into a measuring cylinder, then weigh 625 g of #32.5 ordinary Portland cement with an electronic balance and put it into a beaker, then pour the water in the measuring cylinder into the beaker and stir to prepare cement grout with a water-to-cement ratio of 0.8; according to this method, weigh 555.60, 500, 454.50, and 400 g of #32.5 ordinary Portland cement with an electronic balance and 500 g of pure drinking water was added and stirred to prepare cement grout with water-to-cement ratio of 0.9, 1.0, 1.1, and 1.25, respectively.

The rheological test method: (1) add the prepared cement grouts with different water-to-cement ratios into the outer cylinder of NXS-11A rotary viscometer, insert the measuring head of the inner cylinder vertically into the outer cylinder, and fix it; (2) turn on the power, open the shear speed knob,

Table 1: Basic properties of #32.5 ordinary Portland cements produced by Kunming cement plant [33].

Setting time (min)		Soundness	Flexural strength (MPa)		Compressive strength (MPa)	
Initial set	Final set		3 d	28 d	3 d	28 d
90	400	Conformity	2.5	5.5	11.0	32.5

Table 2: The chemical compositions of #32.5 ordinary Portland cements [34].

Chemical compositions	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3
Content (%)	58.24	24.08	4.72	2.46	1.95	2.31

and control switch to carry out the rheological test; (3) conduct the rheological test with different shear speeds by adjusting the shear speed knob and measure the corresponding shear stress at the same time; (4) the rheological curves of Bingham cement grouts with different water-to-cement ratios can be plotted in the shear speed-shear stress coordinates [35].

2.5. Analysis of Variance. Based on the test results, the rheological parameters (yield stress, plastic viscosity) of Bingham cement grouts combined by time and water-to-cement ratio were analyzed with Minitab software, and the quantitative variation relationship between them was constructed.

3. Results and Analysis

3.1. Rheological Curves and Rheological Equations of Bingham Cement Grouts. The rheological curves of the cement grouts analyzed from the rheological experimental results are shown in Figure 1. Analysis of Figure 1 shows that (1) the trends of the rheological curves of cement grouts with different water-to-cement ratio at six moments are in accordance with the basic rheological curves of Bingham fluid [36, 37], which confirms Ruan and Yang's research results [4, 24]; (2) the flow pattern of the cement grouts does not change with time, which also confirms Ruan's research results [4].

Based on the basic rheological equation (1) [37, 38] of Bingham fluid, the rheological equations of Bingham cement grouts with five water-to-cement ratio at six moments can be obtained as shown in Table 3 according to the rheological curves shown in Figure 1.

$$\tau = \tau_0 + n_p\gamma, \tag{1}$$

where τ is the shear stress, Pa; τ_0 is the yield stress, Pa; n_{p} is the plastic viscosity, Pa·s; γ is the shear speed, s^{-1}; and yield stress and plastic viscosity are usually used to characterise the rheological properties of Bingham fluid.

3.2. Analysis of the Effects of Time and Water-to-Cement Ratio on the Rheological Parameters of Bingham Cement Grouts. According to the rheological equations in Table 3, two-factor variance analysis was used to study the effects of time and water-to-cement ratio on the rheological parameters (yield stress, plastic viscosity) of Bingham cement grouts, the results are shown in Table 4.

In Table 4, *DF*, *SS*, and *MS* are degrees of freedom, regression sum of squares, and mean-squared deviation, respectively. *F* is the distribution value of the test *F*, and *P* is the coefficient of statistical significance, both of which are used to determine whether time or water-to-cement ratio has a significant effect on the yield stress and plastic viscosity of Bingham cement grouts, which is usually compared with $\alpha = 0.05$. If $F > F\alpha$ (the critical value obtained by looking up the table) and $P < \alpha = 0.05$, the yield stress and plastic viscosity of Bingham cement grouts are significantly influenced by time or water-to-cement ratio at $\alpha = 0.05$ [38].

Analysis of Table 4 shows that (1) for plastic viscosity n_{p}, $F = 1210.71 > F_{0.05}$ (5, 20) = 4.76 and $P < 0.05$ corresponding to the time column can be obtained. Meanwhile, $F = 7.08 > F_{0.05}$ (4, 20) = 5.17 and $P < 0.05$ corresponding to the water-to-cement ratio column can be obtained. This indicates that both time and water-to-cement ratio have significant effects on the plastic viscosity n_{p} at $\alpha = 0.05$; (2) For the yield stress τ_0, $F = 16626.75 > F_{0.05}$ (4, 20) = 5.17 and $P < 0.05$ corresponding to the water-to-cement ratio column can be obtained, while $F = 1.75 < F_{0.05}$ (5, 20) = 4.76 and $P = 0.176 > 0.05$ corresponding to the time column can be obtained. This indicates that water-to-cement ratio has a significant effect on the yield stress of Bingham cement grouts, whereas time has no significant effect on it.

3.3. Quantitative Change Relationship of the Coupling Effects of Time and Water-to-Cement Ratio on the Plastic Viscosity of Bingham Cement Grouts

3.3.1. Constructing Quantitative Change Relationship Models. It can be seen from the above section that both time and water-to-cement ratio have a significant effect on the plastic viscosity n_{p} of Bingham cement grouts, so the coupling effects of the two factors must be considered.

However, there are no relevant models for the quantitative change of the coupling effects of time and water-to-cement ratio on the plastic viscosity of Bingham cement grouts. Therefore, this study selects the most basic and widely applied four models in mathematics: the linear, logarithmic, exponential, and power function models. Based on them, numerical analysis method is used to explore the quantitative change relationship of the coupling effects of time and water-to-cement ratio on the plastic viscosity of Bingham cement grouts. Then, the optimal model is determined based on the comprehensive analysis results of statistical theory and verification experiment.

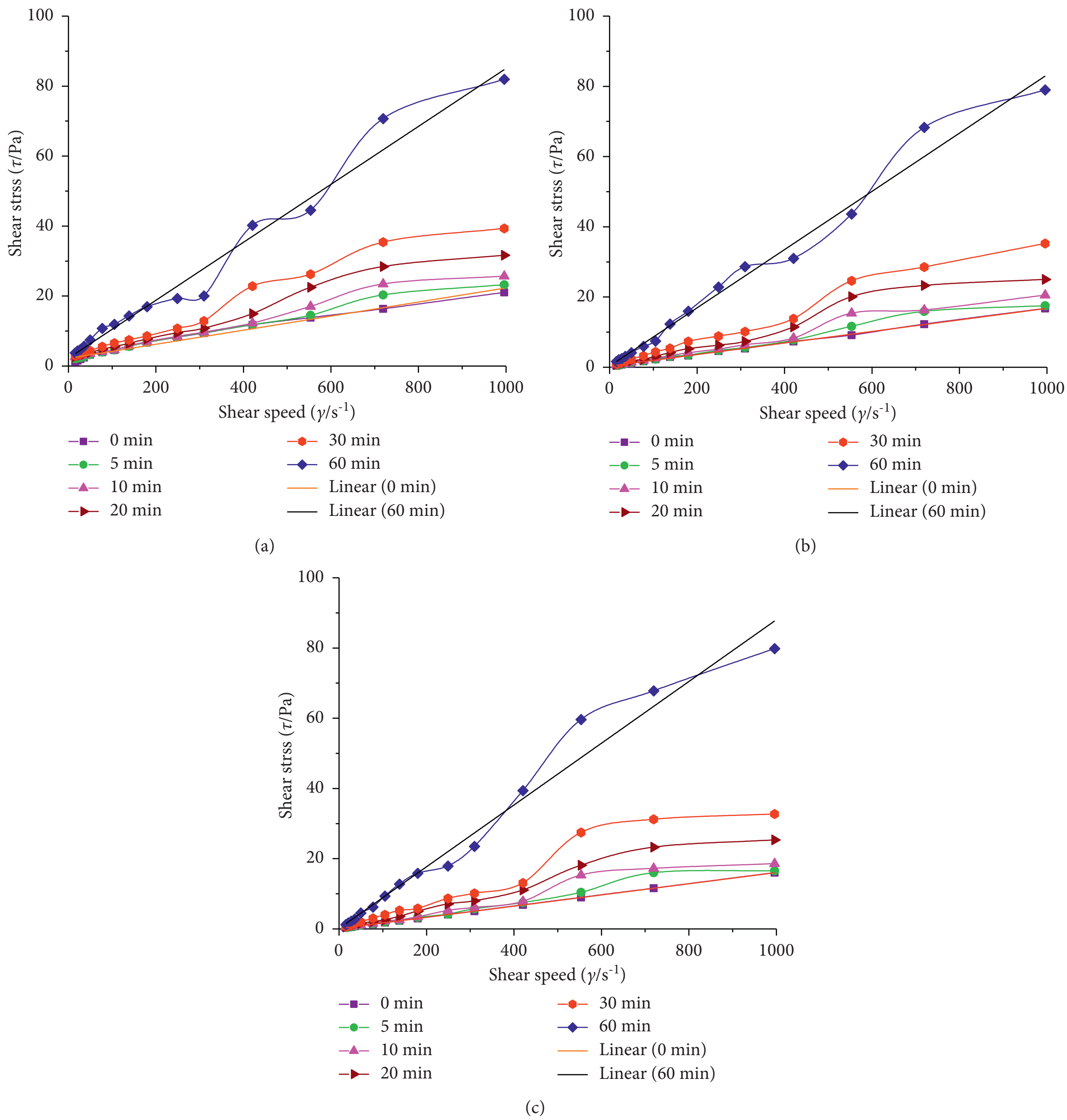

Figure 1: Rheological curve of cement grouts with different water-to-cement ratio (a): $\omega = 0.80$, (b) $\omega = 1.10$, (c) $\omega = 1.25$).

The four quantitative change models and analysis results of the linear, logarithmic, exponential, and power functions between the coupling effects of time and water-to-cement ratio and the plastic viscosity of Bingham cement grouts are shown in Table 5.

In Table 5, R^2 and R^2 (adj) are unadjusted and adjusted coefficients of determination, respectively, and other symbols are same as above. The judgement coefficients are used to judge the goodness of fitting of the fitting model. The larger the coefficient is, the better the goodness of fitting of the fitting model is. F and P corresponding to the regression column are used to test the significance of the fitting model, whereas F and P corresponding to the time and water-to-cement ratio columns are used to test the significance of the regression coefficients of the fitting model. If $F > F\alpha$ (the critical value obtained by looking up the table) and $P < \alpha\,(\alpha = 0.05)$), the fitting model is statistically significant at $\alpha = 0.05$, and otherwise, it is not significant. Only when the fitting model and its regression coefficients pass the significance test, the fitting model can be accepted at $\alpha = 0.05$ from a statistical theoretical point of view, none is indispensable [38].

According to the above statistical test criteria, Table 5 can be analyzed as follows:(1) By comparing the determination coefficients of the four fitting models, R^2 and R^2 (adj) of the exponential model are the largest, which exceed 99%,

Table 3: Rheologic equations of five water-to-cement ratio Bingham cement grouts at six moments.

Time/min	Water-to-cement ratio 0.8	0.9	1.0	1.1	1.25
0	$\tau = 2.2078 + 0.0201\gamma$	$\tau = 1.7876 + 0.0194\gamma$	$\tau = 0.8593 + 0.0169\gamma$	$\tau = 0.3266 + 0.0164\gamma$	$\tau = 0.1136 + 0.0159\gamma$
5	$\tau = 2.1834 + 0.0226\gamma$	$\tau = 1.7985 + 0.0219\gamma$	$\tau = 0.8591 + 0.0192\gamma$	$\tau = 0.3312 + 0.0188\gamma$	$\tau = 0.1113 + 0.0183\gamma$
10	$\tau = 2.2316 + 0.0255\gamma$	$\tau = 1.7553 + 0.0248\gamma$	$\tau = 0.8579 + 0.0219\gamma$	$\tau = 0.3215 + 0.0215\gamma$	$\tau = 0.1125 + 0.0211\gamma$
20	$\tau = 2.1606 + 0.0322\gamma$	$\tau = 1.7730 + 0.0317\gamma$	$\tau = 0.8584 + 0.0283\gamma$	$\tau = 0.3235 + 0.0281\gamma$	$\tau = 0.1132 + 0.0281\gamma$
30	$\tau = 2.2495 + 0.0408\gamma$	$\tau = 1.8046 + 0.0405\gamma$	$\tau = 0.8590 + 0.0365\gamma$	$\tau = 0.3297 + 0.0369\gamma$	$\tau = 0.1158 + 0.0374\gamma$
60	$\tau = 2.2367 + 0.0828\gamma$	$\tau = 1.8195 + 0.0844\gamma$	$\tau = 0.8596 + 0.0790\gamma$	$\tau = 0.3317 + 0.0829\gamma$	$\tau = 0.1146 + 0.0879\gamma$

Table 4: Two factors variance analysis of time and water-to-cement ratio on plastic viscosity, yield stress of Bingham cement grouts.

Rheological parameter	Sources of error	*DF*	*SS*	*MS*	*F*	*P*
Plastic viscosity n_p	Time t	5	2.00×10^{-2}	0.00	1210.71	≤0.001
	Water-to-cement ratio ω	4	0.00	0.00	7.08	≤0.001
	Error	20	0.00	0.00		
	Sum	29	2.00×10^{-2}			
Yield stress τ_0	Time t	5	3.00×10^{-3}	0	1.75	0.17
	Water-to-cement ratio ω	4	19.99	5.00	16626.75	≤0.001
	Error	20	6.00×10^{-3}	0		
	Sum	29	20.00			

Table 5: Four change relationship models and corresponding analysis results between coupling effects of time and water-to-cement ratio and plastic viscosity of Bingham cement grouts.

Models	Fitting model expressions	Source	*DF*	*SS*	*MS*	*F*	*P*	R^2 (%)	R^2 (adj)
Linear model	$n_p = 0.020 + 0.001t - 0.007\omega$	Regression	2	0.02	0.01	268.16	≤0.001	95.21	94.85
		Time t	1	0.02	0.02	535.05	≤0.001		
		Water-to-cement ratio ω	1	0.00	0.00	1.28	0.27		
		Residual error	27	0.00	0.00				
		Sum	29	0.02					
Logarithmic model	$n_p = \ln(0.970t^{0.023}\omega^{-0.007})$	Regression	2	0.01	0.01	31.05	≤0.001	73.84	71.47
		Time t	1	0.01	0.01	61.94	≤0.001		
		Water-to-cement ratio ω	1	0.00	0.00	0.17	0.69		
		Residual error	27	0.02	0.00				
		Sum	29	0.02					
Exponential model	$n_p = 0.025e^{0.026t-0.334\omega}$	Regression	2	8.18	4.09	1673.32	≤0.001	99.20	99.14
		Time t	1	8.10	8.10	3313.24	≤0.001		
		Water-to-cement ratio ω	1	0.08	0.08	33.39	≤0.001		
		Residual error	27	0.01	0.00				
		Sum	29	8.24					
Power function model	$n_p = 0.007t^{0.548}\omega^{-0.299}$	Regression	2	5.63	2.81	74.69	≤0.001	87.16	86.00
		Time t	1	5.58	5.58	147.95	≤0.001		
		Water-to-cement ratio ω	1	0.05	0.05	1.42	0.25		
		Residual error	27	0.83	0.04				
		Sum	29	6.46					

indicating that the exponential model is the best fitting model among the four models; (2) the F values corresponding to the regression and time columns for four fitting models are greater than the critical value $F_{0.05}$ obtained by looking up table ($F > F_{0.05}\ (2,\ 27) = 6.49$ for the regression column and $F > F_{0.05}\ (1, 27) = 9.34$ for the time column), and their P values are all less than $\alpha = 0.05$. As for the water-to-cement ratio column, the F and P values corresponding to exponential model conform to the statistical test criteria ($F = 33.39 > F_{0.05}\ (1, 27) = 9.34$; $P < 0.05$), the F and P values corresponding to the other three models does not conform to the statistical detection criteria ($F < F_{0.05}\ (1,\ 27) = 9.34$; $P > 0.05$). This indicates that among the four fitting models, only the exponential model passes the significant test of the fitting model and its regression coefficients, which is acceptable from a statistical theory point of view at $\alpha = 0.05$.

From the perspective of statistical theory, it can be seen that the exponential model is the optimal model among the four models for the quantitative change relationship of the coupling effects of reaction time and water-to-cement ratio on the plastic viscosity of Bingham cement grouts.

3.3.2. Validation of the Quantitative Change Relationship Models. The selection of fitting model should not only consider statistical theory but also test its applicability and

Table 6: Verification results of four quantitative relationship models between coupling effects of time and water-to-cement ratio and plastic viscosity of Bingham cement grouts.

Test number	Time/min	Theoretical value of fitting model				Test value	Variance analysis/(%)							
		Linear	Logarithm	Exponent	Power function		Linear		Logarithm		Exponent		Power function	
							Variance	Change range	Variance	Change range	Variance	Change range	Variance	Change range
G1	0	0.0141	—	0.0188	0.0000	0.0174	−23.40	39.52	—	39.84	7.45	4.12	—	66.83
	3	0.0171	—	0.0203	0.0134	0.0192	−12.28		—		5.42		−43.28	
	15	0.0291	0.0330	0.0278	0.0324	0.0254	12.71		23.03		8.63		21.60	
	25	0.0391	0.0447	0.0361	0.0429	0.0328	16.11		26.62		9.14		23.54	
	40	0.0541	0.0555	0.0532	0.0555	0.0493	8.87		11.17		7.33		11.17	
	55	0.0691	0.0628	0.0786	0.0661	0.0711	2.89		−13.22		9.54		−7.56	
G2	0	0.0118	—	0.0169	0.0000	0.0155	−31.36	48.26	—	71.51	8.28	4.25	—	38.66
	7	0.0188	0.0132	0.0203	0.0194	0.0189	−0.53		−43.18		6.90		2.58	
	16	0.0278	0.0322	0.0256	0.0305	0.0231	16.91		28.26		9.77		24.26	
	23	0.0348	0.0406	0.0308	0.0372	0.0291	16.38		28.33		5.52		21.77	
	45	0.0568	0.0560	0.0545	0.0538	0.0497	12.50		11.25		8.81		7.60	
	58	0.0698	0.0618	0.0764	0.0618	0.0707	−1.29		−14.40		7.46		−14.40	

Table 7: Four quantitative relationship models and corresponding analysis results between water-to-cement ratio and yield stress of Bingham cement grouts.

Models	Fit model expressions	Source	*DF*	*SS*	*MS*	*F*	*P*	R^2 (%)	R^2 (adj)
Linear model	$\tau_0 = 6.137 - 5.026\omega$	Regression	1	18.49	18.49	343.55	≤0.001	92.46	92.19
		Residual error	28	1.51	0.05				
		Sum	29	19.99					
Logarithmic model	$\tau_0 = \ln(2.857\omega^{-5.135})$	Regression	1	18.94	18.94	502.53	≤0.001	94.72	94.53
		Residual error	28	1.06	0.037				
		Sum	29	20.0					
Exponential model	$\tau_0 = 764.33e^{-6.983\omega}$	Regression	1	35.69	35.69	983.47	≤0.001	97.23	97.13
		Residual error	28	1.016	0.04				
		Sum	29	36.79					
Power function model	$\tau_0 = 0.652\omega^{-6.969}$	Regression	1	34.90	34.90	539.59	≤0.001	95.07	94.89
		Residual error	28	1.81	0.07				
		Sum	29	36.71					

accuracy in practice. To this end, two groups of experiments (numbered G1 and G2) were designed to validate the quantitative relationship models constructed in Table 5 for a cement grout with a water-to-cement ratio of 0.85 at 0, 3, 15, 25, 40, and 55 minutes and a cement grout with a water-to-cement ratio of 1.17 at 0, 7, 16, 23, 45, and 58 minutes. The materials, experimental equipment, and experimental conditions used in the two groups of experiments were consistent with Section 2.

The model validation results of the four quantitative change relationships between the coupling effects of time and water-to-cement ratio and the plastic viscosity of Bingham cement grouts are shown in Table 6.

From the analysis of Table 6, it can be seen that the differences between the theoretical and experimental values obtained from the exponential model are within 10%, and the change between the differences is small, with a maximum change range of 4.25%. Although the differences of more than 80% between the theoretical and experimental values obtained from the three models based on linear, logarithmic, and power functions are greater than 10%, the change between the differences is more than 35%, even up to 71.51%. Therefore, from the perspective of practical applicability and accuracy, the exponential model is also the best model in the four models for the quantitative change relationship of the coupling effects of reaction time and water-to-cement ratio on the plastic viscosity of Bingham cement grouts.

In summary, the exponential model is the optimal model for quantitative change relationship of the coupling effects of reaction time and water-to-cement ratio on the plastic viscosity of Bingham cement grouts, that is,

$$n_p = 0.025e^{(0.026t - 0.334\omega)}. \quad (2)$$

3.4. Quantitative Change Relationship of the Coupling Effects of Time and Water-to-Cement Ratio on the Yield Stress of Bingham Cement Grouts

3.4.1. Constructing Quantitative Change Relationship Models. It can be seen that the water-to-cement ratio has a significant effect on the yield stress of Bingham cement grouts, although time does not have a significant effect on it. Therefore, only the influence of the water-to-cement ratio is considered when analyzing the quantitative change relationship for the coupling effects of time and water-to-cement ratio on the yield stress of Bingham cement grouts.

Similarly, four quantitative change models of linear, logarithmic, exponential, and power functions between the water-to-cement ratio and the yield stress of Bingham cement grouts can be obtained, and the results are shown in Table 7.

In the same way, it can be analyzed that from the perspective of statistical theory, the exponential model is also the optimal model among the four models to reflect to the quantitative change relationship of the water-to-cement ratio on the yield stress of Bingham cement grouts.

3.4.2. Validation of the Quantitative Change Relationship Models. The applicability and accuracy of the four models shown in Table 7 in practice were verified by experiments numbered G1 and G2, and the validation results are shown in Table 8.

By comparing the differences between the theoretical and experimental values obtained from the four models in Table 8, it can be found that the differences between the theoretical and experimental values calculated by the exponential model are the smallest and all within 10%, which indicates that the theoretical values obtained by the exponential model are closer to the experimental values. Therefore, from the point of view of practical applicability and accuracy, the exponential model can better reflect the quantitative change relationship of the water-to-cement ratio on the yield stress of Bingham cement grouts.

Combining the above two results, the optimal model of the quantitative change relationship of water-to-cement ratio on the yield stress of Bingham cement grouts is also the exponential model, that is,

$$\tau_0 = 764.33e^{(-6.983\omega)}. \quad (3)$$

3.5. Rheological Equation of Bingham Cement Grouts with Coupling Effects of Time and Water-to-Cement Ratio.

The rheological equation of Bingham cement grouts with

Table 8: Verification results of four quantitative relationship models between water-to-cement ratio and yield stress of Bingham cement grouts.

Test number	Time/min	Calculated value of fitting model				Test value	Variance analysis/%							
							Linear		Logarithm		Exponent		Power function	
		Linear	Logarithm	Exponent	Power function		Variance	Change range	Variance	Change range	Variance	Change range	Variance	Change range
G1	0	1.8649	1.8843	2.0207	2.0336	1.9507	−4.60	2.12	−3.52	2.10	3.46	1.95	3.60	1.95
	3					1.9801	−6.18		−5.08		2.01		2.15	
	15					1.9633	−5.28		−4.19		2.84		2.98	
	25					1.9902	−6.72		−5.62		1.51		1.65	
	40					1.9549	−4.83		−3.75		3.26		3.40	
	55					1.9604	−5.12		−4.04		2.98		3.12	
G2	0	0.2566	0.2436	0.2163	0.2183	0.2041	20.46	3.51	16.22	3.69	5.64	4.16	6.50	4.12
	7					0.1979	22.88		18.76		8.51		9.34	
	16					0.1951	23.97		19.91		9.80		10.63	
	23					0.2028	20.97		16.75		6.24		7.10	
	45					0.2007	21.78		17.61		7.21		8.06	
	58					0.1977	22.95		18.84		8.60		9.44	

coupling effects of time and water-to-cement ratio can be obtained by combining (1)-(3):

$$\tau = 764.33e^{-6.983\omega} + 0.025e^{0.026t-0.334\omega}\gamma. \quad (4)$$

4. Conclusion

Taking Bingham cement grouts (cement grouts with a water-to-cement ratio of 0.75–1.25), which are widely used in practical engineering, as the object of study, the coupling effects of time and water-to-cement ratio on the rheological properties of Bingham cement grouts at room temperature ($25 \pm 2^{\circ}$C) were investigated by combining experimental research, theoretical discussion, and numerical analysis, and the following conclusions are obtained:

(1) At the level of $\alpha = 0.05$, time has a significant influence on plastic viscosity but has no significant influence on the yield stress of Bingham cement grouts. Water-to-cement ratio has a significant influence on both plastic viscosity and yield stress.

(2) Exponential models obtained by comprehensive analysis from statistical theory, practical applicability, and accuracy are the optimal models to describe quantitative change in the relationships of coupling effects of time and water-to-cement ratio on plastic viscosity and yield stress of Bingham cement grouts. That is,

$$\begin{aligned} n_p &= 0.025e^{0.026t-0.334\omega}, \\ \tau_0 &= 764.33e^{-6.983\omega}. \end{aligned} \quad (5)$$

(3) The rheological equation for Bingham cement grouts with coupling effects of time and water-to-cement ratio was constructed:

$$\tau = 764.33e^{-6.983\omega} + 0.025e^{0.026t-0.334\omega}\gamma. \quad (6)$$

The research results of this study will not only further improve the rheological theory of Bingham cement grouts but also provide technical support for practical engineering.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant no. 41861134008), Muhammad Asif Khan academician workstation of Yunnan Province (Grant no. 202105AF150076), Key R&D Program of Yunnan Province (Grant no. 202003AC100002), and General Program of basic research plan of Yunnan Province (Grant no. 202001AT070043).

References

[1] O. Turan, N. Chakraborty, and R. J. Poole, "Laminar Rayleigh-Bénard convection of yield stress fluids in a square enclosure," *Journal of Non-newtonian Fluid Mechanics*, vol. 171-172, pp. 83–96, 2012.

[2] M. Axelsson and G. Gustafson, "A robust method to determine the shear strength of cement-based injection grouts in the field," *Tunnelling and Underground Space Technology*, vol. 21, no. 5, pp. 499–503, 2006.

[3] M. Axelsson, G. Gustafson, and Å. Fransson, "Stop mechanism for cementitious grouts at different water-to-cement ratios," *Tunnelling and Underground Space Technology*, vol. 24, no. 4, pp. 390–397, 2009.

[4] W. J. Ruan, "Research on diffusion of grouting and basic properties of grouts," *Chinese Journal of Geotechnical Engineering*, vol. 27, no. 1, pp. 69–73, 2005, in Chinese.

[5] N. Roussel, "Steady and transient flow behaviour of fresh cement pastes," *Cement and Concrete Research*, vol. 35, no. 9, pp. 189–199, 2004.

[6] Z. Q. Yang, S. G. Qian, and K. P. Hou, "Time-dependent behavior characteristics of power-law cement grouts applied in geotechnical engineering," *Electronic Journal of Geotechnical Engineering*, vol. 20, no. 22, pp. 1017–1023, 2015.

[7] F. Rosquoët, A. Alexis, A. Khelidj, and A. Phelipot, "Experimental study of cement grout," *Cement and Concrete Research*, vol. 33, no. 5, pp. 713–722, 2003.

[8] N. Roussel, R. Roy, and P. Coussot, "Thixotropy modelling at local and macroscopic scales," *Journal of Non-newtonian Fluid Mechanics*, vol. 117, no. 2, pp. 85–95, 2004.

[9] D. U. Ye, X. J. Pei, R. Q. Huang, and Z. He, "Study on flow characteristics and application of viscosity time-varying grouting material," *Yantu Lixue/Rock and Soil Mechanics*, vol. 38, no. 12, pp. 3498–3504, 2017.

[10] M. Şahmaran, N. Özkann, S. B. Keskin, B. Uzal, I. Yaman, and T. Erdem, "Evaluation of natural zeolite as a viscosity-modifying agent for cement-based grouts," *Cement and Concrete Research*, vol. 38, no. 7, pp. 930–937, 2008.

[11] C. K. Park, M. H. Noh, and T. H. Park, "Rheological properties of cementitious materials containing mineral admixtures," *Cement and Concrete Research*, vol. 35, no. 5, pp. 842–849, 2005.

[12] Z. Toutou and N. Roussel, "Multi scale experimental study of concrete rheology: from water scale to gravel scale," *Materials and Structures*, vol. 39, no. 2, pp. 189–199, 2006.

[13] F. Mahaut, S. Mokéddem, X. Chateau, N. Roussel, and G. Ovarlez, "Effect of coarse particle volume fraction on the yield stress and thixotropy of cementitious materials," *Cement and Concrete Research*, vol. 38, no. 11, pp. 1276–1285, 2008.

[14] N. Viet-hung, R. Sébastien, and G. Jean-louis, "Influence of cement grouts composition on the rheological behaviour," *Cement and Concrete Research*, vol. 42, no. 3, pp. 292–300, 2011.

[15] D. P. Bentz, C. F. Ferraris, M. A. Galler, A. S. Hansen, and J. M. Guynn, "Influence of particle size distributions on yield stress and viscosity of cement-fly ash pastes," *Cement and Concrete Research*, vol. 42, no. 2, pp. 404–409, 2012.

[16] V. Manisha, K. B. Anand, and S. Dhanya, "Effects of fillers on the properties of cement grouts," *Construction and Building Materials*, vol. 246, pp. 1–9, 2020.

[17] W. S. Li, S. Faiz, and L. G. Wang, "Experimental study on shear property and rheological characteristic of superfine cement grouts with nano-SiO2 addition," *Construction and Building Materials*, vol. 228, pp. 1–11, 2019.

[18] A. Costas, “Effect of different superplasticisers on the physical and mechanical properties of cement grouts,” *Construction and Building Materials*, vol. 50, no. 15, pp. 162–168, 2014.

[19] J. Mirza, M. S. Mirza, V. Roy, and K. Saleh, “Basic rheological and mechanical properties of high-volume fly ash grouts,” *Construction and Building Materials*, vol. 16, no. 6, pp. 353–363, 2002.

[20] Z. Q. Yang, X. D. Niu, and K. P. Hou, “Relationships between water-cement ratio and rheological characteristics of power-law cement grouts,” *Electronic Journal of Geotechnical Engineering*, vol. 20, no. 13, pp. 5825–5831, 2015.

[21] J. Mirza, K. Saleh, M.-A. Langevin, S. Mirza, M. A. R. Bhutta, and M. M. Tahir, “Properties of microfine cement grouts at 4°C, 10°C and 20°C,” *Construction and Building Materials*, vol. 47, pp. 1145–1153, 2013.

[22] Z. Q. Yang, K. P. Hou, and T. T. Guo, “Study on the effects of different water-cement ratios on the flow pattern properties of cement grouts,” *Applied Mechanics and Materials*, vol. 71–78, pp. 1264–1267, 2011.

[23] E. Avci and M. Mollamahmutoglu, “UCS properties of superfine cement-grouted sand,” *Journal of Materials in Civil Engineering*, vol. 28, no. 12, pp. 25–31, 2016.

[24] Z. Q. Yang, K. P. Hou, and T. T. Gou, “Study on the effects of different water-cement ratios on the flow pattern properties of cement grouts,” in *Proceedings of the 2011 Conference on Materials and Civil Engineering//D. Sun, W. P. Sung, R . Chen*, Frontiers of Green Building, Hong Kong, Cina, March 2011.

[25] X. M. Guan, Y. L. Wang, and L. Yang, “Research on rheological properties of micro-fine grouting cement,” *Journal of Coal Science and Engineering*, vol. 71-78, no. 1, pp. 67–72, 2003.

[26] Q. Liu, G. Lei, X. Peng, C. Lu, and L. Wei, “Rheological characteristics of cement grout and its effect on mechanical properties of a rock fracture,” *Rock Mechanics and Rock Engineering*, vol. 51, no. 2, pp. 613–625, 2018.

[27] D. Kim, G. Kim, and H. Baek, “Thermal conductivities under unsaturated condition and mechanical properties of cement-based grout for vertical ground-heat exchangers in Korea-A case study,” *Energy and Buildings*, vol. 122, pp. 34–41, 2016.

[28] B. Bohloli, O. Skjolsvold, H. Justnes, R. Olsson, E. Grøv, and A. Aarset, “Cements for tunnel grouting - rheology and flow properties tested at different temperatures,” *Tunnelling and Underground Space Technology*, vol. 91, pp. 103011.1–103011.10, 2019.

[29] J.-Y. Petit, E. Wirquin, and K. H. Khayat, “Effect of temperature on the rheology of flowable mortars,” *Cement and Concrete Composites*, vol. 32, no. 1, pp. 43–53, 2009.

[30] A. K. Schindler, J. M. Ruiz, R. O. Rasmussen, G. K. Chang, and L. G. Wathne, “Concrete pavement temperature prediction and case studies with the FHWA HIPERPAV models,” *Cement and Concrete Composites*, vol. 26, no. 5, pp. 463–471, 2004.

[31] G. De Schutter, “Hydration and temperature development of concrete made with blast-furnace slag cement,” *Cement and Concrete Research*, vol. 29, no. 1, pp. 143–149, 1999.

[32] Z. Q. Yang, K. P. Hou, T. T. Gou, and M. Qiu, “Study of column-hemispherical penetration grouting mechanism based on bingham fluid of time-dependent behavior of viscosity,” *Rock And Soil Mechanics*, vol. 32, no. 9, pp. 2 698–702 703, 2011, in Chinese.

[33] J. Zheng, Y. Wen, and J. Wang, *Geotechnical Engineering Grouting Theory and Engineering Examples*, China Science press, Beijing, China, 2001, in Chinese.

[34] L. Wu, Z. M. Zhao, S. C. Quan, Y. Zhang, and D. Li, “Effect of different external admixtures on properties of metakaolin-based cementitious materials,” *Non-Metallic Mines*, vol. 42, no. 4, pp. 100–103, 2019, in Chinese.

[35] Z. Q. Yang, Y. Ding, and Y. Yang, “Hydration-time-dependent rheological behaviors of Newtonian cement grouts with different water cement ratios,” *Transactions of the Chinese Society of Agricultural Engineering*, vol. 36, no. 19, pp. 161–167, 2020, in Chinese.

[36] C. T. Shen and H. N. Liu, *Non-Newtonian Fluid Mechanics and its Application*, Higher Education Press, Beijing, China, 1989, in Chinese.

[37] X. Y. Kong, *Higher Percolation Mechanics*, Press of University of Science and Technology of China, Beijing, China, 1999, in Chinese.

[38] Z. Chen, S. Q. Xie, and C. Y. Pan, *Probability Theory and Mathematical Statistics*, Higher percolation mechanics, Beijing, China, 2008, in Chinese.