Research Article

Comprehensive Effect of the Time and Water-Cement Ratio on the Rheological Properties of Power-Law Cement Grouts

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The rheological properties of cement grouts are significantly affected by the changes of the time and the water-cement ratio, which determine the diffusion state of grouts in rocks and soils and influence the outcome of projects. In this study, Portland cement grouts with water-cement ratios of 0.50, 0.55, 0.60, 0.65, 0.70, and 0.75 at six moments, including 0 minutes, 5 minutes, 10 minutes, 20 minutes, 30 minutes, and 60 minutes, were evaluated to figure out the comprehensive effect of the time and the water-cement ratio on the rheological properties of power-law cement grouts. The results showed that the water-cement ratio had a great influence on both the consistency coefficient and the rheological index of the power-law cement grouts. The former appeared to have a downward trend with the increase of the water-cement ratio, and the latter appeared to have an upward trend. There was a rising tendency between the time and the consistency coefficient, while the rheological index was less affected by time. The difference between its maximum and minimum values was within 5%. Combined with the perspectives of statistical theory, practical applicability, and accuracy, the exponential model was the optimal model for showing the relationship between the comprehensive effects of the time, water-cement ratio, and consistency coefficient of the power-law cement grouts. The linear model was the optimal model of the rheological index based on the comprehensive effect of time and the water-cement ratio. Based on this, a power-law rheological equation with consideration of the comprehensive effect of time and water-cement ratio was established. The research results could not only improve the rheological theory of power-law cement grouts but also provide technical support for engineering practice.

1. Introduction

In the near surface and mountainous area, the strong activity of geofluid may induce the occurrence of geological disasters

such as landslide, debris flow, and collapse, which will lead to heavy casualties, environmental damage, and huge property losses. Cement grout, as an inorganic cementitious material with low cost and good performance, has been widely used

TABLE 1: Basic properties of ordinary Portland cement No. 32.5 [1].

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

FIGURE 1: NXS-11A rotational viscometer.

in the field of engineering to prevent and control the above geological disasters and has achieved good engineering results [1–3].

According to a large number of engineering practice shows that the rheological properties of cement grout have a very important influence on its application effect in practical engineering. The rheological properties of cement grouts are affected by their composition, water-cement ratios, temperatures, and time. In terms of considering the time effect, Ruan [4] established the viscosity change equation of different cement grout with time effect; Yang et al. [5] discussed the application of time effect on power-law fluids in engineering; Rahman et al. [6] effectively measured the change of grout viscosity with time in engineering by using ultrasonic velocity pressure surface method; Roussel [7, 8] proposed the rheological property model of slurry under transient state. In terms of considering the composition of the grout, Chen et al. [9] analyzed the change of rheological properties of cement paste with CSF powder; Mirza et al., Robert et al., Aboulayt et al., and Zhang et al. [10–13] studied the rheological properties of fly ash grouts in different proportions; Mahaut et al. and Toutou and Roussel [14, 15] considered the influence of the volume fraction of gravel scale on rheological properties. Nguyen et al., Mohammed et al., and Senff et al. [16–18] introduced the rheological properties of some polymer-modified cement grouts; Zou et al. [19] studied the influence of rheological properties of power-law fluids

FIGURE 2: Rheological curve of six cement grouts with different water-cement ratios at the mixture completion time ($t = 0$) of the cement grouts.

on fluid motion propagation; Vasumithran et al. [20] introduced the changes of common slurry fillers on the rheological properties of grouts; Li et al. [21] discussed the rheological properties of ultrafine cement; Costas [22] considered the influence of different water reducers on the rheological

FIGURE 3: Rheological curve of the cement grouts at six different times ((a) $\omega = 0.5$, (b) $\omega = 0.65$, (c) $\omega = 0.75$).

TABLE 2: Rheological equations of six water-cement ratio power-law cement grouts at six different times.

ω t	0.50	0.55	0.60	0.65	0.70	0.75
0	$\tau = 2.9356\gamma^{0.4644}$	$\tau = 2.3525\gamma^{0.4061}$	$\tau = 1.4824\gamma^{0.4660}$	$\tau = 0.6931\gamma^{0.5432}$	$\tau = 0.3408\gamma^{0.6155}$	$\tau = 0.2503\gamma^{0.6474}$
5	$\tau = 3.2541\gamma^{0.4665}$	$\tau = 2.6103\gamma^{0.4233}$	$\tau = 1.6473\gamma^{0.4661}$	$\tau = 0.7718\gamma^{0.5470}$	$\tau = 0.3806\gamma^{0.6205}$	$\tau = 0.2804\gamma^{0.6496}$
10	$\tau = 3.6071\gamma^{0.4793}$	$\tau = 2.8964\gamma^{0.4241}$	$\tau = 1.8306\gamma^{0.4662}$	$\tau = 0.8593\gamma^{0.5458}$	$\tau = 0.4251\gamma^{0.6223}$	$\tau = 0.3141\gamma^{0.6384}$
20	$\tau = 4.4323\gamma^{0.4738}$	$\tau = 3.5661\gamma^{0.4160}$	$\tau = 2.2607\gamma^{0.4664}$	$\tau = 1.0655\gamma^{0.5364}$	$\tau = 0.5302\gamma^{0.6254}$	$\tau = 0.3942\gamma^{0.6339}$
30	$\tau = 5.4462\gamma^{0.4745}$	$\tau = 4.3907\gamma^{0.4234}$	$\tau = 2.7917\gamma^{0.4667}$	$\tau = 1.3210\gamma^{0.5398}$	$\tau = 0.6614\gamma^{0.6216}$	$\tau = 0.4946\gamma^{0.6471}$
60	$\tau = 10.1038\gamma^{0.4675}$	$\tau = 8.1946\gamma^{0.4253}$	$\tau = 5.2575\gamma^{0.4672}$	$\tau = 2.5179\gamma^{0.5472}$	$\tau = 1.2834\gamma^{0.6291}$	$\tau = 0.9772\gamma^{0.6236}$

properties of cement. In terms of considering the water-cement ratio effect, Yang et al. [23, 24] studied the influence of water-cement ratio on cement grout flow pattern; Cao et al., Mirza et al., and Avci and Mollamahmutoglu [25–27] discussed the change of rheological properties with different water-cement ratios. As for the temperature factor, Liu et al., Bohloli et al., Petit et al., and Schutter [28–31] studied the effects of different hydration temperatures on rheological

properties of cement grouts; Schindler et al. [32] established a prediction model of concrete grout variation with different temperatures.

To summarize, the current research has only considered the influence of a single factor (composition, water-cement ratio, temperature, time, etc.) on the rheological properties of cement grouts, while the comprehensive effects of these factors (such as the comprehensive effect of time and

FIGURE 4: Effect of time on the consistency coefficient of the power-law cement grouts.

FIGURE 6: Effect of the water-cement ratio on the consistency coefficient of the power-law cement grouts.

FIGURE 5: Effect of time on the rheological index of the power-law cement grouts.

FIGURE 7: Effect of the water-cement ratio on the rheological index of the power-law cement grouts.

water-cement ratio) have not been well understood. As a result, the current research results are difficult to meet the needs of engineering practice. For example, the value of cement grout rheological parameters cannot be reasonably and scientifically determined in engineering practice. Therefore, in view of the shortage of the current rheological research of cement grout and the technical requirements of engineering practice, in this research, the widely used power-law cement grouts (cement grouts with water-cement ratios of less than 0.75 are typical power-law fluids) were taken as the research object. A research method combined with experimental research, numerical analysis, and theoretical discussion was used to analyze the influences of time and the water-cement ratio on the rheological properties of power-law cement grouts, which were characterized by consistency coefficient and the rheological index. This method was also used to explore the quantitative variation

relationship model between the time and the water-cement ratio comprehensive effect. Based on this, a power-law rheological equation for cement grouts with consideration of the comprehensive effect of time and the water-cement ratio was established. The research results could not only further improve the rheological theory of power-law cement grouts but also provide a basis for determining the rheological parameters of power-law cement grout (cement grout with water-cement ratio less than 0.75) which is widely used in the engineering field.

2. Experimental Materials and Methods

2.1. Experimental Materials. The test material was #32.5 ordinary Portland cement produced by the Kunming Cement Company. This material is widely used in current engineering practice. Its basic physical properties are shown in Table 1.

TABLE 3: Two-factor variance analysis of the comprehensive effect of time and the water-cement ratio on the rheological properties of the power-law cement grouts.

The rheological parameters	Error sources	DF	SS	MS	F	P
Consistency coefficient c	Time t	5	47.82	9.56	9.54	0.01
	W/C ω	5	105.25	21.05	21.00	0.01
	Error	25	25.06	1.00		
	Sum	35	178.12			
Rheological index n	Time t	5	0.00	0.00	0.77	0.56
	W/C ω	5	0.24	0.05	1219.42	0.01
	Error	25	0.00	0.00		
	Sum	35	0.24			

TABLE 4: Four models and the analysis result of the time and water-cement ratio comprehensive effect on the consistency coefficient of the power-law cement grouts.

Model	Fitting equation	Source	DF	SS	MS	F	P	$R^2/\%$	$R^2(\text{adj})/\%$
Linear model	$c = 13.290 + 0.057t - 19.480\omega$	Regression	2	146.03	73.01	75.07	0.00	81.98%	80.89%
		t	1	46.40	46.40	47.71	0.00		
		ω	1	99.62	99.62	102.42	0.00		
		Error	33	32.10	0.97				
		Sum	35	178.12					
Logarithm model	$c = \ln(0.001t^{1.194}\omega^{-13.120})$	Regression	2	130.59	65.29	50.65	0.00	78.95%	77.40%
		t	1	31.69	31.69	24.58	0.00		
		ω	1	98.90	98.90	76.72	0.00		
		Error	33	34.81	1.29				
		Sum	35	165.39					
Exponential model	$c = 695.061e^{0.021t-10.604\omega}$	Regression	2	36.21	18.11	764.37	0.00	97.89%	97.76%
		t	1	6.69	6.69	282.58	0.00		
		ω	1	29.52	29.52	1246.17	0.00		
		Error	33	146.03	0.02				
		Sum	35	46.40					
Power function model	$c = 0.019t^{0.455}\omega^{-6.481}$	Regression	2	28.74	14.37	242.59	0.00	94.34%	93.42%
		t	1	4.61	4.61	77.79	0.00		
		ω	1	24.13	24.13	407.39	0.00		
		Error	33	1.60	0.06				
		Sum	35	30.34					

The experimental water was drinking water.

2.2. Experimental Equipment. The NXS-11A rotational viscometer manufactured by Chengdu Instrument Factory was used in the test (Figure 1(a)). The rotational viscometer was driven by a stepper motor to rotate the inner cylinder, and the outer cylinder was fixed. The inner cylinder speed was controlled by a motor. The stepper motor produced the shear speeds at different shear velocities, and the corresponding shear stresses of the cement grouts were studied (Figure 1(b)) [33]. Finally, the rheological curve of the

cement grouts was obtained in the coordination of the shear velocity and the shear stress [34].

2.3. Experiment Methods. According to Yang et al.'s [24] research results, cement grouts belong to the power-law fluid category when their water-cement ratios are less than 0.75. Therefore, in these tests, cement grouts at different water-cement ratios (W/C) of 0.5, 0.55, 0.6, 0.65, 0.7, and 0.75 were used to study the rheological properties of power-law cement grouts at different time periods (mixture completion times of the cement grouts) of 0 minutes, 5 minutes, 10 minutes, 20

TABLE 5: Four models and the analysis result of the water-cement ratio effect on the rheological index of the power-law cement grouts.

Model	Fitting equation	Source	DF	SS	MS	F	P	R ²	R ² (adj)
Linear model	$n = -0.0193 + 0.874\omega$	Regression	1	0.20	0.20	157.77	0.00	82.27%	81.75%
		Error	34	0.04	0.00				
		Sum	35	0.24					
Logarithm model	$n = \ln(2.183\omega^{0.529})$	Regression	1	0.19	0.19	128.08	0.00	79.02%	78.41%
		Error	34	0.05	0.00				
		Sum	35	0.24					
Exponential model	$n = 0.187e^{1.639\omega}$	Regression	1	0.70	0.70	142.20	0.00	80.70%	80.14%
		Error	34	0.17	0.00				
		Sum	35	0.87					
Power function model	$n = 0.838\omega^{0.992}$	Regression	1	0.68	0.68	118.07	0.00	77.64%	76.98%
		Error	34	0.20	0.01				
		Sum	35	0.87					

minutes, 30 minutes, and 60 minutes. The indoor environment temperature of the rheological test and the water temperature of the cement grouts were kept within the range of $25^\circ\text{C} \pm 2^\circ\text{C}$.

Preparation method of cement grouts: first, 300 g pure drinking water was weighed with an electronic balance and poured into the measuring cylinder. Then, 200 g #32.5 ordinary Portland cement was weighed and put into a beaker. Finally, the water in the measuring cylinder was completely poured into the beaker and stirred to prepare the cement grout with a water-cement ratio of 1.5. According to this method, 150, 60, 30 g #32.5 ordinary Portland cement was weighed by electronic balance, and 300 g pure drinking water was added for mixing. In the same way, cement grout with water-cement ratios of 2.0, 5.0, and 10.0 could be prepared.

3. Results and Discussions

3.1. Rheological Curve and Rheological Equation of the Power-Law Cement Grouts. The rheological curve of the cement grouts based on the rheological test results are shown in Figures 2 and 3.

It can be seen from Figures 2 and 3 that the variation trend of the rheological curve of the six water-cement ratio cement grouts at six different times conformed to the basic characteristics of the rheological curve of a power-law fluid [35, 36]. Thus, the grouts were typical power-law fluids, which confirmed the research result of the literature references [4, 24]. Additionally, the rheological types of the cement grouts did not change with time, which also confirmed the research results in this study [4].

Based on the basic rheological equation of power-law fluid shown in Equation (1) [35, 36], and according to the rheological curve shown in Figures 2 and 3, the rheological equation of the six power-law cement grouts at six different time could be studied, as Table 2 shows:

$$\tau = c\gamma^n. \quad (1)$$

In this equation, τ is the shear stress, n is the rheological index, γ is the shear velocity, and c is the consistency coefficient. The two rheological parameters, the rheological index and the consistency coefficient, are usually used to characterize the rheological properties of power-law fluids.

According to Table 2, the power-law cement grouts could be categorized as pseudoplastic fluids.

3.2. Effect of Time on the Rheological Properties of the Power-Law Cement Grouts. According to the rheological equation in Table 2, the effect of time on the rheological properties of the power-law cement grouts could be studied, as shown in Figures 4 and 5.

As Figures 4 and 5 show, time had a great influence on the consistency coefficient of the power-law cement grouts, showing a trend of growth. The longer the time was, the more obvious the growth trend was. However, the rheological index was less affected by time, and the difference between the maximum value and the minimum value was within 5%.

3.3. Effect of the Water-Cement Ratio on the Rheological Properties of the Power-Law Cement Grouts. In the same way, the effect of the water-cement ratio on the rheological properties (consistency coefficient and rheological index) of the power-law cement grouts could be studied, as shown in Figures 6 and 7.

It can be seen from Figures 6 and 7 that the water-cement ratio had a great influence on both the consistency coefficient and the rheological index of the power-law cement grouts. The former appeared to have a downward trend, while the latter appeared to have an upward trend.

3.4. Comprehensive Effect of Time and the Water-Cement Ratio on the Rheological Properties of the Power-Law Cement Grouts. Based on the discussions in Sections 3.2 and 3.3, this section discusses the comprehensive effect of time and the water-cement ratio on the rheological properties (consistency coefficient and rheological index) of power-law grouts.

TABLE 6: The validation results of the four quantitative variation relationship models of time and the water-cement ratio comprehensive effect on the consistency coefficient of the power-law cement grouts.

Number	Time (min)	Calculate result of four fitting models					Variance analysis (%)					
		Linear model	Logarithm model	Exponential model	Power function model	Experimental result	Linear model		Logarithm model		Exponential model	
							Variance	Change range	Variance	Change range	Variance	Change range
G1	0	2.9656	—	2.5190	0.0000	2.3928	19.31	—	—	—	—	—
	3	3.1366	2.7336	2.6828	1.9178	2.4344	22.39	10.95	10.95	9.26	21.77	-26.94
	15	3.8206	4.6553	3.4517	3.9888	3.1206	18.32	44.13	32.97	52.63	4.58	49.42
	25	4.3906	5.2652	4.2583	5.0325	3.9013	11.14	25.90	25.90	8.38	22.48	—
	40	5.2456	5.8264	5.8350	6.2325	5.4043	-3.03	7.24	7.24	7.38	13.29	—
	55	6.1006	6.2066	7.9955	7.2042	7.4269	-21.74	-19.66	-19.66	7.11	-3.09	—
G2	0	0.0436	—	0.5134	0.0000	0.4876	—	—	—	5.03	—	—
	7	0.4426	0.4756	0.5947	0.5608	0.5455	-23.25	-14.70	-14.70	8.27	2.73	—
	16	0.9556	1.4626	0.7184	0.8168	0.6696	29.93	76.05	54.22	6.79	18.02	30.28
	23	1.3546	1.8959	0.8322	0.9635	0.7707	43.10	59.35	74.05	7.39	20.01	—
	45	2.6086	2.6973	1.3209	1.3076	1.2313	52.80	54.35	54.35	6.78	5.84	—
	58	3.3496	3.0003	1.7355	1.4677	1.6185	51.68	46.06	46.06	6.74	-10.27	—

FIGURE 8: Variation curves of the time, water-cement ratio, and power-law cement slurry consistency coefficient.

3.4.1. Two-Factor Variance Analysis of the Comprehensive Effect of Time and the Water-Cement Ratio on the Rheological Properties of Power-Law Cement Grouts. Origin 2018 was used to conduct a two-factor variance analysis. The comprehensive effect of time and the water-cement ratio on the rheological properties of the power-law grouts is shown in Table 3.

The DF, SS, and MS terms represent the degrees of freedom, Stdev square, and mean square. F represents the F variance test quantity, and P represents the statistical significance coefficient. F and P were both used to estimate the rationality of the effect of time or the water-cement ratio on the consistency coefficient or rheological index of the power-law cement grouts, which was usually compared with the value at $\alpha = 0.05$. If $F > F_{\alpha}$ (the value could be found in a table) and $P < \alpha = 0.05$, it showed that the time or the water-cement ratio had a significant effect on the consistency coefficient or the rheological index of the power-law cement grouts at the $\alpha = 0.05$ level [37].

Table 3 shows that (1) for the consistency coefficient, the $F(t) = 9.54 > F_{0.05}(5, 25) = 2.60$ and the $P(t) = 0.01 < 0.05$. In addition, the $F(w) = 21.00 > F_{0.05}(5, 25) = 2.60$, and the $P(w) = 0.00 < 0.05$. This showed that both the time and the water-cement ratio had a significant effect on the consistency coefficient of the power-law cement. (2) For the rheological index, the $F(w) = 1219.42 > F_{0.05}(5, 25) = 2.60$, and the $P(w) = 0.01 < 0.05$. However, the $F(t) = 0.77 < F_{0.05}(5, 25) = 2.60$, and $P(t) = 0.56 > 0.05$. This showed that the water-cement ratio had a significant effect on the rheological index of the power-law cement grouts, but time had no significant effect on the rheological index. This also confirmed the findings described in Sections 3.2 and 3.3 from a statistical perspective.

3.4.2. Comprehensive Effect of Time and the Water-Cement Ratio on the Quantitative Variation Relationship of the Consistency Coefficient of Power-Law Cement Grouts

(1) Building a Quantitative Variation Relationship Model. The description in Section 3.4.1 showed that both time and the water-cement ratio had a significant effect on the consistency

coefficient of the power-law cement grouts, and it was necessary to consider the influence of their comprehensive effect on the consistency coefficient. However, at the time of this study, there was no quantitative model reflecting the time and water-cement ratio comprehensive effect on the consistency coefficient of power-law cement grouts. Therefore, for this study, four theoretical models most basic of mathematics and most widely used in practice were selected: the linear model, exponential model, power function model, and logarithm model. The four models were combined with the numerical analysis method and Origin 2008 software to discuss the quantitative relationship of time and the water-cement ratio comprehensive effect on the consistency coefficient of the power-law cement grouts. Then, the optimal model was determined from the four models according to statistical theory and experimental verification.

The time and the water-cement ratio comprehensive effect on the consistency coefficient of the power-law cement grouts among four models (linear model, exponential model, power function model, and logarithm model) are shown in Table 4.

In Table 4, $R^2/\%$ and $R^2(\text{adj})/\%$ represent the unadjusted and adjusted determination coefficients, while the meanings of the other symbols are the same as those described above. The determination coefficients were used to estimate the fitness of the model. The larger the percentage was, the better the fitness of the model was. The corresponding F and P values in the regression column were used to analyze the significance of the fitting model. The F and P values corresponding to the water-cement ratio column and the time column were used to analyze the significance of the regression coefficient of the fitting model. If $F > F_{\alpha}$ (the value could be found in a table) and $P < \alpha = 0.05$, it showed that the F and P values were statistically significant at $\alpha = 0.05$. Otherwise, they were not significant. Only the fitting model passed both significance tests, so it could then be accepted as a rational equation [36].

Table 4 shows that (1) by comparing the determination coefficients of the four fitting models, it could be seen that the R^2 and $R^2(\text{adj})$ of the exponential model were the largest,

TABLE 7: The validation results of the four quantitative models for the water-cement ratio effect on the rheological index of the power-law cement grouts.

Number	Time (min)	Calculate result of four fitting models				Experimental result	Variance analysis (%)				Change range	
		Linear model	Logarithm model	Linear model	Logarithm model		Variance Range	Variance	Change range	Variance	Variance Range	Change range
G1	0					0.4003	9.82	10.00	10.21	10.33		
	3					0.4075	8.20	8.39	8.59	8.71		
	15	0.4439	0.4448	0.4458	0.4464	0.4007	9.73	2.59	10.12	10.24	2.67	
	25					0.3998	9.93	10.12	10.32	10.44		
	40					0.4122	7.14	7.33	7.54	7.66		
	55					0.4058	8.58	8.77	8.97	9.09		
G2	0					0.6288	9.36	9.03	10.32	10.01		
	7					0.6314	9.81	9.49	10.77	10.46		
	16	0.5750	0.5767	0.5700	0.5716	0.6286	9.32	0.49	10.28	9.97	0.49	
	23					0.6289	9.37	9.05	10.33	10.02		
	45					0.6295	9.48	9.16	10.44	10.13		
	58					0.6309	9.72	9.40	10.68	10.37		

both exceeding 95%. It was inferred that the exponential model was the best of the four models. (2) The regression column and the F values corresponding to the water-cement ratio and time of the four models were all greater than the critical value $F_{0.05}$ ($F > F_{0.05}(2, 33) = 3.29$, $F(t)$, $F(\omega) > F_{0.05}(1, 33) = 4.14$). Additionally, their $P = 0$ values were all less than $\alpha = 0.05$. This showed that all of the four fitting models passed the significance test of the fitting model and its regression coefficient, and the result could be accepted at the level of $\alpha = 0.05$.

As shown above, the exponential model was the optimal model of the comprehensive effect for the time and water-cement ratio of the consistency coefficient of the power-law cement grouts among the four models.

(2) *Experimental Verification.* The selection of the fitting model had to not only consider the statistical theory but also examine its applicability and accuracy in practice. Therefore, two groups of cement grouts were designed (NO. G1 and G2) with a water-cement ratio of 0.53 at 0 minutes, 3 minutes, 15 minutes, 25 minutes, 40 minutes, and 55 minutes, as well as a water-cement ratio of 0.68 at 0 minutes, 7 minutes, 16 minutes, 23 minutes, 45 minutes, and 58 minutes in order to verify the quantitative model built in Table 5. The materials, test equipment, and environmental conditions used in the two tests were the same as those described in Section 2.

The validation results of the four quantitative variation relationship models are shown in Table 6.

According to Table 6, the difference between the theoretical value and the experimental value of the exponential model was within 10%, and the variation is small. The maximum variation was only 4.58%. The differences between the theoretical value and the experimental value of the linear, logarithmic, and power function models were all more than 10%, and the variations of the differences were all more than 30%. Thus, from the perspectives of practical applicability and accuracy, the exponential model was the optimal model for the consistency coefficient of the power-law cement grouts between the comprehensive effect of time and the water-cement ratio among the four models.

In summary, the optimal model of the comprehensive effect of time and the water-cement ratio of the consistency coefficient for power-law cement grouts was the exponential model:

$$c = 695.061e^{0.021t-10.604\omega} \quad (2)$$

The variation curves of the time, the water-cement ratio, and the power-law cement slurry consistency coefficient is shown in Figure 8.

3.4.3. Comprehensive Effect of Time and the Water-Cement Ratio on the Quantitative Variation Relationship of the Rheological Index of the Power-Law Cement Grouts

(1) *Building a Quantitative Variation Relationship Model.* It can be seen from the discussion in Section 3.4.1 that the water-cement ratio had a significant effect on the rheological

index of the power-law cement grouts, while the time had no significant effect on the rheological index. Therefore, only the effect of the water-cement ratio needed to be considered when building the quantitative relationship model of the rheological index of the power-law cement grouts.

Similarly, the linear, exponential, power, and logarithmic models of the water-cement ratio effect on the rheological index of the power-law cement grouts were fitted. The analysis results are shown in Table 5.

In the same way, from the perspective of statistical theory, the linear model was the optimal model among the four models in terms of the water-cement ratio effect on the rheological index of the power-law cement grouts.

(2) *Experimental Verification.* In order to verify the applicability and accuracy of the four fitting models shown in Table 5, two groups of cement grouts, G1 and G2, were used for comparison and verification. The verification results are shown in Table 7.

According to the results in Table 7, the difference between the theoretical value and the experimental value of the linear model was in the range of 7%-9%. The difference between the theoretical value and the experimental value of the other three models was more than 10%, and the variation of the linear model was no more than that of the other three models. Thus, from the perspectives of applicability and accuracy, the linear model could accurately reflect the quantitative change of the water-cement ratio effect on the rheological index of the power-law cement grouts.

In summary, the optimal model for the effect of the water-cement ratio of the power-law cement grouts rheological index was the linear model:

$$n = -0.0193 + 0.874\omega \quad (3)$$

3.5. *Rheological Equation of the Time and Water-Cement Ratio Comprehensive Effect on the Power-Law Grouts.* The simultaneous solving of Equations (1)–(3) could be used to obtain the rheological equation of the power-law cement grouts, with consideration of the comprehensive effect of time and the water-cement ratio:

$$\tau = 695.061e^{0.021t-10.604\omega} \gamma^{-0.0193+0.874\omega} \quad (4)$$

4. Conclusion

This research was focused on power-law cement grouts (W/C below 0.75), which are widely used in engineering practice. Experimental research, theory discussion, and numerical analysis were used to discuss the comprehensive effect of time and the water-cement ratio on the rheological properties of power-law cement grouts at room temperature ($25^\circ\text{C} \pm 2^\circ\text{C}$). The results showed that

- (1) The water-cement ratio had a great influence on both the consistency coefficient and the rheological index of the grouts. The former appeared to have a

downward trend with the increase of the water-cement ratio, and the latter appeared to have an upward trend. There was a rising tendency between the time and the power-law cement consistency coefficient. While the rheological index was less affected by time, the difference between its maximum and minimum values was within 5%

- (2) Four quantitative change models were built based on the perspectives of statistical theory, practical applicability, and accuracy. The exponential model was the optimal model for showing the relationship between the comprehensive effects of the time, the water-cement ratio, and the consistency coefficient of the power-law cement
- (3) Similarly, the linear model was the optimal model for the quantitative change of the rheological index based on the comprehensive effect of time and water-cement ratio
- (4) A rheological equation of the power-law cement grouts with consideration of the comprehensive effect of time and the water-cement ratio was built

The research results can not only improve the rheological theory of power-law cement grouts but also provide technical support for engineering practice.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no known conflicts of interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

All authors contributed equally in the preparation of this manuscript.

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