

Research Article

Effects of Fly Ash and Chemical Admixtures on the Rheological Properties of High-Concentration Full-Tailing Filling Slurry

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Good fluidity is the precondition to ensure the pipeline transportation of the filling slurry. The admixture in the filling slurry will affect the rheological properties of the slurry. In this paper, yield stress (YS), viscosity coefficient (VC), and expansion (ED) of the filling slurry were measured by the MCR52 rheometer and expansion tester, respectively, and the influence regularities of the three kinds of admixtures including fly ash (FA), polycarboxylate superplasticizer (PS), and polyethylene oxide (PEO) on the rheological properties of the filling slurry were obtained. The results show that when other conditions are fixed, the fluidity of the slurry becomes worse with the increase of the amount of fly ash but improves with the increase of the amount of the polycarboxylate superplasticizer; polyethylene oxide is not suitable for the improvement of the fluidity of the high-concentration full-tailing filling slurry, and the fluidity of the slurry becomes worse rapidly with the increase of the amount of polyethylene oxide.

1. Introduction

As one of the development directions of mine filling, high-concentration full-tailing-cemented filling has obvious characteristics and advantages of “high tailings utilization rate” and “high filling body quality.” [1, 2] Pipeline transportation is generally adopted for the filling slurry of high-concentration full tailings, and problems such as pipe plugging, pipe bursting, and pipeline abrasion become the bottleneck of pipeline transportation, which not only cause the rapid increase of filling cost due to pipeline maintenance but also directly affect the normal operation of the whole filling system [3]. Therefore, it is necessary to carry out research on improving the fluidity of the high-concentration full-tailing filling slurry. When the filling slurry is pipeline-transported by pump pressure, fluidity, plasticity, and stability of the slurry become the key indexes of slurry pumping performance. In the laboratory, yield stress, viscosity coefficient, and other parameters are commonly used in the rheological properties of the slurry, while slump, expansion, and other parameters are mostly used in the engineering site.

The main factors that affect the rheological properties are the solid mass concentration (SC) of the filling slurry, the grain composition of tailings, the transportation flow and the

diameter of the pipe, and the cement-sand ratio of the filling slurry. When these factors are fixed, the way of adding admixtures (such as fly ash and chemical admixtures) is usually adopted to improve the fluidity or stability of the slurry [4–8]. The admixtures in the modification of filling slurry transportation mainly include water-reducing agent, plasticizer, air-entraining agent, and drag-reducing agent, among which water-reducing agent is most commonly used, which can effectively improve the fluidity of the high-concentration slurry. However, drag-reducing agent is mainly used to avoid segregation blockage in the slurry transportation process, but it may lead to a sharp increase in the YS and VC of the slurry. As a kind of active mineral admixture, fly ash can not only partially replace cement as the cementitious material in mine filling but also can effectively improve the workability of the filling slurry, reduce cement segregation, and reduce the abrasion of the filling slurry on the pipeline due to its small density and large specific surface area [9–12]. At present, more attention has been paid to the improvement effect of the water-reducing agent on the fluidity of the filling slurry at home and abroad; however, the research of adding fly ash into the filling material mainly focuses on its influence on the strength formation of the filling body, and the research on the influence

characteristics of the filling slurry is relatively less; due to the thickening effect of the drag-reducing agent, its application in the filling slurry flow performance is extremely rare, but it may be helpful to improve the settlement characteristics of graded discontinuous tailing slurry. Therefore, it is necessary to discuss the influence characteristics of water-reducing agent, drag-reducing agent, and fly ash on the fluidity of the filling slurry.

Taking the lead-zinc full-tailing filling slurry with different SC under the fixed cement-sand (tailings) ratio as the research object, adding the appropriate amount of FA mineral admixture, PS, PEO, and other chemical admixtures, respectively, using the MCR52 intelligent modular rheometer and expansion tester to test the rheological properties and expansion of the slurry, the influence of active mineral admixtures and chemical admixtures on the filling slurry of high-concentration full tailings is obtained. Through the analysis of the influence law and action mechanism of additives on the flow performance of the filling slurry, it can provide reference for the pipeline transportation optimization of the high-concentration full-tailing slurry.

2. Materials and Methods

2.1. Test Materials. The test materials mainly include lead-zinc full tailings, 425# ordinary Portland cement (P.O42.5), FA, PS, PEO, and water.

Lead-zinc tailings are full tailings from a concentrator in the Hunan province. The moisture content, density, volume density, and porosity of the dried tailings are 0.32%, 2.83 t/m^3 , 1.96 t/m^3 , and 35.8%, respectively. The content of recoverable metals in tailings is relatively low, which does not contain or contains a small amount of toxic and harmful elements. The physical and chemical properties of tailings are stable, and their particle size composition is obtained by the Microtrac S3500 laser particle size analyzer, as shown in Figure 1. The particle size ranges from $2.31 \mu\text{m}$ to $592.00 \mu\text{m}$, with a median particle size of $121.9 \mu\text{m}$. After calculation, the coefficient of uniformity $C_u = 29.17$, the coefficient of curvature $C_c = 0.99$, the particle size distribution range of tailings is wide, and the grading is close to continuous. However, the content of $-20 \mu\text{m}$ tailings in the full tailings is 22.5%, which is far higher than the requirement that the content of $-20 \mu\text{m}$ particles in the paste must be greater than 15%.

P.O42.5 purchased from the market is selected as the filling cementitious material, with a density of 3.0 t/m^3 and a specific gravity of 1 : 3. Water needed for the test is directly from urban tap water.

FA is grade I fly ash purchased from the market, with a density of 2.40 t/m^3 , a volume density of 0.78 t/m^3 , a porosity of 62.3%, and a specific surface area of $245 \text{ m}^2/\text{kg}$, and the chemical composition of SiO_2 is 56.74%, Al_2O_3 is 24.59%, CaO is 4.87%, and Fe_2O_3 is 6.53%; PS is white powder, with a nominal water reduction rate of $\geq 25\%$; PEO is a kind of water-soluble nonionic linear polymer with white granular powder.

2.2. Test Equipment. The rheological parameters of the slurry were measured by MCR52, as shown in Figure 2(a). ST24-2D/2V/2V-30 paddle rotor (rotor diameter is 20 mm, and

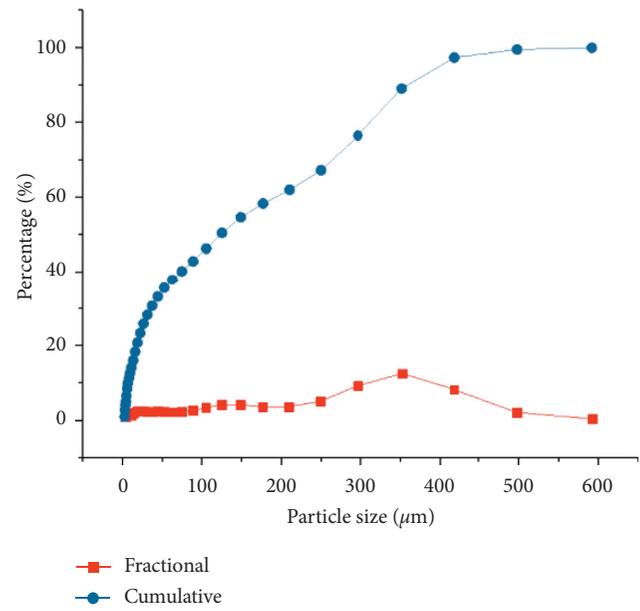


FIGURE 1: Granularity distribution curve of tailings.

height is 40 mm) is selected as the rotor, and control parameters are set on the operation interface by using supporting RheoCompass software to output the shear stress vs. shear rate curve and viscosity vs. shear rate curve in real time. The device has a dual measurement mode of controlling shear stress and shear rate and has more selectivity and flexibility.

In order to observe the fluidity of the slurry more intuitively and analyze the rheological properties of the slurry comprehensively, the expansion tester is used to measure the fluidity of the slurry in the test. The expansion tester is determined by a small cylindrical measuring barrel made of stainless steel, with a diameter of $\Phi = 50 \text{ mm}$ and a height of $H = 100 \text{ mm}$, as shown in Figure 2(b).

2.3. Test Plan. In order to explore the influence of the solid mass concentration (SC), the type of admixture (TA), and the amount of admixture (AA) on the rheological properties of filling slurry under the condition of a certain cement-sand (tailings) ratio, the following settings are selected for the test scheme. During the test, the cement-sand (tailings) ratio was fixed at 1 : 8, and the SC is 76%, 78%, and 80%, respectively. The additives are FA, PS, and PEO. Because the addition of different admixtures is applicable with different dosages, the three levels of each additive dosage are different, as shown in Table 1. According to this, a comprehensive test design was carried out. At the same time, one control group without additives was set for each SC level of the slurry, and a total of 30 groups of tests were carried out.

3. Results

In this paper, the rheological properties of the slurry are characterized by yield stress (YS), viscosity coefficient (VC), and expansion (ED), which are obtained from the MCR52 and expansion tester, and the results are shown in Table 2.

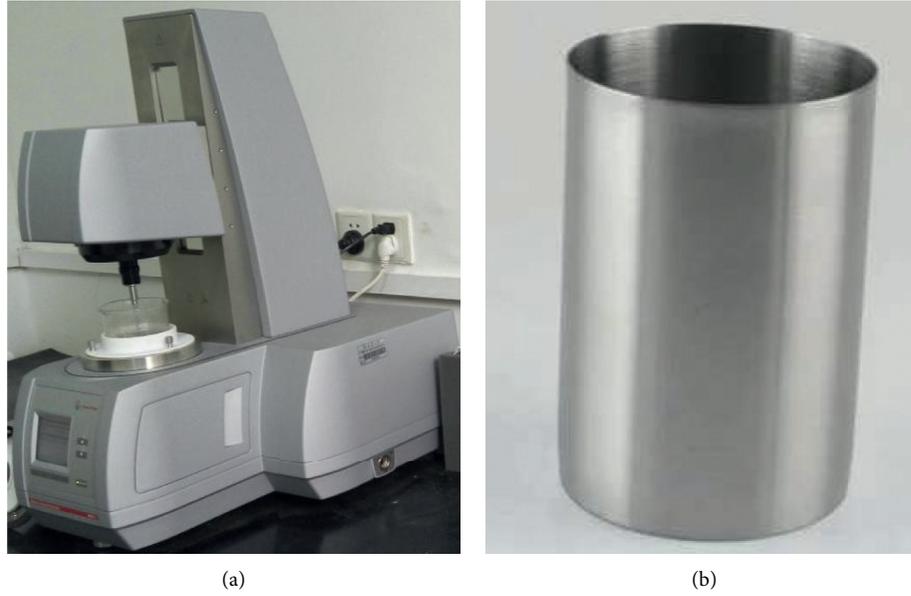


FIGURE 2: Test equipment: (a) MCR52; (b) expansion tester.

TABLE 1: Different levels of admixture addition.

	FA (%)	PS (%)	PEO (%)
Level 1	6	0.6	0.2
Level 2	8	0.7	0.3
Level 3	10	0.8	0.4

3.1. Influence of Fly Ash on the Rheological Properties of the Slurry

3.1.1. Analysis of Single-Effect Characteristics of Fly Ash.

When the SC of the filling slurry is fixed, origin is used to carry out a single-factor regression analysis of the corresponding test results in order to analyze the variation regularities of YS, VC, and ED of the slurry with FA. Through the linear fitting, quadratic polynomial fitting, and exponential fitting of each group of data item by item and then comparing its fitting coefficient R^2 , test coefficient F , and other indexes, the optimal fitting equation is obtained. The results show that the quadratic polynomial fitting is suitable for the fitting of the influence characteristics of FA on the rheological parameters of the filling slurry. The general formula is shown as follows:

$$Y = a + bx + cx^2. \quad (1)$$

The curve of YS with FA is shown in Figure 3(a). When FA is fixed, the YS is positively correlated with the increase of SC of the slurry. When the SC is increased from 78% to 80%, the YS increases to 2.32–3.36 times of the original value; especially, when FA is 0%, it reaches 1112.1 Pa, which is 3.36 times of that when the SC is 78%, which indicates that the rheological properties of the slurry change abruptly. When the SC is fixed, with the increase of FA, the content of fine particles in the filling slurry increases gradually, and the contact and friction frequency between the particles increase, which results in the

TABLE 2: Rheological parameters of the filling slurry.

No.	SC (%)	TA	AA (%)	YS (Pa)	VC (Pa·s)	ED (cm)
A11	76	FA	6	434.8	2.4	14.8
A12	76		8	557.4	3.1	13.7
A13	76		10	550.8	3.2	12.0
A21	76	PS	0.6	98.1	0.4	20.7
A22	76		0.7	75.2	0.3	21.9
A23	76		0.8	27.6	0.1	23.9
A31	76	PEO	0.2	746.6	3.9	13.5
A32	76		0.3	813.3	4.1	12.1
A33	76		0.4	964.2	4.9	10.9
A0	76	—	0	101.7	0.6	15.2
B11	78	FA	6	987.9	5.5	13.2
B12	78		8	1100.1	6.2	12.1
B13	78		10	1076.3	6.1	11.6
B21	78	PS	0.6	76.9	0.6	21.5
B22	78		0.7	73.9	0.5	22.1
B23	78		0.8	54.5	0.3	23.0
B31	78	PEO	0.2	1264.9	6.1	12.2
B32	78		0.3	1579.9	7.6	11.6
B33	78		0.4	1969.1	9.5	10.3
B0	78	—	0	331.0	1.8	13.9
C11	80	FA	6	2288.7	12.8	9.4
C12	80		8	2786.4	15.6	7.6
C13	80		10	2941.7	16.4	6.5
C21	80	PS	0.6	406.5	2.0	20.5
C22	80		0.7	402.1	2.1	21.2
C23	80		0.8	301.0	1.6	21.4
C31	80	PEO	0.2	1861.7	8.9	11.3
C32	80		0.3	1896.7	9.5	10.6
C33	80		0.4	2144.8	10.2	9.6
C0	80	—	0	1112.1	6.2	12.0

increase of friction inside the slurry, and it becomes more difficult for the slurry to overcome the initial shear stress to generate flow. The regression model formula is shown as follows:

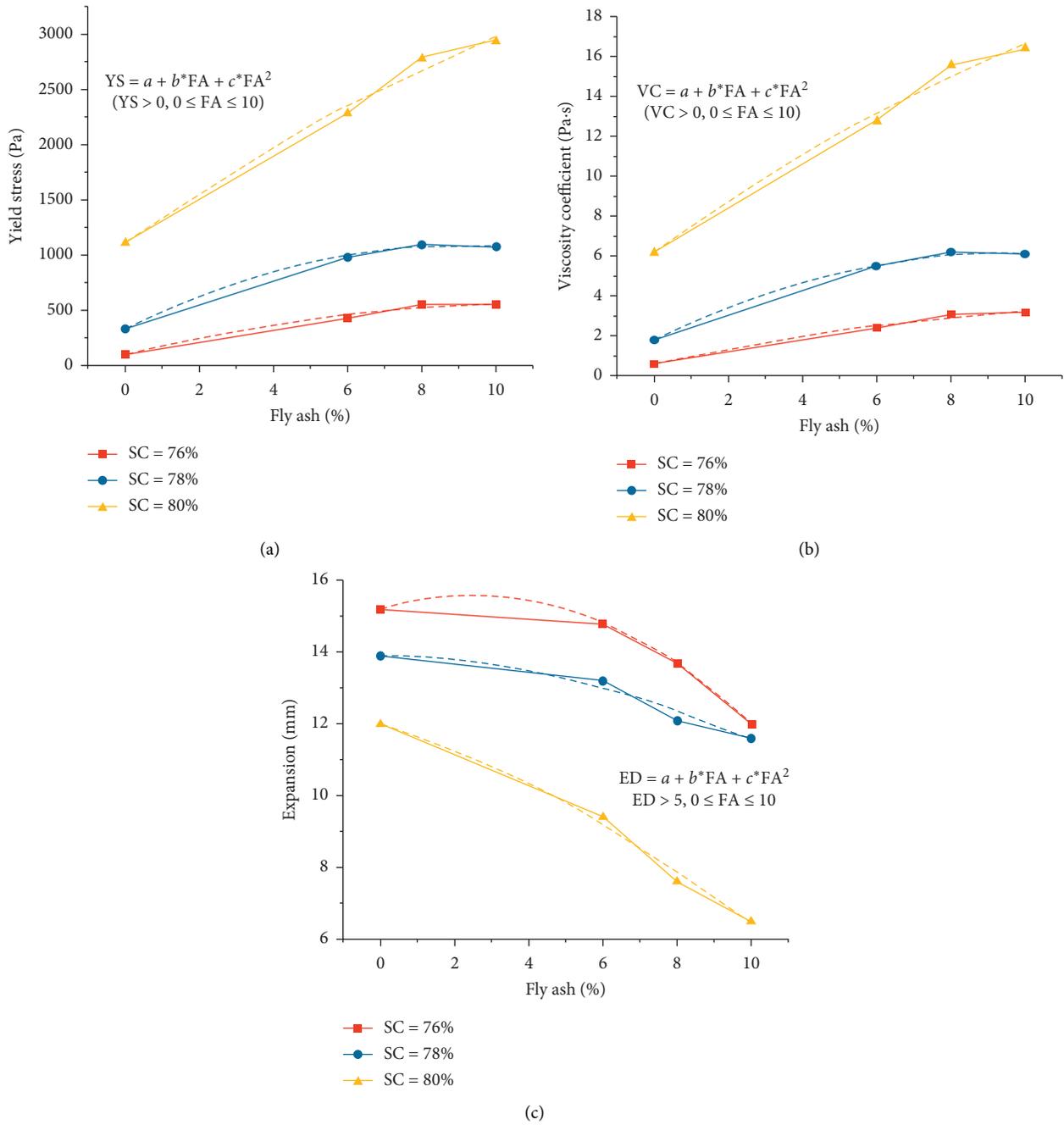


FIGURE 3: Influence of FA on the rheological properties of the filling slurry. (a) Curve of YS with FA. (b) Curve of VC with FA. (c) Curve of ED with FA.

$$YS = a + b \cdot FA + c \cdot FA^2, \quad (YS > 0, 0 \leq FA \leq 10), \quad (2)$$

where “YS” is the yield stress of the slurry, “FA” is the fly ash content, and “b” and “c” are the constants affected by slurry concentration, tailing grading, and other factors, while “a” is a constant mainly affected by slurry concentration, which generally increases with the increase of slurry concentration. The constants and R^2 for the regression curve of Figure 3(a) are shown in Table 3.

The curve of VC with FA is shown in Figure 3(b), and its regularity is very consistent with the YS. Adding a certain

amount of fine particles of fly ash can effectively reduce the settlement, segregation, and bleeding of the slurry and help to form the lubrication layer of the plunger flow and the pipe wall of the conveying pipeline, which is a favorable factor for the preparation of filling paste. However, with the increase of FA, the “thickening effect” of larger specific surface area and smaller density gradually appears, which leads to the obvious increase of viscosity of the slurry and then affects fluidity of the slurry. The regression model formula is shown in formula (3), and the three constants “a,” “b,” and “c” and R^2 are shown in Table 4.

TABLE 3: Constants and R^2 for regression of FA to YS.

	a	b	c	R^2
SC = 76%	99.463	79.332	-3.286	0.987
SC = 78%	329.631	166.752	-9.126	0.998
SC = 80%	1105.551	238.951	-5.141	0.992

TABLE 4: Constants and R^2 for regression of FA to VC.

	a	b	c	R^2
SC = 76%	0.589	0.398	-0.013	0.990
SC = 78%	1.791	0.928	-0.049	0.998
SC = 80%	6.162	1.355	-0.030	0.992

$$VC = a + b * FA + c * FA^2, \quad (VC > 0, 0 \leq FA \leq 10). \quad (3)$$

The curve of ED with FA is shown in Figure 3(c). The ED of the slurry is negatively correlated with the increase of FA; that is to say, the macroscopic fluidity of the slurry decreases with the increase of FA, which is consistent with the rheological properties characterized by YS and VC of the slurry. The regression model formula is shown in formula (4), and the three constants “ a ,” “ b ,” and “ c ” and R^2 are shown in Table 5.

$$ED = a + b * FA + c * FA^2, \quad (ED > 5, 0 \leq FA \leq 10). \quad (4)$$

3.1.2. Two-Factor Analysis of Fly Ash Content and Slurry Concentration. The flow velocity of the slurry, slurry concentration, particle size distribution of filling materials, particle settling velocity, and other factors will affect slurry flow resistance. In the test, we assumed that other factors were fixed values and analyzed slurry concentration and fly ash addition amount by setting them as variables. The single-factor analysis in Section 3.1.1 shows that the changes of the YS, VC, and ED with FA can be fitted by quadratic polynomial. The results in Figure 4 show that bivariate quadratic polynomial fitting can be applied to two-factor analysis. The general formula is shown as follows:

$$Z = Z_0 + ax + by + cx^2 + dy^2 + fxy. \quad (5)$$

Figure 4(a) is the curve chart of the change of YS with SC and FA. It can be seen from the figure that the YS increases significantly with the increase of FA in the high-concentration slurry, while the variation trend of the relatively low-concentration slurry is gentle. When FA is relatively high, the trend of YS increases with the SC being obvious, and its fitting formula is shown in formula (6). Figure 4(a) shows that based on this formula, the YS of different FA and SC can be predicted, so as to guide the precise addition of fly ash in filling engineering and the precise control of the filling slurry system.

$$YS = YS_0 + a * SC + b * FA + c * SC^2 + d * FA^2 + f * SC * FA, \quad (YS > 0, 76 \leq SC \leq 80, 0 \leq FA \leq 10). \quad (6)$$

TABLE 5: Constants and R^2 for regression of FA to ED.

	a	b	c	R^2
SC = 76%	15.198	0.320	-0.639	0.999
SC = 78%	13.917	-0.007	-0.023	0.967
SC = 80%	12.019	-0.327	-0.024	0.992

In the formula, “ YS_0 ,” “ a ,” “ b ,” “ c ,” “ d ,” and “ f ” are the constants related to SC, FA, etc., as shown in Table 6.

Figure 4(b) is the curve chart of the change of VC with SC and FA, and its regularity is very consistent with YS. The fitting formula is shown in formula (7), where constants and R^2 are shown in Table 7.

$$VC = VC_0 + a * SC + b * FA + c * SC^2 + d * FA^2 + f * SC * FA, \quad (VC > 0, 76 \leq SC \leq 80, 0 \leq FA \leq 10). \quad (7)$$

Figure 4(c) is the curve chart of the change of ED with SC and FA. The fitting formula is shown in formula (8), where constants and R^2 are shown in Table 8.

$$ED = ED_0 + a * SC + b * FA + c * SC^2 + d * FA^2 + f * SC * FA, \quad (ED > 5, 76 \leq SC \leq 80, 0 \leq FA \leq 10). \quad (8)$$

Adding fly ash can improve the workability of the coarse aggregate filling slurry, can prevent segregation and bleeding caused by solid particle settlement, and form a lubricating layer on the filling pipe wall, which is of positive significance for improving the pumping performance of the filling slurry. However, for the fine-grained full tailings, the content of $-20 \mu\text{m}$ in the tailings far exceeds the requirement of paste preparation by 15%. When fine-grained fly ash continues to be added, due to its large specific surface area, a large amount of water absorption leads to the reduction of free water in the slurry, which leads to the poor flow performance of the slurry [13]. The results show that the relationship between the YS, VC, and ED of the filling slurry and FA can be expressed by quadratic polynomials. When the SC of the filling slurry is fixed, the YS and VC are positively correlated with FA, respectively, while the ED is negatively correlated with FA. When only for the purpose of improving the slurry fluidity, whether fly ash is added to the filling materials should be determined according to the factors such as the particle grading of the filling aggregate and the SC of the slurry.

3.2. Influence of the Polycarboxylate Superplasticizer on the Rheological Properties of the Slurry

3.2.1. Analysis of Single-Effect Characteristics of the Polycarboxylate Superplasticizer. The method and process of test data analysis and fitting are consistent with the description in Section 3.1.1. Formula (1) is still suitable for the general formula of the relationship between the YS, VC, and ED of the slurry and the PS.

It can be seen from Figure 5(a) that when the SC of the slurry is fixed, the YS of the slurry as a whole decreases with the increase of PS; especially when the SC is higher, the trend is more obvious. When 0.8% PS is added to the slurry of

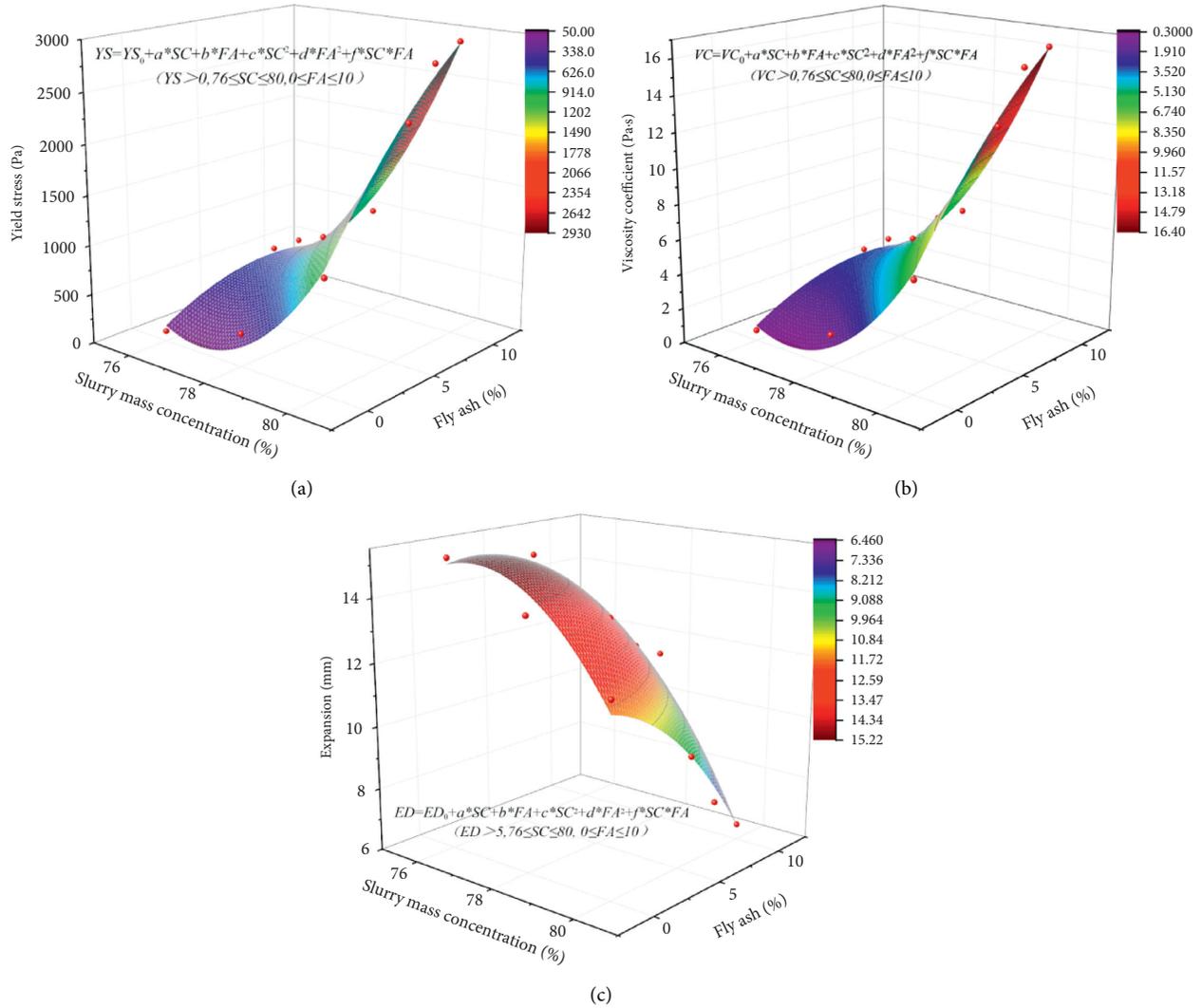


FIGURE 4: Influence curve of SC and FA on the rheological properties of the filling slurry. (a) Curve of YS with SC and FA. (b) Curve of VC with SC and FA. (c) Curve of ED with SC and FA.

TABLE 6: Constants and R^2 for regression of SC and FA to YS.

YS_0	a	b	c	d	f	R^2
699582.741	-18187.555	-2606.829	118.219	-5.851	35.532	0.992

TABLE 7: Constants and R^2 for regression of SC and FA to VC.

VC_0	a	b	c	d	f	R^2
3901.786	-101.440	-14.498	0.659	-0.031	0.197	0.992

TABLE 8: Constants and R^2 for regression of SC and FA to ED.

ED_0	a	b	c	d	f	R^2
-1895.586	49.839	5.219	-0.325	-0.037	-0.067	0.976

SC = 80%, the YS is only 0.27 times of that without PS and 0.37 times of that when 0.6% PS is added, which shows that the addition of PS can effectively reduce the YS of the slurry and improve the fluidity of the slurry, but when PS increases from 0.6% to 0.8%, decreasing of YS tends to be flattened out,

and the water-reducing effect is gradually reduced. At the same time, excessive addition of PS may also lead to the segregation phenomenon of the slurry, which is not good for the stability and plasticity of high-concentration filling slurry. The relationship between the YS of the slurry and the PS is shown in formula (9), and the constants and R^2 for the regression formula are shown in Table 9.

$$YS = a + b * PS + c * PS^2, \quad (YS > 0, 0 \leq PS \leq 0.8). \quad (9)$$

The curve of VC with FA is shown in Figure 5(b); PS achieves the goal of water reduction mainly through the action of dispersion and lubrication. The molecules of PS which are directionally adsorbed on the surface of cement and other fine particles make the surface of particles carry

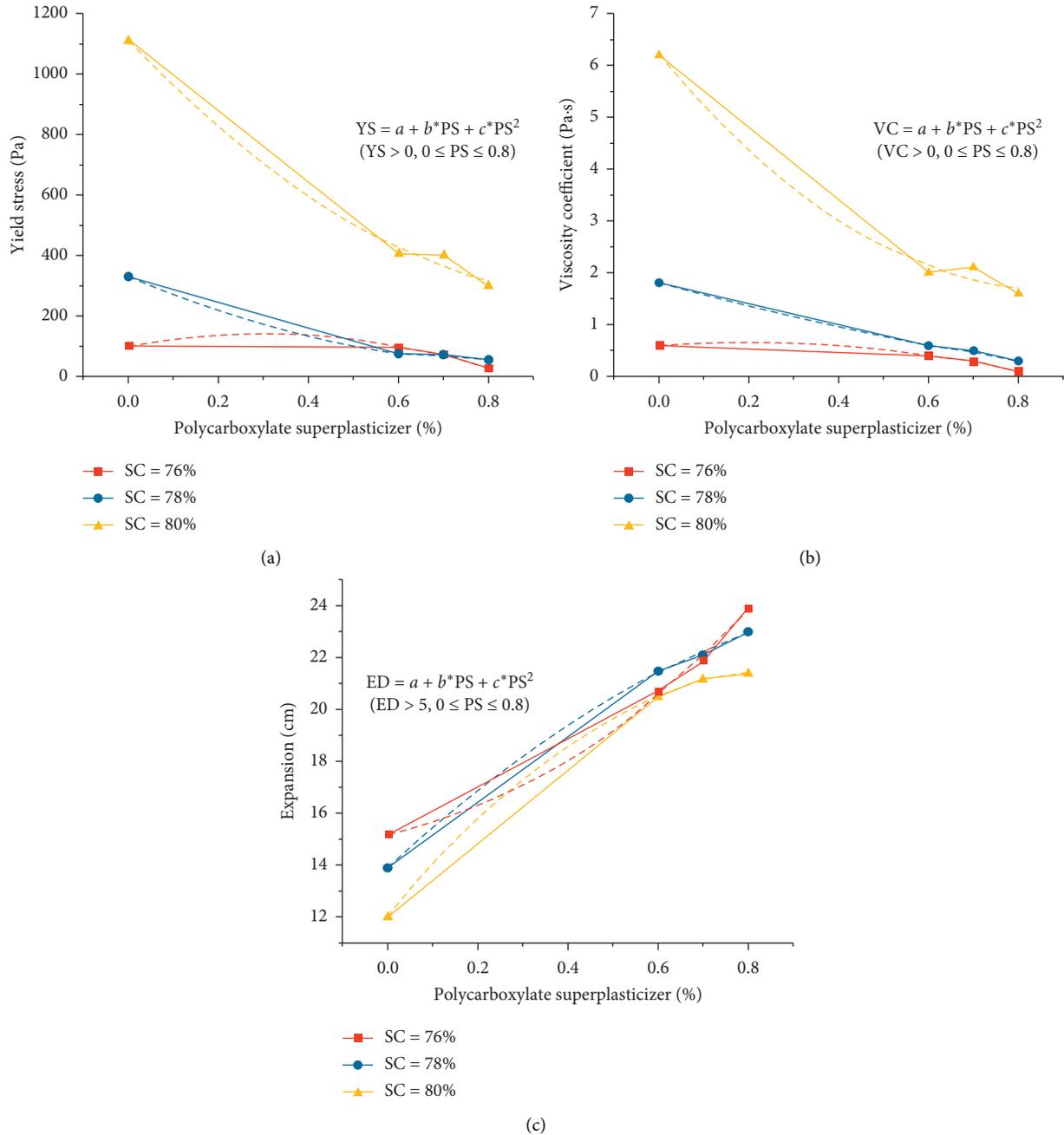


FIGURE 5: Influence curve of PS on the rheological properties of the filling slurry. (a) Curve of YS with PS. (b) Curve of VC with FA. (c) Curve of ED with FA.

the same charge and generate electrostatic repulsion, promote the release and flow of water covered by flocculation, and reduce the viscosity of the slurry. The solvated water film formed by water and molecules of PS on the particle surface has a good lubricating effect, reducing the collision and friction between particles and then reducing the friction resistance inside the slurry [14, 15]. The relationship between the VC and the PS of the slurry is similar with the YS, and the application effect is significant in the high-concentration slurry. When 0.8% PS is added to the slurry of SC = 80%, its VC is only 0.26 times of that without PS. The relationship between the VC of the slurry and

TABLE 9: Constants and R^2 for regression of PS to YS.

	a	b	c	R^2
SC = 76%	101.591	265.960	-444.483	0.988
SC = 78%	330.836	-638.899	372.245	0.998
SC = 80%	1111.332	-1577.291	730.659	0.995

the PS is shown in formula (10), and the constants and R^2 for the regression formula are shown in Table 10.

$$VC = a + b \cdot PS + c \cdot PS^2, \quad (VC > 0, 0 \leq PS \leq 0.8). \quad (10)$$

TABLE 10: Constants and R^2 for regression of PS to VC.

	a	b	c	R^2
SC = 76%	0.560	0.595	-1.509	0.994
SC = 78%	1.799	-2.290	0.545	0.999
SC = 80%	6.195	-10.204	5.737	0.994

It can be seen from Figure 5(c) that, in the process of PS increased from 0% to 0.8%, the ED will increase as a whole, but when PS is greater than 0.6%, the ED will increase slowly, which is basically consistent with the description of YS and VC. This shows that the excessive addition of PS is not significant to further improve the fluidity of the slurry and may become worse due to segregation and sedimentation. The relationship between the ED of the slurry and the PS is shown in formula (11), and the constants and R^2 for the regression formula are shown in Table 11.

$$ED = a + b * PS + c * PS^2, \quad (ED > 5, 0 \leq PS \leq 0.8). \quad (11)$$

3.2.2. Two-Factor Analysis of Polycarboxylate Superplasticizer Content and Slurry Concentration. It can be seen from Figure 6(a) that when PS is 0%, the YS of the slurry increases sharply with the increase of SC, and the trend slows down with the increase of PS. However, when the SC is relatively low, the YS decreases with the increase of PS, as described in Section 3.2.1. According to the comparison of various fitting results, the expression of YS with SC and PS is shown in formula (12) by referring to general formula (5), and the relevant parameters and R^2 are shown in Table 12.

$$YS = YS_0 + a * SC + b * PS + c * SC^2 + d * PS^2 + f * SC * PS, \quad (YS > 0, 76 \leq SC \leq 80, 0 \leq PS \leq 0.8). \quad (12)$$

Figure 6(b) is the curve chart of the change of VC with SC and PS, and its regularity is very consistent with YS. The fitting formula is shown in formula (13), where constants and R^2 are shown in Table 13.

$$VC = VC_0 + a * SC + b * PS + c * SC^2 + d * PS^2 + f * SC * PS, \quad (YS > 0, 76 \leq SC \leq 80, 0 \leq PS \leq 0.8). \quad (13)$$

Figure 6(c) is the curve chart of the change of ED with SC and PS, The fitting formula is shown in formula (14), where constants and R^2 are shown in Table 14.

$$ED = ED_0 + a * SC + b * PS + c * SC^2 + d * PS^2 + f * SC * PS, \quad (ED > 5, 76 \leq SC \leq 80, 0 \leq PS \leq 0.8). \quad (14)$$

PS is a kind of high-performance water-reducing agent, which can achieve better water-reducing effect at a lower dosage. For example, when adding 0.6% PS to the filling slurry of SC = 80%, its YS can be reduced to 0.27 times of the original value. However, for mine filling, the segregation and settlement of the slurry are causes of pipe plugging, abrasion, and other accidents in the pipeline. On the one hand, excessive addition

TABLE 11: Constants and R^2 for regression of PS to ED.

	a	b	c	R^2
SC = 76%	15.204	3.568	8.987	0.998
SC = 78%	13.903	16.218	-6.154	0.999
SC = 80%	11.998	21.611	-12.266	0.999

of PS may lead to the segregation and settlement of the slurry; on the other hand, it will greatly increase the cost of filling, which is not in accordance with the principle of minimum filling cost under the premise of satisfying mining technology. At the same time, based on the test results that the effect is not obvious after the addition amount of PS exceeds 0.6%, if the scheme of adding PS is adopted in filling engineering, it can be optimized within the range of 0–0.6% of PS, and then the economic and reasonable scheme of the dosage can be selected.

3.3. Influence of Polyethylene Oxide on the Rheological Properties of the Slurry

3.3.1. Analysis of Single-Effect Characteristics of Polyethylene Oxide. Drag reducer is a kind of additive which can improve the fluidity by reducing the friction resistance between the fluid and the pipeline wall. It is mainly used in the transportation of oil-soluble and water-soluble liquids. It can greatly reduce the energy dissipation of the fluid in the turbulent state, thus reducing the resistance of the fluid and increasing the flow speed [16]. However, the rheological properties of the high-concentration full-tailing filling slurry are different from those of solid-liquid two-phase flow or Newtonian fluid. Bingham fluid is generally used to describe its characteristics, so theoretically speaking, drag reducer is not suitable for it. However, when coarse-grained tailings are used for water-sand filling or poorly graded filling materials with coarse-grained particles are used for cementation filling, a proper amount of the drag-reducing agent can avoid segregation and blocking in the process of slurry pumping [17]. This part of the test is only to verify the effect of polyethylene oxide drag reducer on the full-tailing filling slurry.

It can be seen from Figure 7(a) that the YS of the slurry increases rapidly when a certain amount of PEO is added to a fixed SC of the full-tailing filling slurry. The addition of PEO increased from 0% to 0.2%, and the YS increased to 1.67–7.34 times of the original value, which was more obvious at the relatively low-concentration slurry. When the content of PEO increased from 0.2% to 0.4%, the YS increased to 1.15–1.56 times of the value when PEO = 0.2%. This shows that when the amount of PEO increases continuously, the change of YS of the slurry tends to slow down. Referring to the optimal fitting method obtained by multiple fitting methods, general formula (1) is also applicable, so its expression is shown in formula (15), and the corresponding constants and R^2 are shown in Table 15.

$$YS = a + b * PEO + c * PEO^2, \quad (YS > 0, 0 \leq PEO \leq 0.4). \quad (15)$$

Due to the strong Newtonian property of the drag-reducer solution, the slurry after adding the drag reducer has obvious thickening effect, resulting in a sharp increase in its viscosity. From Figure 7(b), it can be seen that the change regularity of the VC of the slurry after adding PEO is

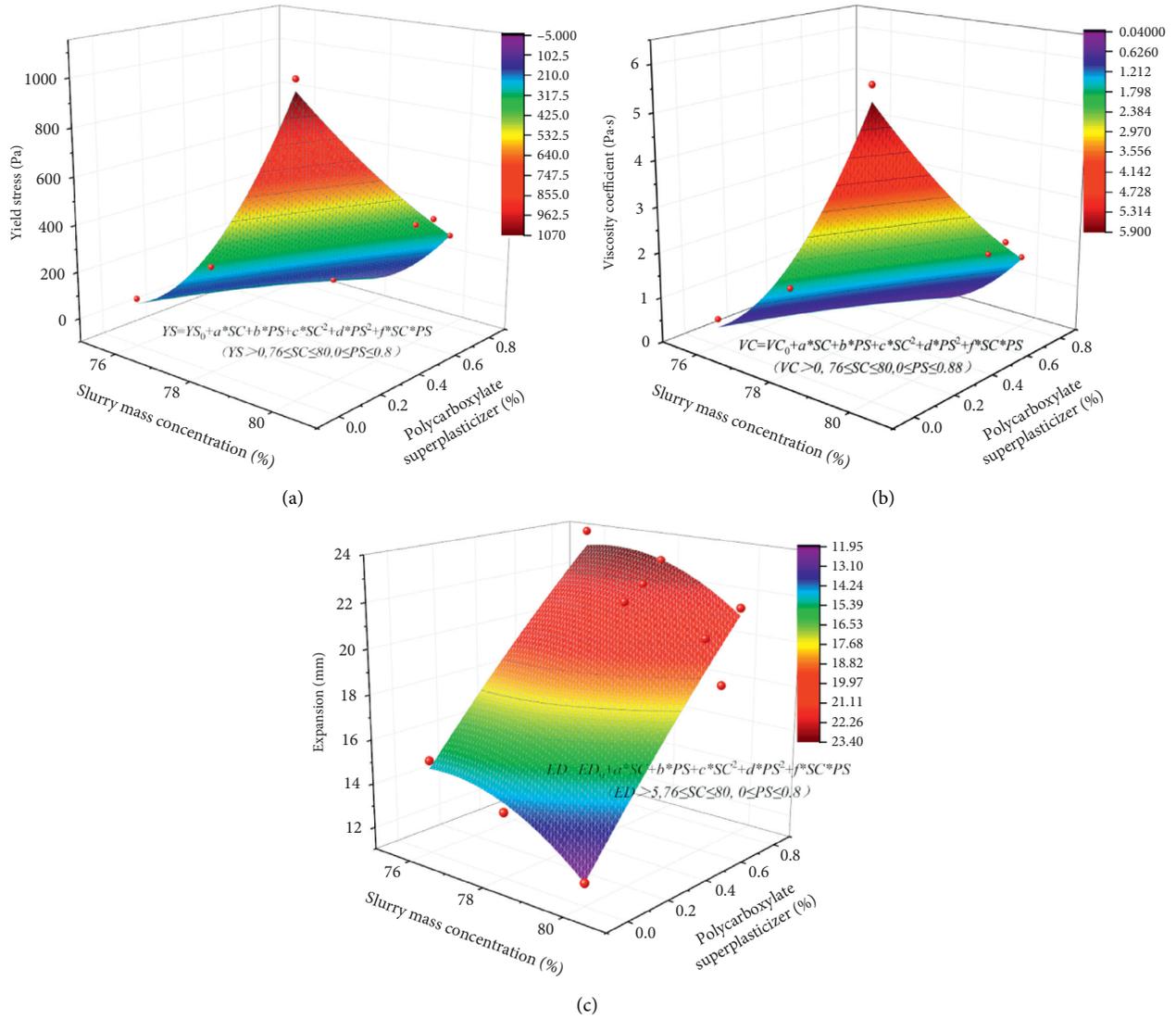


FIGURE 6: Influence curve of SC and PS on the rheological properties of the filling slurry. (a) Curve of YS with SC and PS. (b) Curve of VC with SC and PS. (c) Curve of ED with SC and PS.

TABLE 12: Constants and R^2 for regression of SC and PS to YS.

YS_0	a	b	c	d	f	R^2
257136.832	-6830.098	18217.746	45.366	2199.474	-241.895	0.983

TABLE 13: Constants and R^2 for regression of SC and FA to VC.

VC_0	a	b	c	d	f	R^2
1207.682	-32.273	101.334	0.216	1.591	-1.350	0.974

TABLE 14: Constants and R^2 for regression of SC and FA to ED.

ED_0	a	b	c	d	f	R^2
-1299.066	34.388	-4.314	-0.225	-1.728	0.213	0.955

basically the same as that of the YS. The expression is shown in formula (16), and the corresponding parameters and R^2 are shown in Table 16.

$$VC = a + b * PEO + c * PEO^2, (VC > 0, 0 \leq PEO \leq 0.4).$$

(16)

It can be seen from Figure 7(c) that, in the process of PEO increased from 0% to 0.4%, the ED will reduce as a whole. The relationship between ED of the slurry and PEO is shown in formula (17), and the constants and R^2 for the regression formula are shown in Table 17.

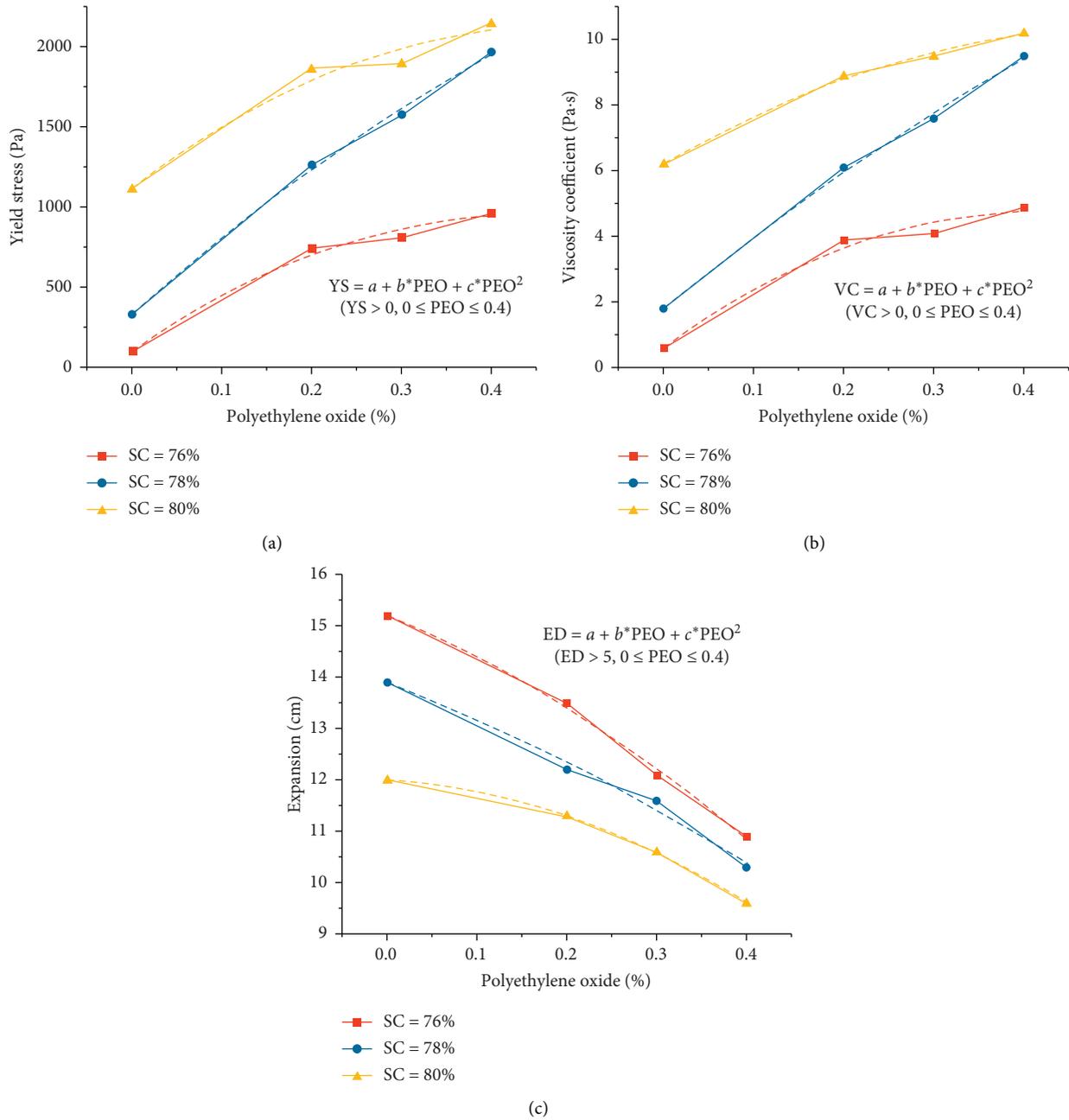


FIGURE 7: Influence curve of the polyethylene oxide drag-reducer content on the rheological properties of the filling slurry. (a) Curve of YS with PEO. (b) Curve of VC with PEO. (c) Curve of ED with PEO.

TABLE 15: Constants and R^2 for regression of PEO to YS.

	a	b	c	R^2
SC = 76%	108.646	3875.968	-4472.955	0.988
SC = 78%	335.786	4956.568	-2272.955	0.998
SC = 80%	1124.090	4194.850	-4332.500	0.974

TABLE 17: Constants and R^2 for regression of PEO to ED.

	a	b	c	R^2
SC = 76%	15.215	-7.177	-9.318	0.997
SC = 78%	13.876	-6.582	-5.455	0.991
SC = 80%	11.998	-0.891	-12.727	0.999

TABLE 16: Constants and R^2 for regression of PEO to VC.

	a	b	c	R^2
SC = 76%	0.643	19.686	-23.409	0.981
SC = 78%	1.823	22.386	-8.409	0.998
SC = 80%	6.216	16.018	-15.455	0.997

$$ED = a + b * PEO + c * PEO^2, (ED > 5, 0 \leq PEO \leq 0.4). \quad (17)$$

3.3.2. Two-Factor Analysis of Polyethylene Oxide Content and Slurry Concentration. Figure 8(a) is the curve chart of the change of YS with SC and PEO. According to the comparison

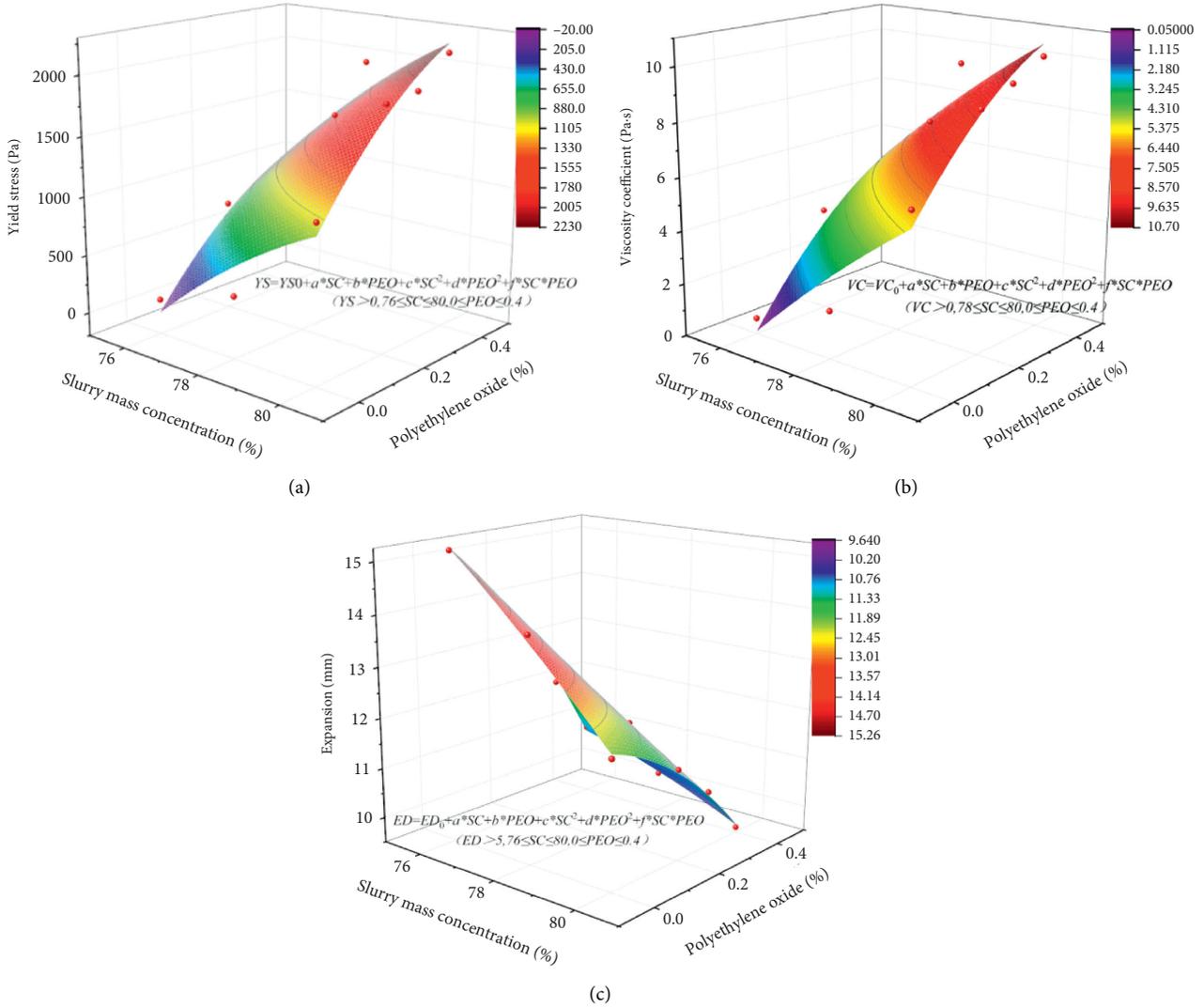


FIGURE 8: Influence curve of SC and PEO on the rheological properties of the filling slurry. (a) Curve of YS with SC and PEO. (b) Curve of VC with SC and PEO. (c) Curve of ED with SC and PEO.

of various fitting results, the expression of YS with SC and PEO is shown in formula (18) by referring to general formula (5), and the relevant parameters and R^2 are shown in Table 18.

$$\begin{aligned}
 YS = & YS_0 + a * SC + b * PEO + c * SC^2 + d * PEO^2 \\
 & + f * SC * PEO, \quad (YS > 0, 76 \leq SC \leq 80, 0 \leq PEO \leq 0.4).
 \end{aligned}
 \tag{18}$$

Figure 8(b) is the curve chart of the change of VC with SC and PEO, and its regularity is very consistent with YS. The fitting formula is shown in formula (19), where constants and R^2 are shown in Table 19.

$$\begin{aligned}
 VC = & VC_0 + a * SC + b * PEO + c * SC^2 + d * PEO^2 \\
 & + f * SC * PEO, \quad (VC > 0, 76 \leq SC \leq 80, 0 \leq PEO \leq 0.4).
 \end{aligned}
 \tag{19}$$

Figure 8(c) is the curve chart of the change of ED with SC and PEO. The fitting formula is shown in formula (20), where constants and R^2 are shown in Table 20.

$$\begin{aligned}
 ED = & ED_0 + a * SC + b * PEO + c * SC^2 + d * PEO^2 \\
 & + f * SC * PEO, \quad (ED > 5, 76 \leq SC \leq 80, 0 \leq PEO \leq 0.4).
 \end{aligned}
 \tag{20}$$

PEO, as a kind of viscous polymer, has the properties of flocculation, thickening, slow release, lubrication, dispersion, drag reduction, water retention, etc. Its application in the mining field is mainly as a flocculant for tailing thickening. However, the drag reduction is a special turbulent phenomenon. In nonturbulent fluid, there is no turbulent vortex dissipation due to the effect of the viscous force of the fluid itself, so addition of the drag-reduction agent cannot play a role but will increase the consistency and viscosity of the fluid. Because the high-concentration tailings do not show turbulence state, adding PEO cannot reduce the drag effect but reduce its fluidity. The above test results also prove this conclusion. However, when the filling aggregate is a poor-graded material containing coarse particles, it can be considered

TABLE 18: Constants and R^2 for regression of SC and PEO to YS.

YS_0	a	b	c	d	f	R^2
-142519.213	3415.772	-2932.152	-20.272	-3692.803	93.264	0.958

TABLE 19: Constants and R^2 for regression of SC and PEO to VC.

VC_0	a	b	c	d	f	R^2
-426.647	9.653	31.064	-0.053	-15.758	-0.150	0.955

TABLE 20: Constants and R^2 for regression of SC and PEO to ED.

VC_0	a	b	c	d	f	R^2
-76.550	3.108	-101.826	-0.025	-9.167	1.243	0.995

to add a proper amount of drag reducer to improve its performance or to use the water reducer and drag reducer together to improve the fluidity of the slurry.

4. Discussion

In order to improve the strength of the filling body, increase the concentration of the filling slurry, reduce the resistance of pipeline transportation, and fully dispose of solid waste resources, addition of various kinds of additional materials has gradually become a hotspot in the theoretical research and engineering application of tailing-cemented filling.

As a kind of cementitious mineral material, fly ash is widely used as a partial substitute of filling cementitious material or as fluidity improver of the filling slurry. The test results show that the addition of fly ash is not conducive to improving the fluidity of the slurry in the cemented filling of full tailings with high content of fine particles. Therefore, reasonable slurry concentration should be determined according to the rheological properties of the slurry in the cemented filling of the full tailings with high content of fly ash. When the tailings with large particle size or discontinuous grading are filled, fly ash can be added to prevent the segregation, settlement, and bleeding of the slurry.

Polycarboxylate superplasticizer is an effective superplasticizer for high-concentration tailing slurry. The test results show that when adding 0.6% superplasticizer for the high-concentration slurry with 80% mass concentration, the rheological parameters such as yield stress and viscosity decrease sharply, showing good water-reducing effect. However, addition of the water-reducing agent may lead to the segregation and settlement of the slurry, which needs to be combined with the segregation and bleeding characteristics of the slurry in the future research and select an economic and reasonable amount of the water-reducing agent. At the same time, another phenomenon is also noteworthy, that is, during the test process, it is not ruled out that the nonuniformity of slurry concentration caused by slurry segregation affects the test results, which requires further improvement of the test method to ensure the accuracy of the test.

PEO is not suitable for the resistance reduction of the filling slurry. The test results show that the yield stress and viscosity of the slurry will increase sharply when PEO is

added to the high concentration of the full-tailing filling slurry, even the yield stress of the slurry will increase to 9.48 times of the original. However, this cannot completely deny the application of PEO in filling engineering. May be adding some drag-reducing agents and water-reducing agents at the same time can improve the flow performance of the slurry with coarse particles and poor-grading filling materials.

This paper does not consider the influence of fly ash, polycarboxylate superplasticizer, polyethylene oxide, and other additives on the setting time of the filling slurry, early strength, and late strength of the filling body. These problems are the key indicators in specific filling engineering, and we will further study these in the future.

5. Conclusions

In order to study the influence of fly ash and chemical admixtures on the rheological properties of high-concentration full-tailing filling slurry, this paper takes the full-tailing filling slurry with different concentrations as the research object and tests the yield stress, viscosity coefficient, and expansion of the filling slurry after adding corresponding admixtures, respectively, and draws the following conclusions:

- (1) Both fly ash and chemical admixtures have great influence on the rheological properties of the high-concentration full-tailing filling slurry. When other conditions are certain, the fluidity of the slurry will be worse with the increase of the fly ash content, but the fluidity of the slurry will be improved with the increase of the water-reducing agent; the drag-reducing agent is not suitable for improving the fluidity of the high-concentration filling slurry, and the fluidity of the slurry will worsen rapidly with the increase of the water-reducing agent.
- (2) The quadratic polynomial $y = a + bx + cx^2$ can be used to fit the change regularities of the yield stress, viscosity coefficient, and expansion degree of the slurry with a single factor of a specific admixture, the binary quadratic polynomial $Z = Z_0 + ax + by + cx^2 + dy^2 + fxy$ can be used to fit the change regularities of the two factors of a specific admixture and slurry concentration, and R^2 of all the fitting formulas is greater than 0.950.
- (3) There are many factors that affect the rheological properties of the filling slurry, and the influence of additives is also affected by these factors. In the project, it is not only based on the above conclusions to determine whether addition of an admixture is reasonable but also based on the specific conditions and main objectives such as the characteristics of the filling aggregate.

Data Availability

All data are available within the article and can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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