Research Article

Experimental Study on Fluid Properties of Cement-Fly Ash Slurry Subjected to Multifactors

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There are many factors affecting the characteristics of cement-fly ash slurry in practical engineering. Thus, this paper studies the influence of multifactors on the fluid properties of cement-fly ash slurry based on water-cement ratio (w/c) (0.75, 1, 1.25, and 1.5), fly ash content (0%, 10%, 20%, 30%, 40%, and 50%) and temperature (20°C, 40°C, 60°C, and 80°C). The bleeding ratio, initial setting time, final setting time, and viscosity were analyzed under coupling conditions. It is found that the water-cement ratio (w/c) is the main factor that affects the rheological properties and bleeding rate of slurry. The temperature affects the stability of the slurry in terms that the bleeding ratio of the slurry decreases as the temperature increases. The addition of fly ash enhances the stability of the slurry under different temperature conditions.

1. Introduction

Since the wide-scale combustion of coal for power generation, millions of tons of ash and related by-products have been produced. The current annual production of coal ash worldwide is estimated around 600 million tons, with fly ash constituting about 500 million tons at 75–80% of the total ash produced [1]. Therefore, the amount of fly ash released by factories and thermal power plants has been increasing worldwide, and the disposal of large amounts of fly ash has become a serious problem. Fly ash is a resource yet to be fully utilized. The geotechnical properties of fly ash (e.g., specific gravity, permeability, internal angular friction, and consolidation characteristics) make it suitable for use in construction of roads, embankments, and structural fill. The pozzolanic properties of the ash, including its lime-binding capacity, make it useful for the manufacture of cement and building material concrete and concrete-admixed products. Nowadays, fly ash has been used in many fields successfully [1–7]. Fly ash has many advantages to cement slurry, for example, reducing the cost and the rate of water separation [8]; the fly ash has been commonly used as a blending agent to enhance various properties of slurry. At the same time, the slurry will be affected by many factors, resulting in changes of the characteristics of the slurry.

It is found that the viscosity of the slurry, as well as thickening time, rheology, and setting time, varied significantly with temperature [9, 10]. Thus, it is necessary to find how the temperature affects the characteristics of the slurry, which is important for the real projects. Du et al. [11] pointed that high temperature is the key factor in the formation of fly ash activity. Fly ash with activity and cement forms a stable cement body. Lee et al. [12] presented that the increase of temperature resulted in lower shear stress of the slurry mixtures. At the same time, the differences of shear stresses showed less sensitivity at high temperatures, indicating that the high temperature accelerated the hydration of fly ash. Alexandersson and Wallevik [13] analyzed the effect of pressure and temperature on cement slurry and found that temperature had a much larger effect on the loss of cement slurries than pressure, which revealed that elevated temperature accelerated the hydration reaction.

The flow behavior of slurry is controlled by the concentration and flocculating extent of the particles. The viscosity
increases with the increase of volume fraction of solids and degree of flocculation [14]. Bentz et al. [15] also pointed out that the rheological properties of cement-based slurry depend strongly on mixture proportions and the characteristics of the components. Thus, the concentration of particles which is usually represented by \( w/c \) is important for understanding the characteristics of the cement-fly ash slurry. The addition of fly ash can change the characteristics of the cement slurry; for example, the proper content of fly ash can reduce the yield stress and plastic viscosity of the slurry [16, 17]. Mirza et al. [18] indicated that the cement grout with fly ash reduced the flow time and drying shrinkage, improved the stability, and attained similar compressive and shear bond strengths as pure cement grouts. Lee et al. [19] investigated the effect of particle size distribution (PSD) of cement-fly ash on the fluidity of the slurry and found that the fluidity increases as the PSD becomes wider. A. Kashani et al. [4] obtained the similar results and found that a small addition of fly ash had a significant effect on workability because of its broad PSD. Xie et al. [20] analyzed the effects of fly ash on shearing thinning and thickening of cement slurry. It was presented that at the shear thinning stage, when fly ash content was less than 50%, the rheological parameters decreased with the increase of fly ash content, while the rheological parameters increased with increasing fly ash content when fly ash content was beyond 50%. At the shear thickening stage, the rheological parameters increased with increasing fly ash content.

In this paper, the properties of cement-fly ash slurry subjected to multiple factors were tested, which were aimed at providing references for underground engineering under complex conditions.

2. Materials and Methods

Portland cement (P.C 32.5R) and fly ash (class II) were prepared in this study, which are presented in Figures 1 and 2. The particle size distribution curves of cement and cement with different contents of fly ash are shown in Figures 3–8.

In this study, the cement with the fly ash content of 0%, 10%, 20%, 30%, 40%, and 50% was made into slurries with different \( w/c \) (\( w/c = 1.5, 1.25, 1, \) and 0.75, respectively) for 24 kinds of slurry samples. The physical composition of the slurries in this study is shown in Table 1. The slurries were prepared by using WT-2000C frequency conversion high-speed mixer, whose maximum speed was 13,000 rpm. The mixing procedure was 10-minute mixing at low speed, 5-minute rest, and another 10-minute mixing at high speed to avoid false set.

In order to analyze the effect of temperature on slurry, the slurries were heated to 20°C, 40°C, 60°C, and 80°C, respectively, by constant temperature water baths. At constant temperature, pipettes were used to suck out bleeding once every 10 minutes and once every 20 minutes after 60 minutes, until there is no bleeding for three consecutive times. Bleeding rate measurement was completed. The bleeding rate test is shown in Figure 9. The slurries of standard consistency were prepared according to the specifications and cured at the set temperature. The initial setting time and final setting time of the slurry were measured with a Vicat apparatus. The setting time test is shown in Figure 10.

After heating the slurries to the set temperature, a six-speed rotary viscometer (ZNN-D6B) was used to measure the rheological properties of the slurries quickly. The slurries were measured from high speed to low speed (from 600 r/min to 3 r/min). The slurry viscosity test is shown in Figure 11.

3. Results and Discussion

3.1. Bleeding Ratio. Experiments were carried out to analyze the effect of different factors on bleeding ratio. The slurry was injected into the beakers with 200 ml volume, and then, the top of the beakers was sealed to prevent evaporation. The results of bleeding ratio are shown in Figures 12–17.

Figures 12–17 indicated that the bleeding ratio of all slurry samples decreased as the temperature increased. The magnitude curves of cement slurries without fly ash showed larger variation than that with fly ash. The bleeding rate curve of cement slurries with low fly ash content decreased greatly at 40°C and became relatively flat with the increase of fly ash content. At the same temperature, the bleeding ratio was positively correlated to the \( w/c \). With the increase of fly ash content, the differences of bleeding ratio under each temperature condition gradually decreased, especially at the fly ash content of 40% and 50%. In addition, fly ash content had significantly larger influence on bleeding rate of high \( w/c \) than that...
Figure 3: PSD of cement.

Figure 4: PSD of cement with 10% fly ash.

Figure 5: PSD of cement with 20% fly ash.
Figure 6: PSD of cement with 30% fly ash.

| Particle (μm) | Content (%) |
|---------------|-------------|
| 0.000-0.400    | 0.00        |
| 0.400-0.843    | 1.64        |
| 0.843-1.780    | 1.52        |
| 1.780-3.754    | 4.00        |
| 3.754-7.921    | 12.05       |
| 7.921-16.700   | 14.77       |
| 16.700-35.240  | 33.32       |
| 35.240-74.350  | 28.82       |
| 74.350-156.800 | 2.41        |
| 156.800-330.900| 1.47        |

Figure 7: PSD of cement with 40% fly ash.

| Particle (μm) | Content (%) |
|---------------|-------------|
| 0.000-1.906   | 0.00        |
| 1.906-3.471   | 0.39        |
| 3.471-6.323   | 1.21        |
| 6.323-11.510  | 1.43        |
| 11.510-20.970 | 2.73        |
| 20.970-38.210 | 7.80        |
| 38.210-69.600 | 6.11        |
| 69.600-126.700| 3.96        |
| 126.700-230.900| 37.06      |
| 230.900-420.600| 39.31      |

Figure 8: PSD of cement with 50% fly ash.
of low water-cement ratio slurry. Before the slurry solidifies, water appeared on the surface, which was a kind of water seepage realization. When the water and cement cannot mix completely and the substance is in a fluid-solid dispersion state, water seepage will occur. The above description shows that cement cannot maintain a stable mixing state with water under low-temperature conditions. It can mix well under high-temperature conditions without separating, resulting in low bleeding rate. Fly ash can mix well with water under all temperature conditions. Thus, temperature is a key factor affecting the bleeding rate of the slurry, and fly ash is a very effective seepage reducer.

Figures 18–21 showed that under the condition of the same w/c, the bleeding ratio of the slurries had the largest change amplitude at 20°C in different fly ash content conditions. Compared to the slurries with fly ash, the bleeding rate
Figure 12: Relationship of bleeding ratio and temperature (0% fly ash).

Figure 13: Relationship of bleeding ratio and temperature (10% fly ash).

Figure 14: Relationship of bleeding ratio and temperature (20% fly ash).

Figure 15: Relationship of bleeding ratio and temperature (30% fly ash).

Figure 16: Relationship of bleeding ratio and temperature (40% fly ash).

Figure 17: Relationship of bleeding ratio and temperature (50% fly ash).
Figure 18: Relationship of bleeding ratio and fly ash content ($w/c = 0.75$).

Figure 19: Relationship of bleeding ratio and fly ash content ($w/c = 1.0$).

Figure 20: Relationship of bleeding ratio and fly ash content ($w/c = 1.5$).

Figure 21: Relationship of bleeding ratio and fly ash content ($w/c = 1.5$).

Figure 22: Relationship of setting time and temperature (0% fly ash).

Figure 23: Relationship of setting time and temperature (10% fly ash).
presented greater variation range for cement slurries without fly ash. When the w/c was 0.75 or 1.0, at 20°C and 40°C, the bleeding rate of the slurries decreased with the increase of the content of fly ash. At 60°C and 80°C, the bleeding rate of the slurries increased with the increase of the content of fly ash. When the w/c was 1.25 or 1.5, at 20°C, 40°C, and 60°C, the bleeding rate of slurries decreased with the increase of fly ash content. The bleeding rate of slurry increased with the increase of fly ash content at 80°C. It can be seen from Figure 21 that under high w/c, the difference of slurries at different temperatures was obvious. Water and cement could not mix completely and were in a fluid-solid dispersion state. This phenomenon was more pronounced under high water-cement ratio. Under the condition of 20°C~60°C, the content of fly ash in the slurry increased, which greatly improved the degree of mixing with water, and the bleeding rate dropped rapidly. At 80°C, cement and water were fully mixed, and the mixing degree was higher than fly ash. Meanwhile, the bleeding rate increased. This indicates that under low-temperature conditions, the cement with high fly ash content can maintain a low bleeding rate. Under high-temperature conditions, the mixing degree of fly ash and water is lower than that of ordinary cement, so cement with low fly ash content can maintain a low bleeding rate.

3.2. Setting Time. The initial and final setting times are basic parameters to evaluate the rheological stage. The setting time has been analyzed under different temperature and fly ash content conditions. The relationship between setting time and temperature is shown in Figures 22–27.
It can be obtained that both the initial setting time and the final setting time decrease as temperature increases. Setting time decreased rapidly from 20°C to 40°C; the setting time decreased slowly from 40°C to 80°C. At the same temperature, the interval between the initial setting time and the final setting time also increased with the increase of the content of fly ash. At the same time, the initial setting time and the final setting time increased as the content of fly ash increased. The results show that the setting time depends on the speed of the hydration reaction between the particles and water. The hydration reaction of cement and water is active while fly ash is inert. The setting time of cement with a high content of fly ash is longer. Temperature has a great influence on the hydration reaction. Under high-temperature conditions, the hydration reaction activity of cement and fly ash increases.

3.3. Viscosity. Viscosity is one of the most important parameters in analyzing characteristics of slurry. The viscosity of slurry under different conditions was studied and presented in Figures 28–31. In fitting equations, \( \tau \) represents the shear stress, and \( \gamma \) represents the shear rate. The relationship of shear stress and shear rate of cement slurry without fly ash is shown in Figures 28–31. The fitting line parameters of cement slurry are shown in Tables 2–5. It can be seen that as w/c decreased, the shear stresses of the slurry gradually increased. The cement slurry was typically in Bingham type, except that under conditions of 1.5 of w/c, 20°C and 40°C, the slurries were Newtonian which is shown in Figure 28. At the temperature of 80°C, the shear stress was greater than that in other conditions, especially at
0.75 of \( w/c \), which is shown in Figure 31. Thus, it can be seen that the rheological properties of the cement slurries were significantly affected by high temperature. Except for the condition of 80°C, the shear stresses did not show significant difference at 20°C, 40°C, and 60°C. The slope of the fitting lines indicated the viscosity of the slurries. At high water-cement ratio, the viscosity of the slurries at different temperatures was approximately the same. At low water-cement ratio, the viscosity of high-temperature slurries was much greater than that of low-temperature slurries. The results show that the \( w/c \) affects the viscosity of the slurry. A decrease in the \( w/c \) means a high solid concentration, which directly leads to an increase in the number of particle-particle contacts, thereby increasing the gel formation rate. At the same time, temperature also affects the viscosity of the slurry. Under high-temperature conditions, the hydration reaction accelerates, resulting in a large number of gel products, which increases the shear stress of the slurry.

The relationship of shear stress and shear rate of the slurry with \( w/c \) of 1.5 and different fly ash contents is shown in Figures 32–36. The fitting line parameters of cement slurry with a \( w/c \) of 1.5 are shown in Tables 6–10. The slurries with a \( w/c \) of 1.5 were Bingham fluid under various temperature conditions regardless of fly ash content. When the slurries contained 10%, 20%, and 30% fly ash, the shear stress at 80°C was larger than that in other temperatures. The shear stress increased with the increase of temperature. However, when the slurries contained 40% or 50% fly ash...
ash, the change of shear stress was not obvious with temperature. It can be seen from the slope of the fitting lines that the viscosity of high-temperature slurries was much greater than that of low-temperature slurries at low fly ash content. With high fly ash content, the viscosity of high-temperature slurries was very close to that of low-temperature slurries. It is summarized that in slurries with high fly ash content, a large amount of fly ash is adsorbed on the surface of the cement particles, which acts as a lubrication for the mixed slurry. At the same time, steric hindrance forms between cement particles, which increases the distance between the particles, resulting in an insignificant effect of temperature on the slurry.

The relationship of shear stress and shear rate of the slurry with a w/c of 1.25 and different fly ash contents is shown in Figures 37–41. The fitting line parameters of cement slurry with a w/c of 1.25 are shown in Tables 11–15. The slurries with a w/c of 1.25 were Bingham fluid under all temperature conditions regardless of fly ash content. With the increase of fly ash content, the influence of temperature on the shear stress of slurry became smaller. According to the fitting lines of slurries containing 40% or 50% fly ash, the shear stress and viscosity of slurry at 60°C were higher than those of other temperatures. This shows that under
Figure 40: Viscosity of cement slurry with a w/c of 1.25 (40% fly ash).

Figure 41: Viscosity of cement slurry with a w/c of 1.25 (50% fly ash).

Figure 42: Viscosity of cement slurry with a w/c of 1.0 (10% fly ash).

Figure 43: Viscosity of cement slurry with a w/c of 1.0 (20% fly ash).

Figure 44: Viscosity of cement slurry with a w/c of 1.0 (30% fly ash).

Figure 45: Viscosity of cement slurry with a w/c of 1.0 (40% fly ash).
Figure 46: Viscosity of cement slurry with a w/c of 1.0 (50% fly ash).

Figure 47: Viscosity of cement slurry with a w/c of 0.75 (10% fly ash).

Figure 48: Viscosity of cement slurry with a w/c of 0.75 (20% fly ash).

Figure 49: Viscosity of cement slurry with a w/c of 0.75 (30% fly ash).

Figure 50: Viscosity of cement slurry with a w/c of 0.75 (40% fly ash).

Figure 51: Viscosity of cement slurry with a w/c of 0.75 (50% fly ash).
Table 2: Fitting line parameters of cement slurry with a w/c of 1.5.

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00538y + 0.28635$ | 0.95476 |
| 40°C line     | $\tau = 0.00559y + 0.41617$ | 0.94752 |
| 60°C line     | $\tau = 0.00552y + 0.57185$ | 0.97529 |
| 80°C line     | $\tau = 0.00588y + 1.56598$ | 0.95505 |

Table 3: Fitting line parameters of cement slurry with a w/c of 1.25.

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00554y + 0.33160$ | 0.95006 |
| 40°C line     | $\tau = 0.00566y + 0.25790$ | 0.92251 |
| 60°C line     | $\tau = 0.00523y + 1.14035$ | 0.98817 |
| 80°C line     | $\tau = 0.00626y + 2.26900$ | 0.87904 |

Table 4: Fitting line parameters of cement slurry with a w/c of 1.0.

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00812y + 2.18322$ | 0.94968 |
| 40°C line     | $\tau = 0.00702y + 2.57572$ | 0.88841 |
| 60°C line     | $\tau = 0.01289y + 4.02923$ | 0.85417 |
| 80°C line     | $\tau = 0.02359y + 5.37658$ | 0.91821 |

Table 5: Fitting line parameters of cement slurry with a w/c of 0.75.

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.02023y + 2.81153$ | 0.99473 |
| 40°C line     | $\tau = 0.02317y + 4.05143$ | 0.93401 |
| 60°C line     | $\tau = 0.02656y + 7.88834$ | 0.92246 |
| 80°C line     | $\tau = 0.05422y + 13.56824$ | 0.87535 |

Table 6: Fitting line parameters of cement slurry with a w/c of 1.5 (10% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00179y + 1.10208$ | 0.64749 |
| 40°C line     | $\tau = 0.00184y + 1.13701$ | 0.67400 |
| 60°C line     | $\tau = 0.00563y + 1.38457$ | 0.92246 |
| 80°C line     | $\tau = 0.00577y + 1.72187$ | 0.87535 |

Table 7: Fitting line parameters of cement slurry with a w/c of 1.5 (20% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00231y + 1.00712$ | 0.71350 |
| 40°C line     | $\tau = 0.00256y + 0.98716$ | 0.83594 |
| 60°C line     | $\tau = 0.00608y + 0.99677$ | 0.89206 |
| 80°C line     | $\tau = 0.00588y + 1.26649$ | 0.91687 |

Table 8: Fitting line parameters of cement slurry with a w/c of 1.5 (30% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00290y + 1.08761$ | 0.81126 |
| 40°C line     | $\tau = 0.00334y + 1.02191$ | 0.84168 |
| 60°C line     | $\tau = 0.00434y + 1.09564$ | 0.91004 |
| 80°C line     | $\tau = 0.00488y + 1.10883$ | 0.93151 |

Table 9: Fitting line parameters of cement slurry with a w/c of 1.5 (40% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00361y + 0.89554$ | 0.88311 |
| 40°C line     | $\tau = 0.00391y + 0.94384$ | 0.91420 |
| 60°C line     | $\tau = 0.00479y + 0.88938$ | 0.95390 |
| 80°C line     | $\tau = 0.00443y + 1.09727$ | 0.93335 |

Table 10: Fitting line parameters of cement slurry with a w/c of 1.5 (50% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00352y + 1.14304$ | 0.88672 |
| 40°C line     | $\tau = 0.00393y + 1.26980$ | 0.88245 |
| 60°C line     | $\tau = 0.00445y + 1.10675$ | 0.91255 |
| 80°C line     | $\tau = 0.00420y + 1.29237$ | 0.90046 |

Table 11: Fitting line parameters of cement slurry with a w/c of 1.25 (10% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00195y + 1.28122$ | 0.69199 |
| 40°C line     | $\tau = 0.00320y + 1.38678$ | 0.81746 |
| 60°C line     | $\tau = 0.00641y + 1.30169$ | 0.98364 |
| 80°C line     | $\tau = 0.00775y + 1.75856$ | 0.95716 |

Table 12: Fitting line parameters of cement slurry with a w/c of 1.25 (10% fly ash).

| Fitting lines | Fitting equations | $R^2$ |
|---------------|-------------------|-------|
| 20°C line     | $\tau = 0.00311y + 1.18156$ | 0.89933 |
| 40°C line     | $\tau = 0.00595y + 0.65804$ | 0.96231 |
| 60°C line     | $\tau = 0.00636y + 1.28504$ | 0.98034 |
| 80°C line     | $\tau = 0.00761y + 1.63880$ | 0.96079 |

the conditions of high temperature and high fly ash content, the viscosity reduction effect caused by the lubricating effect of fly ash on the slurries is greater than the viscosity increase effect formed by the accelerated hydration at high temperature.
The relationship of shear stress and shear rate of the slurry with a w/c of 1.0 and different fly ash contents is shown in Figures 42–46. The fitting line parameters of cement slurry with a w/c of 1.0 are shown in Tables 16–20.

Under the condition of low fly ash content, the viscosity of the slurries increased obviously with the increase of temperature. Under the condition of high fly ash content, the viscosity of the slurries at each temperature was almost the same. As the w/c of the slurries reduced, the viscosity of the slurries at different temperatures varied greatly when the fly ash content was 10%. The reduction of water-cement ratio resulted in a greater influence of physical composition and temperature on the viscosity of the slurries.
All other cases were Bingham fluid to lubricate the mixed slurry. At the same time, steric hindrance from the adsorption of fly ash can be adsorbed on the surface of cement particles, increasing the steric hindrance between cement particles and reducing the contact, which is conducive to gel formation. In the case of low water-cement ratio, the slurry was Bingham fluid, and in the case of high water-cement ratio (water-cement ratio of 1.5), it was Newtonian fluid.

The steric hindrance, which was formed by the adsorption of fly ash, at a temperature of 20 °C and 40°C. The slurry in all other cases were Bingham fluid. The w/c, slurry temperature, and fly ash content are the main factors affecting the rheological properties of the slurries. The w/c determines the solid concentration in the slurry, and the number of contacts between particles affects the rate of gel formation. The slurry temperature controls the rate of cement hydration reaction, thereby affecting the rate of gel product formation. Fly ash can be adsorbed on the surface of cement particles to lubricate the mixed slurry. At the same time, steric hindrance is formed between the cement particles, which increases the distance between the particles, resulting in insignificant influence of temperature on the slurry. The flowability is an important parameter relative to grout design. The slurry with high water-cement ratio and high fly ash content has good fluidity and low viscosity and is preferably injected into small cracks or increases the distance of penetration into the cracks. The slurry with a low water-cement ratio and a low fly ash content with a higher viscosity might be preferred to limit penetration or fill wider fractures.

### Table 23: Fitting line parameters of cement slurry with a w/c of 0.75 (30% fly ash).

| Fitting lines | Fitting equations       | $R^2$ |
|---------------|-------------------------|-------|
| 20°C line     | $\tau = 0.02052y + 5.34630$ | 0.86686 |
| 40°C line     | $\tau = 0.02366y + 6.75101$ | 0.82060 |
| 60°C line     | $\tau = 0.02322y + 7.16873$ | 0.84023 |
| 80°C line     | $\tau = 0.02203y + 8.15868$ | 0.74869 |

### Table 24: Fitting line parameters of cement slurry with a w/c of 0.75 (40% fly ash).

| Fitting lines | Fitting equations       | $R^2$ |
|---------------|-------------------------|-------|
| 20°C line     | $\tau = 0.02104y + 5.64867$ | 0.79386 |
| 40°C line     | $\tau = 0.02210y + 5.98633$ | 0.82143 |
| 60°C line     | $\tau = 0.02167y + 6.91662$ | 0.73942 |
| 80°C line     | $\tau = 0.02001y + 7.48812$ | 0.70589 |

### Table 25: Fitting line parameters of cement slurry with a w/c of 0.75 (50% fly ash).

| Fitting lines | Fitting equations       | $R^2$ |
|---------------|-------------------------|-------|
| 20°C line     | $\tau = 0.01694y + 5.07298$ | 0.82282 |
| 40°C line     | $\tau = 0.01831y + 5.25300$ | 0.84752 |
| 60°C line     | $\tau = 0.01915y + 5.59929$ | 0.82224 |
| 80°C line     | $\tau = 0.01755y + 6.03016$ | 0.80373 |

The relationship of shear stress and shear rate of the slurry with a w/c of 0.75 and different fly ash contents is shown in Figures 47–51. The fitting line parameters of cement slurries with a w/c of 0.75 are shown in Tables 21–25.

When w/c is 0.75, the slurries were also Bingham fluid. The shear stresses of the slurries with 10% fly ash at 80°C were much larger than those of the slurry at lower temperature, which was similar to the rheological behavior of the cement slurries without fly ash. With the increase of fly ash content, the shear stress of slurries at 80°C decreased rapidly. When the slurries contained 30%, 40%, and 50% fly ash, the shear stress of slurries was almost the same at each temperature. The steric hindrance, which was formed by the adsorption of fly ash particles on the surface of cement particles, makes the slurry insensitive to temperature.

The slurries were Newtonian fluid only with a w/c of 1.5, no fly ash, at a temperature of 20 °C and 40°C. The slurries in all other cases were Bingham fluid. The w/c, slurry temperature, and fly ash content are the main factors affecting the rheological properties of the slurries. The w/c determines the solid concentration in the slurry, and the number of contacts between particles affects the rate of gel formation. The slurry temperature controls the rate of cement hydration reaction, thereby affecting the rate of gel product formation. Fly ash can be adsorbed on the surface of cement particles to lubricate the mixed slurry. At the same time, steric hindrance is formed between the cement particles, which increases the distance between the particles, resulting in insignificant influence of temperature on the slurry. The flowability is an important parameter relative to grout design. The slurry with high water-cement ratio and high fly ash content has good fluidity and low viscosity and is preferably injected into small cracks or increases the distance of penetration into the cracks. The slurry with a low water-cement ratio and a low fly ash content with a higher viscosity might be preferred to limit penetration or fill wider fractures.

### 4. Conclusions

This work considers the influence of multifactors on fluid properties of cement-fly ash slurry. The bleeding rate, setting time, and viscosity of slurry were tested and analyzed. The following conclusions can be drawn:

1. The water-cement ratio is a key factor affecting the rheology of the slurry. A low water-cement ratio means a high solid concentration and a large amount of particle contact, which is conducive to gel formation. In the case of low water-cement ratio, the slurry was Bingham fluid, and in the case of high water-cement ratio (water-cement ratio of 1.5), it was Newtonian fluid.

2. The temperature affects the stability of the slurry. High temperature can increase the hydration reaction speed, leading to a rapid increase in gelling components, which can greatly shorten the initial setting time and final setting time, and increase the viscosity of the slurry. Therefore, the setting time of the cement slurry can be adjusted by the temperature and the fluidity of the slurry can be improved by the temperature.

3. Fly ash can mix well with water under any temperature conditions. Fly ash can prolong the solidification time of the slurry. In addition, fly ash can be adsorbed on the surface of cement particles, increasing the steric hindrance between cement particles and reducing the influence of temperature on the rheological properties of the slurry.

### 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 there is no conflict of interest regarding the publication of this paper.

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