Study on Rheological Properties of Vibrating Mixing Concrete Based on Orthogonal Test

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Abstract. In order to study the different effects of amplitude, vibration frequency, mixing linear velocity and mixing time on the rheological properties of C60 high-performance concrete, the orthogonal test study was carried out. Through the method of range and variance analysis to analyse the yield stress and plastic viscosity of the fresh concrete, the main order of the influence of various factors on the rheological properties of the fresh concrete was the amplitude → mixing time → mixing linear velocity → vibration frequency. The influence of various factors on the rheological properties of concrete and its influencing mechanism were analyzed by test data. The results show that the application of vibration during the mixing process can significantly improve the fluidity of fresh concrete.

1. Introduction
Concrete is a widely used building material. The performance of fresh concrete, such as workability and pumpability, is difficult to accurately evaluate. With the continuous development of rheological research, the use of rheological knowledge to analyze and evaluate the performance of fresh concrete is considered to be a relatively effective approach and method at present [1].

For a long time, fresh concrete has been regarded as Bingham fluid. It is reasonable to use Bingham model to describe the rheological properties of concrete [2-3]. The slump is only used to describe the yield stress of fresh concrete, but it cannot characterize its plastic viscosity [4], G H Tattersall and Banfill in the UK advocated a two-point test method, considering yield stress and plastic viscosity as the basic parameters describing the rheological properties of fresh concrete [5]. Since the turn of the century, domestic and foreign scholars have proposed the use of slump data to determine the yield stress and the use of inverted slump data to determine the plastic viscosity. The calculation method used in this test is based on the formula proposed by Ferrari, Cao Mingli et al. [6-7].

On the research direction of fresh concrete rheology, on the one hand, the effects of different admixtures, mix ratios and admixtures on rheological properties of concrete [8-11]; on the other hand, the effect of different mixing methods, mixing time, etc. on rheological properties of concrete. The research shows that vibration mixing can improve the workability of concrete, increase concrete slump and expansion, reduce the slump time [12-14]; appropriate increase of mixing time can increase the concrete expansion and increase Homogenization. At present, there are few researches on the influence of vibration stirring parameters on rheological properties of fresh concrete. In this paper, the multi-factor orthogonal test is used to analyze the influence law and influence degree of stirring parameters (amplitude, vibration frequency, stirring line speed and stirring time) on the rheological properties of fresh concrete.
2. Raw materials and test methods

2.1. Raw materials and mix ratio

The test concrete strength grade is designed as C60. For raw materials, P·O 42.5 grade Portland cement is used, limestone crushed stone with 5~20mm continuous grade is used as coarse aggregate, and medium sand with fineness modulus is 2.4 as fine aggregate, standard high performance water reducer with effective water reduction rate of 20% as admixture, level of fly ash is grade II, and the mixed water used in the test is tap water. The concrete mix used in the test is shown in Table 1.

| Match ratio | Cement marking | Water/kg | Cement/kg | Fly ash/kg | Fine aggregate/kg | 5-10mm Coarse aggregate/kg | 10-20mm Coarse aggregate/kg | Water reducing agent/kg |
|-------------|----------------|----------|-----------|------------|-------------------|---------------------------|---------------------------|------------------------|
| P·O 42.5    | 170            | 435      | 95        | 700        | 315               | 735                       | 4.8                       |

2.2. experiment method

The fresh concrete has rheological properties and can be considered to conform to the Bingham model. The yield stress and plastic viscosity can be used together to reflect the rheology of the concrete.

The Bingham model expression is:

\[ \tau = \tau_0 + \eta \frac{dv}{dt} \]  

(1)

Where, \( \tau \) ——— Shear stress, Pa;  
\( \tau_0 \) ——— Yield stress of concrete, Pa;  
\( \eta \) ——— Plastic viscosity of concrete (viscosity coefficient), Pa·s;  
\( \frac{dv}{dt} \) ——— Shear rate.

In this test, the yield stress and plastic viscosity were calculated by measuring the slump of the fresh concrete, the fall time and the apparent density of the concrete. The calculation method of the yield stress \( \tau_0 \) is based on the calculation formula proposed by Ferraris according to the test [6]:

\[ \tau_0 = \frac{\rho}{347} (300 \cdot L) + 212 \]  

(2)

Where, \( \rho \) ——— Apparent density of fresh concrete, kg/m³;  
\( L \) ——— Slump of fresh concrete, mm.

The calculation method of shear stress \( \tau \) and shear rate \( \frac{dv}{dt} \) refers to the calculation formula proposed by Cao Mingli et.al [7]:

\[ \tau = f \cdot \rho \cdot h \]  

(3)

Where, \( \rho \) ——— Apparent density of fresh concrete, kg/m³;  
\( h \) ——— Slump bucket height, mm;  
\( f \) ——— Concrete friction coefficient.

Shear rate \( \frac{dv}{dt} \) calculation formula:

\[ \frac{dv}{dt} = \frac{9h}{4\tau} \]  

(4)

Where, \( t \) ——— the fall time of the slump.

Through the equation (2), the yield stress of the fresh concrete can be obtained, and the plastic viscosity can be reversed by the above equations (2), (3) and (4).
3. Test design

3.1. Orthogonal test plan design
In this test, the mixing equipment adopts DT60ZBW type double-shaft vibration mixing test machine produced by Detong Vibration Mixing Co., Ltd., as shown in Figure 1, the machine has two modes of common forced mixing and vibration mixing test. An orthogonal test scheme was designed by adjusting the vibration stirring parameters (amplitude, vibration frequency).

Figure 1. Double horizontal shaft vibration mixing test machine

Orthogonal test is an effective method to arrange multi-factor and multi-level test. In order to study the influence of amplitude, vibration frequency, mixing linear velocity and mixing time on the rheological properties of concrete, and reduce the number of tests, four factors are selected for each of the four levels. The factor level table is shown in Table 2, and the 16 group mix ratios are listed in Table 3.

| Factor | A | B | C | D |
|--------|---|---|---|---|
| Amplitude | Vibration frequency | Mixing linear velocity | Mixing time |
| 1 | 1.44 | 23 | 1.4 | 80 |
| 2 | 1.75 | 24 | 1.5 | 100 |
| 3 | 1.93 | 25 | 1.6 | 120 |
| 4 | 2.00 | 26 | 1.7 | 140 |

3.2 test result
The test results are shown in Table 3.

| Test number | A | B | C | D | Test results |
|-------------|---|---|---|---|--------------|
| Test number | Amplitude | Vibration frequency | Mixing linear velocity | Mixing time | Yield stress | Plastic viscosity | Segregation situation |
| 1 | 1 | 1 | 1 | 1 | 1356.38 | 560.86 | well |
| 2 | 1 | 2 | 2 | 2 | 1091.37 | 209.66 | well |
| 3 | 1 | 3 | 3 | 3 | 916.70 | 164.19 | well |
| 4 | 1 | 4 | 4 | 4 | 790.21 | 118.41 | well |
| 5 | 2 | 1 | 2 | 3 | 1019.09 | 636.60 | well |
| 6 | 2 | 2 | 1 | 4 | 1007.04 | 534.61 | well |
| 7 | 2 | 3 | 4 | 1 | 1103.41 | 719.59 | well |
| 8 | 2 | 4 | 3 | 2 | 1266.03 | 682.33 | well |
| 9 | 3 | 1 | 3 | 4 | 982.95 | 218.10 | well |
| 10 | 3 | 2 | 4 | 3 | 790.21 | 75.97 | well |
| 11 | 3 | 3 | 1 | 2 | 1043.18 | 435.89 | well |
| 12 | 3 | 4 | 2 | 1 | 995.00 | 445.36 | well |
| 13 | 4 | 1 | 4 | 2 | 778.17 | 304.66 | well |
| 14 | 4 | 2 | 3 | 1 | 772.14 | 305.79 | well |
| 15 | 4 | 3 | 2 | 4 | 754.07 | 172.55 | well |
| 16 | 4 | 4 | 1 | 3 | 772.14 | 305.41 | well |

4. Analysis of test results

4.1. Analysis of range and variance results
In order to investigate the influence of amplitude, vibration frequency, mixing linear velocity and mixing time on the yield stress and plastic viscosity of fresh concrete and find the significant influence factors. The statistical analysis software spss is used to analyze the results of the test. The range analysis results are shown in Table 4.

Table 4. Range Analysis Table

| Source | A (Amplitude) | B (Vibration frequency) | C (Mixing linear velocity) | D (Mixing time) |
|--------|---------------|-------------------------|---------------------------|-----------------|
| Yield stress | K1 4154.66 | 4136.59 | 4178.74 | 4226.93 |
|          | K2 4395.57 | 3660.76 | 3859.53 | 4178.75 |
|          | K3 3811.34 | 3817.36 | 3937.82 | 3497.44 |
|          | K4 3076.52 | 3828.38 | 3462 | 3534.27 |
|          | k1 1038.67 | 1034.15 | 1044.69 | 1056.73 |
|          | k2 1098.89 | 915.19 | 964.88 | 1044.69 |
|          | k3 952.84 | 954.34 | 984.46 | 874.36 |
|          | k4 769.13 | 955.85 | 865.5 | 883.57 |
| Plastic viscosity | K1 1053.12 | 1720.22 | 1836.77 | 2031.6 |
|          | K2 2573.13 | 1126.03 | 1464.17 | 1632.54 |
|          | K3 1175.32 | 1492.22 | 1370.41 | 1182.17 |
|          | K4 1088.41 | 1551.51 | 1394.32 | 1043.67 |
|          | k1 263.28 | 430.06 | 459.19 | 507.9 |
|          | k2 643.28 | 281.51 | 366.04 | 408.14 |
|          | k3 293.83 | 373.06 | 342.60 | 295.54 |
|          | k4 272.10 | 387.88 | 348.58 | 260.92 |
| Plastic viscosity | K1 1053.12 | 1720.22 | 1836.77 | 2031.6 |
|          | K2 2573.13 | 1126.03 | 1464.17 | 1632.54 |
|          | K3 1175.32 | 1492.22 | 1370.41 | 1182.17 |
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|          | k3 293.83 | 373.06 | 342.60 | 295.54 |
|          | k4 272.10 | 387.88 | 348.58 | 260.92 |

The variance analysis results are shown in Table 5.

Table 5. Variance analysis table

| Source | Class III square sum | Degrees of freedom | Mean square | F | Significant |
|--------|-----------------------|-------------------|-------------|---|-------------|
| Yield stress | Amplitude | 7401111.836 | 3 | 246703.945 | 11.012 | 0.000 |
|          | Vibration frequency | 90366.258 | 3 | 30122.086 | 1.345 | 0.276 |
|          | Mixing linear velocity | 200182.858 | 3 | 66727.619 | 2.978 | 0.045 |
|          | Mixing time error | 351088 | 3 | 117029.333 | 5.224 | 0.004 |
| Plastic viscosity | Amplitude | 1215066.341 | 3 | 405022.114 | 21.944 | 0.000 |
|          | Vibration frequency | 117613.685 | 3 | 39204.562 | 2.124 | 0.115 |
|          | Mixing linear velocity | 160424.819 | 3 | 53474.940 | 2.897 | 0.049 |
|          | Mixing time error | 445998.814 | 3 | 148666.271 | 8.055 | 0.000 |
|          | error | 645011.567 | 35 | 12053.216 |

The yield stress is used to describe the internal friction between the components of the concrete, and the plastic viscosity is used to describe the extent to which internal components of concrete impede relative flow. The data in Table 4 shows that the factors affecting the concrete yield stress and plastic viscosity are ranked from high to low as amplitude > mixing time > mixing linear velocity > vibration frequency. Combined with the variance analysis in Table 5, the amplitude and mixing time significance level is less than 0.01, and the mixing linear velocity significance level is less than 0.05.
The following conclusions can be drawn: amplitude and mixing time are extremely significant factors affecting the yield stress, and mixing linear velocity is a significant factor.

Among the influencing factors, although the vibration frequency does not reach a significant level, the sum of the squares of the deviations is larger than the square of the deviation of the errors, indicating that the results of this orthogonal test are reasonable.

4.2. The influence law of various factors

![Figure 2. Influence law of amplitude and vibration frequency](image)

Figure 2 shows a visual representation of the effects of amplitude and vibration frequency on yield stress and plastic viscosity by a line graph. In Figure 2(a), the yield stress and plastic viscosity of fresh concrete increase first and then decrease with increasing amplitude, when the amplitude is 1.75mm, the maximum is obtained. It is considered that the application of large amplitude is more likely to damage the viscous connection between the material particles. The cement particles which are originally in the aggregate state are dispersed, and the hydration reaction is more sufficient. The generated cement slurry can play a lubricating role, thereby reducing the plastic viscosity and yield stress of the concrete.

In Figure 2(b), the yield stress and plastic viscosity of fresh concrete decrease first and then increase with the increase of vibration frequency, the minimum value is at the vibration frequency of 24Hz, and the overall trend is reduced. It is considered that increase the vibration frequency can increase the number of vibrations per unit time. The high-frequency vibration helps to accelerate the rate of destruction of the agglomerated materials. The materials are more easily contacted, and the hydration reaction is easier to carry out, reducing the yield stress and plastic viscosity of the concrete.

![Figure 3. Influence law of mixing linear velocity and mixing time](image)

Figure 3 shows a visual representation of the effects of mixing linear velocity and mixing time on yield stress and plastic viscosity by a line graph. In Figure 3(a), the yield stress of fresh concrete decreases with the increase of linear velocity; the plastic viscosity decreases with the increase of linear velocity and finally stabilizes, and the overall trend of both decreases. It is considered that the increase of the linear velocity leads to an acceleration of the agitation process, the frequency of the materials participating in the movement and the frequency of the intersection of the movement trajectories are increased, the agglomeration of the material is reduced, and the yield stress and the plastic viscosity are lowered.

In Figure 3(b), the yield stress of fresh concrete decreases with the increase of stirring time and finally stabilizes; the plastic viscosity decreases significantly with the increase of stirring time and is always in a decreasing state. It is considered that increasing the stirring time can make the distribution of cement and other materials more uniform in the mixture, and the uniform dispersion of the
admixture makes the cement better hydration reaction, the fluidity of the concrete is improved, and the yield stress and plastic viscosity are lowered.

The analysis of the test results shows that the amplitude and stirring time are the main parameters affecting the rheology of the concrete. The larger the amplitude, the better the fluidity of the fresh concrete, so the amplitude can be 2mm. The vibration stirring can complete the mixing process ahead of the ordinary static stirring, the mixing time can be taken 120s, the stirring line speed takes the maximum value of 1.7m/s. Although the vibration frequency influence is not significant, the appropriate value of 24Hz can be selected, which is preferable in this test. This combination of parameters can effectively improve the fluidity of concrete.

4.3. Analysis of the influence mechanism of vibration stirring

Studies have shown that the concrete mixture with uniform macroscopic performance after mixing does not achieve microscopic uniformity. When the cement contacts with water, it will form flocculation clusters, some of the water in the flocculation group cannot participate in the hydration reaction; The surface of the cement particles gathered together is covered by the hydration product to prevent the water from entering, forming an internal dry cement agglomerate. The surface forces of the two agglomerated structures make the hydration reaction insufficient, and the fluidity of the fresh concrete decreases. Figure 4(a) shows the cement particles agglomerated into agglomerates.

At present, the stirring methods commonly used in engineering are mostly self-falling and forced, and the cement particles that cannot be completely destroyed by static stirring. The vibration stirring method studied by our research group will force the material to be in the “fluctuating” state with a certain amplitude and vibration frequency. On the one hand, it can aggravate the irregular movement of materials, improve the relative movement speed between various components of concrete, thereby destroying the dry powder agglomerates, so that the water can fully contact the surface of the material, reduce the internal friction of the material contact surface, and reduce the yield stress of the fresh concrete, which is manifested by an increase in concrete slump. On the other hand, the vibration will destroy the flocculation group, after the water is released, it will fully contact with the cement to form a hydration reaction. The generated hydrate will be wrapped on the surface of the material, which has good flowability and reduces the plastic viscosity of the fresh concrete, which is manifested by the emptying time of the bucket is reduced. By means of vibration mixing, the fresh concrete can reach the uniform distribution as shown in Figure 4(b) as much as possible, and the concrete flow performance can be effectively improved.

5. Conclusion

• Through orthogonal test, it is concluded that the primary and secondary order of the influencing factors of yield stress and plastic viscosity of fresh concrete are amplitude > mixing time > mixing linear velocity > vibration frequency. Amplitude and mixing time are extremely significant factors. The mixing linear velocity is a significant factor, and the vibration frequency has an effect but is not significant.

• Selecting the appropriate vibration stirring parameters can effectively improve the fluidity of the fresh concrete. According to the test results, the amplitude can be 2mm, the mixing time can be 120s,
the stirring line speed can be 1.7 m/s, and the vibration frequency can be 24 Hz. This combination of parameters can effectively improve the fluidity of concrete.

- The analysis of the test results shows that when vibration is applied during the agitation process, the flocculating clusters formed by the cement particles and the dry powder particles are significantly destroyed, and the hydration reaction is more sufficient, which can effectively improve the fluidity of the fresh concrete.

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