Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 4966062, 12 pages
https://doi.org/10.1155/2021/4966062

Research Article

Improved Powder Equivalence Model for the Mix Design of Self-Compacting Concrete with Fly Ash and Limestone Powder

Jingbin Zhang[1], **Miao Lv**[2], **Xuehui An**[2], **Dejian Shen**[1], **Xinyi He**[1] **and Ding Nie**[3]

[1]*College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China*
[2]*State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China*
[3]*China Institute of Water Resources and Hydropower Research, Beijing 100038, China*

Correspondence should be addressed to Miao Lv; lvm19@mails.tsinghua.edu.cn

Received 21 July 2021; Accepted 6 September 2021; Published 22 September 2021

Academic Editor: Shengwen Tang

Copyright © 2021 Jingbin Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The use of fly ash (FA) limestone and powder (LP) in combination with cement in concrete has several practical, ecological, and economic advantages by reducing carbon dioxide emissions, reducing the excessive consumption of natural resources, and contributing to a cleaner production of self-compacting concrete (SCC). A mix design method for SCC based on paste rheological threshold theory can guide the SCC mix design by paste tests. This method can be visualized by the self-compacting paste zone (SCP zone), a plane area where all the mix points meet the paste threshold theory, and SCC zone, a plane area consisting of all the mix points satisfying the criteria of qualified SCC. In the case of cement SCC, the SCP zone coheres with the SCC zone. However, in the case of the addition of FA or LP with different granulometry and shape characteristics from cement, experimental results indicate that the SCP zone is separated from the SCC zone. This work quantitatively studied the influence of FA and LP on the movement of the SCP zone by introducing the improved powder equivalence model. The improved model was obtained by powder equivalence coefficients calculated through the mortar test results with or without FA or LP, instead of SCC tests in the former method. The equivalence coefficients by volume of FA and LP are 0.55 and 0.79, respectively, which means that 1.82 unit volume of FA or 1.27 unit volume of LP is equivalent to one unit volume of cement. The improved powder equivalence model was verified by the successful preparation of SCC incorporating FA or LP simply and effectively. The equivalent SCP zone cohered better with the SCC zone than the former SCP zone, which could guide the quick mix design of SCC without SCC premix tests.

1. Introduction

As a kind of high-performance concrete, self-compacting concrete (SCC) can flow through the gaps of dense reinforced bars under its gravity without vibration and fill up the voids without segregation and excessive bleeding, to ensure the compaction of the structure, shorten the construction period, and eliminate vibration noise [1, 2].

To obtain SCCs with excellent workability, the Bingham model was applied [3] and researchers [4–10] exploited a mix proportion design method for SCC based on paste rheological properties for its advantages of revealing the basic principles involved in physical phenomena and time-saving trial mixtures. Saak et al. [4] presented that the segregation resistance and flowability of fresh concrete largely depended on the rheology of cement paste. Moreover, to predict the flow behavior of the corresponding SCC, Lachemi et al. [11] established relationships between the fresh properties (e.g., slump flow and V-funnel time) of concrete with high content of fly ash (FA) and the yield stress and plastic viscosity of a paste. Wu and An [9] predicted pure cement SCC's workability according to paste rheology and set up the threshold theory. According to the threshold theory, when the yield stress and plastic viscosity of the paste satisfy the threshold theory, the SCC with the same mix proportion as the paste has good working performance. Nie and An [12] visualized the threshold theory by the self-compacting paste (SCP) zone, which is the set of all points satisfying the theory. Higher costs, higher hydration heat, and greater shrinkage during drying may occur as a result of

SCC with a large amount of cement [13–15]. Therefore, mineral admixtures such as FA and LP are usually used to replace partial cement [16–22], which may reduce hydration heat, optimize the particle packing, and maintain the SCC workability [23–26]. Additionally, incorporating FA or LP can reduce carbon footprint and increase waste reutilization. However, the paste rheological threshold theory was not verified with concrete experiments incorporating FA or LP.

The effects of FA replacing partial cement on the workability of concrete have been investigated by many researchers. Douglas [27] found that adding FA can reduce the superplasticizer/powder ratio (SP%) and increase the SCC workability. Shen et al. [28] recorded that the slump of concrete increased from 164 mm to 189 mm with the replacement ratio of FA from 0% to 50%. However, Zhang and Li [29] drew the conclusion that the slump and the slump flow (*SF*) of concrete increased firstly and then decreased when FA content was increasing, which were highest when the FA content was 15% by mass. The different particle size distribution and different morphology [30] resulted in the different influences of FA on the concrete's workability.

The effects of LP replacing partial cement on the workability of concrete also have been investigated by many researchers. Beeralingegowda and Gundakalle [23] concluded that concrete was more flowable with LP's replacement percentage up to 20%. Recent work [31] indicated that the SF of SCC incorporating LP was more than that of SCC only with cement as powder. Other scholars [32, 33] also found that adding some LP can improve the workability of concrete. However, some studies [34, 35] showed that more superplasticizer (SP) or water was needed in SCC with LP to keep the same rheological properties as SCC without LP. This is because the finer LP granules can fill the voids between the coarser cement granules, which increases the package density of powder. Hence, the above opposite conclusions may be attributed to the different morphology and fineness of a variety of LPs [26].

Based on the paste rheological threshold theory, Nie [36] carried out several paste experiments by using different FA proportions and obtained SCP zones. However, no SCCs were conducted to validate the SCP zones. Zhang et al. [37] obtained the SCC zone consisting of the mix points of SCC with satisfied working performances by SCC test experiments. Based on the SCP zone and SCC zone, they conducted concrete experiments to validate the SCP zone and found the separation of the SCP zone and the SCC zone [37]. To deal with this problem, Zhang et al. [37] studied the difference of cement, FA, and LP from the perspective of powder equivalence. Based on SCC workability with different properties between cement and other powders such as FA and LP considered, other powders can be turned into equivalent cement according to the equivalence coefficients. At last, the goal of the match of the SCC zone and the SCP zone was realized. However, the powder equivalence coefficients are obtained by comparing the equivalent SCP zone with the SCC zone until they coincide mostly, and some time-consuming concrete experiments have to be conducted inevitably [37, 38].

To deal with this problem, the powder equivalence model will be enhanced from the perspective of obtaining powder equivalence coefficients by comparing the results of mortars with/without FA/LP instead of the comparison of the equivalent SCP zone and the SCC zone in the previous study.

2. Theoretical Research

2.1. Materials. Figure 1 shows the micromorphology images of cement, FA, and LP. It indicates that the particle size and morphology of the three powders are different. The particle size distributions of the three kinds of powders are shown in Figure 2. The fineness of cement, FA, and LP is 473 m^2/kg, 5370 m^2/kg, and 3650 m^2/kg, respectively. The densities of cement, FA, and LP are 3080 kg/m^2, 2500 kg/m^2, and 2700 kg/m^2, respectively. The three powders have continuous gradation. The median particle size of cement, FA, and LP is 20.30 μm, 17.82 μm, and 19.28 μm, respectively. Cement has the largest median particle size while FA has the least median particle size of the cement, as shown in Figure 2.

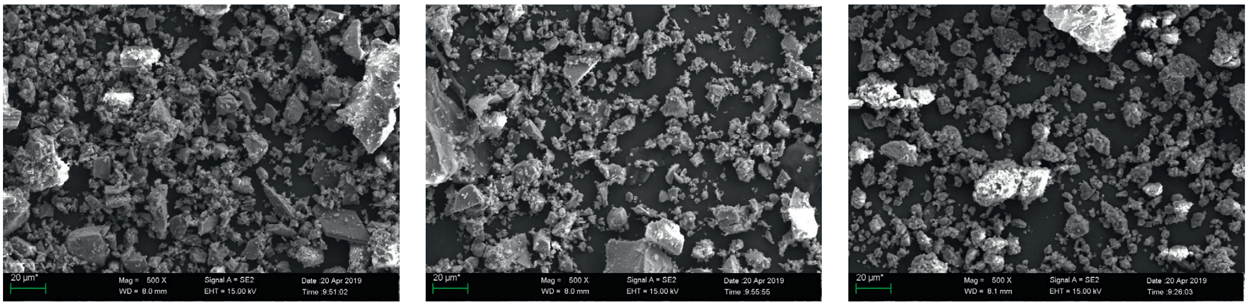
The performance of SCC is affected by mineral fillers replacing cement. The reasons are summarized in the following three aspects.

2.1.1. Ball Bearing Effect. FA contains many ball glass beads. LP contains superfine ball-like particles that can be obtained by breaking, crushing, and grinding brittle limestone. Generally, FA and LP particles are much closer to a sphere than those of cement. These ball-like particles can not only reduce the friction between particles but also make the cement particles not stick together.

2.1.2. Filler Effect. Particle size ranges of FA and LP are similar and are much wider than cement. About 10% of the particles of FA or LP are finer than those of cement. The finer particles can fill the voids among the coarser particles, making the solid skeleton more compactable and increasing the bulk density.

2.1.3. Adsorption Effect. Different powders have different adsorption capacities to polycarboxylate superplasticizers molecules, which also affects the workability of SCC. The previous research [39] indicated that cement has twice the adsorption capacity to superplasticizer as LP with the same finesses.

Polycarboxylate superplasticizer was used herein in this study with a solid content of 20% and a density of 1.03 g/cm^3. A crushed quartz sand (QS) was regarded as a fine aggregate in the validation of the equivalence coefficients of FA in Section 4.1. The particle size range of QS is 0.075–4.75 mm, and the density of QS is 2.64 g/cm^3. Crushed limestone sand (LS) was regarded as a fine aggregate in the validation of the equivalence coefficients of LP with the density of 2.70 g/cm^3 in Section 4.2. Crushed gravel was regarded as the coarse aggregate (CA) with particle size ranging from 4.75 mm to 20 mm, and its density and packing density are 2.70 g/cm^3 and 1.36 g/cm^3, respectively. The particle size distribution



(a) (b) (c)

Figure 1: SEM images (500x) of three kinds of powder: (a) cement, (b) FA, and (c) LP.

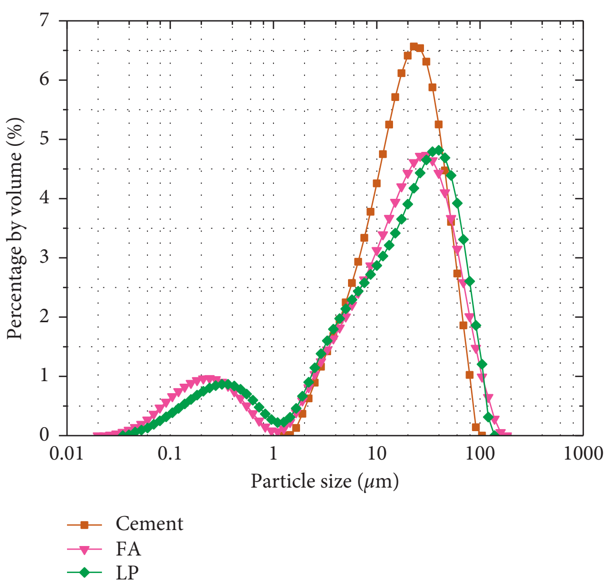


Figure 2: Particle size distribution curves of cement, FA, and LP.

curves of the QS, LS, and crushed gravel are shown in Figure 3.

2.2. Mix Design Method for SCC Based on Paste Rheological Properties. SCC is composed of gravel and mortar [8, 40]. Furthermore, sand and paste comprise mortar. The SCC's workability relies on the gravel content, gravel properties, and mortar rheology. The mortar rheology is related to sand ratio, sand properties, and paste rheology. The essence of the paste rheological threshold theory is quantitatively limiting the paste rheological properties to get good SCCs. Based on the two mechanical models [41] and the relationship between mortar rheological properties and paste rheological properties, equations (1) and (2) can determine the rheological criteria of SCC formulated paste.

$$\tau_{\text{paste}} \leq \tau_{\text{threshold}} = \frac{\rho_{\text{mortar}} g \left(B + 2\delta_{\text{mortar}}\right)^2}{2\left(A + 2\delta_{\text{mortar}}\right)} \left(1 - \frac{\phi}{\phi_{\max}}\right)^n, \quad (1)$$

where τ_{paste} and $\tau_{\text{threshold}}$ are the paste yield stress and paste yield stress threshold; ρ_{mortar} represents the mortar density; g equals 9.81 m/s^2; δ_{mortar} represents the thickness of mortar covering the gravel; A represents that the average width of gravel is equal to $2r$; B represents that the average height is equal to $0.9r$; r represents the average radius of gravel [10]; ϕ represents the actual sand-mortar volumetric ratio; and $\phi_{\max}$ represents the theoretical maximum of the sand-mortar volumetric ratio; the coefficient of n was obtained to be 4.2 in the study of Toutou and Roussel [42]. The calculation of $\phi_{\max}$ and δ_{mortar} is given in the research of Wu and An [9].

$$\eta_{\text{paste}} \geq \eta_{\text{threshold}} = \frac{2\Delta\rho g r^2}{\delta_{\text{mortar}}} \left(1 - \frac{\phi}{\phi_{\max}}\right)^{[\eta]\phi_{\max}}, \quad (2)$$

where η_{paste} and $\eta_{\text{threshold}}$ are, respectively, the paste plastic viscosity and the threshold of paste plastic viscosity; $\Delta\rho$ represents the density difference between gravel and mortar around; and $[\eta]$ is approximated to be 2.5 in the study of Krieger and Dougherty [43].

Based on the research of Roussel et al. [44] and Chidiac et al. [45], the paste yield stress (τ_{paste}) can be calculated through equation (3) and the paste plastic viscosity (η_{paste}) can be calculated through equation (4).

$$\tau_{\text{paste}} = \frac{225 \rho_{\text{paste}} g V_{\text{cone}}^2}{128 \pi^2 \left(\text{SF}_{\text{paste}}/2\right)^5} - \lambda \frac{\left(\text{SF}_{\text{paste}}/2\right)^2}{V_{\text{cone}}}, \quad (3)$$

$$\eta_{\text{paste}} = \frac{2 \rho_{\text{paste}} g h_{\text{cone}} V_{\text{cone}}}{3\pi \times \text{slump} \times \text{SF}_{\text{pres}}^2} T_{200}, \quad (4)$$

where ρ_{paste} is the paste density; V_{cone} and h_{cone} represent minislump cone's inner volume and height; SF_{paste} represents the SF for paste at stoppage; SF_{pres} equals to 200 mm; T_{200} is defined by the time it spends when SF is up to 200 mm; slump represents slump value with SF_{pres} equaling to 200 mm; and λ equals to 0.0005 [37].

Combining the bilinear interpolation method and the relationship between paste rheological properties and the water/powder volumetric ratio (V_W/V_P) and SP% [12], the SCP zone can be obtained by selecting the paste mixtures whose rheological characteristics meet the paste rheological thresholds. In other words, the SCP zone is an intersection where equations (1) and (2) can be satisfied simultaneously.

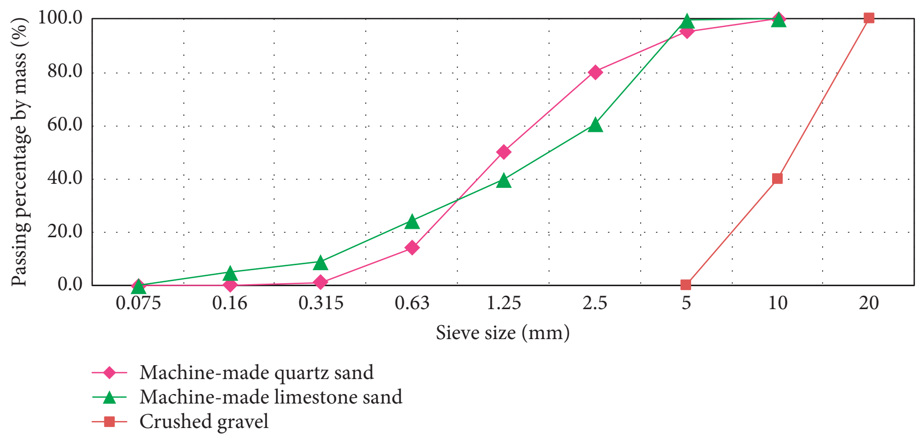


FIGURE 3: Particle size distribution curves of sand and crushed gravel.

2.3. Improved Powder Equivalence Model

2.3.1. The Powder Equivalence Model. When cement is the only powder in paste and concrete, the SCP zone satisfying the paste rheological thresholds coincides most with the SCC zone. For a paste with FA or LP replacing part of cement, the SCP zone moves towards the area where V_W/V_P and SP% become less when the obtained paste thresholds are the same. And the SCC zone with FA or LP replacing part of the cement also moves to the area where V_W/V_P and SP% become less when the good SCC criteria remain unchanged. However, V_W/V_P and SP% of the SCP zone are still less than those of the SCC zone, making the SCP zone with mineral admixtures separate from the SCC zone with mineral admixtures, as shown in Figure 4. To solve the problem, Zhang et al. [37] proposed a powder equivalence model. According to the same SCC workability, a powder coefficient can be used to set up an equivalence relationship between different kinds of powders and cement to realize the purpose of regional coincidence between the equivalent SCP zone and the SCC zone. Equations (5) and (6) show the calculation of $[V_W/V_P]_{eq}$ and $[SP\%]_{eq}$ through the powder equivalence coefficients.

$$\left[\frac{V_W}{V_P}\right]_{eq} = \frac{V_W}{V_C + k_{FA}V_{FA} + k_{LP}V_{LP}}, \quad (5)$$

where $[V_W/V_P]_{eq}$ is the equivalent water-powder ratio by volume; V_W, V_C, V_{FA}, and V_{LP} are the volume of water, cement, FA, and LP, respectively; and k_{FA} and k_{LP} are the volumetric powder equivalence coefficients of FA and LP.

$$[SP\%]_{eq} = \frac{m_{SP}}{m_C + K_{FA}m_{FA} + K_{LP}m_{LP}}, \quad (6)$$

where $[SP\%]_{eq}$ is the equivalent mass ratio of superplasticizer to powder; m_{SP}, m_C, m_{FA}, and m_{LP} are the mass of superplasticizer, cement, FA, and LP, respectively; and K_{FA} and K_{LP} are the powder equivalence coefficients of FA and LP by mass.

2.3.2. The Improved Powder Equivalence Model. Powder equivalence coefficients for FA and LP provided a good reference for the SCC mix design. However, the obtaining of the coefficients was based on a trial-and-error process and at least 9 groups of SCCs, leading to a lot of experiments. To solve this weak point, this paper works on the improved powder equivalence coefficients for FA and LP, which can be obtained by conducting mortar experiments instead of the time-consuming SCC experiments.

When FA or LP replaced part of cement as powder material, three mortar tests should be carried out. The first mortar test is the cement mortar, which is set as the reference mortar. Then, keeping the SP% constant, two mortars with FA or LP are obtained by adjusting the water usage. The linear interpolation of SF and water usage can be obtained, by which the water usage of mortar with FA or LP having the same SF as the reference mortar is found. Finally, the powder equivalence coefficient can be calculated by comparing the results of mortar tests. The calculation process of the equivalence coefficient of FA and LP based on the mortar experiments will be introduced in the next section.

3. Results and Discussion

According to the frequently used sand ratio and superplasticizer dosage recommended by the manufacturer, the sand ratio was fixed at 45% and the polycarboxylate-based superplasticizer was fixed at 1% by mass. Moreover, the cement replacement ratio by FA or LP was fixed at 30% by mass. Finally, the mortar mix proportions used to determine the powder equivalence coefficients for FA or LP are shown in Table 1. For the reference mortar, pure cement was used and the water usage M_0 can be adjusted to obtain a mortar with good flowability. Then, M_1 for testing mortar was adjusted to obtain mortar with the same SF as the reference mortar. Considering the difficulty of obtaining mortars with the same SF, two mortars with different SF were conducted.

Based on the linear interpolation method, the water usage for mortar with the same SF as the reference mortar was obtained. Test results are shown in Table 2.

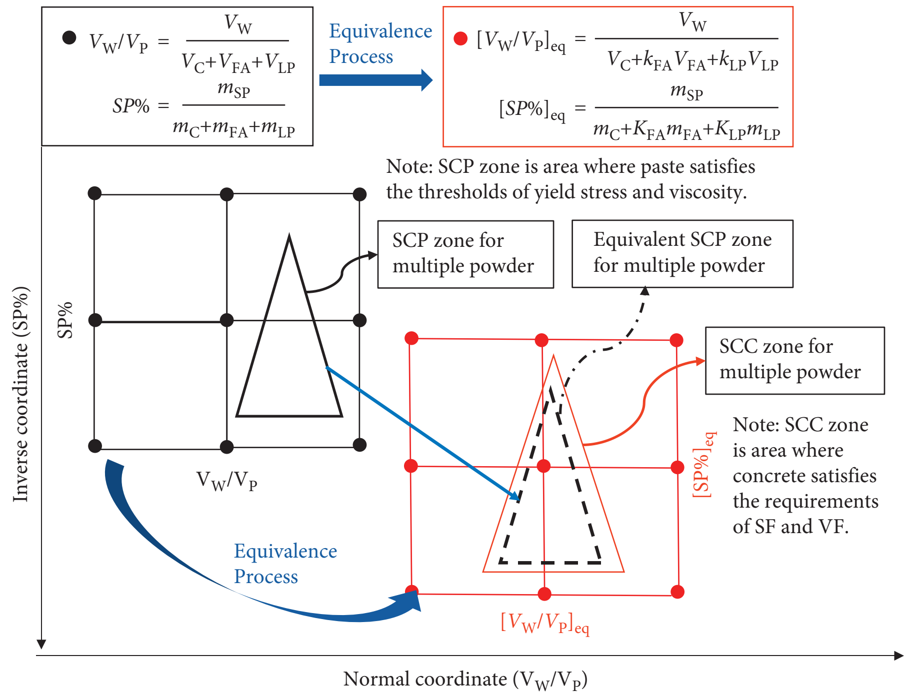


Figure 4: The theoretical framework of the powder equivalence model.

Table 1: Mortar mix proportions for powder equivalence coefficients of FA or LP.

Mortar type	Cement (g)	FA or LP (g)	Water (g)	SP (g)	Sand (g)
Reference mortar	250	0	M_0	2.5	358.6
Testing mortar	175	75	M_1	2.5	358.6

Table 2: Mortar results for the equivalence coefficients of FA and LP.

No.	Mortar	Cement (g)	FA/LP (g)	Water (g)	SP (g)	Sand (g)	SF (mm)
1	Reference mortar	250	0	96.2	2.5	358.6	290.5
2	Testing mortar	175	75 (FA)	85.0	2.5	358.6	278.0
3	Testing mortar	175	75 (FA)	90.0	2.5	358.6	311.0
4	Reference mortar	250	0	81.2	2.5	358.6	295.0
5	Testing mortar	175	75 (LP)	80.0	2.5	358.6	296.0
6	Testing mortar	175	75 (LP)	87.5	2.5	358.6	302.0

Figure 5 shows the linear interpolation process to get the water usage of mortar with the same SF as the reference mortar. Water usage for the mortar incorporating FA was 86.9 g based on the hypothesis that the SF of the mortar incorporating FA was 290.5 mm, the same as that of the reference mortar while the water usage of the mortar incorporating LP was 78.8 g, based on the hypothesis that the SF of mortar incorporating LP was 295.0 mm, the same as that of the reference mortar.

Based on the results above, the equivalence coefficients of FA can be calculated as follows. The water usage of one unit volume of cement and FA can be calculated by equations (7) and (8).

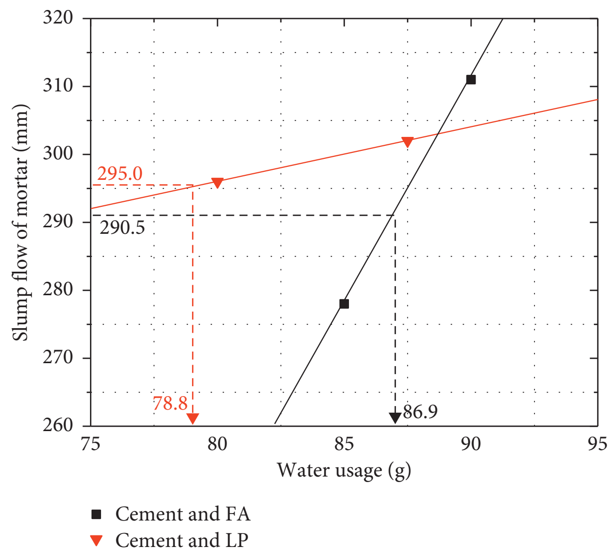


Figure 5: Relationship between slump flow of mortar and water usage.

$$V_{W,C} = \frac{M_0/\rho_W}{250/\rho_C} = \frac{96.2/1000}{250/3080} = 1.19, \quad (7)$$

$$V_{W,FA} = \frac{(M_1 - 175M_0/250)/\rho_W}{75/\rho_{FA}} = \frac{(86.9 - 175 \times 96.2/250)/1000}{75/2500} = 0.65. \quad (8)$$

Then, the powder equivalence volumetric coefficient of FA is defined in the following equation:

$$k_{\mathrm{FA}} = \frac{V_{W,\mathrm{FA}}}{V_{W,C}} = \frac{0.65}{1.19} = 0.55, \quad (9)$$

where k_{FA} represents the equivalent volumetric coefficient of FA; $V_{W,\mathrm{FA}}$ represents the water usage for one unit volume of FA; and ρ_W and ρ_{FA} are the density of water and FA, respectively.

Then, the equivalent coefficient of FA by mass, K_{FA}, is calculated as follows [37]:

$$K_{FA} = k_{FA}\frac{\rho_C}{\rho_{FA}} = 0.55 \times \frac{3080}{2500} = 0.68. \quad (10)$$

Likewise, the equivalence coefficients of LP can be calculated as follows:

$$V_{W,C} = \frac{M_0/\rho_W}{250/\rho_C} = \frac{81.2/1000}{250/3080} = 1.00, \quad (11)$$

$$V_{W,\mathrm{LP}} = \frac{(M_1 - 175M_0/250)/\rho_W}{75/\rho_{\mathrm{LP}}} = \frac{(78.8 - 175 \times 81.2/250)/1000}{75/2700} = 0.79, \quad (12)$$

$$k_{\mathrm{LP}} = \frac{V_{W,\mathrm{LP}}}{V_{W,C}} = \frac{0.79}{1.00} = 0.79, \quad (13)$$

where k_{LP} represents the equivalent volumetric coefficient of LP by volume; $V_{W,LP}$ represents the water usage for one unit volume of LP; and ρ_{LP} is the densities of LP.

Then, the equivalent coefficient of LP by mass, K_{LP}, is calculated as follows [37]:

$$K_{LP} = k_{LP}\frac{\rho_C}{\rho_{LP}} = 0.79 \times \frac{3080}{2700} = 0.90. \tag{14}$$

It can be seen that the equivalent coefficients of FA and LP are both less than 1, so V_W/V_P is smaller than $[V_W/V_P]_{eq}$ and SP% is smaller than $[SP\%]_{eq}$. An area composed of $[V_W/V_P]_{eq}$ and $[SP\%]_{eq}$ was obtained, and the equivalent SCP zone where the paste rheological thresholds are satisfied was drawn in the new area. The equivalence coefficients quantify the relationship between cement and other powders from the perspective of rheology and the effect of powder incorporation on the SCP zone movement. Specifically, k_{FA} indicates that $1/k_{FA}$ unit volume of FA equals the influence of per unit volume of cement from the standpoint of water usage. For LP, k_{LP} means that $1/k_{LP}$ unit volume of LP equals the effect of a unit volume of cement. From the standpoint of superplasticizer usage, K_{FA} means that $1/K_{FA}$ unit mass of FA equals the influence of per unit mass of cement, whereas K_{LP} indicates that $1/K_{LP}$ unit mass of LP equals the influence of a unit mass of cement.

4. Experimental Validation

4.1. Validation of Equivalence Coefficients for FA. First, pastes with FA replacing 20% of the cement by volume were carried out to obtain an SCP zone. The mini-SF test results and rheological properties of the pastes are shown in Figure 6. It can be seen from equations (1) and (2) that the paste rheological thresholds are related to V_W/V_P but not related to SP %. The paste yield stress thresholds for V_W/V_P (i.e., 0.98, 1.08, and 1.18) are 1.37 Pa, 1.36 Pa, and 1.34 Pa, respectively. The paste plastic viscosity thresholds for V_W/V_P (i.e., 0.98, 1.08, and 1.18) are 22.8 Pa·s, 24.4 Pa·s, and 26.0 Pa·s, respectively. With the equivalence coefficients of FA obtained from mortar experiments, $[V_W/V_P]_{eq}$ was calculated through equation (5), and $[SP\%]_{eq}$ was calculated through equation (6), respectively, as shown in Figure 6. The paste yield stress and the paste plastic viscosity are slightly changed compared with those before the equivalence process. Now, the paste yield stress thresholds for V_W/V_P (i.e., 1.09, 1.20, and 1.31) are 1.35 Pa, 1.34 Pa, and 1.32 Pa, respectively. The paste plastic viscosity thresholds for V_W/V_P (i.e., 1.09, 1.20, and 1.31) are 24.6 Pa·s, 26.3 Pa·s, and 27.7 Pa·s, respectively. The bilinear interpolation method [12] was used to determine the SCP zones. The rheological criteria are such that τ_{paste} is lower than or equal to $\tau_{threshold}$ and η_{paste} is greater than or equal to $\eta_{threshold}$. Therefore, the area pointed by the arrow, in Figures 6(a) and 6(b), satisfies the yield stress criterion and the plastic viscosity criterion.

Based on the above data, the SCP zone and the equivalent SCP zone were drawn according to the steps in the research of Zhang et al. [37], as shown in Figures 6(a) and 6(b).

Flowability, passing ability, and segregation resistance are summed up as the workability of SCC, which was predicted through the slump flow test and V-funnel test in this research. The flowability was quantified by SF of the slump flow test, and the passing ability and segregation resistance were quantified by VF from the V-funnel test. The criteria of qualified SCC that SF is between 600 mm and 800 mm while VF between 4 s and 25 s were adopted [46, 47]. An intersection called SCC zone can be obtained if the SF range and VF range were satisfied by the results of the slump flow test and the V-funnel test simultaneously. The SCCs with FA replacing 20% of cement were performed by changing V_W/V_P and SP%, as shown in Figure 7. The SCC results (SF and VF) were processed using the bilinear interpolation, and then the satisfactory area meeting the required criteria that SF ranges from 600 mm to 800 mm and VF ranges from 4 s to 25 s was obtained [37], as shown in Figure 7. The SCC zone would be used to compare with the SCP zone.

Figure 8 shows that there is no intersection between the SCP zone and the SCC zone. With the improved powder equivalence model, most of the equivalent SCP zone lies within the SCC zone, which validates the applicability of the powder equivalence model and the feasibility of obtaining the powder equivalence coefficients by mortar experiments. From the standpoint of water usage, the FA equivalence coefficient of 0.55 by volume means that 1.82 unit volume of FA is equivalent to the effect of one unit volume of cement. From the standpoint of SP usage, the FA equivalence coefficient of 0.68 by mass means that 1.47 unit mass of FA is equivalent to the influence of one unit mass of cement.

It should be noted that the enhanced powder equivalence model still has some shortcomings. The area of the equivalent SCP zone is only about a third of that of the SCC zone, as shown in Figure 8. Also, the area of the SCP zone is a little bigger than that of the equivalent SCP zone although their shapes are similar. Considering the fact that the equivalent SCP zone is contained in the SCC zone, the enhanced equivalence model can determine SCC mix proportion quickly.

4.2. Validation of Equivalence Coefficients for LP. In this section, pastes and SCCs were conducted to verify the LP equivalence coefficients, with LP replacing 21% of the cement by volume. First, mini-SF tests on pastes with LP replacing 21% of the cement by volume were conducted, as shown in Figure 9(a).

The paste yield stress thresholds for V_W/V_P (i.e., 0.85, 0.92, and 0.99) are 3.43 Pa, 3.39 Pa, and 3.36 Pa, respectively. The paste plastic viscosity thresholds for V_W/V_P (i.e., 0.85, 0.92, and 0.99) are 29.9 Pa·s, 32.3 Pa·s, and 24.4 Pa·s, respectively. With the equivalence coefficients of LP obtained from mortar experiments, $[V_W/V_P]_{eq}$ was calculated through equation (5), and $[SP\%]_{eq}$ was calculated through equation (6), respectively, as shown in Figure 9(b). The paste yield

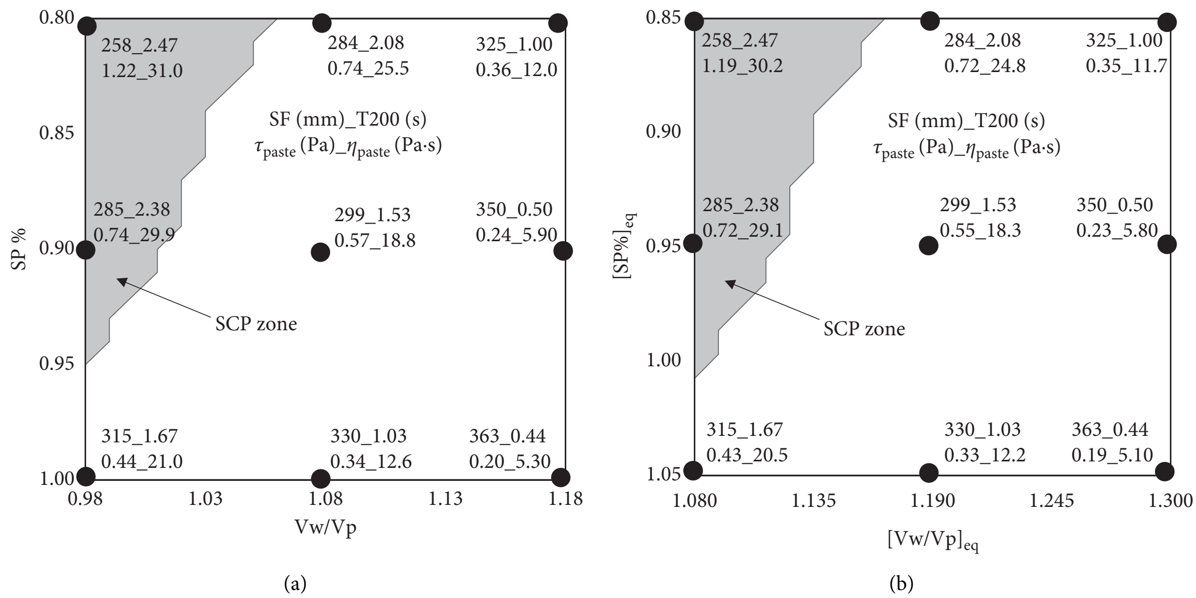


Figure 6: Results of the mini-SF tests on pastes with cement and FA as powder (a) before equivalence; (b) after equivalence.

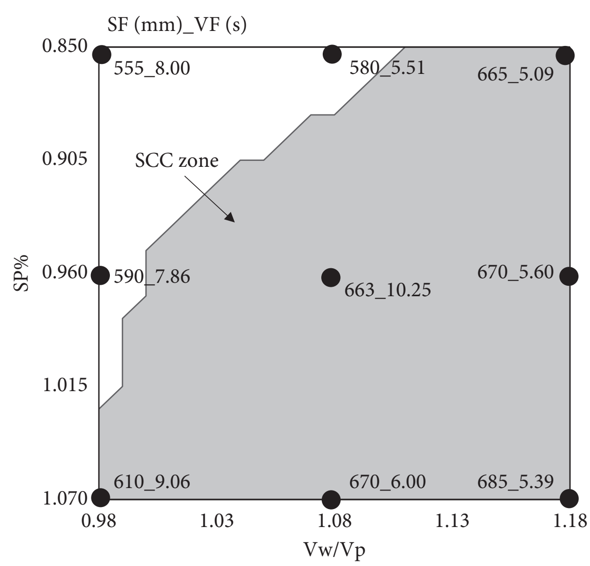


Figure 7: Results of SCC with cement and FA as powder.

stress and the paste plastic viscosity are slightly changed compared with those before the equivalence process. Now, the paste yield stress thresholds for V_W/V_P (i.e., 0.90, 0.97, and 1.05) are 3.41 Pa, 3.37 Pa, and 3.33 Pa, respectively. The paste plastic viscosity thresholds for V_W/V_P (i.e., 0.90, 0.97, and 1.05) are 31.3 Pa·s, 33.7 Pa·s, and 35.9 Pa·s, respectively. Based on the above data, the SCP zone and the equivalent SCP zone were drawn according to the steps in the research of Zhang et al. [37], as shown in Figures 9(a) and 9(b).

The SCCs with LP replacing 20% of cement were performed by changing V_W/V_P and SP%, as shown in Figure 10. Based on the results of SCCs, the SCC zone was obtained, as shown in Figure 10, according to the steps in the research of Zhang et al. [37].

The SCC zone is an intersection that agrees with the requirements of SF and VF concurrently. Based on the results of SCCs and the good SCC criteria, the SCC zone was also obtained through the steps in the research of Zhang et al. [37], as shown in Figure 11.

The SCP zone, the equivalent SCP zone, and the SCC zone are drawn together in Figure 11. It shows that there is a small intersection between the SCP zone and the SCC zone. About half of the SCP zone is overlapping with the SCC zone, which means that the original model has only a 50% probability of successfully predicting the SCC zone.

On the other hand, the equivalent SCP zone moves towards the SCC zone, almost overlapping the SCC zone, which validates the applicability of the enhanced powder

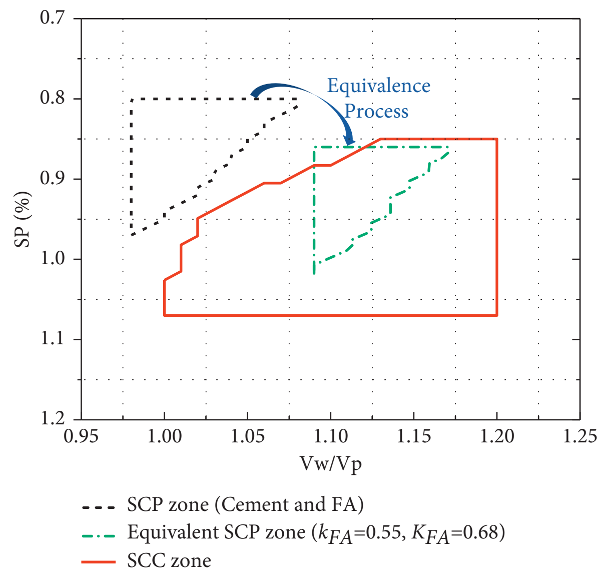


FIGURE 8: Comparison of different zones with cement and FA as powder.

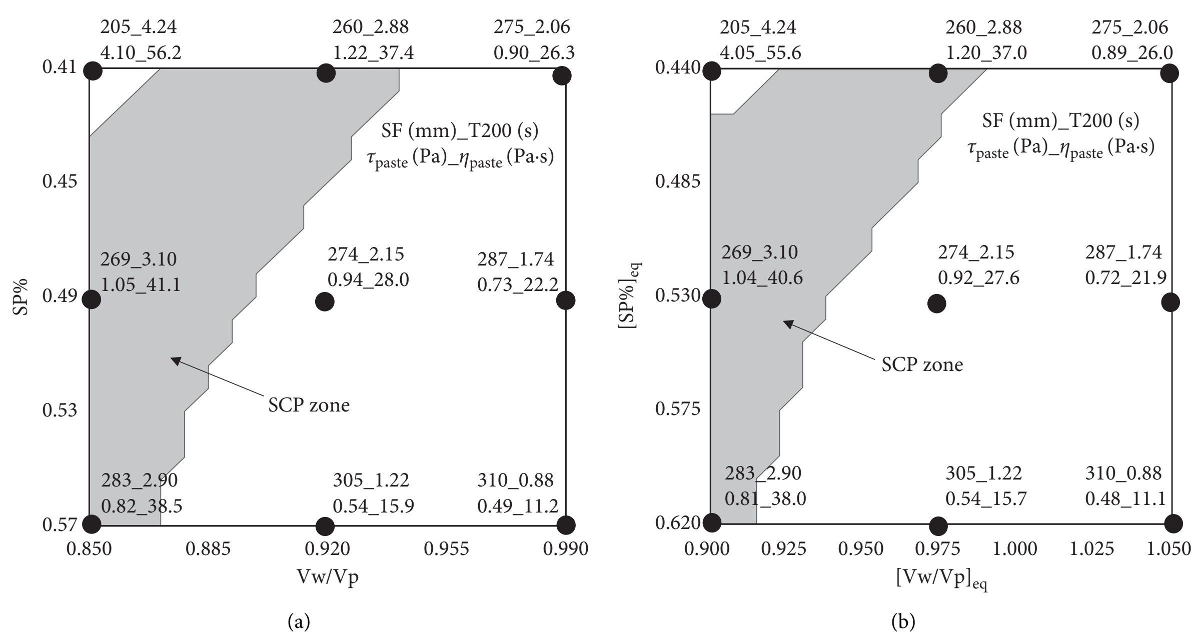


FIGURE 9: Results of the mini-SF tests on pastes with cement and LP as powder (a) before equivalence; (b) after equivalence.

equivalence model and the feasibility of obtaining the powder equivalence coefficients by mortar experiments. From the standpoint of water usage, the LP volumetric equivalence coefficient of 0.79 means that 1.27 unit volume of LP equals the influence of one unit volume of cement. From the standpoint of SP usage, the LP equivalence coefficient of 0.90 by mass means that 1.11 unit mass of LP equals the influence of per unit mass of cement.

Although the equivalent SCP zone is only about half of that of the SCC zone, as shown in Figure 11, the enhanced equivalence model is still useful and can determine SCC mix proportion quickly considering the fact that most of the equivalent SCP zone lies in the SCC zone.

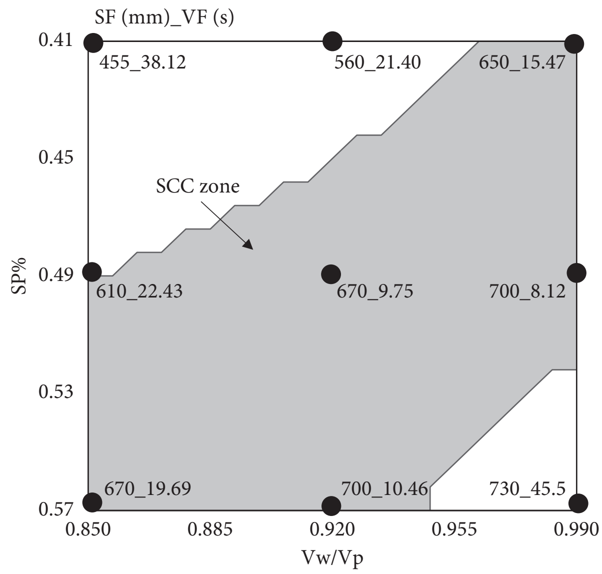


Figure 10: Results of SCC with cement and LP as powder.

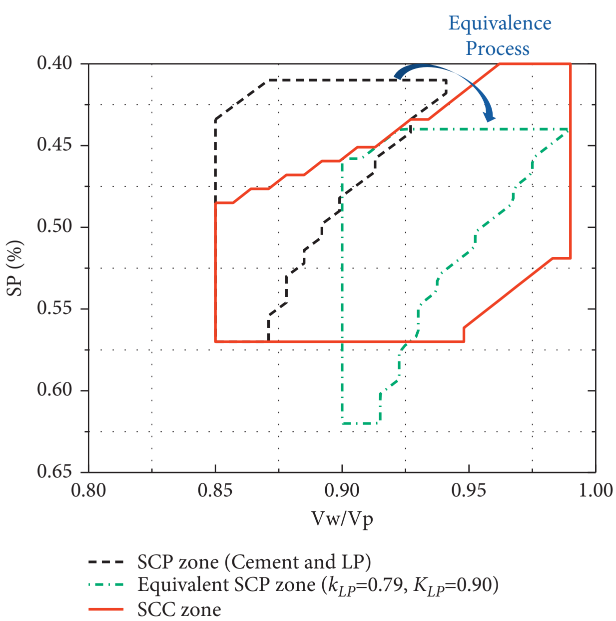


Figure 11: Comparison of different zones with cement and LP as powder.

5. Conclusions

The effect of FA and LP on the SCP zone of SCC was quantitatively studied by introducing powder equivalence coefficients. The powder equivalence model was enhanced by comparing the mortar results to obtain powder equivalence coefficients. Combined with the paste rheological theory, the enhanced powder equivalence model was validated and exploited to predict the SCP zone of SCC. The following conclusions were drawn from the obtained results.

(1) The application and popularization of the paste rheological theory may be restricted by the differences between cement and FA and LP, which may result in the mismatch between the SCP zone and the SCC zone. Once mixed with LP or FA, a smaller V_W/V_P or SP% was needed to maintain the same workability as SCC with pure cement as powder. This is attributed to the different properties of cement, FA, and LP.

(2) By comparing the mortar results to obtain powder equivalent coefficients, the powder equivalence model was enhanced. The equivalent coefficients of FA are 0.55 by volume and 0.68 by mass. The equivalent coefficients of LP are 0.79 by volume and 0.90 by mass.

(3) The enhanced model was verified through SCCs, and the SCC zones coincided better with the equivalent SCP zones than SCP zones.

(4) The equivalent SCP zone could guide the quick mix design of SCC without SCC premix tests, providing a reference for the application of this method in practical engineering.

The equivalence coefficients may be related to the physical properties of LP and FA, which will be studied in the future, considering FA and LP with different properties.

Data Availability

Some or all data, models, or codes generated during this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by the Fundamental Research Funds for the Central Universities (B210201012), the Jiangsu Planned Projects for Postdoctoral Research Funds (2021K055A), and the National Natural Science Foundation of China (52109153 and 51909280).

References

[1] H. Okamura and M. Ouchi, "Self-compacting concrete," *Journal of Advanced Concrete Technology*, vol. 1, no. 1, pp. 5–15, 2003.

[2] X. An, Q. Wu, F. Jin et al., "Rock-filled concrete, the new norm of SCC in hydraulic engineering in China," *Cement and Concrete Composites*, vol. 54, pp. 89–99, 2014.

[3] I. González-Taboada, B. González-Fonteboa, J. Eiras-López, and G. Rojo-López, "Tools for the study of self-compacting recycled concrete fresh behaviour: workability and rheology," *Journal of Cleaner Production*, vol. 156, pp. 1–18, 2017.

[4] A. W. Saak, H. M. Jennings, and P. S. Surendra, "New methodology for designing self-compacting concrete," *Materials Journal*, vol. 98, no. 6, pp. 429–439, 2001.

[5] V. K. Bui, Y. Akkaya, and S. P. Shah, “Rheological model for self-consolidating concrete,” *Materials Journal*, vol. 99, pp. 549–559, 2002.
[6] N. Roussel, “A theoretical frame to study stability of fresh concrete,” *Materials and Structures*, vol. 39, no. 1, pp. 81–91, 2006.
[7] S. E. Chidiac and F. Mahmoodzadeh, “Plastic viscosity of fresh concrete - a critical review of predictions methods,” *Cement and Concrete Composites*, vol. 31, no. 8, pp. 535–544, 2009.
[8] J. Hu and K. Wang, “Effect of coarse aggregate characteristics on concrete rheology,” *Construction and Building Materials*, vol. 25, no. 3, pp. 1196–1204, 2011.
[9] Q. Wu and X. An, “Development of a mix design method for SCC based on the rheological characteristics of paste,” *Construction and Building Materials*, vol. 53, no. 53, pp. 642–651, 2014.
[10] J. Zhang, X. An, and D. Nie, “Effect of fine aggregate characteristics on the thresholds of self-compacting paste rheological properties,” *Construction and Building Materials*, vol. 116, pp. 355–365, 2016.
[11] M. Lachemi, K. M. A. Hossain, R. Patel, M. Shehata, and N. Bouzoubaâ, “Influence of paste/mortar rheology on the flow characteristics of high-volume fly ash self-consolidating concrete,” *Magazine of Concrete Research*, vol. 59, no. 7, pp. 517–528, 2007.
[12] D. Nie and X. An, “Optimization of SCC mix at paste level by using numerical method based on a paste rheological threshold theory,” *Construction and Building Materials*, vol. 102, pp. 428–434, 2016.
[13] P. Li, W. Lu, X. An, L. Zhou, and S. Du, “Effect of epoxy latexes on the mechanical behavior and porosity property of cement mortar with different degrees of hydration and polymerization,” *Materials*, vol. 14, no. 3, p. 517, 2021.
[14] L. Wang, M. Jin, S. Zhou, S. Tang, and X. J. M. Lu, “Investigation of microstructure of CSH and micro-mechanics of cement pastes under NH4NO3 dissolution by 29Si MAS NMR and microhardness,” *Measurement*, vol. 185, Article ID 110019, 2021.
[15] D. Shen, Y. Jiao, Y. Gao, S. Zhu, and G. Jiang, “Influence of ground granulated blast furnace slag on cracking potential of high performance concrete at early age,” *Construction and Building Materials*, vol. 241, Article ID 117839, 2020.
[16] H. Zhao, W. Sun, X. Wu, and B. Gao, “The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures,” *Journal of Cleaner Production*, vol. 95, pp. 66–74, 2015.
[17] W.-J. Long, Y. Gu, J. Liao, and F. Xing, “Sustainable design and ecological evaluation of low binder self-compacting concrete,” *Journal of Cleaner Production*, vol. 167, pp. 317–325, 2017.
[18] M. Omrane, S. Kenai, E.-H. Kadri, and A. Aït-Mokhtar, “Performance and durability of self compacting concrete using recycled concrete aggregates and natural pozzolan,” *Journal of Cleaner Production*, vol. 165, pp. 415–430, 2017.
[19] P. Li, T. Zhang, X. An, and J. Zhang, “An enhanced mix design method of self-compacting concrete with fly ash content based on paste rheological threshold theory and material packing characteristics,” *Construction and Building Materials*, vol. 234, Article ID 117380, 2020.
[20] P. Li, J. Ran, D. Nie, and W. Zhang, “Improvement of mix design method based on paste rheological threshold theory for self-compacting concrete using different mineral additions in ternary blends of powders,” *Construction and Building Materials*, vol. 276, Article ID 122194, 2021.
[21] D. Shen, C. Liu, M. Wang, J. Kang, M. Li, and B. Materials, “Effect of polyvinyl alcohol fiber on the cracking risk of high strength concrete under uniaxial restrained condition at early age,” *Construction and Building Materials*, vol. 300, Article ID 124206, 2021.
[22] D. Shen, X. Liu, B. Zhou, X. Zeng, and J. Du, “Influence of initial cracks on the frequency of a 60-year-old reinforced-concrete box beam,” *Magazine of Concrete Research*, vol. 73, no. 3, pp. 121–134, 2021.
[23] B. Beeralingegowda and V. D. Gundakalle, “The effect of addition of limestone powder on the properties of self-compacting concrete,” *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 2, no. 9, p. 4996, 2013.
[24] M. C. S. Nepomuceno, L. A. Pereira-de-Oliveira, and S. M. R. Lopes, “Methodology for the mix design of self-compacting concrete using different mineral additions in binary blends of powders,” *Construction and Building Materials*, vol. 64, pp. 82–94, 2014.
[25] G. Ling, Z. Shui, T. Sun et al., “Rheological behavior and microstructure characteristics of SCC incorporating metakaolin and silica fume,” *Materials*, vol. 11, no. 12, pp. 1–16, 2018.
[26] D. Wang, C. Shi, N. Farzadnia, Z. Shi, and H. Jia, “A review on effects of limestone powder on the properties of concrete,” *Construction and Building Materials*, vol. 192, pp. 153–166, 2018.
[27] R. P. Douglas, “Properties of self-consolidating concrete containing Type F fly Ash,” Northwestern University, Evanston, IL, USA, Master of Science, 2004.
[28] D. Shen, W. Wang, Q. Li, P. Yao, and G. Jiang, “Early-Age behavior and cracking potential of fly ash concrete under restrained condition,” *Magazine of Concrete Research*, vol. 72, pp. 1–53, 2018.
[29] P. Zhang and Q. Li, “Combined effect of polypropylene fiber and silica fume on workability and carbonation resistance of concrete composite containing fly ash,” *Journal of Materials: Design and Applications*, vol. 227, pp. 1–9, 2012.
[30] L. Wang, F. Guo, Y. Lin, H. Yang, S. J. C. Tang, and B. Materials, “Comparison between the effects of phosphorous slag and fly ash on the CSH structure, long-term hydration heat and volume deformation of cement-based materials,” *Construction and Building Materials*, vol. 250, Article ID 118807, 2020.
[31] D. Boukhelkhal, O. Boukendakdji, S. Kenai, and S. Bachene, *Effect of mineral Admixture Type on Stability and Rheological Properties of Self-Compacting concrete*, HAL, Bayonne, France, 2015.
[32] G. Sua-iam and N. Makul, “Use of limestone powder during incorporation of Pb-containing cathode ray tube waste in self-compacting concrete,” *Journal of Environmental Management*, vol. 128, pp. 931–940, 2013.
[33] R. Derabla and M. L. Benmalek, “Characterization of heat-treated self-compacting concrete containing mineral admixtures at early age and in the long term,” *Construction and Building Materials*, vol. 66, pp. 787–794, 2014.
[34] A. Yahia, M. Tanimura, and Y. Shimoyama, “Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and W/C ratio,” *Cement and Concrete Research*, vol. 35, no. 3, pp. 532–539, 2005.
[35] S. Grzeszczyk and P. Podkowa, “The effect of limestone filler on the properties of self compacting concrete,” *Cement Wapno Beton*, vol. 15, no. 6, pp. 340–347, 2010.
[36] D. Nie, *Research on optimizing mix proportion of self-compacting concrete based on paste rheological theory*, Ph.D. thesis, Tsinghua University, Beijing, China, 2016, in Chinese.

[37] J. Zhang, X. An, and P. Li, "Research on a mix design method of self-compacting concrete based on a paste rheological threshold theory and a powder equivalence model," *Construction and Building Materials*, vol. 233, Article ID 117292, 2020.
[38] S. Yang, J. Zhang, X. An, B. Qi, D. Shen, and M. Lv, "Effects of fly ash and limestone powder on the paste rheological thresholds of self-compacting concrete," *Construction and Building Materials*, vol. 281, Article ID 122560, 2021.
[39] N. Feng, *Technology of HPC and UHPC*, China Architecture& Building Press, Beijing, China, 2015, in Chinese.
[40] M. R. Geiker, M. Brandl, L. N. Thrane, and L. F. Nielsen, "On the effect of coarse aggregate fraction and shape on the rheological properties of self-compacting concrete," *Cement, Concrete and Aggregates*, vol. 24, no. 1, pp. 3–6, 2002.
[41] J. Zhang, X. An, Y. Yu, and D. Nie, "Effects of coarse aggregate content on the paste rheological thresholds of fresh self-compacting concrete," *Construction and Building Materials*, vol. 208, pp. 564–576, 2019.
[42] Z. Toutou and N. Roussel, "Multi scale experimental study of concrete rheology: from water scale to gravel scale," *Materials and Structures*, vol. 39, no. 2, pp. 189–199, 2006.
[43] I. M. Krieger and T. J. Dougherty, "A mechanism for non-Newtonian flow in suspensions of rigid spheres," *Transactions of the Society of Rheology*, vol. 3, no. 1, pp. 137–152, 1959.
[44] N. Roussel, C. Stefani, and R. Leroy, "From mini-cone test to Abrams cone test: measurement of cement-based materials yield stress using slump tests," *Cement and Concrete Research*, vol. 35, no. 5, pp. 817–822, 2005.
[45] S. E. Chidiac, O. Maadani, A. G. Razaqpur, and N. P. Mailvaganam, "Controlling the quality of fresh concrete-a new approach," *Magazine of Concrete Research*, vol. 52, no. 5, pp. 353–363, 2000.
[46] CECS 203-2006, *Technical Specifications for Self Compacting Concrete Application*, China Planning Press, Beijing, China, 2006.
[47] P. L. Domone, "Self-compacting concrete: an analysis of 11 years of case studies," *Cement and Concrete Composites*, vol. 28, no. 2, pp. 197–208, 2006.