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Review Paper

Influence of supplementary cementitious materials on the rheology of fresh concrete: A review

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Abstract: The application of supplementary cementitious materials (SCMs) in concrete preparation is an important strategy for advancing the high-performance and low-carbon development of modern concrete. However, the addition of SCMs alters the rheological properties of concrete mixtures, which in turn affects the workability of fresh concrete. This paper presents a review of relevant studies on the influence of SCMs on the rheology of fresh concrete. The rheological models applicable to fresh concrete, such as the Bingham model, the Herschel-Bulkley model, the modified Bingham model, and other models, are introduced in detail. The influence of SCMs, including fly ash, granulated blast-furnace slag (GBFS), silica fume, limestone powder, and steel slag powder, on the rheological properties of fresh concrete is comprehensively analysed and discussed. The intrinsic relationship between the rheology and workability of fresh concrete, as well as the influence of SCMs on flowability and stability, are systematically elaborated.

Keywords: SCMs; Fresh concrete; Rheology; Flowability; Stability

1. Introduction

Concrete is an engineering composite material prepared by binding aggregates with cementitious materials, and it is currently the most widely produced and used construction material worldwide. Typically, concrete consists of cement and supplementary cementitious materials (SCMs) as binders, sand and gravel as aggregates, along with chemical admixtures and water mixed in specific proportions. Owing to its cost-effectiveness and good performance, concrete is extensively used in civil engineering, such as building construction and infrastructure development. Concrete that has not yet set and hardened after the mixing of various component materials is referred to as fresh concrete, also known as the concrete mixture. The fresh properties of concrete play a crucial role in determining the late-age mechanical strength and durability performance of hardened concrete [1,2].

Rheology can serve as an effective tool for characterising the fresh properties of concrete. Due to the simple expression form of the Bingham model, the two parameters (yield stress and plastic viscosity) in the constitutive equation of this model are frequently adopted to assess the rheological properties of fresh concrete [3]. Yield stress is the minimum shear stress required to initiate flow and deformation in the concrete mixture. During the early stage of cement hydration, a three-dimensional network of C-S-H flocculent structure forms between the unhydrated particles in the concrete mixture, impeding the flow and deformation of fresh concrete. When the shear stress exceeds the yield stress, the flocculent structure within the concrete

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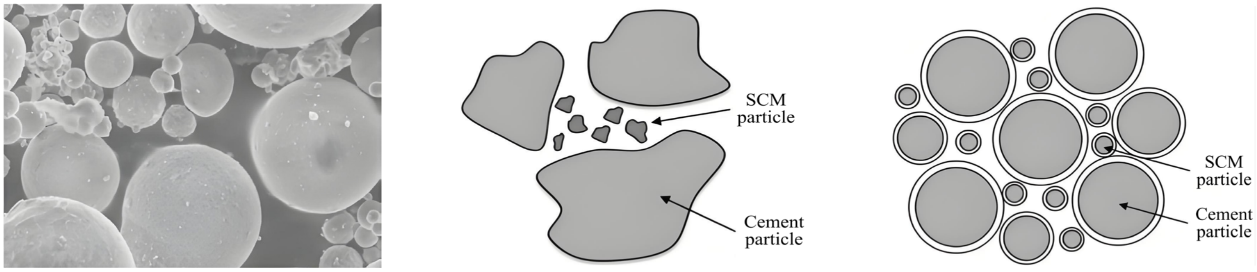
mixture is disrupted, transitioning fresh concrete from a stationary state to a flowing state. Conversely, when the shear stress is below the yield stress, the flocculent structure gradually recovers and fresh concrete reverts from a flowing state to a stationary state. Plastic viscosity is the ratio of shear stress to shear rate during the flow of fresh concrete. The magnitude of plastic viscosity is governed by factors such as van der Waals forces, Brownian motion, and viscous forces within the concrete mixture, and it directly affects the flow rate and deformation behaviour of fresh concrete. The greater the plastic viscosity, the more difficult it is for fresh concrete to flow and deform.

Cement is an indispensable component in the preparation of concrete. However, its production is accompanied by significant energy consumption and CO_2 emissions. Consequently, numerous studies [4-8] have been devoted to expanding the range of cementitious materials used in concrete. The most common substitutes for cement are SCMs derived from other industrial by-products. The incorporation of SCMs into concrete not only substantially reduces the energy consumption and CO_2 emissions associated with cement production, but also effectively promotes the recycling and reutilisation of industrial waste residues. At present, the commonly used SCMs include fly ash, granulated blast-furnace slag (GBFS), silica fume, limestone powder, and steel slag powder. Under the alkaline condition within concrete, reactive SCMs can react with $Ca(OH)_2$ produced from cement hydration to generate beneficial hydration products such as C-S-H gels. This reduces the $Ca(OH)_2$ content and results in finer hydration product particles, which helps to improve the microstructure of concrete, such as reducing the overall porosity of the paste and increasing the densification of the interfacial transition zone between the paste and aggregates. As for SCMs that do not participate in the chemical reaction, if their particle size is sufficiently small, they can fill voids, thereby refining the pore structure of the paste, or deposit in the interfacial transition zone, thereby strengthening this porous and weak region. Importantly, the proper use of SCMs can modify the rheological properties of concrete mixtures, which effectively improves the workability of fresh concrete and makes it easier for construction.

The mechanisms by which SCMs influence the rheology of fresh concrete mainly include the morphology effect theory, the filling and packing theory, and the water film theory [9]. The morphology effect theory (see Fig. 1(a)) states that the morphology characteristics of SCM particles, such as angularity and sphericity, affect the interparticle interactions within the concrete mixture. SCM particles with lower angularity can increase their sphericity, thereby reducing the frictional resistance between particles, which in turn improves the flow and deformation of fresh concrete. For example, adding spherical-shaped fly ash particles can significantly reduce the yield stress and plastic viscosity of fresh concrete [10,11]. In contrast, GBFS particles with irregular polygonal shapes have a lower sphericity, and their addition may increase the yield stress and plastic viscosity of fresh concrete [12]. The filling and packing theory (see Fig. 1(b)), inspired by the aggregate grading principle, proposes that finer SCM particles can fill the voids between cement particles, releasing the free water originally trapped between them, thereby increasing the free water content and promoting the flow and deformation of fresh concrete. For example, adding limestone powder with different fineness levels can form an appropriate particle gradation, which helps to effectively improve the flowability of fresh concrete [13,14]. The water film theory (see Fig. 1(c)) suggests that free water first fills the voids between particles, and excess water subsequently forms a certain thickness of water film on the particle surfaces, acting as a lubricant. SCMs with a finer particle size, such as ultra-fine GBFS and silica fume, have a larger specific surface area, which will consume more free water to form the water film, resulting in a reduction of free water in the system and thus hindering the flow and deformation of fresh concrete [15-19]. Additionally, some studies [20,21] point out that SCMs may participate in and influence the hydration process of cement, thereby affecting the rheology of fresh concrete. In most cases, the influence of SCMs on the rheological properties of fresh concrete results from the combined action of these mechanisms discussed above.



(a) Morphology effect theory (b) Filling and packing theory (c) Water film theory

Fig. 1 Influence mechanisms of SCMs on the rheology of fresh concrete [9]

With the growing application of SCMs in concrete preparation under the low-carbon context, studying their effects on the rheological properties of concrete mixtures is crucial for selecting appropriate SCMs to control the workability of fresh concrete, as well as ensuring the mechanical strength and durability performance of hardened concrete. Therefore, this paper presents a review of the influence of SCMs on the rheology of fresh concrete based on the findings of existing studies. Firstly, the rheological models applicable to fresh concrete, such as the Bingham model, the Herschel-Bulkley model, the modified Bingham model, and other models, are introduced in detail. After that, the influence of SCMs, including fly ash, GBFS, silica fume, limestone powder, and steel slag powder, on the rheological properties of fresh concrete is comprehensively analysed and discussed. Finally, the intrinsic relationship between the rheology and workability of fresh concrete, as well as the influence of SCMs on flowability and stability, are systematically elaborated. As a result, this work can provide a more comprehensive and in-depth understanding of how SCMs affect fresh concrete rheology and its relationship to workability.

2. Rheological models of fresh concrete

Fresh concrete undergoes continuous flow and deformation during the processes of mixing, transportation, pumping, pouring, and vibration compaction. Therefore, since the advent of rheology, researchers worldwide have paid great attention to the rheological properties of fresh concrete. At present, various models are used to characterise the rheological behaviour of fresh concrete, with their parameters effectively capturing key fresh properties. The most widely used rheological models include the Bingham model, the Herschel-Bulkley model, and the modified Bingham model. Additionally, the rheological models such as the Casson model, the Exponential model, and the Parabolic model are also commonly used. The following sections will provide a detailed introduction to these rheological models.

2.1 Bingham model

Tattersall and Banfill [22] proposed that the rheological properties of fresh concrete could be characterised using the Bingham model, with the constitutive equation of the model expressed as follows:

$$\tau = \tau_0 + \eta_p \dot{\gamma} \qquad (1)$$

Due to the fluid-like nature of fresh concrete, the stress and strain rate in the Bingham model correspond to the shear stress (τ) and shear rate ($\dot{\gamma}$), respectively. As fresh concrete exhibits yield stress during the fresh state, the limiting shear stress in the Bingham model is usually referred to as the yield stress (τ_0). Moreover, the rheological parameter η_p in the Bingham model is termed as the plastic viscosity, which is employed to characterise the viscosity of fresh concrete during flow.

From a practical application perspective, the Bingham model has become the most widely used model for studying the rheological properties of fresh concrete due to its simple expression form and the clear physical meaning of its parameters. In practice, the rheological parameters can be tested and calculated using a concrete rheometer. The yield stress and plastic viscosity in the Bingham model are commonly used to evaluate the fresh properties of concrete and serve as important references for mix proportion design [23-25]. However, the Bingham model is a linear rheological model. With the widespread use of SCMs in modern concrete, some studies [26-28] have found that as the shear rate increases, some fresh concrete materials exhibit a deviation from linearity in the shear stress and shear rate curve, showing phenomena such as shear thinning or shear thickening (see Fig. 2). In such cases, the use of the Bingham model may introduce certain errors, necessitating the adoption of more appropriate rheological models that can better reflect the actual conditions.

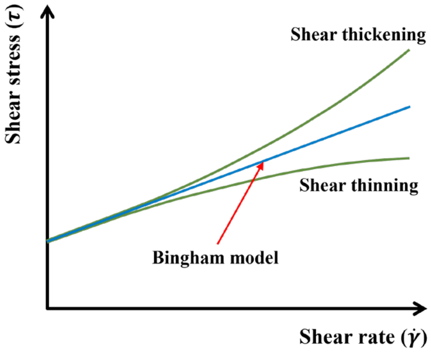


Fig. 2 Rheological curves of the relationship between shear stress and shear rate for fresh concrete

2.2 Herschel–Bulkley model

The Herschel-Bulkley model, improved by introducing an exponent term, can effectively characterise the nonlinear rheological behaviour of fresh cement-based materials. This rheological model was initially proposed by Herschel and Bulkley [29], and it was first applied by Jones and Taylor [30] to study the rheological properties of cement pastes. Later, de Larrard et al. [31] and Hafid et al. [32] found that this model could also characterise the rheological properties of cement mortars and concrete. The constitutive equation of the Herschel-Bulkley model is expressed as follows:

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{2}$$

where τ is the shear stress, τ_0 is the yield stress, K is the consistency, $\dot{\gamma}$ is the shear rate, and n is the power-law exponent, which reflects the degree to which the rheological behaviour deviates from linearity.

The Herschel-Bulkley model, also known as the power-law model with a yield value or yield pseudoplastic model, is one of the predominant models for cement-based material rheology. When $n < 1$, fresh concrete exhibits shear thinning behaviour; when $n > 1$, fresh concrete exhibits shear thickening behaviour; and when $n = 1$, fresh concrete behaves as a Bingham fluid.

2.3 Modified Bingham model

Based on the Bingham model, Yahia and Khayat [33] introduced a quadratic term to modify the model and proposed the modified Bingham model to characterise the nonlinear rheological behaviour of fresh cement-based materials. The constitutive equation of this model is expressed as follows:

$$\tau = \tau_0 + \eta_p\dot{\gamma} + c\dot{\gamma}^2 \tag{3}$$

where τ is the shear stress, τ_0 is the yield stress, η_p is the plastic viscosity, $\dot{\gamma}$ is the shear rate, and c is the coefficient of the quadratic term, which reflects the degree to which the rheological behaviour deviates from linearity.

In the expression of the modified Bingham model, when $c < 0$, fresh concrete exhibits shear thinning behaviour; when $c > 0$, fresh concrete exhibits shear thickening behaviour; and when $c = 0$, fresh concrete behaves as a Bingham fluid.

2.4 Other models

Besides the Herschel-Bulkley and modified Bingham models, there are other rheological models capable of effectively characterising the nonlinear shear thinning or shear thickening behaviour, such as the Casson model, the Exponential model, and the Parabolic model.

The constitutive equation of the Casson model is expressed as:

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_\infty\dot{\gamma}} \tag{4}$$

where τ is the shear stress, τ_0 is the yield stress, η_∞ is the limiting viscosity, and $\dot{\gamma}$ is the shear rate.

The Casson model is based on the following two assumptions. The particles are suspended in a Newtonian fluid, and there is an attractive force between these particles. When the shear stress is low, these particles gather into a rigid rod, and the length of the rod is inversely proportional to the shear stress.

The constitutive equation of the Exponential model is expressed as:

$$\dot{\gamma} = a + b\tau^{c} \tag{5}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, $a < 0$, $b > 0$, and c can be any positive real number.

In the expression of the Exponential model, when $c > 1$, fresh concrete exhibits shear thinning behaviour; when $0 < c < 1$, it exhibits shear thickening behaviour; and when $c = 1$, Eq. (5) can be regarded as another form of the Bingham model. Note that the fitting accuracy of the exponential term c in the Exponential model is generally lower than that of the exponential term n in the Herschel-Bulkley model. Therefore, the rheological parameters obtained based on the Herschel-Bulkley model are typically more reliable than those obtained based on the Exponential model.

The constitutive equation of the Parabolic model is expressed as:

$$\dot{\gamma} = a + b\tau + c\tau^{2} \tag{6}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, $a < 0$, $b > 0$, and c can be any real number.

In the expression of the Parabolic model, when $c > 0$, fresh concrete exhibits shear thinning behaviour; when $c < 0$, it exhibits shear thickening behaviour; and when $c = 0$, Eq. (6) can be regarded as another form of the Bingham model. It should be noted that when fresh concrete exhibits shear thickening behaviour, both a and c in the Parabolic model must take negative values, which complicates the processing of experimental data and the application of the model.

Among these nonlinear rheological models, the Herschel-Bulkley and modified Bingham models are more commonly used for characterising the nonlinear shear thinning or shear thickening behaviour of fresh cement-based materials, as they have fewer parameters and simpler expression forms. Additionally, for a particular fresh concrete material, there can only be one true yield stress value. However, the yield stress values obtained based on different rheological models are different. Therefore, there must be one most suitable rheological model for this type of concrete.

Overall, different rheological models have their own characteristics and advantages. It is essential to clarify the applicable scope of each model, as this can provide valuable insight and guidance for addressing different rheological issues. Table 1 summarises the commonly used rheological models. In most cases, the Bingham model is sufficient to describe the rheological properties of fresh concrete. However, with the addition of various SCMs in modern concrete, the concrete mixture system becomes quite complex and sometimes exhibits shear thinning or shear thickening behaviour. In such cases, the Herschel-Bulkley and modified Bingham models can better characterize the nonlinear rheological behaviour of fresh concrete. Wallevik et al. [34] pointed out that the rheological properties of most conventional concretes could be characterised by the Bingham model, while some special types of concretes, such as high-flowing concrete and self-compacting concrete, might exhibit nonlinear rheological behaviour and could be better characterised by the Herschel-Bulkley model or modified Bingham model. Liu et al. [35] also found that the Herschel-Bulkley and modified Bingham models could better characterise the rheological behaviour of mixtures containing SCMs compared to the Bingham model. In their study, the Herschel-Bulkley model presented better stability among these models, while the modified Bingham model exhibited superior applicability. Yahia and Khayat [36] reported that the Herschel-Bulkley and Casson models were found to be adequate for use with highly pseudoplastic mixtures. In addition, Li [37] pointed out that the solution of Couette inverse problem based on Herschel-Bulkley and modified Bingham models had some theoretical errors, so that the rheological parameters of these two rheological models could not be correctly measured with rheometer. At this point, using Exponential and Parabolic models could solve this problem. However, further research is urgently needed to determine the most suitable rheological model for different types of SCM-concrete systems.

Table 1 Summary of commonly used rheological models

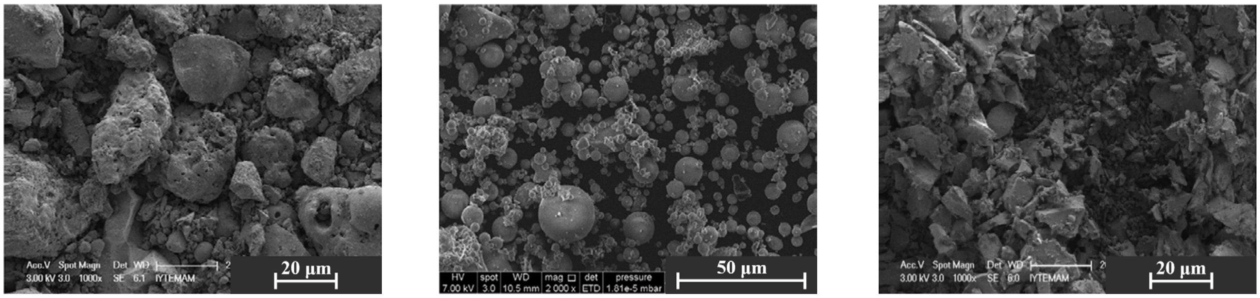
Rheological model	Constitutive equation	Characteristic
Bingham model	$\tau = \tau_0 + \eta_p \dot{\gamma}$	A linear rheological model, and the most widely used model to characterize the rheological properties of cement-based materials.
Herschel-Bulkley model	$\tau = \tau_0 + K\dot{\gamma}^n$	If $n < 1$, it exhibits shear thinning behaviour; if $n > 1$, it exhibits shear thickening behaviour; and if $n = 1$, it behaves as a Bingham fluid.
Modified Bingham model	$\tau = \tau_0 + \eta_p \dot{\gamma} + c\dot{\gamma}^2$	If $c < 0$, it exhibits shear thinning behaviour; if $c > 0$, it exhibits shear thickening behaviour; and if $c = 0$, it behaves as a Bingham fluid.
Casson model	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_\infty \dot{\gamma}}$	Assumption: the particles are suspended in a Newtonian fluid, and there is an attractive force between these particles; and when the shear stress is low, these particles gather into a rigid rod and the length of the rod is inversely proportional to the shear stress.
Exponential model	$\dot{\gamma} = a + b\tau^c$	If $c > 1$, it exhibits shear thinning behaviour; if $0 < c < 1$, it exhibits shear thickening behaviour; and if $c = 1$, it behaves as a Bingham fluid.
Parabolic model	$\dot{\gamma} = a + b\tau + c\tau^2$	If $c > 0$, it exhibits shear thinning behaviour; if $c < 0$, it exhibits shear thickening behaviour; and if $c = 0$, it behaves as a Bingham fluid.

3. Influence of SCMs on rheology

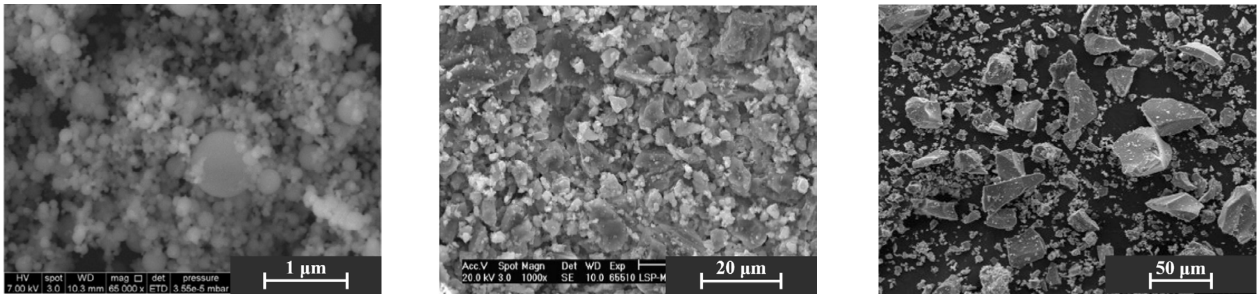
SCMs have a significant influence on the rheology of fresh concrete, and the pattern and extent of their influence largely depend on the type of SCMs. This section will provide a comprehensive analysis and discussion on the effects of fly ash, GBFS, silica fume, limestone powder, and steel slag powder on the rheological properties of fresh concrete. The basic properties of fly ash, GBFS, silica fume, limestone powder, and steel slag powder are presented in Table 2. The microscopic morphology images of these SCMs collected from relevant studies [38-40] are shown in Fig. 3.

Table 2 Basic properties of SCMs

SCM	Average density (g/cm^3)	Average Blaine specific surface area (m^2/kg)	Average particle size (μm)
Fly ash	2.1-2.5	300-500	10-30
GBFS	2.8-3.1	350-600	5-25
Silica fume	2.1-2.3	20,000-25,000	0.1-0.3
Limestone powder	2.6-2.8	450-700	1-20
Steel slag powder	3.1-3.6	400-600	10-30



(a) Class C fly ash (b) Class F fly ash (c) GBFS



(d) Silica fume (e) Limestone powder (f) Steel slag powder

Fig. 3 Microscopic morphology images of SCMs [38-40]

3.1 Fly ash

Fly ash is a solid waste product formed from the combustion of coal. It is a volcanic ash material with high content of SiO_2 and Al_2O_3, and low content of CaO. The average density of fly ash ranges from 2.1 g/cm^3 to 2.5 g/cm^3, the average Blaine specific surface area is from 300 m^2/kg to 500 m^2/kg, and the average particle size is between 10 μm and 30 μm. Fly ash is categorized into two types, class C and class F, depending on the coal type used in combustion. Fly ash produced from lignite combustion is brownish-yellow and is referred to as class C fly ash, while fly ash produced from bituminous coal or anthracite combustion is grey or dark grey and is referred to as class F fly ash. In comparison to class C fly ash, class F fly ash has a smoother particle surface and better sphericity [41].

The influence of fly ash on the rheology of fresh concrete based on existing studies is summarised in Fig. 4. In Fig. 4, the horizontal axis in the coordinate system represents the yield stress, while the vertical axis represents the plastic viscosity. The positive and negative directions of the axes indicate the positive and negative effects on the results of yield stress and plastic viscosity, respectively. The green box and blue box reflect the degrees of significant and slight effects on this influence, respectively. Laskar and Talukdar [42] found that the low dosage of fly ash reduced the yield stress of concrete mixtures, thereby improving the flow and deformation capacity of fresh concrete. However, when the fly ash dosage was higher, the yield stress tended to increase slightly. In the study by Jalal et al. [10], it was reported that spherical fly ash particles could significantly reduce the yield stress and plastic viscosity of concrete mixtures through the ball rolling effect. Beycioğlu and Aruntaş [11] also noted that the incorporation of fly ash obviously decreased the yield stress and plastic viscosity of concrete mixtures, which could be attributed to the spherical shape and smooth surface of fly ash particles [43] (see Fig. 5). The findings of Park et al. [44] indicated that while the addition of fly ash decreased the yield stress and plastic viscosity of concrete mixtures, a slight increase in both of them occurred with higher fly ash dosages. Furthermore, Rahman et al. [45] observed that the incorporation of fly ash increased the viscosity and flocculation rate of the concrete mixture, thereby further affecting the rheological properties of fresh concrete.

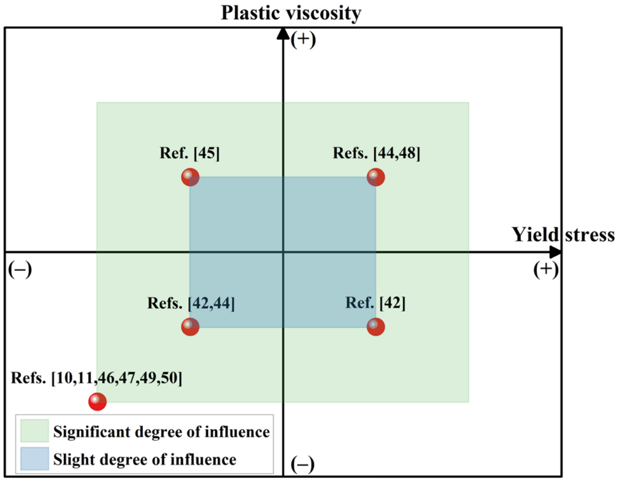


Fig. 4 Influence of fly ash on the rheology of fresh concrete [10,11,42,44-50]

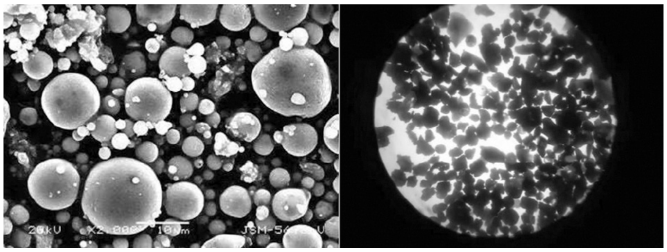


Fig. 5 The morphology of fly ash particles under the microscope [43]

The type and particle size of fly ash have also been shown to significantly influence the rheological properties of fresh concrete. Ahari et al. [46] investigated the effects of different dosages of class C and class F fly ash on the rheological properties of fresh concrete. They found that class F fly ash was more effective in reducing the plastic viscosity of the concrete mixture than class C fly ash, which might be attributed to the difference in the surface morphology of the two types of fly ash particles. Ferraris et al. [47] explored the influence of fly ash with different particle sizes on the rheology of fresh concrete, and the results indicated that when 12% by mass of cement was replaced, the yield stress of concrete mixtures with fly ash having an average particle size of 5.7 μm was approximately twice that of fly ash with an average particle size of 18.0 μm. In addition to the effects of fly ash type and particle size, unburned carbon in fly ash can adsorb water and water-reducing agents, leading to an increase in the plastic viscosity of the mixture [48]. This factor requires particular attention when using fly ash containing unburned carbon.

In recent years, the application of fly ash microspheres, which are collected and sorted from ordinary fly ash, has become increasingly widespread in practical engineering. Compared to ordinary fly ash, fly ash microspheres have smaller particle sizes, with an average diameter of only a few microns. These microspheres can better fill the voids between cement particles, thereby improving the particle gradation. Additionally, fly ash microsphere particles typically exhibit a standard spherical morphology and a smooth surface, which helps to reduce the internal frictional resistance within the concrete mixture. Most existing studies [49,50] have demonstrated that the incorporation of fly ash microspheres can significantly reduce the yield stress and plastic viscosity of the mixture.

3.2 Granulated blast–furnace slag

GBFS, an industrial by-product of blast furnace ironmaking, is widely used as a SCM to improve the workability of fresh concrete as well as the mechanical strength and durability performance of hardened concrete. Consequently, GBFS is commonly incorporated into concrete materials. The main chemical compositions of GBFS are CaO, SiO_2, and Al_2O_3, with their mass content reaching 80-90%. The average density, Blain specific surface area, and particle size of GBFS range from 2.8 g/cm^3 to 3.1 g/cm^3, 350 m^2/kg to 600 m^2/kg, and 5 μm to 25 μm, respectively.

The influence of GBFS on the yield stress and plastic viscosity of concrete mixtures is depicted in Fig. 6. The findings of Park et al. [44] indicated that with the increase in GBFS content, the yield stress of the concrete mixture initially decreased and then increased, while the plastic viscosity continuously decreased. Ahari et al. [38] found that if GBFS was added to replace a portion of cement, both yield stress and plastic viscosity of the concrete mixture were reduced. In particular, when the water-to-binder ratio was 0.44, adding 18% by mass of GBFS could reduce the thixotropic area by approximately 10%. The research by Derabla and Benmalek [51] also showed that the incorporation of GBFS into concrete lowered the plastic viscosity of the mixture. In their study, the plastic viscosity of the concrete mixture was reduced from 150 Pa·s to 121 Pa·s with the addition of GBFS. For the same dosage, the plastic viscosity of the concrete mixture with the addition of crystalline GBFS was reduced from 150 Pa·s to 91 Pa·s. However, some studies have pointed out that the incorporation of GBFS may sometimes increase the plastic viscosity of the concrete mixture. For instance, Tattersall [52] found that when the cement dosage was relatively low, the addition of GBFS slightly increased the plastic viscosity of the concrete mixture, even though it lowered the yield stress. Tang et al. [12] investigated the rheological behaviour of high-content GBFS composite mixtures, and the results showed that under the same flowability conditions, the addition of GBFS increased the water demand of cementitious materials, leading to an increase in the plastic viscosity of the mixture.

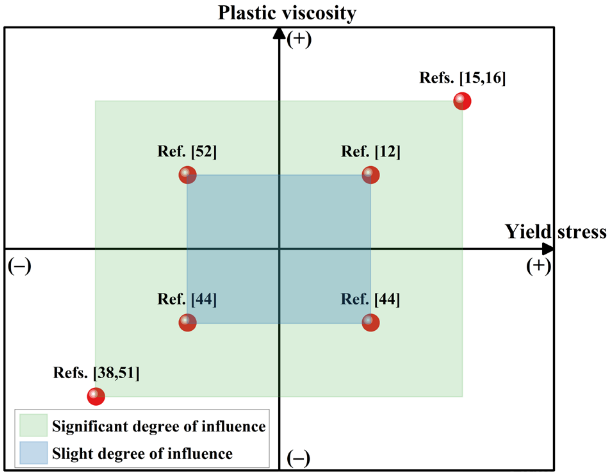


Fig. 6 Influence of GBFS on the rheology of fresh concrete [12,15,16,38,44,51,52]

Additionally, ultra-fine GBFS has gradually become a commonly used SCM in the preparation of high-performance concrete. Ultra-fine GBFS is the product of mechanical grinding of GBFS, with an average particle size of only a few microns, and its specific surface area is significantly higher than that of ordinary GBFS. Some studies [15,16] have indicated that due to the smaller particle size and larger specific surface area of ultra-fine GBFS particles, its incorporation requires a higher water demand, which consequently increases the yield stress and plastic viscosity of the mixture.

3.3 Silica fume

Silica fume is collected from the smoke during the smelting of silicon or ferro-silicon alloys in ferro-silicon alloy production plants. It is an ultra-fine powder with an average particle size ranging from 100 nm to 300 nm. Due to its extremely fine particle size, silica fume can fill the voids between solid particles and increase the packing density of the cementitious material system, making it one of the most important raw materials for the preparation of high-performance concrete. The Blain specific surface area of silica fume is approximately 20,000 m^2/kg to 25,000 m^2/kg, which is several tens of times higher than that of cement particles. This exceptionally high specific surface area leads to an increased water demand and higher adsorption of the water-reducing agent in the cementitious material system [53,54].

The influence of silica fume on the rheology of fresh concrete is shown in Fig. 7. Currently, the vast majority of studies [17-19] have indicated that the incorporation of silica fume significantly increases the yield stress and plastic viscosity of concrete mixtures. Therefore, silica fume is commonly used as an inorganic thickening agent, suitable for concrete types requiring high homogeneity and cohesiveness, such as shotcrete, pumped concrete, and underwater concrete. However, some studies have shown that the addition of silica fume can have other effects on the rheological properties of fresh concrete. For example, Ahari et al. [38,46] found that while silica fume increased the yield stress of concrete mixtures, it simultaneously reduced the plastic viscosity. Zhang and Han [55] reported that the incorporation of silica fume reduced both the yield stress and plastic viscosity of the mixture. Yun et al. [56] demonstrated that adding silica fume significantly enhanced the flow resistance of fresh concrete, although it slightly decreased the plastic viscosity.

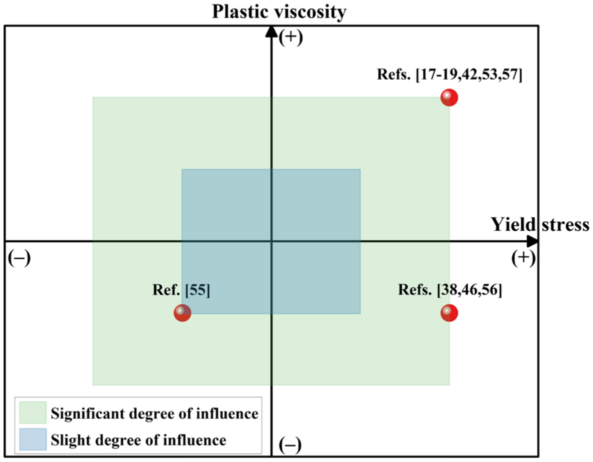


Fig. 7 Influence of silica fume on the rheology of fresh concrete [17-19,38,42,46,53,55-57]

The influence of silica fume on the rheological properties of fresh concrete is also governed by other factors such as the water-to-binder ratio and the type of water-reducing agents. For instance, the research by Nanthagopalan et al. [53] showed that after adding silica fume, the increase in yield stress and plastic viscosity of concrete mixtures became more pronounced as the water-to-binder ratio decreased. Liu et al. [57] also noticed that the influence of silica fume on rheology gradually lost its regularity as the water-to-binder ratio increased. Laskar and Talukdar [42] found that while the incorporation of silica fume enhanced the yield stress of concrete mixtures when using polycarboxylate superplasticizers, it reduced the yield stress when naphthalene-based superplasticizers were employed. Moreover, the dispersion of silica fume particles in the mixture has an important impact on the rheological properties of fresh concrete [57]. Fig. 8 presents the microstructure of the mixture containing silica fume under the microscope when the mixture is formed for 60 minutes. In Fig. 8, the red circles highlight the obvious flocculated structure. Among these images, the flocculated structure in the first group is the most severe, which is detrimental to the rheology and workability of the mixture.

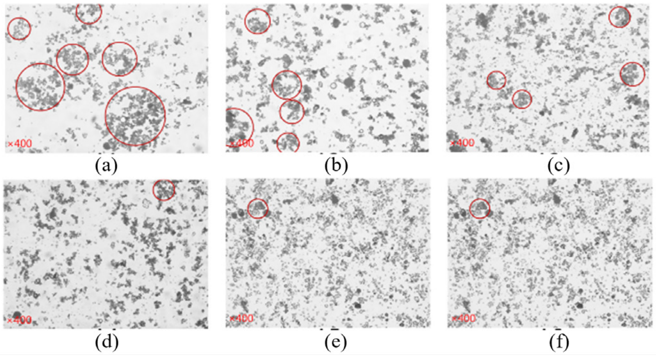


Fig. 8 Microstructure of the mixture containing silica fume [57]

In addition, nano-silica is a very efficient pozzolanic material having glassy particles about 1,000 times smaller than the cement particles. It is reported that the incorporation of nano-silica with extremely high specific surface area in fresh concrete significantly increases the water requirement to maintain the required flowability. This is due to the increased friction between particles and the dense packing of nano-silica in the mixture, leading to higher yield stress and plastic viscosity [58-60]. Safi et al. [61] tested both nano-silica in powder form and in suspension with a superplasticizer solution, and they found that the suspension solution form yielded the more suitable rheological parameters. Wang et al. [62] employed ultrasonic technology to obtain a nano-silica suspension in distilled water, and they observed a gradual increase in plastic viscosity and a significant increase in yield stress when nano-silica was added.

3.4 Limestone powder

Compared to fly ash, GBFS, and silica fume, limestone powder has the advantages of large resource reserves, wide distribution, and low cost. Its utilization can bring significant economic and environmental benefits. Therefore, there is an increasing amount of research on using limestone powder as a SCM. The main chemical composition of limestone powder is $CaCO_3$. The average density, Blaine specific surface area, and particle size of limestone powder range from 2.6 g/cm^3 to 2.8 g/cm^3, 450 m^2/kg to 700 m^2/kg, and 1 μm to 20 μm, respectively. It should be noted that finer limestone powder can be obtained by increasing the grinding time.

The influence of limestone powder on the yield stress and plastic viscosity of concrete mixtures is displayed in Fig. 9. Corinaldesi and Moriconi [63] found that the incorporation of limestone powder had no significant effect on the yield stress of the concrete mixture, but it increased both plastic viscosity and thixotropy. Notably, the particle size of limestone powder plays an important role in the rheological properties of concrete mixtures. Schankoski et al. [64] reported that when the limestone powder content was 42%, the yield stress of the mixture with particle sizes of 16 μm and 25 μm increased by 60% and 40%, respectively, compared to the particle size of 38 μm. Similarly, Ma et al. [65] noticed that as the particle size of limestone powder decreased, both the yield stress and plastic viscosity of the mixture increased. Vance et al. [66] observed that the addition of limestone powder enhanced the yield stress and plastic viscosity of the mixture, and as the D_{50} value of particle size of limestone powder increased from 0.7 μm to 15 μm, both yield stress and plastic viscosity exhibited a decreasing trend. They stated that the addition of finer particles than the cement typically increased yield stress and plastic viscosity, while the addition of coarser particles than the cement had the opposite effect. This was because fine particles could reduce the inter-particle spacing and increase the particle-to-particle contact, whereas coarse particles could increase the inter-particle spacing and reduce the shear resistance of the mixture.

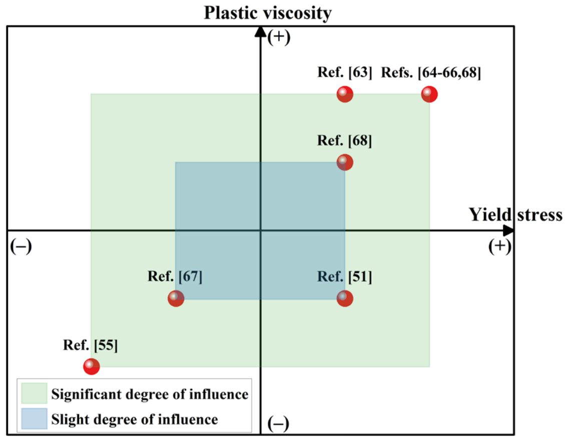


Fig. 9 Influence of limestone powder on the rheology of fresh concrete [51,55,63-68]

In addition to the aforementioned findings, Gallias et al. [67] found that limestone powder had minimal impact on the water demand of the concrete mixture and resulted in a slight reduction in plastic viscosity. Zhang and Han [55] reported that the addition of limestone powder decreased both the yield stress and plastic viscosity of the mixture. Derabla and Benmalek [51] indicated that limestone powder increased the yield stress of the concrete mixture while reducing its plastic viscosity. Furthermore, Salman et al. [68] found that replacing 10% by mass of cement with limestone powder did not significantly affect the rheology of fresh concrete, but when the replacement amount of limestone powder exceeded 20%, the plastic viscosity of the concrete mixture noticeably increased.

3.5 Steel slag powder

Steel slag powder is an industrial by-product generated during the steelmaking process, with its discharge amounting to approximately 15% of crude steel production. However, the current comprehensive utilization rate of steel slag powder remains below 30%. The efficient utilization of steel slag powder can help to mitigate the environmental issues associated with its large-scale accumulation. In particular, exploring the use of steel slag powder as a SCM in concrete production is of significant importance for the sustainable development of construction industry. The main chemical compositions of steel slag powder are CaO, SiO_2, and Fe_2O_3. The average density, Blaine specific surface area, and particle size of steel slag powder range from 3.1 g/cm^3 to 3.6 g/cm^3, 400 m^2/kg to 600 m^2/kg, and 10 μm to 30 μm, respectively.

The influence of steel slag powder on the rheology of fresh concrete based on existing studies is presented in Fig. 10. Yu et al. [69] investigated the rheological properties of fresh concrete containing steel slag powder. They found that compared to the concrete mixture without steel slag powder, the yield stress and thixotropic values of the concrete mixture decreased when the steel slag powder content exceeded 20%. Furthermore, as the steel slag powder content increased, the reduction in yield stress and thixotropic values became more pronounced, while the impact on plastic viscosity was less significant. Zhu et al. [70] reported that when the steel slag powder content increased from 8% to 40%, there was a consistent decline in yield stress, plastic viscosity, and thixotropy. This was attributed to the low reactivity of steel slag powder. As the steel slag powder content increased, the corresponding reduction in cement content led to a less pronounced flocculation network structure in the cementitious material system [71-73], resulting in a decrease in yield stress, plastic viscosity, and thixotropy with increasing steel slag powder content [74,75].

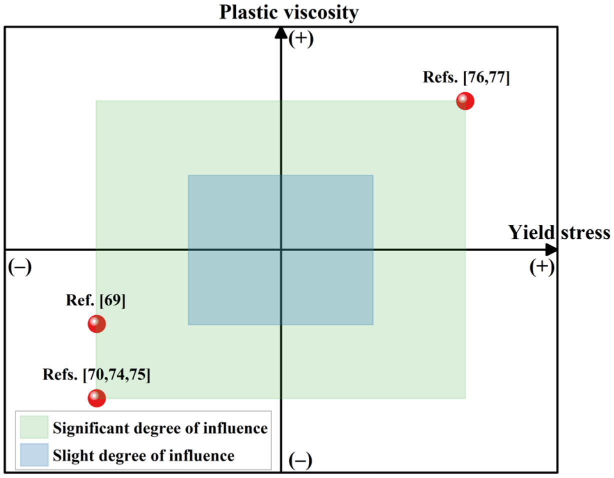


Fig. 10 Influence of steel slag powder on the rheology of fresh concrete [69,70,74-77]

Additionally, the particle size of steel slag powder also has a certain impact on the rheology of fresh concrete. For example, Zhao et al. [76] investigated the influence of four different particle sizes of steel slag powder on the rheological properties of fresh concrete. They found that as the particle size decreased, the yield stress, plastic viscosity, and thixotropy of the concrete mixture increased. Yang et al. [77] investigated the influence of two types of ultra-fine steel slag powder on the rheological properties of the mixture. These two types of ultra-fine steel slag powder had specific surface areas of 1,697 m^2/kg and 2,549 m^2/kg, with particle size distributions ranging from 0.314 μm to 58.9 μm and 0.276 μm to 58.9 μm, respectively. The D_{50} values of the two were 5.0 μm and 3.3 μm, respectively. When the steel slag powder content was 40%, the first type of steel slag powder increased the yield stress and plastic viscosity of the mixture by 78.1% and 174.8%, respectively, while the second type of steel slag powder resulted in increases of 87.3% and 276.7% in yield stress and plastic viscosity, respectively.

Overall, the influence of SCMs on the rheology of fresh concrete varies depending on factors such as their type, surface morphology, specific surface area, and particle size. The addition of SCMs with low angularity and high sphericity, such as fly ash, usually leads to an obvious reduction in the yield stress and plastic viscosity of the concrete mixture. The incorporation of SCMs with very small particle sizes, such as silica fume, ultra-fine GBFS, and ultra-fine limestone powder, tends to increase the yield stress and plastic viscosity of the concrete mixture. As for the influence of ordinary GBFS and limestone powder on the rheological properties of fresh concrete, the patterns reported in different literature sources are somewhat inconsistent. Moreover, the addition of low-activity SCMs, such as steel slag powder, generally reduces the yield stress and plastic viscosity of the concrete mixture. However, note that when the particle size of steel slag powder is particularly fine, its incorporation will increase the yield stress and plastic viscosity. Through the above analysis and discussion, it can be seen that strategic selection of appropriate SCMs can effectively alter the rheological properties of the concrete mixture, which not only helps to improve the workability of fresh concrete but also contributes to the mechanical strength and durability performance of hardened concrete.

4. Relationship between rheology and workability

The incorporation of different SCMs alters the rheological properties of fresh concrete, thereby affecting its workability. Workability refers to the ease with which fresh concrete can undergo various construction operations (such as mixing, transportation, pumping, pouring, and vibration compaction) and achieve a uniform quality and dense formation. This implies that fresh concrete is required to have sufficient flowability for easy construction, as well as good stability to ensure the quality of the project. This section will systematically elaborate the intrinsic relationship between the rheology and workability of fresh concrete, as well as the influence of different SCMs on flowability and stability.

4.1 Relationship between rheology and flowability

Flowability refers to the ability of fresh concrete to flow under its own weight or mechanical vibration, ensuring uniform and dense filling of the formwork. The quality of flowability has a significant impact on both the workability of concrete during the fresh stage and its performance after setting and hardening. Insufficient flowability in fresh concrete may lead to difficulties in evenly filling the formwork during construction, resulting in defects such as honeycombing, voids, and exposed reinforcement bars, which in turn affect the mechanical strength and durability performance of hardened concrete [78,79]. Conversely, excessive flowability can lead to instability issues such as segregation, settlement, and bleeding, which also compromise the quality of hardened concrete [80,81]. In a broader sense, the flowability of fresh concrete also includes other properties such as the passing ability through gaps and the filling ability, which are typically evaluated through the testing methods such as slump, slump flow, T_{500}, L-box, and V-funnel.

The slump test is widely used for evaluating the flowability of fresh concrete due to its simplicity and convenience. Some researchers have attempted to establish functional relationships between slump and rheological parameters to explore the influencing factors and prediction methods for the flowability of fresh concrete. For example, through conducting extensive experiments, Ferraris and de Larrard [82] provided the relationship between the slump test results (slump and slump flow) and rheological parameters (yield stress and plastic viscosity) of fresh concrete. Similarly, Zerbino et al. [83] established a functional relationship between T_{500} and plastic viscosity. Based on experimental studies and theoretical analysis, Roussel [84] proposed an empirical equation relating slump to yield stress, allowing an estimation of the yield stress of the concrete mixture from slump test results. Additionally, an equation was developed for the relationship between slump flow (greater than 200 mm) and yield stress for high-flowing concrete. Laskar [85] and Neophytou et al. [86] attempted to analyse the rheological behaviour of concrete mixtures through the slump test and linked flowability indicators such as slump, slump flow, and slump time with rheological parameters. Cai et al. [87,88] developed numerical models based on computational fluid dynamics to simulate the slump, L-box, and V-funnel tests, and then predicted the flow performance of fresh concrete using rheological parameters. Furthermore, Meng and Khayat [89] proposed a linear relationship between the V-funnel flow time and plastic viscosity for high-flowing concrete. Through extensive experimental comparisons, Wallevik [90] found that there was a strong linear relationship between slump and yield stress, whereas the correlation between slump and plastic viscosity was relatively weak. Moreover, Ling et al. [91] also observed that the flowability of fresh concrete decreased linearly with increasing yield stress.

4.2 Influence of SCMs on flowability

In order to improve the performance of concrete materials, the use of SCMs in modern concrete has become increasingly widespread. The influence of SCM incorporation on the flowability of fresh concrete based on existing studies is summarised in Fig. 11. Beycioğlu and Aruntaş [11] observed that the spherical shape and smooth surface characteristics of fly ash contributed to reducing the water demand of the cementitious material system, thereby enhancing the flowability of fresh concrete. Jalal et al. [10] found that incorporating 15% by mass of fly ash increased the slump flow of self-compacting concrete from 800 mm to 870 mm and reduced the T_{500} flow time from 1.7 s to 1.1 s. Similarly, Zhang et al. [92] pointed out that high-quality fly ash had a standard spherical shape and low water demand, which could significantly improve the flowability of fresh concrete. The incorporation of fly ash into concrete could obviously reduce the water demand while maintaining the same level of mixture flowability. This not only improved the workability but also helped to ensure the mechanical strength in the later stage. The particle size or particle size distribution of fly ash also affects the flowability of fresh concrete. For instance, Ferraris et al. [47] and Li and Wu [93] noticed that as the particle size of fly ash increased, the flowability of fresh concrete first decreased and then increased. Lee et al. [94] found that a broader particle size distribution range of fly ash enhanced the flowability of fresh concrete. In addition, several studies [49,50] have shown that the addition of fly ash microspheres can obviously improve the flowability of fresh concrete.

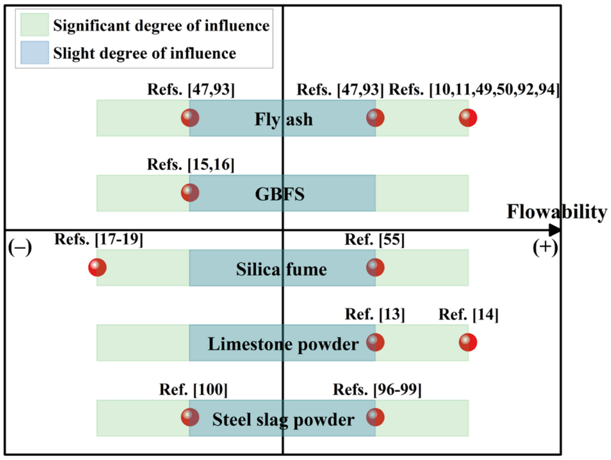


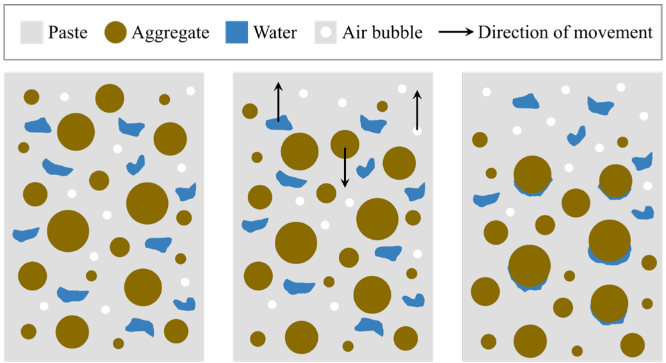
Fig. 11 Influence of SCMs on the flowability of fresh concrete [10,11,13-19,47,49,50,55,92-94,96-100]

Compared to fly ash, the influence of GBFS on the slump and slump flow of fresh concrete is not pronounced, thus its role in regulating the flowability of fresh concrete is relatively limited. However, the use of GBFS has certain advantages in other aspects, such as improving the late-age mechanical strength and durability performance of concrete [95]. In addition, some studies [15,16] have indicated that due to the higher specific surface area and water demand of ultra-fine GBFS, it can reduce the flowability of fresh concrete. As for the influence of silica fume on the flowability of fresh concrete, numerous studies [17-19] have demonstrated that the incorporation of silica fume tends to reduce the flowability of fresh concrete. However, Zhang and Han [55] pointed out that due to the micro filling and lubricating effects, the addition of silica fume might, in some cases, reduce the yield stress and plastic viscosity of the concrete mixture, thereby improving its flowability to some extent.

Vikan and Justnes [13] observed that limestone powder particles helped to disperse cement particles, and as the replacement level of limestone powder increased, the flow resistance of the concrete mixture decreased. Zhang et al. [14] similarly found that the incorporation of limestone powder improved the flowability of fresh concrete, especially when the dosage was 10% or higher, where the improvement was particularly significant. Wang et al. [96,97] pointed out that steel slag power had lower reactivity and required less water to achieve plasticity. When steel slag power was used as a partial replacement for cement, the water demand of the cementitious material system was lower than that of an equal mass of pure cement. Therefore, theoretically, when the water content remained constant, the addition of steel slag power could increase the flowability of fresh concrete. Pan et al. [98] and Calmon et al. [99] also found that the addition of steel slag powder could enhance the flowability of the concrete mixture. In contrast, some researchers have reached opposing conclusions in their experiments. Guo et al. [100] reported that due to its high specific surface area, the use of steel slag powder in concrete resulted in a reduction in flowability.

4.3 Relationship between rheology and stability

The stability of fresh concrete refers to the ability of its component materials to maintain a uniform distribution during transportation, pumping, pouring, and vibration compaction processes. Under the action of gravity or shear force, due to the insufficient cohesion within the concrete mixture and the density difference among various raw materials, the relative movement and redistribution of each component are likely to occur, with the segregation phenomenon being particularly prominent, as shown in Fig. 12. Segregation is a common issue during construction, and it not only affects the workability of fresh concrete but also leads to problems after the concrete hardens, such as local shrinkage and cracking, reduced mechanical strength, and diminished resistance to chemical attacks. Previous studies have shown that fresh concrete with severe segregation tends to block aggregate particles when encountering obstacles like reinforcement bars, which adversely affects construction efficiency [101,102]. During the pumping process, segregation may lead to quality issues in the pumped concrete, and in severe cases, even cause blockages in the pipeline [103]. Particularly under the action of vibration, fresh concrete tends to exhibit more noticeable segregation, significantly increasing its heterogeneity [104]. After the concrete hardens, segregation results in a higher concentration of cement pastes on the surface, exacerbating the risk of shrinkage and cracking [105]. Moreover, segregation leads to significant heterogeneity in the mechanical strength and permeability of the concrete cover along the pouring height [106], and forms voids at the reinforcement bar/concrete and aggregate/paste interfaces [107,108], which severely impacts the durability and service life of reinforced concrete [109-112].



Uniform state　Segregation process　Non-uniform state

Fig. 12 Schematic diagram of non-uniform distribution of various components caused by segregation

SCMs can induce changes in the rheological properties of concrete mixtures, which are closely related to the stability of fresh concrete. It is generally believed that increasing the yield stress and plastic viscosity of the concrete mixture can improve the stability of fresh concrete by reducing particle segregation tendencies. The yield stress determines whether the constituent particles of the mixture are stable and the tendency for segregation to occur, while the plastic viscosity governs the speed at which unstable particles move [113]. It should be noted that even when the yield stress of the mixture is low, the particles in a mixture with a high plastic viscosity can still be considered stable, as the movement speed of particles undergoing segregation is very slow, and their displacement can be negligible [114]. Wu et al. [115] pointed out that the rheological characteristics of fresh concrete determined its flowability, cohesion, and subsequently its stability. Mueller et al. [116] suggested that the yield stress and plastic viscosity of the concrete mixture were the key parameters to ensure good stability. In the study by Safawi et al. [117,118], it was reported that during the vibration compaction of fresh concrete, stability depended more on plastic viscosity than yield stress, and the concrete mixture with lower plastic viscosity was more prone to segregation and settlement than that with higher plastic viscosity. Zhang et al. [119] noted that there was still a lack of effective models relating the rheological parameters of fresh concrete to its stability, and conducting related research could be beneficial for the scientific evaluation and regulation of the stability of fresh concrete.

4.4 Influence of SCMs on stability

The influence of SCMs on the stability of fresh concrete varies depending on their type, primarily because different SCMs influence the rheological properties of the concrete mixture in distinct ways. It is generally believed that SCMs, which help to increase the yield stress and plastic viscosity of the mixture, can improve the stability of fresh concrete. Additionally, the morphology and particle size distribution of SCMs also affect the stability of fresh concrete. The influence of various SCMs on the stability of fresh concrete is shown in Fig. 13. Amini et al. [120] found that the addition of fly ash increased the segregation index of the concrete mixture. This is because fly ash is a smooth and spherical particle that reduces the frictional resistance between the raw material particles when incorporated into concrete, thereby lowering the yield stress and plastic viscosity of the mixture. Similarly, Corinaldesi and Moriconi [63] observed that the addition of fly ash resulted in a more pronounced separation between coarse aggregate particles and the surrounding paste. Furthermore, Nili et al. [121] replaced 5% to 25% by mass of cement with fly ash, and they found that with increasing fly ash content, the degree of segregation of fresh concrete increased compared to the mixture without fly ash and the segregation degree became more significant with higher fly ash content.

Ghoddousi et al. [122] reported that the incorporation of GBFS negatively impacted the stability of fresh concrete due to the dilution effect. Mahdikhani and Ramezanianpour [123] demonstrated that due to the large fineness and specific surface area of silica fume particles, replacing a portion of cement with silica fume could significantly increase the yield stress and plastic viscosity of the mixture and had a significant stabilizing effect on fresh concrete, especially at high water-to-binder ratios. As for the influence of limestone powder and steel slag powder on stability, Libre et al. [124] suggested that while limestone powder could improve the flowability to some extent, it did not significantly enhance the stability of fresh concrete. Ghoddousi et al. [122] found that partial replacement of cement with limestone powder led to a greater tendency for segregation. They attributed it to the lower specific surface area of the limestone powder used, resulting in a thicker water layer covering the particles and, consequently, a decrease in stability. Lin et al. [125] pointed out that compared to the concrete mixture without steel slag powder, the incorporation of steel slag powder improved the flowability of the mixture, which was determined by the surface characteristics of the steel slag powder. This surface property formed a smooth moving surface between cement particles. However, the resistance to segregation of fresh concrete decreased.

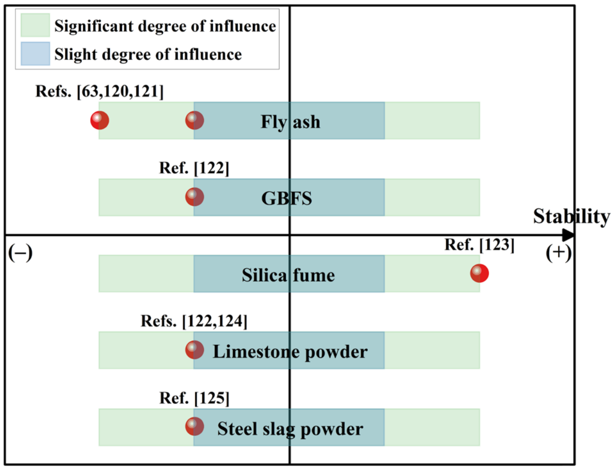


Fig. 13 Influence of SCMs on the stability of fresh concrete [63,120-125]

Overall, different application scenarios have specific requirements for the rheological properties and workability of fresh concrete. For example, pumped concrete requires moderate yield stress and plastic viscosity to balance flowability and segregation resistance; self-compacting concrete requires low yield stress and relatively high plastic viscosity to achieve self-leveling and segregation resistance; shotcrete requires high yield stress and thixotropy to ensure it does not flow after spraying and sets rapidly; and 3D printed concrete requires low dynamic yield stress for ease of extrusion and high static yield stress to support interlayer stacking. The use of SCMs plays an important role in improving the rheological properties and workability of different types of concrete mixtures. Taking two typical cases as examples. On the one hand, if fresh concrete lacks sufficient flowability, it may cause blockages during pumping or 3D printing. Adding high-quality fly ash (with spherical particles and smooth surfaces) can obviously reduce the yield stress and plastic viscosity of the mixture, thereby improving its flowability. However, it should be noted that the flowability and stability are often a contradictory pair of properties. The excessive dosage of fly ash may lead to instability issues such as aggregate settlement and water bleeding. On the other hand, although self-compacting concrete has good flowability, it is prone to segregation and bleeding. Due to the larger fineness of silica fume particles, replacing part of the cement with silica fume can significantly enhance the homogeneity of the mixture. Currently, it is common to use a combination of two or more SCMs to comprehensively improve the rheology and workability of fresh concrete.

5. Summary and outlook

Based on the review of the influence of SCMs on the rheology of fresh concrete, the following summary and outlook can be drawn:

(1) The Bingham model, due to its simplicity and the clear physical significance of its rheological parameters (yield stress and plastic viscosity), has become the most widely used model for studying the rheological properties of fresh concrete. With the widespread use of SCMs in modern concrete, the rheological behaviour of fresh concrete has become increasingly complex. In this context, the Herschel-Bulkley model or modified Bingham model is more effective in characterising the nonlinear rheological behaviour of fresh concrete. However, further research is urgently needed to determine the most suitable rheological model for different SCM-concrete systems.

(2) The influence mechanisms of SCMs on the rheology of fresh concrete primarily include the morphology effect theory, the filling and packing theory, and the water film theory. Additionally, SCMs may also participate in and affect the hydration process of cement, thus influencing the rheology of fresh concrete. Overall, the influence of SCMs on the rheological properties of fresh concrete is the result of the combined action of multiple interrelated and complementary mechanisms.

(3) The influence of SCMs on the rheology of fresh concrete varies significantly depending on factors such as the type, surface morphology, specific surface area, and particle size. Through strategic SCMs selection, the rheological properties of the concrete mixture can be effectively modified, which not only helps to improve the workability of fresh concrete but also contributes to the mechanical strength and durability performance of hardened concrete.

(4) SCMs that help to reduce the yield stress and plastic viscosity of the mixture generally enhance the flow and deformation of fresh concrete, resulting in improved flowability. However, it is important to note that the flowability and stability are often a contradictory pair of properties. If the flowability of fresh concrete is too high, it may lead to instability issues such as aggregate settlement and water bleeding.

(5) This paper provides a comprehensive review of the individual effect of fly ash, GBFS, silica fume, limestone powder, and steel slag powder on the rheology and workability of fresh concrete. However, when these SCMs are used in combination, their influence on the fresh properties of concrete becomes more complex, which is not addressed in this paper. In further investigating this issue, a holistic approach accounting for interactive effects between different SCM characteristics should be employed.

Declaration of competing interest

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

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