Effect of constituents on rheological properties of fresh concrete—A review

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Abstract

The rheology is an effective tool to characterize workability, consistency, flowability, and predict stability, pumpability, shootability, pressure of formwork, multi-layer casting. This paper presents a critical review on the rheological properties of fresh concrete in recent publications. The applicable rheological models for the flow of concrete are revealed. The effects of constituents of fresh concrete, including cement, supplementary cementitious materials (fly ash, ground blast furnace slag, and silica fume), limestone powder, coarse and fine aggregates, and chemical admixtures (superplasticizer, viscosity modifying agent and air-entraining agent) on the rheological properties are discussed in detail. The applications of rheograph and workability box in mixture proportioning and quality control are also illustrated.

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1. Introduction

Concrete is the most widely used civil engineering material in the world. Its output was nearly 30 billion cubic meters in 2015. The properties of fresh concrete are of great importance because of their effects on construction quality of casting and forming process, and also the properties of hardened concrete. The behavior of fresh concrete is often described by workability, consistency, flowability, mobility, pumpability, compactibility and finishability. However, these terms are empirical, qualitative and subjective, and lack of quantitative basis [1]. Take the workability as an example, the practitioner is quite able to identify "more workable", called operator-sensitive, which has been discussed in the book by Tattersall and Banfill [2]. In order to minimize the artificial errors, it is necessary to characterize fresh properties of concrete by using fundamental physical quantities.

The term of rheology was first proposed by Bingham in 1920 [3]. In the following years, rheology was born as a new subject with the establishment of the Rheology Society and Journal of Rheology. Rheology is an important tool for scientists and engineers in many industries, including plastics, paint, printing inks, detergents, oils, etc. [3]. The rheology of cement and concrete mainly involves the evolution of viscosity, plasticity and elasticity of cement-based materials under shear stress. The rheological properties have significant influences on constructing, forming or casting process. Yen et al. [4] found that rheological method could obtain more stable results in describing the workability of high-performance concrete, comparing with these single-point tests such as slump and slump flow. Banfill et al. [5] pointed out that there was a relationship between the rheological parameters of unvibrated fresh concrete and the velocity of vibration. Roussel [6,7] established a link between the yield stress or thixotropy of fresh concrete and casting processes, which provided a practical tool to predict the formwork filling, pressure formwork and multilayer casting occurrence. Feyes et al. [8] discussed the influence of rheology and flow rate on pumping pressure of concrete, which varied from pumpable conventional vibrated concrete to segregating self-compacting concrete. Furthermore, concrete rheology can also be used in some special applications, such as a simple and fast assessment in minimizing rebound could be made by establishing a correlation between the rheological properties and the rebound, before conducting any spray experiments [9].

From the above discussion, it is clear that rheology is an effective tool to characterize the workability, predict the flow behavior, stability and even compactability of cement paste, mortar and
concrete. The properties of fresh concrete have effects on the mechanical strength, durability, and engineering applications. It is vital for the preparation of high-performance concrete. This paper presents a critical review on the rheological properties of fresh concrete in recent publications based on the rheological model, influence of concrete composition and applications of rheology in mixture proportioning.

2. Rheology models of concrete

Numerically describing and predicting the flow and deformation of complicated fluids are difficult. Fresh concrete is a very complicated fluid which not only contains particulate materials ranging from μm to mm, but also contains organic and inorganic materials. What’s more, the rheological behavior of concrete evolves with time because of cement hydration, which is a complicated subject. At a low applied shear strain rate, the variation of shear stress with time is shown in Fig. 1. At the beginning, the shear stress increases gradually with time but there is no flow. When the stress reaches the static yield stress, the concrete begins to flow, and the stress required to maintain steady flow is reduced to the dynamic yield stress, which is also called thixotropic behavior. Roussel [10] found that the static yield stress increased as a linear function of time, and proposed a thixotropic model, as shown in Eqs. (1) and (2).

\[ \tau = (1 + \lambda)\tau_0 + \mu\dot{\gamma} \]  
\[ \frac{d\lambda}{dt} = -a\dot{\lambda}\gamma \]  

where \( \lambda \) is flocculation state of concrete, \( T \) is characteristic time of flocculation, and \( \alpha \) is thixotropic parameter. Assuming that the characteristic time of de-flocculation is short compared to that of flocculation, the flocculation rate of fresh concrete at rest can be derived as:

\[ A_{thix} = \frac{\tau_0}{T} \]  

The thixotropy has significant effects on the application performance of concrete such as pumpability, formwork pressure development, multilayer casting, etc [7,11–15]. It is worth mentioning that additive manufacturing and digital fabrication construction techniques such as 3D printing also strongly depend on the thixotropic behavior of concrete [16]. The static yield stress is associated to the network of colloidal interactions and rigid links between cement particles, which are affected by CSH nucleation [17]. As long as the steady state flow is reached, the rheological behavior of fresh concrete can be described using a yield stress model such as Bingham model, Herschel-Bulkley model and modified Bingham model.

The Bingham model has a linear relationship between shear stress, \( \tau \), and shear strain rate, \( \dot{\gamma} \). This defines yield stress \( \tau_0 \) and plastic viscosity \( \mu \). Their relationship is expressed by Eq. (4):

\[ \tau = \tau_0 + \mu\dot{\gamma} \]  

As can be seen from Eq. (4), fresh concrete starts to flow once shear stress is higher than yield stress. The plastic viscosity is the ratio of shear stress to shear rate. The Bingham model, which can describe the rheological properties of cement paste, mortar and part of fresh concrete, given that the yield stress and plastic viscosity are constant in time. However, de Larrard et al. [18] pointed out that the relationship between torque and rotation speed was not exactly linear and even a negative yield stress encountered with the Bingham model in their rheological tests with BTRHEOM rheometer. While the Herschel-Bulkley (H-B) model appears to offer some benefits in describing the flow behavior of concrete, which can be expressed by Eq. (5):

\[ \tau = \tau_0 + a\dot{\gamma}^b \]  

where \( \tau \) and \( \tau_0 \) are shear stress and yield stress, respectively; \( \dot{\gamma} \) is shear rate, \( a \) is consistency factor, and \( b \) is flow index changing from less than 1 (called shear thinning) to more than 1 (called shear thickening). By using the least square method, the equivalent plastic viscosity could be calculated as:

\[ \mu' = \frac{3a}{b + 1}\frac{\dot{\gamma}^{b-1}}{\dot{\gamma}_{max}} \]  

It was found that the coefficients of variation from the regressions rheological testing resulting were close to 1% with the H-B model [18], which indicated that the H-B model provided an excellent approximation to the measurements. The yield stress is always positive and the exponent \( b \) differs significantly from 1, which covers the limits of the Bingham model. However, the yield stress from H-B model provides a worse ranking of the mixtures than that from Bingham model, with respect to the slump, as shown in Fig. 2, and the control of 3 parameters is very difficult to handle in the optimization of mixture proportion.

In view of the shear thickening behavior of self-compacting concrete and the negative yield stress when extrapolating the Bingham model, Feys et al. [19,20] proposed a modified Bingham model, as described by Eq. (7):

\[ \tau = \tau_0 + \mu\dot{\gamma} + c\dot{\gamma}^2 \]  

where \( \tau \) and \( \tau_0 \) are shear stress and yield stress, respectively; \( \dot{\gamma} \) is shear rate, \( \mu \) is plastic viscosity, and \( c \) is second order parameter. The \( c/\mu \) gives an indication of shear thinning or shear thickening behavior. Compared to the H-B model, the modified Bingham model does not contain a parameter with a variable dimension and without the mathematical restriction in the region of low shear rates [19].

The fundamental physical parameters for describing rheological properties mainly include yield stress and plastic viscosity. The yield stress is the minimum stress when concrete initiates to flow. It is caused by the force required to break down the network structure formed by the colloidal interaction and rigid links between cement particles, as well as the adhesion and friction between aggregate particles. The magnitude of yield stress depends on the solid volume fraction, packing fractions [21], size and surface roughness of solid particles, interactions between particles, and
specifically on the effect of superplasticizer. The yield stress can be used to characterize the filling ability and stability of fresh concrete. The plastic viscosity is defined as the proportional coefficient between shear stress and shear rate under a state of steady shear, and it is greatly affected by colloidal particle interaction forces, Brownian forces, hydrodynamic forces and viscous forces between particles [3,22,23]. The plastic viscosity depends on the ratio of volume fraction and packing density of particles in the mixture, and is a good indicator for the compactibility, machinability and segregation resistance. The fundamental physical quantities can be obtained using rheometers. However, the rheometers are usually not available at most concrete laboratories. Therefore, it is necessary to investigate the relationship between the fundamental parameters and the traditional parameters, such as slump, slump flow and flow time. For fresh concrete, the yield stress and plastic viscosity are correlated to the slump or slump flow and the flow time, respectively [24–27]. An excellent relationship between the yield stress and the slump has been obtained. Based on numerous experiments, Murata et al. [24] proposed a relationship between the yield stress \( \tau_0 \) and the slump flow \( S \) that does not depend on the mold geometry, as shown in Eq. (8).

\[
\tau_0 = 714 - 473 \log(S/10) \tag{8}
\]

Considering the density of concrete, Sedran and de Larrard [25] established equations predicting the yield stress and the plastic viscosity, shown with Eqs. (9) and (10):

\[
\tau_0 = (808 - S) \frac{\rho g}{11740} \tag{9}
\]

\[
\mu = \frac{\rho g}{10000} (0.0265 - 2.39T_{500}) \tag{10}
\]

where \( S \) (mm) is slump flow, \( \rho \) (kg/m\(^3\)) is density of concrete, \( g \) (= 9.81 m/s\(^2\)) is gravity, \( T_{500} \) (s) is the time to reach a 500 mm diameter spread. Similar empirical equations have been obtained in Ref. [26]. Considering the density of concrete, the lubrication and volume fraction of matrix and the relevance of viscometers, Wallevik [27] established an empirical expression as shown in Eq. (11):

\[
S = 300 - 0.416 \left( \frac{\tau_0 + 394}{\rho} \right) + \alpha \left( \tau_0 - \tau_0^{ref} \right) V_m - V_m^{ref} \tag{11}
\]

where \( S \) (mm) is slump flow, \( \rho \) (kg/m\(^3\)) is density of concrete, \( \rho^{ref} \) (kg/m\(^3\)) is density of water, \( V_m \) (m\(^3\)) is volume fraction of matrix, the term \( (\tau_0 - \tau_0^{ref}) \) refers to the lubrication effect, and the term \( V_m - V_m^{ref} \) treats the effect of matrix volume fraction. \( \alpha (\tau_0 - \tau_0^{ref}) (V_m - V_m^{ref}) \) is only based on empirical consideration depending on the angularity, density and grading of the aggregates used. The tests results have shown that Eq. (11) works well in predicting the slump for a given yield stress. Except for the above attempts to relate slump with yield stress, Roussel and Coussot [28] developed theoretical analytical solutions of the slump test by including different flow regimes, pure shear flow and pure elongational flow, according to the ratio between the radius (R) and the height (H) of the slump cone. For large slumps, the pure shear flow could express the dimensionless yield stress as a function of dimensionless slump, as is shown in Eq. (12):

\[
\tau'_c = \sqrt{\frac{2\pi}{15\rho}} H^{5/3} (1 - S')^{5/2} \tag{12}
\]

where \( S' = S/H_0 \) and \( \tau'_c = \tau_c/\rho g H_0 \) are dimensionless slump and yield stress, \( \Omega \) is sample volume, \( H_0 \) is initial sample height, \( \rho \) is material density, and \( g \) is gravity. For small slumps, the pure elongational flow could express the dimensionless yield stress as a function of dimensionless slump, as is shown in Eq. (13):

\[
\tau'_c = \frac{1 - S'}{\sqrt{3}} \tag{13}
\]

Based on the three-dimensional numerical simulations and experimental data with a large range of yield stress, it was proved that these solutions may provide a further practical tool to estimate the yield stress containing coarse aggregates [28].

3. Effect of constituents on the rheological properties

Concrete is a sort of composite material containing cement, mineral admixtures, water, aggregates and chemical admixtures. Its rheological properties depend on the quality of each constituent used in the concrete mixture and their interactions. Some researchers considered fresh concrete as a concentrated suspension in which solids are dispersed in the fluid phase water [29,30] while others [31,32] regarded fresh concrete as a two-phase system that coarse aggregates are dispersed in the mortar. Fresh concrete is viewed as a two-phase system in this paper, i.e. fluid paste and solid phase aggregates. The influence of paste volume (containing cement, supplementary cementitious materials and limestone filler), aggregate, and chemical admixture on the rheological properties are reviewed in this section.

3.1. Paste

Paste is an essential component of concrete which coats aggregates, fills the spaces between aggregates, and provides the flowability. Koehler [22] confirmed that increase of paste volume resulted in an increase in slump, reduction in yield stress and plastic viscosity. The decline rate gradually lowered as the amount of paste went up. Recently, Westerholm et al. [33,34] demonstrated that negative effects of poorly graded and shaped aggregates could be eliminated or significantly reduced with additional paste volume. As can be seen from Fig. 3, the paste can be divided into two parts: one is the paste filled the spaces between aggregates, the other, called excess paste, is the paste coated and separated aggregates. The excess paste volume can be calculated with Eq. (14) [35]:

![Fig. 2. Yield stress from Bingham and H-B models VS slump (data from Ref. [18]).](image-url)
where \( V_{\text{paste,ex}} \) is volume of excess paste, \( V_{\text{paste}} \) is total paste volume, \( V_{\text{A, void}} \) is volume of voids between aggregates, \( m_A \) and \( \rho_A \) are mass and density of aggregates, respectively, \( \rho_{A, \text{bulk}} \) is loose bulk density of aggregates. If same paste layer thickness for each spherical aggregate is assumed, the thickness of excess paste can be described by Eq. (15):

\[
V_{\text{paste,ex}} = \frac{4}{3} \pi \sum_i n_i \left( r_i^3 - t_{\text{paste,ex}}^3 \right)
\]

where \( r_i \) and \( n_i \) are radius and number of a particle of class \( i \), respectively, \( t_{\text{paste,ex}} \) is the thickness of excess paste layer. It should be noted that Eq. (15) is a very rough approximation of an average thickness of excess paste.

Yammine et al. [21] demonstrated that there existed an obvious transition in the rheological behavior of concrete between friction and hydrodynamic domination. At relatively high paste volume fraction, the interactions between particles or fluid and particle are hydrodynamic. When the concrete is flowing, the motions of particles imply some flow of paste that induces additional energy dissipation. Thus the plastic viscosity decreases with the increase of paste volume fraction. At relatively low paste volume fraction, i.e. high aggregate volume fraction, the rheological behavior is dominated by the direct frictional contacts between aggregate particles. The thickness of excess paste is a suitable parameter to describe the consistency of fresh concrete varied with the paste volume fraction [35]. However, the differences regarding mineral admixtures or paste compositions led to different rheological behaviors.

The quantitative relationship between the rheological parameters and the thickness of excess paste is not clear yet.

### 3.1.1. Cement

The mineral composition of Portland cement clinker is mainly composed of \( \text{C}_3\text{S}, \text{C}_2\text{S}, \text{C}_3\text{A} \) and \( \text{C}_4\text{AF} \). Appropriate level of gypsum is added to clinker for grinding cement. The hydration rate and water demand of reaction of each mineral composition are different. It can be expected that the rheological properties of cement paste may be affected by mineral composition of cement. Various ions may be released into water when cement contacts with water, such as \( \text{SO}_4^{2-}, \text{OH}^-, \text{Na}^+, \text{K}^+ \). These ions may affect the adsorption of superplasticizer onto cement particles and thus affect the rheological properties of cement paste. Fineness of cement (about 350–400 m\(^2\)/kg for conventional cement) also has great influence on rheological properties of cement paste, because fine cement needs more water for a given flowability and fine cement particles hydrate faster than coarser ones.

The effects of chemical composition and physical characteristics of cement on the rheological properties had been studied by many researchers. Hope et al. [36] studied the effects of cement composition on water requirement for a given slump. They found that the water requirement increased for the cement with high \( \text{Al}_2\text{O}_3 \) or \( \text{C}_2\text{S} \) contents and decreased for the cement with high ignition loss, high carbonate addition, or high \( \text{C}_3\text{S} \) content. Mork et al. [37] examined the effect of sulfate to hemihydrate ratio of cement on concrete rheology, and stated that, for cement with high contents of \( \text{C}_3\text{A} \) and alkalis, a reduction in the ratio of gypsum to hemihydrate resulted in a decrease in yield stress, but little change in plastic viscosity. For the cement with lower \( \text{C}_3\text{A} \) and alkalis content, the effects of gypsum to hemihydrate ratio were less pronounced. Furthermore, a reduction in the sulfate content from 3 to 1% caused a decrease in both yield stress and plastic viscosity. Dils et al. [38] investigated the effects of chemical composition and fineness of cement on rheological properties of ultra-high performance concrete for a given slump flow. They found that the cement with high \( \text{C}_3\text{A} \) and specific surface, high alkali content and lower of \( \text{SO}_3 \) content gave the worst workability.

Chen et al. [39] showed that the influence of superfloury cement on rheological properties depended on the water content in cement paste. The addition of superfloury cement increased yield stress and apparent viscosity at \( \text{W/C} \geq 0.24 \). When \( \text{W/C} \leq 0.22 \), the addition of superfloury cement decreased yield stress and apparent viscosity. At lower water content, the addition of fine particles fills the voids, increases the packing density, releases the water between cement particles, significantly increases the water films coating the particles in the cement paste, and consequently improves the rheological properties of cement paste. At higher water content, the increase of superfloury cement content did not show an obvious effect on the water film thickness because the high specific surface area of superfloury cement increased the yield stress and plastic viscosity.

### 3.1.2. Fly ash

Fly ash, high in \( \text{SiO}_2 \) and \( \text{Al}_2\text{O}_3 \), low in \( \text{CaO} \), is one type of pozzolanic material, which is sufficiently reactive when mixed with water and \( \text{Ca(OH)}_2 \) at room temperature [40]. It consists of crystal, vitreous and a small amount of unburnt carbons. The vitreous includes smooth and spherical shaped vitreous particles, irregular-shaped and low porosity small particles. Unburnt carbon presents loose and porous shape. The chemical and phase compositions depend on the mineral composition of the coal, the combustion conditions and the collector setup. Physically, fly ash presents as fine particles with the particle size ranging from 0.4 to 100 \( \mu \text{m} \), low specific gravity (2.0–2.2 g/cm\(^3\)), high specific surface area (300–500 m\(^2\)/kg) and light texture [41]. The type of fly ash
The addition of fly ash has a great influence on the rheological properties of concrete, as shown in Fig. 5. Laskar et al. [43] found that low levels of fly ash could lead to reduction of yield stress, while a slight increase in yield stress could be observed at high content of fly ash. Beycioğlu et al. [44] indicated that fly ash positively affected the flowability, passing ability and viscosity of self-compacting concrete due to its spherical geometry and smooth surface which caused a reduction in water demand. Jalal et al. [45] found that the ball bearing-shaped fly ash particles resulted in an improvement in the rheological properties of fresh self-compacting concrete (SCC), and led to an increase in the slump flow diameter from 800 mm to 870 mm and reduction of yield stress and plastic viscosity slightly increased with the increase of fly ash content. Rahman et al. [11] observed that fly ash significantly increased the flocculation rate and plastic viscosity of SCC.

Ahari et al. [42,52] studied the influence of FAF and FAC contents on the rheological properties of SCC. They found that FAF significantly decreased plastic viscosity in comparison to the mixtures with FAC. The fineness or particle size distribution of fly ash could also significantly affect the workability. Ferraris et al. [50] and Li et al. [53] reached the same conclusion that as the mean size of fly ash particles increased, the slump flow decreased to a certain value and then gradually increased, and the optimum size was about 3 μm. Lee et al. [54] pointed out that the flowability of paste increased as the particle size distribution became wider.

Fly ash has a lower specific gravity than cement. The replacement of cement with the same mass of fly ash increases the volume of paste, proportionally decreases the cement concentration in paste and therefore reduces the number of flocculation cement particle connections, namely “dilution effect” [55,56]. The spherical geometry and smooth surface of fly ash particles promote particles sliding and reduce frictional forces between angular particles, which is called “ball bearing effect”. This effect can be magnified with the particle size distribution of fly ash slightly coarser than cement due to the increase of separation distance between neighboring particles [48]. The addition of fine fly ash improved the flowability due to the filling effect. The packing density of paste improved, and the water retained inside the particle flocs decreased, consequently, the flowability of the paste increased. In addition, fly ash can delay the early hydration and lengthen the setting time. It is worth to mention that the unburnt carbons in fly ash can greatly adsorb superplasticizer molecules or water, even result in negative zeta potential [57], which leads to higher viscosity.

3.1.3. Ground blast furnace slag (GBFS)

GBFS, finely granular and almost fully noncrystalline, is a by-product of the iron manufacturing industry. Its glass content is predominantly by water quenching rate. The mass content of CaO, SiO2 and Al2O3 is up to 90%. GBFS has hydraulic activity, but slower than that of Portland cement. The specific gravity of slag is approximately 2.90, and its bulk density varies in the range of 1200–1300 kg/m³. The specific surface area of GBFS measured by Blaine method are 375–425 m²/kg, 450–550 m²/kg, and 350–450 m²/kg in the United Kingdom, United States and India, respectively. In China, the specific surface area of GBFS is higher than 450 m²/kg [58].

Since the replacement of cement with slag improves the workability of mixtures and reduces CO2 emissions, GBFS has been widely used in cement paste, mortar, and concrete. Effects of GBFS on the rheological properties of cement-based materials from literature are shown in Fig. 6. As can be seen from Fig. 6, most studies find that the addition of GBFS decreases plastic viscosity, while the effect of GBFS on yield stress is uncertain. Park et al. [46] indicated that the yield stress decreased first and then increased, but the plastic viscosity decreased with the increase of GBFS content. Ahari et al. [42] stated that the replacement of Portland cement with GBFS decreased the yield stress and plastic viscosity of...
the mixtures, regardless of the water-to-binder (w/b) ratio. They also found that replacement of 18% cement with GBFS in the mixture with w/b ratio of 0.44 reduced the breakdown area approximately by 10%. Derabla et al. [59] found that the activity of granulated slag and crystallized slag with specific surface areas of 228 m²/kg and 485 m²/kg both are near to that of cement. Even though the specific surface area of granulated slag is lower than that of cement, the plastic viscosity of the mixture containing granulated slag decreased from 150 Pa.s to 121 Pa.s due to the absorption of superplasticizer particles. At the same replacement level, the plastic viscosity of the mixture containing crystallized slag decreased from 150 Pa.s to 91 Pa.s. However, the addition of GBFS increased the plastic viscosity in some cases. Tattersall [60] reported that, for the mixtures with low cement content (200 kg/m³), the addition of GBFS reduced yield stress and increased plastic viscosity. Tang et al. [61] studied the rheological properties of cement paste with a high volume of GBFS under different slump flows by varying the dosage of superplasticizer. They found that the pastes with GBFS had apparently higher plastic viscosity, poorer stability and lower velocity of flow, comparing to ordinary cement paste under the same slump flow. This can be contributed to the fact that high volume of ground slag with high specific surface area requires a larger amount of water than cement.

Generally, GBFS has high specific surface area and high chemical activity, which may have positive or negative effect on the rheological properties of cement-based materials. The rheology properties of cement and concrete are improved by the following reasons: entrapped water within cement particles may be released by the micro-filling effect of fine GBFS particles, and high specific area may lead to more adsorption of superplasticizer. However, high specific surface area and high chemical activity of GBFS require a large amount of water than cement particles. Thus the rheological properties may be decreased.

3.1.4. Silica fume

Silica fume is the by-product of electric arc furnace produced silica metal and silica alloys. It is extremely fine powder and has average particle size of about 0.1–0.3 μm. Particles below 0.1 μm are more than 80%. The specific surface area of silica fume is 20000–28000 m²/kg, which is 80–100 times and 50–70 times higher than that of cement and fly ash, respectively. The particles are round, and tend to be agglomerated. Therefore, superfine silica fume particles can fill the voids between other particles, improves the gradation, increases the packing density of cementitious materials and even has lubrication effect. The high specific surface area of silica fume even could adsorb superplasticizer molecules with multi-layers [43,46,67]. Silica fume, high in SiO₂ (85–96%), with very fine vitreous particles, has higher chemical activity than fly ash. The high fineness and high chemical activity of silica fume can increase the water demand and inter-particle friction [68–70].

Effects of silica fume on the rheological properties of cement-based materials from literature are shown in Fig. 7. As can be seen from Fig. 7, many studies found that the addition of silica fume increased both yield stress and plastic viscosity, and reduced the flowability of cement-based materials. The addition of silica fume also significantly increased the flocculation rate [11,42]. As a result, silica fume can be used in the concrete which requires high uniformity and cohesiveness, e.g. pumping concrete, underwater concrete and shotcrete, as an inorganic viscosity modifying agent. However, the addition of silica fume may have different effects on the rheological properties. Zhang et al. [49] stated that silica fume could decrease the viscosity and yield stress of cement paste. Ahari et al. [42,52] found that the incorporation of silica fume reduced the plastic viscosity, increased the yield stress and breakthrough area. Yun et al. [72] found that silica fume led to a remarkable increase in flow resistance while slightly reduced torque viscosity. The addition of silica fume could obtain different results with different superplasticizer types [61] at water-to-binder ratios. Laskar et al. [43] found that silica fume increased the initial yield stress of fresh concrete in case of poly-carboxylic and decreased it in case of sulfonated naphthalene polymer. Effects of water-to-powder (w/p) ratio (by volume) and silica fume on yield stress and plastic viscosity are shown in Fig. 8. As can be seen from Fig. 8, the increments of both yield stress and plastic viscosity increase with the decrease of w/p ratio. Therefore, it is necessary to understand the interactions between silica fume and superplasticizer type or content when investigating the effects of silica fume on rheology of ordinary concrete.

3.1.5. Limestone powder

Limestone powder is a kind of high quality and cheap mineral admixture. Its main component is calcium carbonate, CaCO₃. Limestone particles is irregular and rough [73,74], which increases the adhesion and friction between cement particles. The mean particle size of limestone powder used in concrete is from below 1 μm to more than several tens of μm. Limestone particles have high adsorption capacity of superplasticizer, which increases the dispersing ability of concrete system. On the other hand, limestone particles are often ground to finer powders than cement. Consequently, more water is needed for paste with the limestone powder.

The influences of limestone powder on rheological properties from literature are summarized in Fig. 9. Some researchers found that the incorporation of limestone powder increased the yield stress and plastic viscosity, leading to a reduction in the workability of concrete. While others showed that the addition of limestone powder resulted in a decrease in yield stress and plastic viscosity. In addition, Rahman et al. [11] stated that increasing amounts of limestone powder led to an increase in flocculation rate significantly. For instance, the flocculation rate of concrete with 15% limestone powder was about 1.5 times higher than that of reference concrete. The influence of limestone powder on rheological properties depends on the particle packing and water demand, which could be transferred into specific surface area or particle size distribution [48]. Ma et al. [74] noted that yield stress and plastic viscosity increased with the decrease of particle size of limestone powder. Vance et al. [48] found that as the particle size of limestone powder increased from 0.7 to 15 μm, there was a decrease in both yield stress and plastic viscosity. They stated that particles finer than the ordinary Portland cement usually increased the yield stress and plastic viscosity, while the addition of particles coarser
than cement induced an opposite effect. This is because the fine particles reduce the particle spacing and increase inter-particle contacts, while the coarse particles could increase particle spacing and reduce the shear resistance of the suspension. Furthermore, large limestone particles exhibited a decrease in the area of water films and provide more extra water [75], and thus reduced the possibility of flocculation.

Although the effect of particle size distribution is very important, the production methods of limestone powder cannot be ignored. Felekoglu et al. [57] considered that the fine limestone filler did not significantly change the viscosity while the coarse limestone filler was effective in increasing the viscosity. The fine limestone filler is a filtration system by-product of crushed stone production. However, the coarse limestone powder is a special production of whitened limestone filler with lower adsorptivity. In a word, the effect of limestone powder on rheological properties can be ascribed to the morphologic effect, filling effect and adsorption effect by particle size distribution and production methods of limestone powder.

3.1.6. Ternary binder system

Ternary binder system is a good way to enhance various properties of cement-based materials, including workability, rheological properties, strength, durability, cost, and CO2 emissions. This section discusses the rheological properties of ternary blends containing fly ash and slag or silica fume or limestone. Laskar et al. [43] observed that the rheological parameters of concrete with ternary-binder-system lied in between the values with the single mineral admixture at each replacement levels. Tattersall [2], Park et al. [46] and Gesoğlu et al. [77] observed the same phenomena. Kashani et al. [78] investigated the rheological behavior of cement-blast furnace slag-fly ash ternary pastes. They showed that the width of the particle size distribution was the key parameter controlling the yield stress of ternary pastes. As a result, even a low volume of fly ash also has a significant effect on workability, and any other mineral additives with a broad particle size distribution may have a comparable effect. Vance et al. [48] found that in ternary pastes containing limestone and low fly ash contents (5%), the plastic viscosity increased with the replacement of fine limestone, and remained unchanged for coarse limestone. However, at higher fly ash contents (10%), the yield stress decreased even for pastes containing fine limestone. Although the particle spacing reduces and the number of inter-particle contacts increases with the addition of fine limestone, the ball shaped fly ash separates the solid grains, compensating the positive effect of fine particle additions, and thus reduces the yield stress and plastic viscosity.

The addition of ultrafine mineral admixtures such as silica fume can increase the packing density, fill into the voids between cement particles and release the water entrapped in agglomerate structure to form excess water films for lubrication. But at the same time, the water film thickness will be thinned down due to its large surface area. By adding a cementitious material whose fineness between

![Fig. 7. Effects of silica fume on rheological properties (data from Refs. [11,22,42,43,46,49,50,68,71]).](image)

![Fig. 8. Effect of replacement of silica fume on rheological parameters [69].](image)

![Fig. 9. Effects of limestone powder on rheological properties (data from Refs. [11,48,49,59,66,76]).](image)
cement and silica fume, such as fly ash, the water entrapped in the agglomerate structure can be released without excessively increasing the surface area [79]. In this way, a larger water film thickness and better flowability can be obtained. Moreover, the addition of mineral admixtures with a broader particle size distribution also can increase the particle packing and the excess water, and therefore efficiently separate the cement particles. In this case, the intensity of colloidal interaction between particles will drop substantially, leading to the destruction of percolated network of particles, which will then results in yield stress reduction [78].

3.2. Aggregates

Aggregate accounts for more than 75% of the total volume of conventional vibrated concrete, and 60% of SCC. From the rheological point of view, aggregates with large grain size and rough surface restrict the flow of concrete and increase the yield stress and plastic viscosity of concrete than that of cement paste. Generally, the chemical compositions of aggregate have little effect on the plastic viscosity and yield stress are emphatically discussed in this paper. In this part, the effects of physical properties of aggregates on the plastic viscosity and yield stress are emphatically discussed.

The first to derive the viscosity of a dilute suspension of rigid spheres is Einstein [80,81]. He showed that the addition of the second phase to a liquid led to an increase in the bulk viscosity proportional to volume fraction of particles:

$$\eta_r = 1 + \phi$$

(16)

where \(\eta_r\) is relative viscosity, \(\phi\) is concentration of particles, and \(\eta\) is intrinsic viscosity. Krieger and Dougherty [82] used the maximum packing volume fraction and intrinsic viscosity parameter for a non-Newtonian suspension with rigid spheres, and proposed a generalized version of Einstein's equation, called Krieger and Dougherty equation:

$$\eta_r = \left(1 - \phi \phi_m\right)^{1-\eta/\eta_m}$$

(17)

where \(\phi\) and \(\phi_m\) are the concentration of particles and maximum packing fraction, respectively.

Considered fresh concrete as a suspension with multiple sizes of particle, assuming the relative sizes are sufficient to have the condition of zero interaction, the viscosity can be calculated from the unimodal viscosity of each size, namely Farris model [83]:

$$\eta_r = \eta_s \left(1 - \frac{\phi_f}{\phi_m}\right)^{1-\eta/\eta_m}$$

(18)

If aggregates in fresh concrete are divided into coarse and fine aggregates [84], the Farris model can be used in the following form:

$$\eta_r = \eta_p \left(1 - \frac{S}{S_{lim}}\right)^{1-\eta/\eta_m}$$

(19)

where \(S\) and \(S_{lim}\) are sand volume fraction and maximum solid volume, respectively; \(G\) and \(G_{lim}\) are gravel volume fraction and maximum gravel solid volume, respectively; \(\eta_p\) is viscosity of paste; \(\eta_{lim}\) and \(\eta_{lim}\) are intrinsic viscosity of fine and coarse aggregate, respectively.

The yield stress can be predicted accurately from the measured \(T_{sd}\) and flow spread of the mix in a slump test using a corrected Lagrangian smooth particle hydrodynamics [85]. This estimation of yield stress requires a trial and error approach: for a given mixture and plastic viscosity an arbitrary initial trial yield stress is assumed and the mixture flow was simulated using the smooth particle hydrodynamics method from the moment the cone is lifted, until the mixture stops flowing [86]. Mahaut et al. [87] stated that the relationship between the yield stress of suspensions and the particle volume fraction fitted well with the Chateau-Ovarlez-Trung model [88], as shown in Eq. (20). They showed that the yield stress of suspensions only depended on the yield stress value of suspending cement paste and was independent of its physicochemical properties.

$$\frac{\tau_c(\phi)}{\tau_c(0)} = \left(1 - \phi / \phi_m\right)^{1-\eta/\eta_m}$$

(20)

Noor et al. [84] proposed an empirical model to predict the yield stress of fresh concrete, which was assumed to be a function of yield stress of mortar and the volume fraction of aggregates, and the equation is as follows:

$$\tau_c = \tau_m + f(t)$$

(21)

where \(\tau_c\) and \(\tau_m\) are the yield stress of mortar and concrete, respectively. \(f(t)\) is the total apparent aggregate volume.

From Eqs. (19)–(21), it can be concluded that the rheological properties of concrete are obviously affected by the packing density and volume fraction of aggregates. It is well known that the types, gradation and particle size distribution of aggregates significantly affect their packing density. Therefore, these parameters will be discussed in detail.

3.2.1. Type

The type of aggregate influences the workability of concrete by packing density and surface morphology. Crushed stone aggregates have angular shape and rough surface, which increase the specific surface area and reduce the content of free water. Furthermore, the angular shape is not conducive to the flow of particles and increases the inter particle friction resistance, and thus significantly increases the yield stress and plastic viscosity [89–92], reduces the mixture flowability [20,93]. The smooth surface of rounded aggregates or natural aggregates reduces the inter particle friction and results in an increase in the flowability. The flat and elongated particles can increase the particle collision due to their shape. Therefore, the concrete mixtures containing flat and elongated particles led to a significant increase in plastic viscosity and yield stress [93], as shown in Fig. 10. It is worth mentioning that the particle shape of aggregate strongly affected the plastic viscosity than the yield stress [33,60].

With the increasing demand on protecting the natural environment, waste materials, such as recycled aggregates, have been widely used. As the largest source of construction and demolition (C&D) waste, recycled aggregates are characterized by the higher water absorption due to the higher porosity from the adhering mortar. Kenai et al. [95] stated that the substitution of 50% or 100% of natural aggregates by recycled concrete aggregates gave SCC excellent rheological properties which are comparable to that of the reference SCC, while reduced the stability against bleeding. Güneyisi et al. [96] revealed that the rheological properties and fresh properties of SCC were remarkably improved by the replacement levels of fine recycled concrete aggregates due to their smoother surface. Ke et al. [97] indicated that the substitution of fine aggregate with small waste glass particles reduced the flowability of mixture while replacing coarse aggregate with large waste glass particles increased the flowability of the mixture. The smooth surface of waste glass reduces the inter-particle friction and improves the fluidity of concrete.
3.2.2. Volume fraction

Many studies [89,91,92,98] hold the opinion that yield stress and plastic viscosity of concrete generally increased along with the volume fraction of coarse aggregate, while increasing the fine aggregate volume raised yield stress but lowered plastic viscosity of the concrete. The addition of coarse aggregate increases the mortar covering the surface aggregate, reduces the adhesive effect between aggregate and cement paste, and lowers the friction among aggregates. With the increase of fine aggregate volume fraction, surface area of solid particles and water demand raise, the friction among coarse aggregates reduces, which results in an increase in yield stress and a reduction in plastic viscosity. Westerholm et al. [33] indicated that fine natural aggregate had virtually no effect on the plastic viscosity of mortar, while for the mortars with crushed fine aggregates, the plastic viscosity showed a minimum at a certain fines content. This result can be owing to the particle friction. If fines content is too low to fill the voids between the larger aggregate particles, internal friction will be high and cause high viscosity. However, as the content of fines aggregates become higher, the enlargement of total surface area can lead to higher plastic viscosity either.

The rheological properties of concrete are highly influenced by the sand-to-aggregate ratio [99]. Low sand-to-aggregate ratio has a negative effect on the flowability. This is due to the absence of sufficient mortar filled the high voids of coarse aggregate. However, high sand-to-aggregate ratio also decreases the flowability of concrete because the high specific surface area of fine aggregates reduces the cement layer thickness which lubricates aggregate particles.

3.2.3. Gradation and particle size

The gradation and maximum particle size of aggregates play predominant roles on rheological properties of concrete. The larger the maximum particle size is, the smaller the specific surface area is and the less the amount of mortar requirement is needed, thus the lower the values of rheological parameters of concrete [99], the weaker the shear thickening behavior [20]. Santos et al. [100] indicated that mixtures with continuous gradation exhibited higher slump flow values, less risk of segregation and higher mechanical strength. The yield stress of the continuous graded concrete was less sensitive than those of the uniform gradation. The excess paste theory can well explain the effect of aggregate on concrete flowability. In the case of well graded aggregates, the packing density and specific surface area decrease, thus the cement required to fill the voids becomes less and additional quantity can be utilized for surface coating of aggregate, and finally reduces the friction force and improves the flowability of fresh concrete. Westerholm et al. [101] believed that washed aggregates which removed particles smaller than 40 μm decreased the specific surface area, could significantly reduce the yield stress of mortar due to the low water demand and low colloidal forces. While the mortars with washed aggregate showed slightly higher plastic viscosity owing to the lack of fines filling the voids and acting as lubricant.

3.3. Chemical admixtures

With the wide application of high performance concrete, chemical admixtures have become an indispensable part of concrete. The type of chemical admixtures has great influences on the rheological properties of fresh concrete.

3.3.1. Superplasticizer

Due to economic and technical benefits, superplasticizers are almost used for all modern concretes. The yield stress and viscosity of cement-based materials can be dramatically decreased by the addition of superplasticizer under the action of electrostatic or/and steric hindrance effects. The efficiency of superplasticizer depends on the adsorption of superplasticizer molecules onto cement particles and the repulsive force developed by the adsorbed molecules. For the new generation of superplasticizer, it seems that steric hindrance effect becomes dominate over electrostatic effect [102]. The mechanism of yield stress of suspensions containing superplasticizer can be explained using the YODEL model. The YODEL (Yield Stress mODEL) [103], which links the physical parameters of suspension to the yield stress, can predict accurately the yield stress dependent on concentration for colloidal particles suspension. The basic expression is as follows:

$$
\tau_0 = m \frac{A_0 d^{*}}{f^{2}} \phi^2 (\phi - \phi_{perc}) \phi_{m}(\phi_{m} - \phi)
$$

where $m$ is a pre-factor, which depends on the particle size distribution, $d$ is particle average diameter, $d^{*}$ is radius of curvature of the contact points, $H$ is surface to surface separation distance at contact pints, $A_0$ is non retarded Hamaker constant, $\phi_{perc}$ is percolation threshold, $\phi$ is solid volume fraction and $\phi_{m}$ is maximum packing fraction of the powder. With the increase of superplasticizer, the average surface to surface separation distance increases, the colloidal interaction between particles decreases and therefore the yield stress and the degree of flocculation decreases [104]. Beyond that, the addition of superplasticizer leads to a higher surface coverage by polymers, causing an increase in effective layer thickness and a reduction in the maximum attraction between the particles, thus decreases the sites number available for nucleation and increases the bridging distance between the particles, consequently improves the rheological properties of fresh concrete [105,106].

The efficiency of superplasticizer depends on the type and the structure. Fig. 11 demonstrates the rheological properties of SCC made with different types of superplasticizer. It can be observed from Fig. 11 that the concrete mixtures with polycarboxylate-based superplasticizer give higher yield stress and lower plastic viscosity than those with naphthalene sulphonate based superplasticizer at the same slag content. Papo et al. [107] found that modified polyacrylic was the most effective superplasticizer to improve the rheological properties of cement paste among three types of superplasticizers based on melamine resin, modified lignosulphonate and modified polyacrylate. The naphthalene superplasticizer is beneficial for dispersing cement, with a low air-entraining effect and slump retention effect. The polycarboxylate superplasticizer consists of a backbone of polyethylene, grafted chains of PEO and carboxylic groups as adsorbing functional groups. It has a potential to disperse cement particles, restrain the slump loss and shorten
the setting time \[62,108,109\]. Toledano-Prados et al. [110] found that the liquid polycarboxylate proved more effective than the solid polycarboxylate. Different admixtures which had the same main chain and same polymer structure but different molecular weights and different side chain densities of carboxylic acid groups have a great effect on rheological properties of SCC [111]. The yield stress of SCC mixtures was only affected by superplasticizer dosage, while increasing both the molecular weight and side chain density of carboxylic acid groups increased the plastic viscosity due to the increase in steric hindrance.

3.2.2. Viscosity modifying agent

Viscosity modifying agents (VMA) are relatively new admixtures used to improve the rheology of the concrete with higher uniformity and better cohesiveness. The incorporation of VMA in concrete can reduce the risk of separation of the heterogeneous concrete and obtain a stable concrete for underwater repair, curtain walls and deep foundation walls. The mode of action of VMA depends on the type and concentration of the polymer in use. The mechanism of action with welan gum and cellulose derivatives can be classified in three categories, i.e. adsorption effect, association effect and intertwining effect [112]. The adsorbed cellulose ether can slow down the nucleation of calcium silicates, generate repulsive steric forces to replace van der Waals attractive forces, and then form a new interaction network which could bridge the cement grains [113]. The inorganic VMA with high surface area increases the content of fine particles and the water retaining capacity of paste, and thereby the thixotropy.

The concrete modified with a VMA exhibits high plastic viscosity, high yield value and shear thinning behavior. The efficiency of VMA depends on the type and concentration [112]. Schmidt et al. [114] stated that the influence of the VMA on yield stress was much stronger than the effect of polycarboxylate ether superplasticizer (PCE) at 20 °C, and the mixtures with VMA based on modified potato starch retained the performance better than those with VMA based on Diutan Gum, independent of the PCE type. Yun et al. [72] found that VMA based on hydroxypropyl methyl cellulose had a tendency to reduce the flow resistance and increase the torque viscosity of high-performance wet-mix shotcrete, worsening the shootability and pumpability. Leemann et al. [115] showed that VMA based on polysaccharide caused the highest increase in yield stress and VMA based on microsilica had the lowest at an equivalent plastic viscosity. Assaad et al. [116] showed that the addition of VMA significantly increased the thixotropy for high flowability concrete. Brumaud et al. [113] found that the critical deformation increased with VMA dosage. One possible explanation is that the number of bridging grains increases and therefore increases the probability of large inter-particle relative displacement. Another possible explanation comes from the fact that the hydrophobic interactions of high VMA concentrations could form aggregates with large size, which could tolerate higher stretching [117,118].

Different types of VMA may have the same effect. Benaicha et al. [68] showed that the concrete made with 10% of silica fume and the one with 0.1% VMA had the same characteristics in resistance of sieve segregation, plastic viscosity, yield stress, and even mechanical properties. They believed that the VMA could be replaced by silica fume, depending on the availability of materials.

VMA is often used in combination with superplasticizer to improve the rheological properties and mechanical strength. The presence of two dissimilar chemicals can lead to a number of issues of incompatibility that affect the properties of concrete. Khayat [112,119] stated that cellulose derivatives were always used in conjunction with melamine-based superplasticizer because of their incompatibilities with naphthalene-based superplasticizer. Prakash et al. [120] indicated that the flowability of pastes produced with combinations of superplasticizer based on sulfonated naphthalene formaldehyde or polycarboxylic ether and VMA based on welan gum was satisfactory. The only difference was that the polycarboxylic ether - welan gum combination showed evidence of thixotropy, the same was not observed for sulfonated naphthalene formaldehyde - welan gum combinations. In addition, the rheological behavior of the mixtures with VMA is in general dependent upon shear stress. Bouras et al. [121] found that, at sufficiently low shear stress, the mixtures with VMA exhibited shear thinning, while at relatively high shear stress, the pastes became shear thickening. At low shear stress, the flow of paste induces the defloculation of solid particles and VMA polymer disentanglement and alignment.

3.3. Air-entraining agent

Air-entraining agent has been widely used to improve resistance to freezing and thawing damage, and to a lesser extent, the workability of concrete. Air-entraining agent is a mixture of various surfactants [122]. The chemical nature of air-entraining agent contains the hydrophilic head, having a strongly attraction for water, and the hydrophobic tails, having repulsion for water. From the rheological point of view, entrained air bubbles play a role in lubrication and increasing paste volume, together with the character of air-entraining agent, affect the consistency of cement-based materials.

There are many studies about the effect of air-entraining agent on rheological properties. He et al. [123] found that consistency of mortar showed slowly increasing trend with the mixing amount of air entraining increasing while the consistency in general was not high. Yun et al. [72] found that the use of air-entraining agent tended to reduce both flow resistance and torque viscosity,
effectively improved the pumpability of high-performance wet-mix shotcrete, and while the reduction rate of torque viscosity decreased with the increase of air content. Tattersall et al. [2] demonstrated that the flow resistance and torque viscosity continued to decrease until the air content reached 5% and then stabilized beyond that point. This can be contributed to the lubrication effect and volume effect of air bubbles. However, Carlsward et al. [124] and Wallevik et al. [125] revealed that the addition of air-entraining agent strongly reduced the plastic viscosity, while the effect on yield stress was not significant. Strubbe et al. [126] indicated that the yield stress increased and the plastic viscosity decreased with increase of air content, which was also reported by Rahman and Nehdi [127]. An explanation for the increase in yield stress is proposed that air bubbles are attracted to cement particles to form bubble bridges and thus increase bonding between particles. Once the bubble bridges are broken and paste is able to flow, the air bubbles reduce plastic viscosity, apparently acting as a lubricant. Thus, there is competition between these two actions: without shear, the bubbles act as flocculating particles to increase yield stress and with shear, the bubbles act as lubricant to reduce plastic viscosity [128]. Moreover, the rheological behavior of suspensions with bubbles also depends on the shear rate due to the fact that surface tension could prevent entrained bubbles from deforming at low shear rate [129].

4. Application of rheology in concrete mixture design

The graph of yield stress against plastic viscosity is an effective approach to describe the complex variations of rheological parameters. The first application of this kind of graph is in Ref. [130] and then has been adopted by many researchers [94,124,131].

The graph of yield stress against plastic viscosity can reflect the effect of ingredients on the rheological properties of typical concrete, as shown in Fig. 12. In 1983, Wallevik [132] systematically established rheographs of fresh concrete. The graph of yield stress against plastic viscosity can be served as a guideline for the mix proportion design of concrete. The first step is to determine a workability box [94] consisting of an optimum area within a rheograph through many experiments data, and then obtaining the desired rheology by optimizing the various components of concrete into workability box, i.e. rheological mix design [133]. The work-ability box consists of several pointed regions without an exact and clear boundary, and each one represents an optimal range of yield stress and plastic viscosity for a specific concrete. Wallevik et al. [94] developed a new graph for different types of SCCs based on data from almost 100 different Confec devices around the world, as shown in Fig. 13. As can be seen from Fig. 12, there are several ways to change and control the rheological behavior of fresh concrete. It should be clear that the individual effects by changing the composition of concrete are additive [134], which is called vectorized-rheograph approach [94].

5. Conclusions

Based on the review on the rheological properties of concrete in the literature, the following conclusions can be drawn:

1. The yield stress at rest increases as a linear function of time, which can be expressed by a thixotropic model:

\[ \tau = (1 + \lambda)\tau_0 + \mu \dot{\gamma} \]

\[ \frac{\partial \lambda}{\partial t} = \frac{1}{\tau} \alpha \lambda \dot{\gamma} \]

When the steady state flow is reached, the rheological behavior of fresh concrete can be described using a yield stress model such as Bingham model, Herschel-Bulkley model and Modified Bingham model.

2. The chemical composition and physical characteristics of cement have significantly influences on rheological properties. Generally, cement with high C3A, high alkali content, high loss on ignition, high fineness and specific surface area, and low content of S3O decreases the workability.

3. The rheological properties of concrete are significantly influenced by the type, chemical composition, content, packing density, fineness, surface texture, particle size distribution of mineral admixtures, owing to filling effect, morphology effect, dispersion effect and adsorption effect.

4. The viscosity and yield stress of fresh concrete can be calculated by the Farris model and Chateau-Ovarlez-Trung model, which are respectively expressed as follows:

\[ \eta = \eta_0 \left( 1 - \frac{\phi_1}{\phi_m} \right)^{-\frac{\eta_2}{\phi_m}} \left( 1 - \frac{\phi_2}{\phi_m} \right)^{-\frac{\eta_3}{\phi_m}} \]

\[ \frac{\tau_c(\phi)}{\tau_c(0)} = \sqrt{\frac{1 - \phi}{1 - \phi / \phi_m} \frac{\eta_0}{\eta_0(0)}} \]

Therefore, the type, volume fraction, graduation and particle size of aggregates strongly influence the rheological properties of concrete by controlling the amount of free cement paste and inter particles friction resistance.

5. The YODEL model can predict accurately the yield stress dependent on concentration for colloidal particles suspension. The addition of superplasticizer improves the dispersion of cement particles, decreases the colloidal interaction and repulsion between particles, and thus has great effects on the rheological properties of concrete.

6. The mechanisms for viscosity modifying agent of welan gum and cellulose derivatives can be classified in three categories, i.e. adsorption effect, association effect and intertwining effect. Its efficiency depends on the type and concentration of viscosity modifying agent, the type of superplasticizer and the applied shear stress.

7. Since the air bubbles attract cement particles to form bubble bridges and also could act as a lubricant, air-entraining agent may have two opposite effects on yield stress and plastic viscosity.

8. The rheograph namely graph of yield stress against plastic viscosity and workbility box can be served as a guideline for the mix proportion design of concrete. The workability box consists of several pointed regions without an exact and clear boundary, and each one represents an optimal range of yield stress and plastic viscosity for a specific concrete. Wallevik et al. [94] developed a new graph for different types of SCCs based on data from almost 100 different Confec devices around the world, as shown in Fig. 13. As can be seen from Fig. 12, there are several ways to change and control the rheological behavior of fresh concrete. It should be clear that the individual effects by changing the composition of concrete are additive [134], which is called vectorized-rheograph approach [94].

![Fig. 12. Effect of ingredients on the rheology of a typical concrete [130].](image-url)
the mix proportion design of concrete and also used to control the quality of concrete for the engineering application.

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