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Effects of mineral additions on the rheological properties of self-compacting concrete: A review

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Abstract

The rheological study of concrete is crucial for the construction sector due to its influences on the casting process and hardened properties. This is even more important when designing and producing self-compacting concrete (SCC). By controlling yield stress and plastic viscosity, it is possible to predict and optimize the flowability of SCC. Understanding the rheological behaviour of SCC is a major step in achieving adequate flow behaviour to fill the formwork without any sign of segregation or blockage and hence yielding satisfactory performance of hardened concrete. This paper provides a critical and detailed review on rheological properties of SCC based on studies published in recent years. The rheological models for characterising the flow behaviour of fresh concrete are briefly assessed. The influence of water to cementitious materials ratio on SCC properties is also discussed. A comprehensive review on the influence of fine additions (i.e., fly ash, ground blast furnace slag, silica fume, metakaolin, and limestone powder) on SCC rheology has also been presented in this review.

Keywords

Fresh concrete; cementitious materials; rheological properties; viscosity; yield stress

List of notations

σ	stress of material
ε	strain of material
τ	shear stress
τ_0	yield stress
$\dot{\gamma}$	rate of shear strain
η	apparent viscosity
η_p	plastic viscosity
η_∞	limit shear viscosity
η_0	initial shear viscosity
K	consistency coefficient
n	liquidity index
c	decay constant

1. Introduction

Concrete is by far the most widely used construction material, with an annual worldwide consumption of around 30 billion tonnes (Zhao et al., 2021). The rheological investigation of concrete is of great significance for the construction industry due to its effects on the casting and forming process, which also may influence the mechanical properties of hardened concrete in the long term. The rheological properties are even more crucial when designing self-compacting concrete (SCC) mix (Ghanbari and Karihaloo, 2009). SCC is designed to have low yield stress in order to ensure high flowability while at the same time exhibiting moderate viscosity to maintain its homogeneity (Khayat, 1998). SCC should flow through areas of congested reinforcements under its weight, without any external vibration, to fill the formworks without undergoing complexities such as segregation and blocking.

SCC has lower rheological characteristics in terms of plastic viscosity and yield stress, compared to conventional concrete. This is because SCC mixes are proportioned with higher content of cement, powder materials, and chemical admixtures to achieve the desired rheological and deformability properties (Diamantonis et al., 2010). The high volume of cement in SCC may cause problems such as hydration heat, high cost and high autogenous shrinkage in certain types of structures (Rasekh et al., 2020). Furthermore, the carbon dioxide emissions and consumption of natural resources associated with cement manufacturing can also cause serious environmental consequences (Ouldakhaoua et al., 2020). Nevertheless, it is essential to increase the paste content to obtain a better-quality of SCC. Hence, mineral additives and industrial by-products have become essential components in the design of modern SCC. The use of mineral additions can limit the environmental impact of SCC production and be more sustainable in addition to reducing the cost. However, fine additives (e.g., fly ash, slag, silica fume, limestone powder, etc) can remarkably affect the rheological and mechanical properties of SCC but to various degrees (Gupta et al., 2021).

With respect to significant environmental and performance considerations, there is a pressing need to understand how mineral additives impact the fresh and rheological performance of SCC. This paper aims to provide a critical review of the existing knowledge regarding the effects of

mineral additions and water to cementitious materials ratios on the rheological properties of SCC. The lack of standardized practices and established methods for assessing the rheology of cementitious composites necessitates a thorough examination of existing research findings. Such an investigation is essential for devising innovative design strategies for SCC rheology, to enhance the comprehension of the factors that optimize its rheological attributes and to improve the sustainability of SCC.

This paper is organized as follows. Section 2 details the rheological properties of fresh SCC. This is followed by Section 3 which describes the effect of water to cementitious ratio on the rheological behaviour of SCC. A comprehensive review relating to the effects of cement and main mineral additions are presented in Section 4. In Section 5, concluding remarks are given based on the review and conclusion.

2. Analysis of Rheological Dynamics of SCC

2.1 Rheological models of SCC

The main research focus in understanding rheology is to establish the constitutive relationship between matter and material based on experimental or theoretical methods and to use this constitutive relationship and conservation laws to analyse the rheological properties of the given system. However, it is challenging to numerically describe and predict the flow and deformation of complex fluids such as SCC (Yahia and Khayat, 2001). The most widely used rheological models are summarized in Table A1. Due to the inherent complexity of the interactions among various components in the flow process of SCC, to obtain the overall characteristics of SCC flow, the numerical model needs to be appropriately simplified. Among many SCC rheological models described based on the relationships between shear stress and shear rate, the Bingham model and Herschel-Bulkley model have gained widespread recognition (Wallevik and Wallevik, 2011) (see Figure 1).

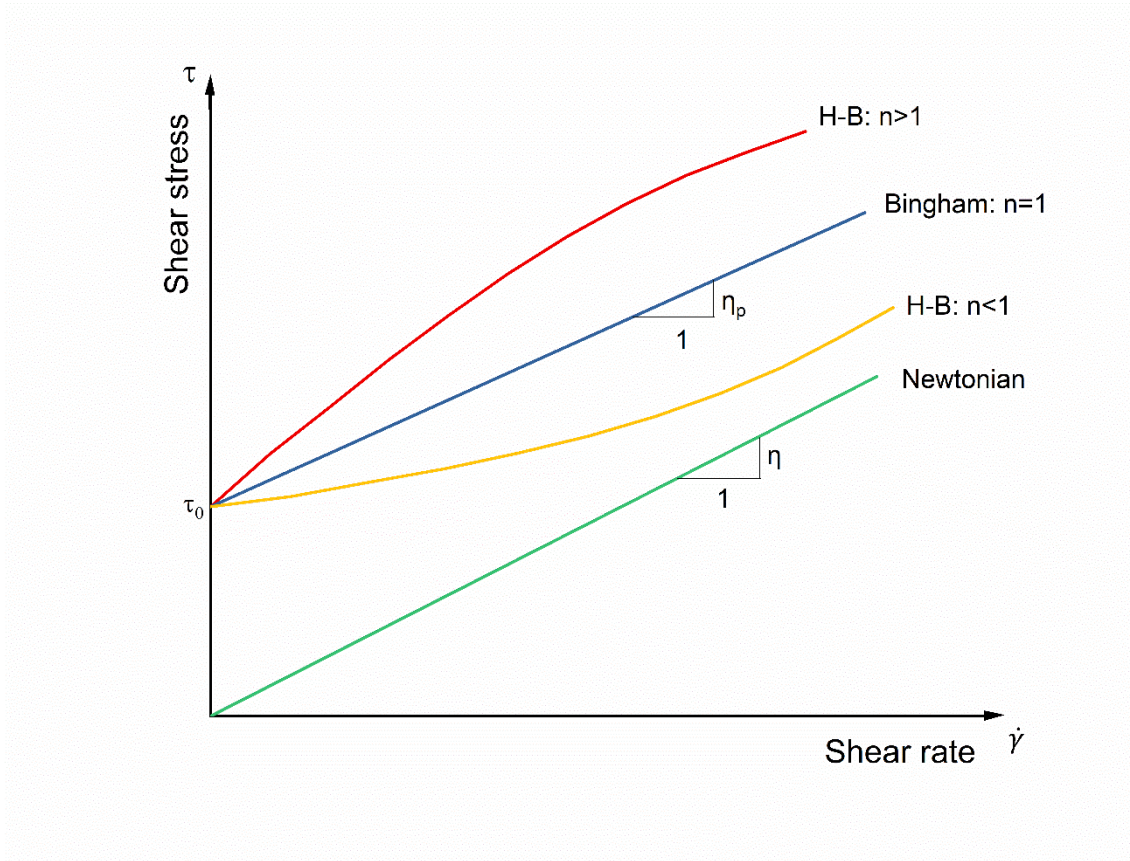


Figure 1. Different types of rheological models

It is assumed in the Bingham model that the shear stress is linearly proportional to the shear rate, after exceeding certain yield stress (Heirman et al., 2008). This linear ratio is named as the plastic viscosity which is the measure of the material resistance to flow. The flow stops once the shear stress of SCC mix reaches the yield stress (Sonebi and Yahia, 2020). Although the Bingham model is valid in most cases, fresh SCC cannot always be regarded as the Bingham model. Recent studies show SCC with high superplasticizer levels can display non-linear behaviour, occasionally indicating negative Bingham yield stress (Feys et al., 2008). Thus, the Herschel-Bulkley model, less prone to negative yield stress (Wallevik and Wallevik, 2011), often better describes SCC's flow, making it preferred for modelling SCC's non-linear rheological properties.

2.2 Factors influence the rheology of cement paste

Evaluating the rheological properties of cement paste involves understanding the intricate interplay between various factors that influence its behaviour (Feys et al., 2017). The complex

nature of cement particles, which straddle the line between non-colloidal and colloidal sizes, is crucial, with their rheological behaviour heavily dictated by interparticle forces like electrostatic repulsion and Van der Waals dispersion (Roussel et al., 2010). Moreover, these properties evolve over time due to ongoing chemical reactions (Wallevik, 2009). Factors such as particle size distribution, shape, the w/cm, superplasticizer concentration, cement additives, and external conditions such as temperature and pressure all play significant roles in shaping the plastic viscosity of the paste (de la Rosa et al., 2020; Lachemi et al., 2004; Mikanovic and Jolicoeur, 2008). The structural build-up within the cement paste, significantly affected by these parameters, is key to understanding its rheological characteristics.

2.3 Measurement of rheological properties of SCC

In the last decade, around a hundred methods to measure concrete flow have been developed, primarily to assess concrete quality on job sites or to determine the optimal mix for specific uses. Despite their prevalence, these methods largely rely on empirical approaches rather than directly measuring rheological properties. Key resources such as the RILEM report (Bartos et al., 2002) and the ACI 238 (ACI Committee 238, 2008) report provide comprehensive overviews of these tests.

Recently, the industry has shifted towards more objective measures using rheometers to assess concrete rheology. These instruments, which evaluate critical rheological parameters such as plastic viscosity and yield stress, promise a deeper understanding of concrete's fresh state. However, variability among rheometer models can lead to differing results for the same mixture, though they reliably offer qualitative distinctions between mixes. Challenges in capturing precise rheological parameters in fundamental units highlight the complexity of concrete's behaviour and the limitations of current testing apparatus (Feys, 2006; Feys et al., 2017; Vasilić, 2015). In this study, variations in measurement methods and equipment have not been accounted for. This omission reflects a focused approach, where a broader understanding of rheological behaviour is prioritized over the specificities introduced by diverse testing methodologies.

3. Effect of water to cementitious materials ratio on rheology properties of SCC

It was pointed out that increasing the water to cementitious materials ratio (w/cm) of SCC mixes can expand the diameter of the slump flow and reduce the flow time at the same time, which means that a high w/cm ratio can produce the reduction of yield stress and plastic viscosity of SCC mixes (Siddique et al., 2012; Firoozi et al., 2018; Nematollahzade et al., 2020). Compared to normal vibrated concrete (NVC), SCC has very low yield stress that can impart high fluidity and retain the kinetic energy of the mixture. However, in order to maintain the low level of yield stress, increasing w/cm reduces the plastic viscosity and may cause severe segregation. Hence, controlling the w/cm within a reasonable range is an essential prerequisite for assessing the flow performance of SCC mixes and designing experiments. Girish et al. (2010) investigated the effect of the w/cm on the flow properties of SCC by keeping the water content constant. It was concluded in their study that the slump flow spread of mixes with a higher w/cm was less, which can be attributed to less powder content available for lubrication, thereby decreasing the shear deformability of the mixes.

It is known that the rheological properties of fresh SCC mixes change from the time when the mix is produced; for instance, the slump flow diameter decreases and flowing time increases. It was found in the study of Kostrzanowska-Siedlarz and Gołaszewski (2016) that the effect of time could be more negligible when the w/cm was higher. Esmaeilkhani et al. (2014) investigated the effects of w/cm on dynamic stability of SCC using the T-box test. A significant decrease in the dynamic segregation of mixtures was observed when the w/cm decreased from 0.40 to 0.33 due to an increase in both yield stress and plastic viscosity of concrete. Felekoğlu et al. (2007) produced five groups of SCC mixes with different combinations of w/cm and superplasticizer dosage levels. A typical example observed in the study showed that reducing the w/cm while increasing the superplasticizer dosage increased V-funnel times significantly. The effect of water reduction on V-funnel flow times appears to be more significant than the impact of superplasticizer dosage. Additionally, the reduction in water content was found to influence mix viscosity, and increasing the dosage of superplasticizer alone could not fully compensate this effect.

However, the impact of chemical admixtures cannot be ignored while evaluating the effect of w/cm on rheological properties of SCC. Li et al. (2017) tested rheological properties of three SCC types, finding yield stress rose with increased w/powder ratios, contrary to plastic viscosity. This deviation is attributed to reduced superplasticizer in higher w/cm ratios enhancing particle attraction, thus raising yield stress (Banfill, 2011; Saleh Ahari et al., 2015). A regression analysis on the relationship between w/cm and plastic viscosity was given based on the data collected from published sources as shown in Figure 2.

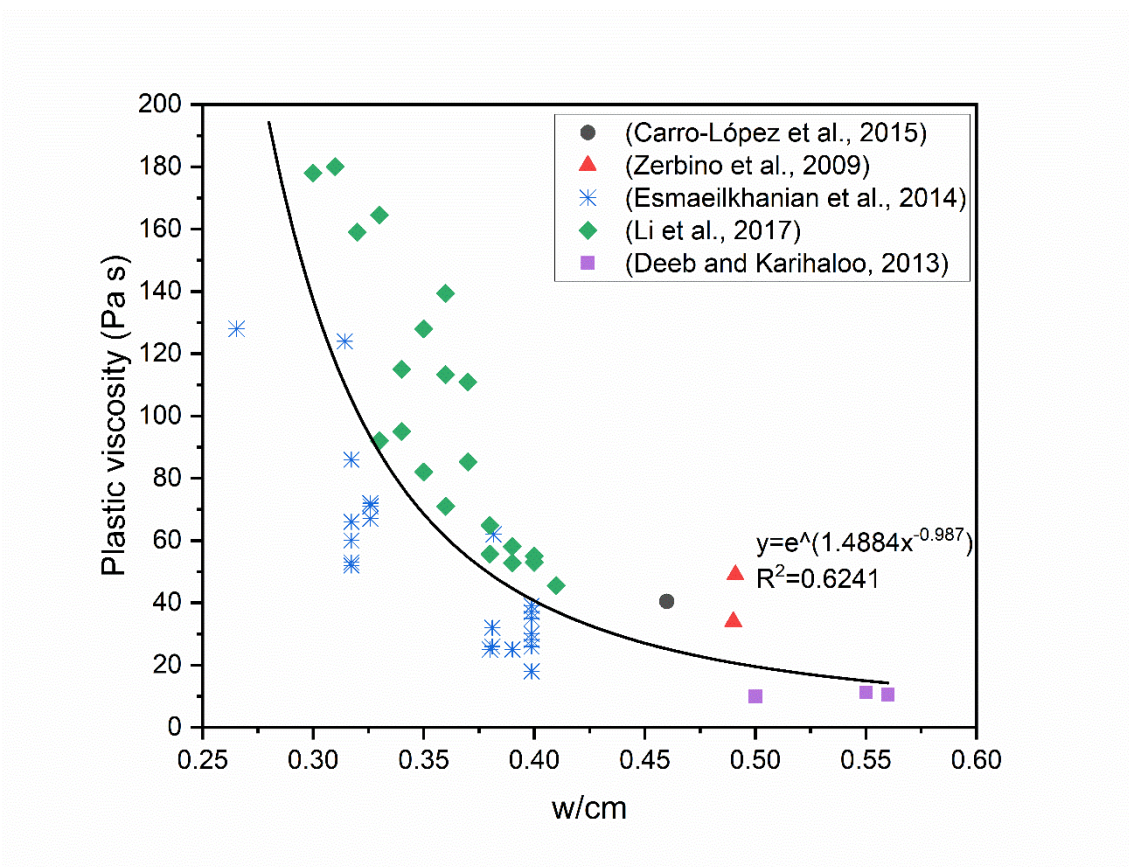


Figure 2. The relationship between w/cm and plastic viscosity of SCC

4. Effect of mineral additions on rheology properties of SCC

To produce more sustainable SCC with high performance, mineral additions are introduced as fillers or partial replacements of cement. This section summarises the effect of five widely used mineral additions on SCC rheological properties based on recent publications. The effect of mineral additions on rheological properties of SCC are summarized in Tables A2-A6. Figures 3-7 show the relationship between two main rheological parameters (i.e., yield stress and plastic

viscosity) of different types of mineral additives regardless of other parameters. Due to the absence of directly reported rheological parameters in some studies, some results are estimated based on the correlation charts proposed by Badry et al. (2014) and Benaicha et al. (2017). This approach was necessary to fill the gaps in the available data and to ensure a comprehensive analysis of the rheological properties of SCC.

4.1 Fly ash

Fly ash is a solid fine-grained material produced by the combustion of pulverized coal in the furnace of a power station. The chemical and mineral composition of fly ash depends on the characteristics and composition of coal burned in the power plants. Due to the rapid cooling of the material, fly ash mainly (50-90%) consists of minerals in the form of glassy particles. Fly ash is particularly rich in SiO_2 , Al_2O_3 and Fe_2O_3 , and also contains other oxides, such as CaO , MgO , MnO , TiO_2 , Na_2O , K_2O , SO_3 , etc. Particularly, fly ash with high CaO content (15% to 40%) may be considered hydraulically latent and can cause the weakening of mortar and concrete. Physically, the specific surface or fineness of fly ash measured by the Blaine method varies from 250 to 550 m^2/kg (Wesche, 1991). Figure 3 summarises the effects of fly ash on SCC rheological properties as reported in the literature.

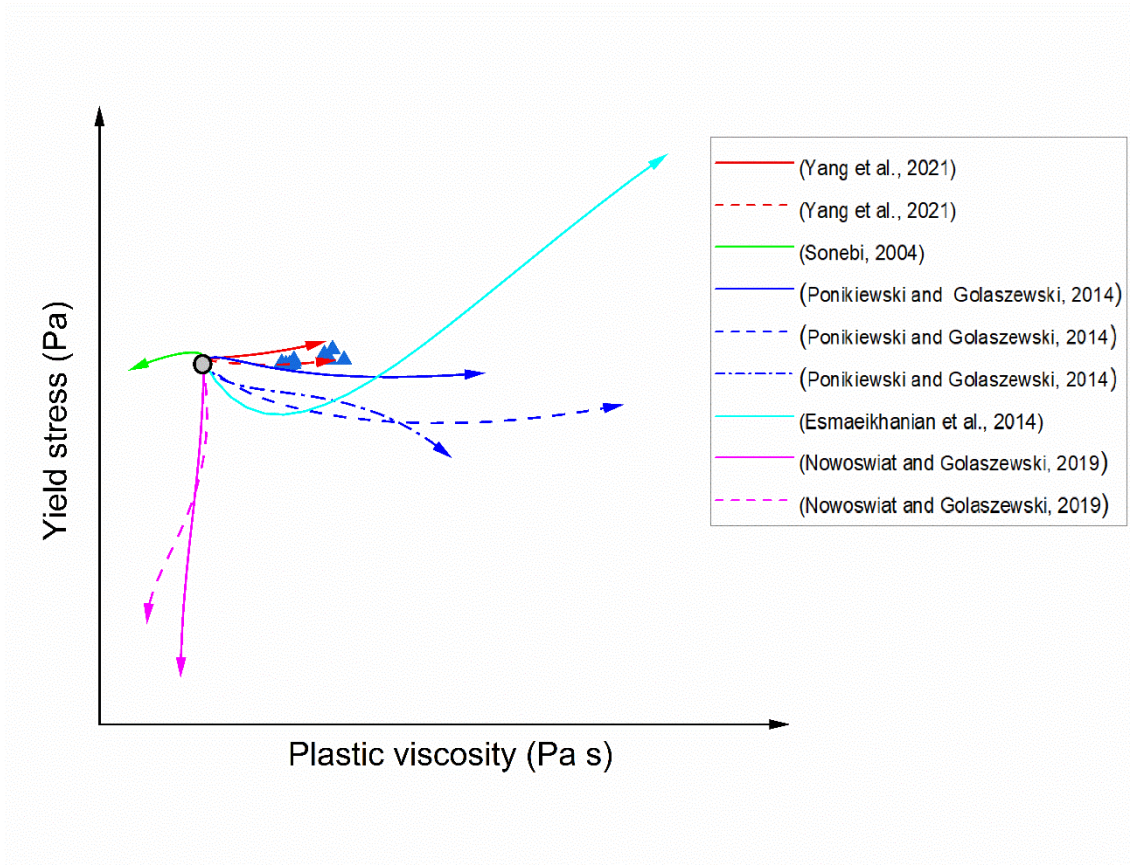


Figure 3. Effects of fly ash on rheological properties of SCC

Studies on high volumes of fly ash in concrete have been carried out since the 1990s (Berry et al., 1990; Feldman et al., 1990; Atiş, 2002). It was demonstrated that better mechanical properties of concrete could be achieved by replacing cement with fly ash with a proportion of more than 40% (Habert and Roussel, 2009; Wang and Park, 2015; Kurad et al., 2017). Nevertheless, the use of high levels of fly ash can significantly impact the rheological properties of concrete (Bentz et al., 2013; Khodair and Bommarreddy, 2017), especially for SCC (Van Der Vurst et al., 2017). Thus, the properties of fly ash play a vital role in the performance of fresh SCC.

Matos et al. (2019) found that replacing cement with fly ash improved the fluidity of SCC, thereby reducing the content of superplasticizers. This could be because the spherical and smooth texture of fly ash particles promoted the bearing effect and reduced the friction between the mixture particles. In the study of Yang et al. (2021), cement was substituted by 20% and 30% of fly ash by volume, to understand the effect of fly ash content on the rheological thresholds of SCC pastes.

In the original model, the paste plastic viscosity threshold increases slightly from 20% to 30% of FA, contrary to the trend observed in the paste yield stress threshold. However, in the modified model that introduces a fitting coefficient and considers the intrinsic viscosity of FA, a significant decrease was observed in the plastic viscosity threshold for 30% of FA compared to 20% of FA.

As the mineral additive, high calcium fly ash is widely used as the main component of cement or directly in SCC. Mohammed et al. (2022) produced a considerable number of SCC mixes with fly ash and slag as the filler. The statistical results showed that additional fly ash had a greater impact than slags on SCC fresh properties. The spherical particles of fly ash played an important role in increasing the flow rate and reducing the flow time. Similar findings were also reported in the study of Concha and Baccay (2020), in which SCC mixes were produced with increasing fly ash content. All mixes satisfied the recommended standard for flow tests with a higher amount of fly ash registered higher spread diameters and recorded shorter time in V-funnel tests. Spherical fly ash particles can improve fluidity of SCC through the ball bearing effect between the aggregated particles, which makes the lubrication effect stronger and reduces the cohesion between the particles. On the other hand, Ponikiewski and Gołaszewski (2014) reported that, the incorporation of high-calcium fly ash negatively impacts the flowability, as evidenced by reduced spread, increased flow time and hindered passing ability.

Saleh Ahari et al. (2015) investigated the effect of different types of fly ash on the rheological properties of SCC. The mixtures with various amounts of Class F fly ash (FAF) and Class C fly ash (FAC) with similar particle size distribution were demonstrated to have increased plastic viscosity and yield stress of control mixtures which consist of water, cement, water-reducing admixture and aggregates. Furthermore, the higher plastic viscosity and lower yield stress value obtained by FAC mixtures may be related to its particle shape. FAF particles are spherical in shape, usually better filled than irregularly shaped FAC particles, and can produce a higher ball bearing effect to reduce friction between particles, thereby improving workability and reducing plastic viscosity, which corroborates the observations made by Concha and Baccay (2020). In a word, fly ash notably impacts SCC's rheological properties and workability, with its effectiveness

linked to the type (Class F vs. Class C), mineral composition, and replacement ratio. High volumes typically enhance fluidity, with calcium content being a key factor in defining its influence on SCC.

4.2 Ground granulated blast furnace slag (GGBS)

Blast furnace slag is the waste slag that leaves the blast furnace during pig iron making. It is a fusible mixture and can be processed into recycled materials with multiple uses by various processes. After blast furnace slag is quenched with a large amount of water, it can be made into fine-grained slag mainly containing glass body, which can show hydraulic cementing performance under the action of activators such as cement clinker, lime, gypsum, etc. Generally, the specific gravity of GGBS is about 2.90 with the bulk density varies in the range of 1200-1300 kg/m³. The reactivity of GGBS is determined by its surface area. But surface area of GGBS varies region to region due to the influence of processing factors used in practice. The surface area of GGBS in the United Kingdom is 375-425 m²/kg, while the surface area of some slags in the United States is 450-550 m²/kg; this value is 450 m²/kg and 350 to 450 m²/kg in Canada and India, respectively (Pal et al., 2003). Apart from physical characteristics, properties that affect the reactivity of GGBS are usually glass content, chemical composition, mineral composition, grinding fineness and so on (Hooton and Emery, 1983). The effects of GGBS on SCC rheological properties, reported in the literature, are summarised in Figure 4.

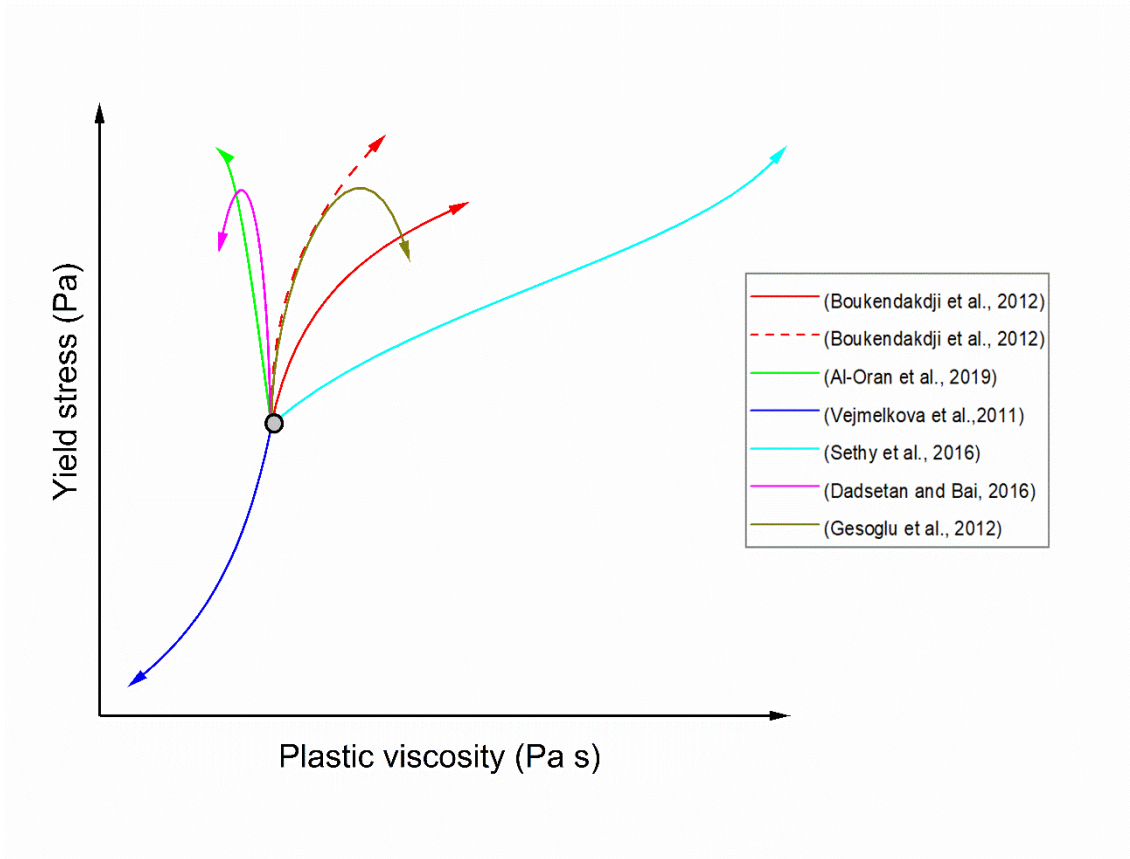


Figure 4. Effects of GGBS on rheological properties of SCC

Several studies have investigated the effect of GGBS on the performance of SCC, and it is found that GGBS improves the rheological properties and greatly prolongs the setting time of cement slurry. Al-Oran et al. (2019) found that substituting GGBS for cement up to 25% enhances mixture fluidity due to GGBS's larger particle size, which reduces surface area and slows chemical reactions, and its lower yield stress compared to cement, thereby decreasing internal friction and improving fluidity. In the study conducted by Boukendakdji et al. (2009), under constant w/cm ratio and SP content, the slump spread increased while yield stress and viscosity decreased the most when the cement was replaced by GGBS content with 15%. Equivalent findings demonstrated that 15% GGBS content showed the best viscosity and yield stress (Boukendakdji et al., 2012). Zhao et al. (2015) observed that the addition of GGBS up to 40% resulted in improving flowability of the mixes. This can be explained that spherical GGBS used to replace cement increased the volume of the paste, thereby reducing the friction between aggregates and

cementitious pastes. The results obtained by Tadi and Rao (2022) showed a good agreement, and they illustrated that plastic viscosity decreased with increasing slag content.

Some researchers focused on using much higher volume fraction of GGBS. Vejmelková et al. (2011) tested the fresh properties of SCC mixtures with CEM III/A 32.5N containing 56% of GGBS, which exhibited Newtonian fluid properties and showed zero yield stress and significantly higher plastic viscosity. In the study of Gesoğlu et al. (2012), 10% Portland cement and 90% GGBS were cooled and bonded into agglomerated artificial slag aggregate (ASA) in a tilted pan. The rheological behaviour of the SCC mixture is the same as that of cement replaced by GGBS, mixtures with a higher level of ASA content exhibited a decrease time in both slump and V-funnel tests and lower viscosity. In general, research indicates that incorporating GGBS into SCC enhances its rheological properties by improving fluidity and extending the setting time of cement slurry, attributed to GGBS's larger particle size, lower yield stress, and the subsequent reduction in internal friction.

4.3 Silica fume (SF)

Silica fume (SF) is collected from ferrosilicon alloy plants and metal plants smelting ferrosilicon alloy or metallic silicon, which is widely used as the supplementary cementitious material due to pozzolanic properties and physical filling ability. Typically, 95% of silica fume (SF) particles are less than 1µm in size, approximately 100 times smaller than ordinary cement particles, with a surface area ranging from 13,000 to 30,000 m²/kg (Khan and Siddique, 2011). Silicon powder includes 85% to 98.5% silicon oxide and a small amount of iron, magnesium and alkali metal oxides. Recycling and utilization of SF have great potential for environmental protection. Using SF as an addition in the concrete industry can not only reduce the cost but also improve the performance of concrete. The effects of SF on SCC rheological properties, reported in literature, are summarised in Figure 5.

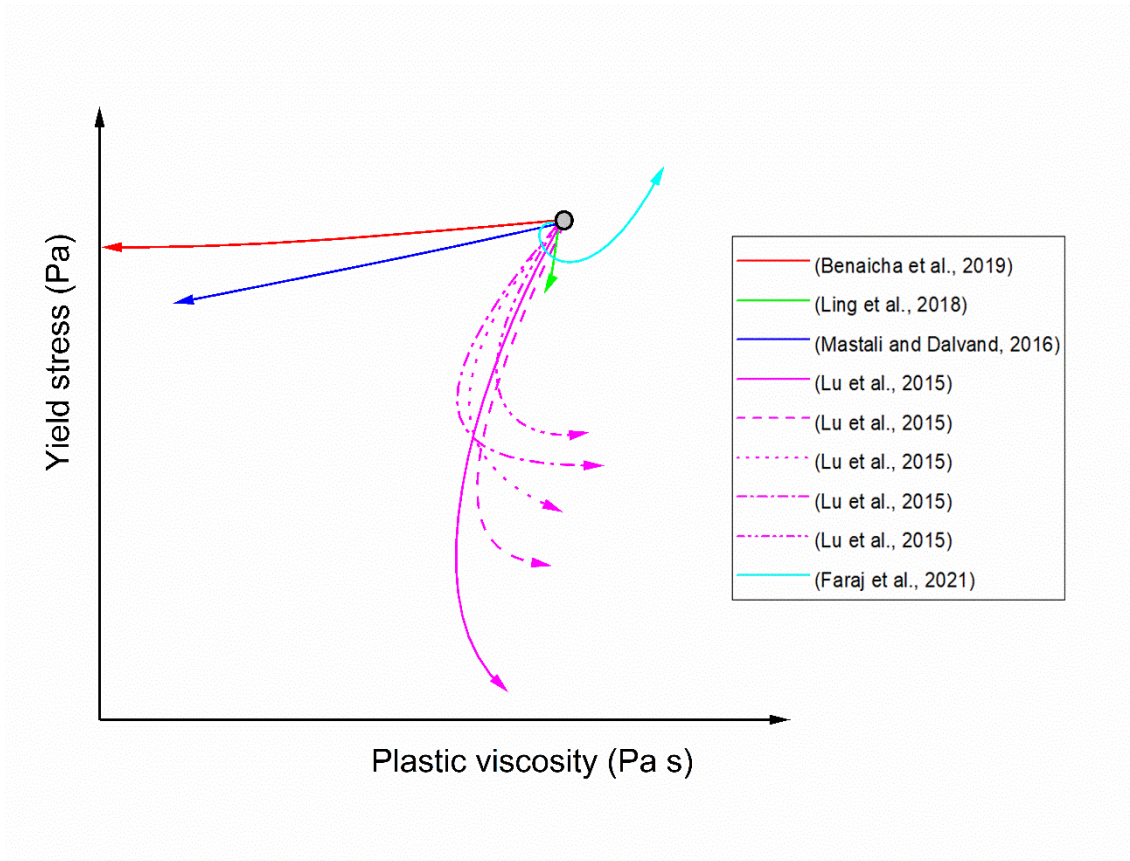


Figure 5. Effects of SF on rheological properties of SCC

Numerous studies have been performed on SCC with SF as a supplementary cementitious material in recent years. However, there is no uniform observations or concluding evidence detailing the effect of SF on the rheological properties of SCC. In the study of Benaicha et al. (2019), different dosages of CEM I 52.5 R was replaced by SF. The findings of the investigation showed that SF increased yield stress and plastic viscosity as the addition of silicon powder could increase the water required to reach a certain level of workability. Ling et al. (2018) carried out a study with a similar perspective, wherein the fly ash content in SCC mixes was partially replaced by SF. It was shown that the yield stress and plastic viscosity increased with the increasing content of SF when the replacement ratio is larger than 2%. It is because the high activity of SF promoted the hydration process, and hydration products prevented the relative movement of the particles by covering particle surface. In the study of Mastali and Dalvand (2016), the workability of SCC was investigated by replacing cement with silica fume. Increasing the replacement ratio of SF from 7% to 14% increased the plastic viscosity and reduced the flowability of mixes. Lu et

al. (2015) found that increasing SF in SCC mixtures raised yield stress and caused plastic viscosity to initially decrease before increasing.

Benli et al. (2018) reported that the SCC mortar containing SF showed lower plastic viscosity than SCC with fly ash. However, there was no significant relationship found between the dosage of SF and yield stress. It should be noted that the viscosity of SCC mortar containing SF was higher than that of ordinary mortar as increasing the rotational speed of the viscometer. In another investigation, Faraj et al. (2021) studied the influence of SF on the rheological properties and workability of SCC. Incorporating 10% SF into SCC mixtures was found to reduce flow time in fresh tests, decrease plastic viscosity, and increase shear stress. Similar to other cementitious materials, the effects of SF on rheological parameters of SCC depend on various factors, including surface activity, particle size distribution, cement type and water reducing agent type.

4.4 Metakaolin (MK)

Metakaolin (MK) is anhydrous aluminium silicate ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) formed by dehydrating kaolin ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$) at moderately high temperatures, ranging from 650 to 800°C (Sabir et al., 2001; Badogiannis et al., 2005). Due to attractive pozzolanic activity of MK, the most extensive application prospect for MK is in high-performance concrete. Numerous research results showed that in terms of the strength of cement mortar, the influence of adding MK can reach or even exceed the impact of adding SF. Figure 6 shows the effects of MK on rheological properties of SCC according to observations reported in literature.

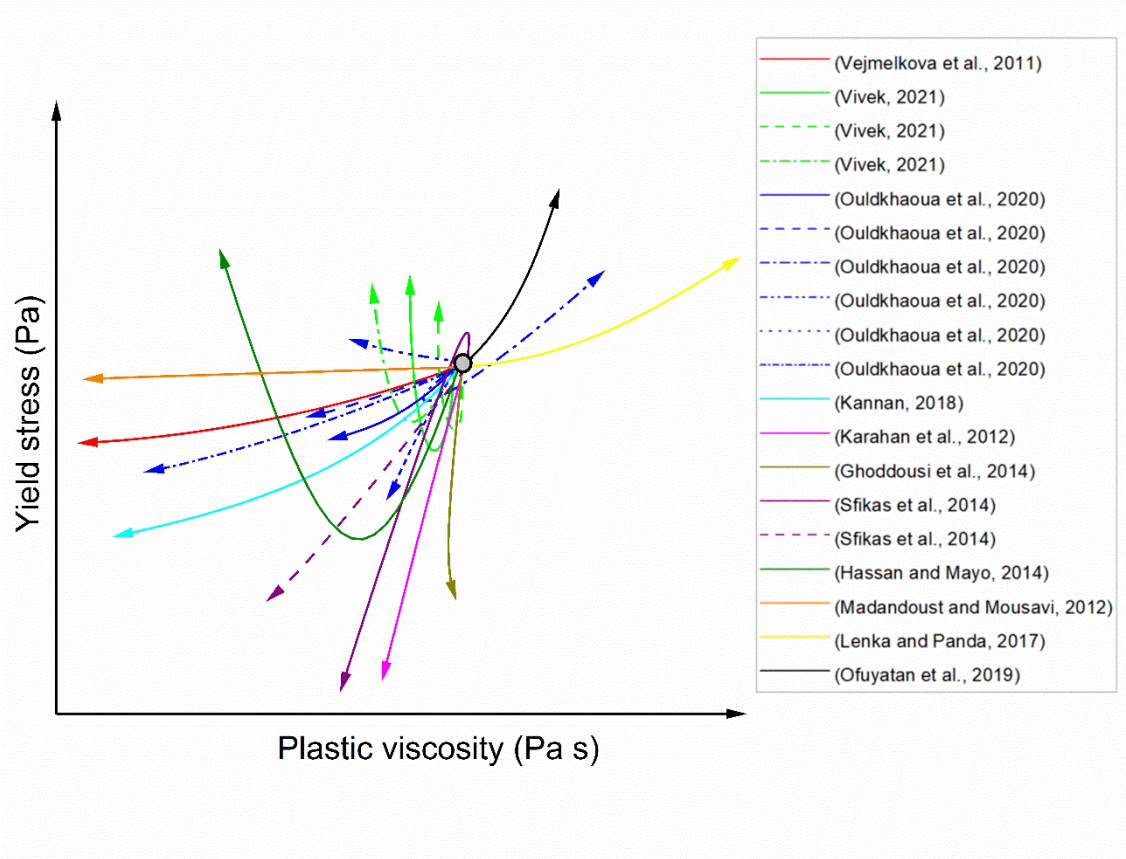


Figure 6. Effects of MK on rheological properties of SCC

Most researchers claim that MK improves the mechanical performance of SCC, whereas it has adverse effects on its rheological properties (Al-Oran et al., 2019; Vejmelková et al., 2011). Vivek (2021) evaluated the rheology properties of SCC, in which 5%-15% cement was substituted by MK. The results showed that adding 15% MK to the SCC mixture increased the flow time, indicating the increase of viscosity. This could be explained by the improvements of bond properties of MK due to its creamy nature, thereby preventing adverse effects such as segregation and bleeding. Ouldkaoua et al. (2020) reported that SCC mixtures with 15% MK exhibited remarkable decrease in the slump flow diameter. In addition, the inclusion of MK increased the flow time and viscosity by up to 15%. It was noted that more water and superplasticizer were required to achieve adequate self-compacting characteristics because of the high specific surface area of MK (Melo and Carneiro, 2010). Similar observations were reported by Kannan (2018) and Karahan et al. (2012), where the MK addition in SCC reduced slump flow diameter value and increased V-funnel time significantly. Ghoddousi et al. (2014) explored how particle packing

density affects SCC's rheology with minerals, finding MK additions increase SCC's yield stress and plastic viscosity.

Similar findings were reported in the study of Sfikas et al. (2014). It was shown that substituting cement or limestone with MK in SCC reduces slump spread and increases V-funnel flow time, indicating a higher viscosity and altered rheological properties. Hassan and Mayo (2014) demonstrated that the inclusion of MK increased plastic viscosity of SCC, thereby reducing the workability of mixtures. However, the passing ability, which is the difference between the slump flow and J-ring flow diameter, increased as the replacement of MK was increased. This could be explained by the fact that increasing MK replacement led to improved suspension capacity of aggregates. In the study of Madandoust and Mousavi (2012), slump spread values were controlled within the range of 660-715mm whereas the V-funnel time increased with the addition of MK. In summary, MK affects rheological properties of SCC by increasing viscosity, yield stress, leading to reduced workability as indicated by longer flow times and decreased spread diameters. The addition of MK requires more water and superplasticizer to maintain the self-compacting characteristics, due to MK's high specific surface area and its impact on the suspension capacity of aggregates.

4.5 Limestone powder (LP)

Limestone powder (LP) is the powdery material with a certain purity of limestone as a raw material, which is ground to a specified fineness. LP is an economical mineral additive compared to cement due to its wide-spread availability and simple processing technology (Wang et al., 2018). LP's role in cement-based materials stems from its physical filling and chemical activity effects. While its low activity typically designates it as an inert filler, LP also serves as a nucleation agent, accelerating and engaging in the cement hydration process. Limestone particles can provide nucleation points for hydration products by absorbing Ca^{2+} released during hydration process of C_3S and reducing the concentration and orientation of $\text{Ca}(\text{OH})_2$ crystals at the interface, thereby increasing the content of C-S-H at the interface (Péra et al., 1999). Figure 7 shows the effects of LP on SCC rheological properties based on observations presented in existing literature.

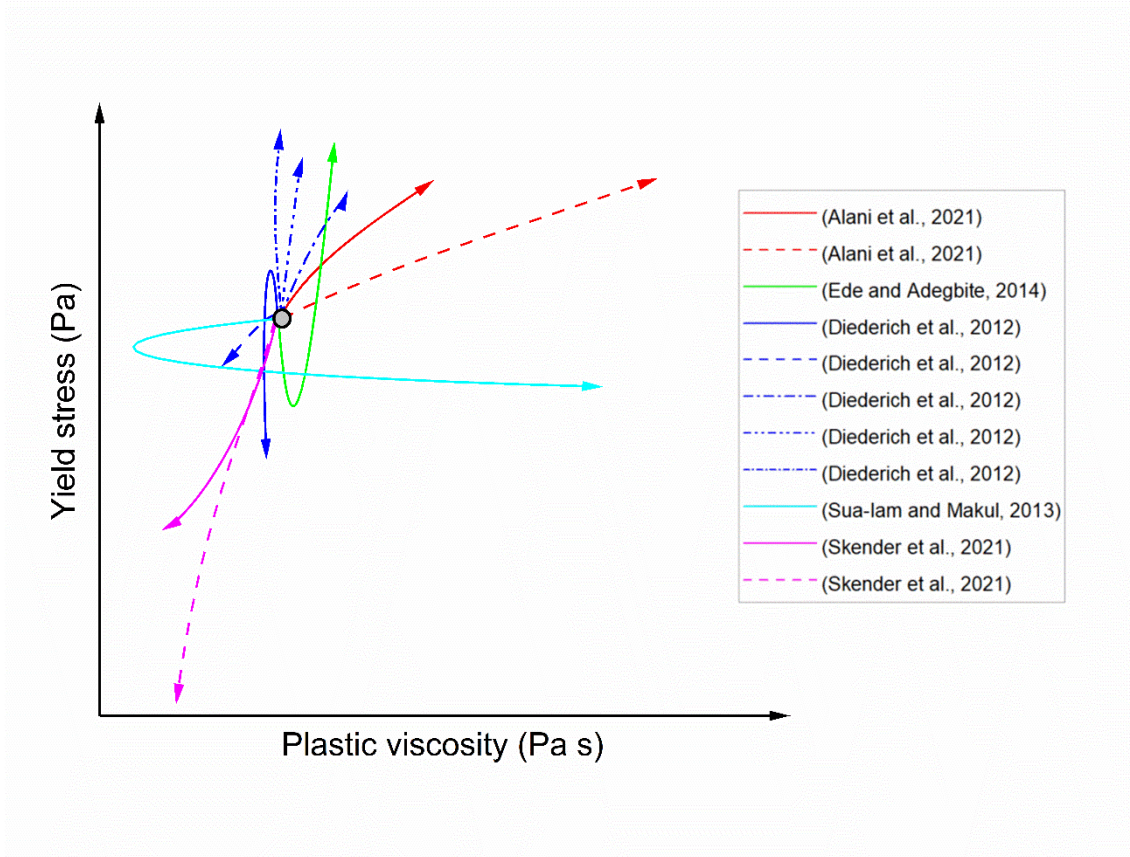


Figure 7. Effects of LP on rheological properties of SCC

Many researchers demonstrated that the addition of LP could reduce bleeding and segregation of cement-based material mixtures and reduce the flow resistance (Vikan and Justnes, 2007; Petit and Wirquin, 2010). For example, in the study of Uysal and Yilmaz (2011), SCC mixes containing LP provided more slump flow spread and lower plastic viscosity. Indeed, the influence of LP on the rheological properties of SCC is closely related to its fineness, characterized by the specific surface area and the proportion of particles under $5\mu\text{m}$. Enhanced fineness correlates with increased specific surface area and a higher percentage of fine particles. Consequently, stronger Van der Waals forces prevail between individual atoms in agglomerated particles. Hence, finer LP particles exhibit a more pronounced effect in reducing mortar viscosity (Diederich et al., 2012). These findings underscore the importance of considering LP in discussions of SCC rheological properties, as it plays a crucial role in improving workability and flow behaviour.

However, some studies have revealed contrasting effects of LP. The study by Yahia et al. (2005) showed that the viscosity of SCC was influenced significantly by the w/cm and the limestone content. And introducing LP within particular ranges can not influence the flowability of SCC for the given w/cm. However, increasing the amount of LP beyond these ranges increased the rheological properties. Li et al. (2015) proposed that adding a small amount of nano LP would lead to lower flowability of SCC. In a study conducted by Skender et al. (2021), the slump flow diameter decrease was observed in cases of sand and cement substituted by LP, whereas the slump flow time and V-funnel flow time increased. Alani et al. (2021) found that incorporating Burnt Lime Powder (BLP) into SCC reduces slump flow spread and prolongs V-funnel time, signifying an increase in mix viscosity. Therefore, the addition of LP to SCC enhances workability and flow behaviour, primarily due to LP's filling effects and its role as a nucleation agent in cement hydration, which reduces bleeding, segregation, and flow resistance while improving flow spread and reducing plastic viscosity.

5. Concluding remarks

SCC relies on increased cement and admixture levels to attain desired rheological properties, making the study of its rheology essential for superior performance, with mineral additions playing a key role in producing sustainable construction materials. This review elucidates the evaluation models and impacts of mineral additions on SCC's rheological behaviour, offering a clear roadmap for researchers and engineers to tailor SCC mixtures with mineral additions for achieving optimal fresh state characteristics. As the most intuitive variable affecting the fluidity of concrete, the influence of water to cementitious materials ratio has also been discussed.

Specifically, due to its the spherical and smooth particles, fly ash enhances the flowability of SCC by facilitating a ball-bearing effect, reducing superplasticizer requirements. Its impact varies with the type (Class F vs. Class C), mineral composition, replacement ratio, and calcium content. GGBS improves SCC's rheological behaviour through its filling properties and by slowing chemical reactions, attributed to its larger particle size than cement, reducing the surface area and internal friction. SF particles, due to their high activity, expedite the hydration process, which elevates both yield stress and plastic viscosity in SCC mixes by forming hydration products that

hinder the movement of particles by enveloping their surfaces. The influence of SF on SCC's rheological properties varies based on factors such as surface activity, particle size distribution, cement type, and the type of water-reducing agents used. Incorporating MK into SCC mixes increases plastic viscosity and yield stress, consequently reducing workability. This effect necessitates an increased demand for superplasticizers and water to preserve SCC's self-compacting qualities, primarily due to MK's extensive specific surface area and its significant influence on the suspension behaviour of aggregates. LP enhances SCC's rheological behaviour through its filling effect and as a nucleation agent in cement hydration, effectively minimizing bleeding, segregation, and flow resistance, and thereby increasing slump flow spread and decreasing plastic viscosity.

The variations in the effects observed across different studies underscore the complexity of SCC's rheological behaviour and the necessity for a tailored approach in the design and optimization of SCC mixtures. The findings of this review suggest that future research should focus on developing standardized practices for the rheological assessment of SCC and further exploring the synergistic effects of combined mineral additives to optimize both environmental sustainability and material performance.

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Appendix

Table A1. Commonly used rheology models

Model	Formula	Main application
Ellis model	$\frac{\eta}{\eta_0} = 1 + \left(\frac{\tau}{\tau_{1/2}}\right)^{\alpha-1}$	Shear stress dependent viscosity
Carreau model	$\frac{\eta_0 - \eta_\infty}{\eta - \eta_\infty} = [1 + (\lambda\dot{\gamma})^2]^{(n-1)/2}$	Non-Newtonian fluids at low shear rates
Bingham model	$\tau = \tau_0 + \eta_p \dot{\gamma}$	Bingham plastic fluids
Herschel-Bulkley model	$\tau = \tau_0 + K\dot{\gamma}^n$	Non-linear Bingham fluids
Modified Bingham model	$\tau = \tau_0 + \eta_p \dot{\gamma} + c\dot{\gamma}^2$	Non-linear Bingham fluids
Casson model	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_p} \sqrt{\dot{\gamma}}$	Biomedical fluids
Sisko model	$\eta = \eta_\infty + \eta_p \dot{\gamma}^{n-1}$	Calculate ultimate shear viscosity
Williamson model	$\eta = \frac{\eta_0}{1 + (K\dot{\gamma})^n}$	Viscosity generated at low shear rates

Table A2. Effect of fly ash on rheological properties of SCC

Reference	w/cm ratio	Replacement ratio %	Evaluation of Rheology	Rheological Properties
(Matos et al., 2019)	0.38	40, 50, and 60	Slump flow, V-funnel and L-box tests	Substituting cement with fly ash enhances the flowability of SCC, leading to decreased requirements for superplasticizer content.
(Yang et al., 2021)	0.33, 0.36 and 0.4	20 and 30	The rheological properties were calculated using Equations based on mini-slump test results.	In the original model, the paste plastic viscosity threshold slightly increases with 30% compared to 20% fly ash, whereas, in the modified model, it significantly decreases for 30% relative to 20% fly ash.
(Mohammed et al., 2022)	0.25	10, 20, 30, 40, 50 and 60	V-funnel and slump flow tests	The spherical particles of Fly Ash significantly contributed to faster speeds and shorter flow times.
(Concha and Baccay, 2020)	-	15 and 25	V-funnel, slump flow, L-box, U-box, and screen stability tests.	The ball-bearing effect of spherical fly ash particles enhances the fluidity of SCC by improving lubrication and reducing cohesion among aggregated particles.
(Ponikiewski and Gołaszewski, 2014)	0.41 and 0.38	10, 20 and 30	V-funnel, slump flow, L-box tests	Self-compacting properties and overall workability of the mix decline with the addition of more ash, while also accelerating the rate at which workability is lost over time.
(Saleh Ahari et al., 2015)	0.44, 0.50, 0.56	18 and 36	Coaxial cylinder concrete rheometer (ConTec 4SCC). The protocol gradually increased the impeller speed to 0.7 rps over 36 seconds and then decreased it stepwise to	The partial replacement of PC by fly ash have increased plastic viscosity and yield stress of control mixes. Higher plastic viscosity values in type C fly ash mixtures compared to class F fly ash are attributed to the grain shape, thus improving workability and decreasing plastic viscosity.

measure torque,
generating
torque-rotational
velocity data that
linearly
corresponded to
a Bingham fluid
model.

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Table A3. Effect of GGBS on rheological properties of SCC

Reference	w/cm ratio	Replacement ratio	Evaluation of Rheology	Rheological Properties
(Al-Oran et al., 2019)	0.38	15, 20, 25 and 30	Slump flow, V-funnel and L-box tests.	Increasing GGBS up to 25% improves viscosity and reduces flow time due to its larger particle size and lower yield stress compared to cement, facilitating quicker initiation of flow and enhancing overall workability.
(Boukendakdji et al., 2012)	0.4	10, 15, 20 and 25	Slump flow, V-funnel and J-ring tests.	Optimal flowability and reduced T50 flow time are achieved at 15% GGBS content, beyond which both segregation and viscosity increase, compromising workability.
(Zhao et al., 2015)	0.35	20, 30 and 40	Slump flow, L-box tests and GTM screen stability test.	The incorporation of GGBS enhances mix flowability by increasing paste volume and reducing friction between aggregates and cementitious materials, owing to GGBS's spherical nature.
(Tadi and Rao, 2022)	0.32	10, 20, 30, 40, 50 and 60	Slump flow, V-funnel and L-Box tests.	Increasing slag content decreases plastic viscosity and improves flowability, as evidenced by reduced T50cm slump test times, with mixtures containing 40%, 50%, and 60% GGBS showing notably better results.
(Vejmelková et al., 2011)	0.26	56	Slump flow, J-ring test. Rotary rheometer Con Tec Viscometer with coaxial cylinders was applied, with yield stress and plastic viscosity determined from the rotational moment measurements	SCC mix containing GGBS exhibited characteristics of Newtonian fluids, with zero yield stress and increased viscosity

			at speeds ranging from 0.4 to 0.08 rps, aligning with controlled rates, stresses, and a standard adjustment model.	
(Gesoğlu et al., 2012)	0.32	Replacement of the Coarse aggregate at level of 20, 40, 60, 80, and 100%	Slump flow, V-funnel, and L-box tests.	SCC mixtures with GGBS demonstrated improved workability, evidenced by reduced times in slump and V-funnel tests and lower viscosity.

Table A4. Effect of SF on rheological properties of SCC

Reference	w/cm ratio	Replacement ratio	Evaluation of Rheology	Rheological Properties
(Benaicha et al., 2019)	0.37	10, 15, 20, 25, 30, 35 and 40	Slump flow and V-Funnel test; concrete rheometer R/S.	The addition of SF in SCC increased yield stress, plastic viscosity, and V-Funnel flow time, while reducing slump flow diameter, indicating a decrease in flowability.
(Ling et al., 2018))	0.33	Replacement of fly ash at level of 4, 9, 13, and 18%	R/S-SST soft-solid rheometer, measuring shear stress from 6 to 200 Pa and shear rate up to 1000 rpm, with data analysed in real-time via Rheo V2.8 software, employing a controlled rate and stress testing method.	Yield stress and plastic viscosity rise as the content of SF exceeds a 2% replacement ratio, negatively impacting flowability.
(Mastali and Dalvand, 2016)	0.44	7 and 14	Slump flow and V-Funnel test	Elevating the SF replacement ratio from 7% to 14% heightened plastic viscosity and reduced the flowability of the mixes.
(Lu et al., 2015)	0.35	2, 4, 6, 8, 12 and 16	Slump flow test, J-ring test and; ConTec Viscometer, following Bingham model.	As the SF content increases, Bingham yield stress rises more sharply, while plastic viscosity initially decreases at lower SF levels and then progressively increases at higher concentrations.
(Benli et al., 2018)	0.44, 0.45, 0.47 and 0.50	5, 10, 15 and 20	Slump flow and V-Funnel tests; Brookfield DVE model viscometer across various	Flowability improved with higher SF content, leading to lower plastic viscosity in SCC mortar with SF compared to that with fly ash, though no significant correlation was observed between SF dosage and yield stress.

			speeds (1, 2.5, 5, 10, 20, 50, 60, and 100 rpm).	
(Faraj et al., 2021)	0.35	10	Slump flow, L-box and V-Funnel tests	Incorporating 10% SF into resulted in lower plastic viscosity and higher shear stress, enhancing flowability of SCC mixes.

679

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Table A5. Effect of MK on rheological properties of SCC

Reference	w/cm ratio	Replacement ratio	Evaluation of Rheology	Rheological Properties
(Vivek, 2021)	0.40	5,10 and 15	Slump flow, V-funnel, L-box, and U-box tests	Adding MK extends the T500 and V-funnel test durations, indicating higher mix viscosity and mitigating issues such as segregation and bleeding.
(Ouldkhao-ua et al., 2020)	0.40	5,10 and 15	Slump flow, V-funnel and L-box tests	MK addition increased flow time and viscosity in V-funnel tests, reducing the flowability as seen in the slump flow diameter.
(Kannan, 2018)	0.50	5,10,15,20, 25 and 30	Slump flow, V-funnel, and L-box tests	Increasing the replacement of MK, the slump flow gradually decreases while the time increases in the V-funnel.
(Melo and Carneiro, 2010)	0.50 and 0.70	5 and 35	Slump flow, V-funnel test for SCC; Mini slump and Marsh cone tests for the paste.	As the fineness and content of MK, the higher demand of superplasticizer.
(Ghoddousi et al., 2014)	0.45	20	Coaxial rheometer	Increased yield stress and plastic viscosity with the addition of MK.
(Sfikas et al., 2014)	0.60	Replacement of cement at level of 6.9, 10.6, 14, and 20%; Replacement of LP at level of 13.7, 21.1, 28, and 40%	Slump-flow, V-Funnel, L-Box tests	The addition of MK, whether replacing cement or LP, affected workability, requiring a higher superplasticizer content. This increased V-Funnel flow time and caused minor blocking issues with higher MK content, with no bleeding or segregation observed.

(Hassan and Mayo, 2014)	0.40	5,10,15, 20 and 25	Slump flow, V-funnel, L-box, J-ring tests	The addition of MK up to 20% leads to increased viscosity and reduced flowability in SCC. As MK content increases, there's a noticeable increase in the demand for superplasticizer to maintain workability.
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Table A6. Effect of LP on rheological properties of SCC

Reference	w/p ratio	Replacement ratio %	Evaluation of Rheology	Rheological Properties
(Uysal and Yilmaz, 2011)	0.33	10, 20 and 30	Slump flow and L-box tests	The addition of LP improved workability, with higher slump flow values and reduced T500.
(Yahia et al., 2005)	0.35, 0.40 and 0.45	20, 30 and 40	Slump flow and V-funnel tests	Within certain limits, LP addition did not alter the fluidity of a mixture with a fixed W/C and HRWR dosage, but beyond a critical dosage, it significantly increased viscosity.
(Li et al., 2015)	0.16 to 0.22	Nano LP: 1, 2, 3 and 4	Flowability test (ASTM C 1437)	Increasing the content of nano-limestone powder led to lower flowability due to its fine particle sizes, which have higher surface areas that absorb water
(Skender et al., 2021)	0.4	Replacement of cement at level of 0, 5, 10, 15, 20 and 25%; Replacement of sand at level of 0, 5, 10, 15, 20 and 25%	Slump flow, V-funnel, and L-box tests	Adding LP up to 20% as partial replacement for sand and cement improved SCC properties at the fresh state. The addition of LP lengthens V-funnel flow times, more noticeably in mixes with sand substituted by LP
(Alani et al., 2021)	0.35	16, 23 and 29	Slump flow, V-funnel, L-box tests	Incorporating LP into SCC resulted in reduced slump flow spread and increased V-funnel time, indicating a decrease in flowability and an increase in the viscosity.