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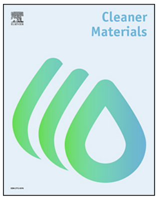

Enhancement of self-compactability of fresh self-compacting concrete: A review

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ABSTRACT

The main characteristics of self-compating concrete (SCC) are its ability to flow into every corner of the formwork and even in congested reinforcement arrangements under its weight and without segregation. This paper reviews the recent progress in the enhancement of the self-compatibility of SCC in a fresh state. The main approaches to achieve this aim was observed to be the employment of air entrainment, and the utilization of various supplementary cementitious materials (SCMs) such as fly ash, silica fume, ground-granulated blast-furnace slag and rice husk ash. Entraining suitable air bubbles had the potential to enhance the self-compatibility of fresh concrete while also being very beneficial in reducing the cement content of the SCC. The workability and rheological properties of fresh SCC was observed to be enhanced by the utilization of SCMs. SCMs also possess the advantages of pozzolanic and filler effects which are not in play for entrained air. For future work, researchers can explore statistical and intelligent multi-objective optimisation techniques for getting the best amount of SCMs that will maximize the fresh properties whilst considering its deleterious effect on the hardened properties.

Contents

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Introduction

To realize durable concrete structures, sufficient compaction is required (Ofuyatan et al., 1036). One solution for the achievement of durable concrete structures independent of the quality of construction work is the employment of self-compacting concrete (SCC) (Okamura and Ouchi, 1998). SCC, which is a type of high-performance concrete, is concrete that can be compacted into every corner of a formwork, purely through its weight and without the need for vibrating compaction (Gupta et al., 2021; Faraj et al., 2020).

It was initially developed by Okamura, in 1988 to improve the durability of concrete structures (Okamura and Ouchi, 2003) and opened up new advancements for the use of this product all over the world. This type of concrete compromises the best solutions for high workability, passing ability through confined and densely reinforced spaces, economical and environmentally friendly development of the concrete industry (Mujedu et al., 2020; Revilla-Cuesta et al., 2020). Hence economically and technically, the SCC offers very attractive benefits over normally vibrated concrete (Singh et al., 2020). Geiker (2008) discussed that the employment of SCC potentially improves the working environment during construction, the homogeneity, productivity, and quality of the concrete. Also, SCC offers larger architectural freedom in structural design (Geiker, 2008).

SCC has been used primarily in structural elements with confined reinforcement or complicated formwork since its development in 1988. SCC, on the other hand, has not been commonly used due to its high unit cost. To achieve SCC with adequate self-compatibility, a large amount of cement is needed, which reduces SCC's sustainability. Cement content in SCC mix proportions is roughly twice that of standard concrete, which is one of the main factors in achieving self-compatibility in traditional SCC. Aggregate content is also lower than normal concrete (Okamura and Ouchi, 2003). Various studies have been conducted in the last two decades to reduce the unit cost of traditional SCC, thus reducing its environmental effect and improving SCC self-compatibility.

Therefore, this review paper is aimed at presenting the recent research findings conducted by researchers on enhancing the self-compatibility of fresh SCC in the recent times. The overall goal was to synthesize the literature and discuss recent findings in the research area. Based on these, the review will then highlight key points of significant research progress and discuss future perspectives in the research area. Ultimately, this would lead to the proffering of some recommendations for enhancing the self-compatibility of fresh SCC.

Enhancement of self-compatibility of SCC

The main characteristics of SCC are its ability to flow into every corner of the formwork and even in congested reinforcement arrangements under its weight and without segregation. Hence, the key properties of fresh SCC are filling ability, passing ability, and segregation resistance (Ofuyatan et al., 2020). To achieve adequate self- compatibility; SCC requires suitable deformability and viscosity of the mortar and paste. Commonly, according to Ozawa et al. (1992), the self-compatibility of fresh concrete can be attained by three main approaches. These approaches include using a low water-powder ratio, limiting the aggregate content, and engaging a superplasticizer (Ozawa et al., 1992).

Currently, many studies aim to enhance the self-compatibility of SCC so that the amount of cement in SCC can be reduced for environmental sustainability purposes (Ighalo and Adeniyi, 2020). The main approaches to enhance the self-compatibility of SCC are the employment of air entrainment, partial cement replacement with supplementary cementitious materials (SCMs) such as fly ash, silica fume, ground-granulated blast-furnace slag and rice husk ash. These are explained in this section.

Enhancement of self-compatibility of SCC with entrained air

The primary advantage of entraining air for concrete is to increase the freezing and thawing resistance of concrete in a cold environment. The sufficient air content to resist the freezing and thawing effect depends on the severity of the cold condition which is recommended as in the range of 4.5–6.0% (JSCE, 1998). Besides the minor advantage of entrained air for normal concrete has been reported which is workability improvement. The slump of fresh concrete increased approximately 10 to 50 mm by increasing entrained air by approximately 5% (Okumara et al., 1993). And also there are a few research findings related to flowability enhancement of SCC by entrained air.

In concrete, there are two types of air: entrained air and entrapped air (Fig. 1). Entrained air is the air that has been intentionally introduced into a structure using an air-entraining cement or an air-entraining agent (AE). During the mixing, consolidating, or placing of concrete, entrapped air is formed by mistake. Both non-air-entrained concrete and air-entrained concrete will have entrapped air (Attachaiyawuth et al., 2016).

The use of air entrainment to increase the freeze–thaw resistance of concrete subjected to extreme weather conditions has been discovered to be beneficial. Concrete serving in cold-weather countries has been no exception to entraining air to concrete (Chatterji and Gudmundsson, 1977; Lianxiang and Kevin, 2005). Air entrainment has also been shown to minimize bleeding and improve concrete's plasticity. While air entrainment improves the toughness of concrete in the hardened stage, the higher the air content, the lower the concrete's strength. The compressive strength of concrete was decreased by around 5% for every percent of air content in the mix (Kosmatka et al., 2003). Air-entrainment has also been found to be an effective

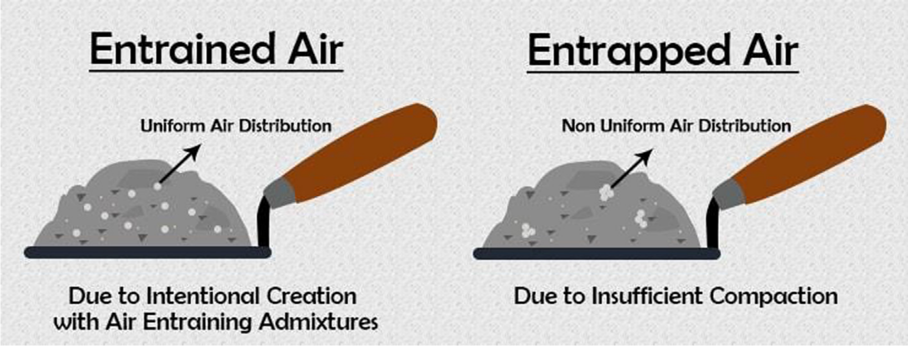

Fig. 1. Entrained and entrapped air in SCC (Patel, 2019).

way to reduce the usage of cement in SCC (Attachaiyawuth and Ouchi, 2014; Attachaiyawuth et al., 2015; Sovannsathya et al., 2016). Based on the observations of Attachaiyawuth and Ouchi (2014), the flowability of self-compacting mortar (SCM) was effectively improved by adding a specific type of air-entraining agent. Since entrained air bubbles increase the total volume of the SCC, the volume of all other components, including cement, can be reduced to an equivalent volume. Also, the fine aggregate content of the mortar (s/m) can be increased if air bubbles with suitable characteristics can be entrained; this can further reduce cement usage. Even though increasing the air content can significantly reduce the compressive strength of SCC, suitably chosen air content allows adequate compressive strength to be obtained (Attachaiyawuth and Ouchi, 2014).

Air entrainment is known to offer the potential for reducing the cement content in SCC. Since entrained air bubbles replace a certain portion of the SCC volume, the total volume of all other components, including cement, can be reduced by an equivalent amount. The effects of entrained air bubbles on the self-compatibility of fresh concrete have also been studied (Attachaiyawuth et al., 2016; Attachaiyawuth and Ouchi, 2014; Attachaiyawuth et al., 2015; Rath et al., 2017) to allow a further increase in the aggregate content and therefore reducing the cement content in SCC. In their recent work, Sovannsathya et al. (2016) investigated how entraining air bubbles can enhance the self-compatibility of fresh concrete, as measured in terms of concrete fill height. Fresh concretes with various dosages of the air-entraining agent (AEA) and mixing methods were tested. The investigation revealed that the fill height of SCC tends to increase as the total surface area of all entrained air bubbles rises (Sovannsathya et al., 2016).

Attachaiyawuth et al. (2015) developed an SCC with lower cement concrete by using entrainment of air so that the cost may be similar or lesser than conventional concrete. According to their findings, the enhancement of self-compatibility by entrained air is a ball-bearing effect (Attachaiyawuth et al., 2015). Due to the fine air bubbles (less than450 μm), the efficiency of entrained air bubbles in reducing friction between mortar and coarse aggregate is found to be primarily dependent on the air size distribution acting as compressible bearings and deformation of large air bubbles (>450 μm) (Puthipad et al., 2018). Furthermore, the stability of entrained air was critical because air volume had a direct impact on friction reduction. As the proportion of fine entrained air bubbles increases, friction between mortar and coarse aggregate tends to decrease. This is due to the relatively free shear motion between the mortar and coarse aggregate, which is aided by fine air bubbles acting as compressible bearings. The friction between mortar and coarse aggregate is found to be increased by large air bubbles. This may be because large bubbles can distort a lot when compressed between aggregate particles. As a result, the distance between aggregate particles that serve as constraints to the mortar matrix is decreased (Puthipad et al., 2018). In conclusion, they found that a higher proportion of fine entrained air bubbles reduces friction between mortar and coarse aggregate, whereas a higher entrained air content increases the total volume of SCC. This indicates that entraining enough air bubbles has the potential to improve fresh concrete's self-compatibility while also lowering the cement content of SCC.

Enhancement of self-compatibility of SCC with SCMs

According to ASTM C 125, an admixture is defined as a material, other than basic raw materials, used in mortar and concrete to improve its certain properties and added immediately before or during mixing (Fig. 2) (Ajay et al., 2012). It is also to reduce cement utilization because of its deleterious environmental effects (Ighalo and Adeniyi, 2020). The admixtures are divided into two categories, namely mineral admixtures and chemical admixtures. Mineral admixtures or supplementary cementitious materials (SCMs) are classified as cementitious, highly pozzolanic, normally pozzolanic, cementitious and pozzolanic, and weak pozzolanic (Ramanathan et al., 2020). Pozzolans are siliceous and aluminum materials having few or no cementitious properties by themselves as well as finely grounded; they react with calcium hydroxide in the presence of moisture at ordinary temperature to form compounds of cementitious properties (ASTM C595). Chemical admixtures ensure the quality of concrete during mixing, transporting, placing, and curing (Cavusoglu et al., 2021).

Because of its high fluidity and segregation-resisting strength, SCC may integrate a variety of minerals and chemical admixtures, ensuring that the self-consolidating concrete's homogeneity and uniformity are unaffected by workability or the shape and bar arrangement of structural elements (Okumara et al., 1993). Because of the high flowability requirement of SCC, mineral admixtures such as fly ash, blast furnace slag, silica fume, and rice husk ash are used in its production. As a result, the mineral admixtures and chemical admixtures used in the SCC to improve its fresh properties have been explored in this paper.

Fly ash (FA)

Fly ash (FA) is a finely divided residue produced by the combustion of powdered coal that is carried by fuel gases and collected using an electrostatic precipitator (Senapati, 2011). Pulverized FA is another name for it. It is abundant because it is a by-product of coal combustion in electric power plants, and there is a need to increase its reuse (Sanna et al., 2012). FA is divided into two classes by ASTM: Class F and Class C. Class C FA possessed both cementitious and pozzolanic characteristics, while class F FA possessed only pozzolanic characteristics. FA is a cost-effective and environmentally safe concrete material alternative. The addition of FA to concrete enhanced its fresh and

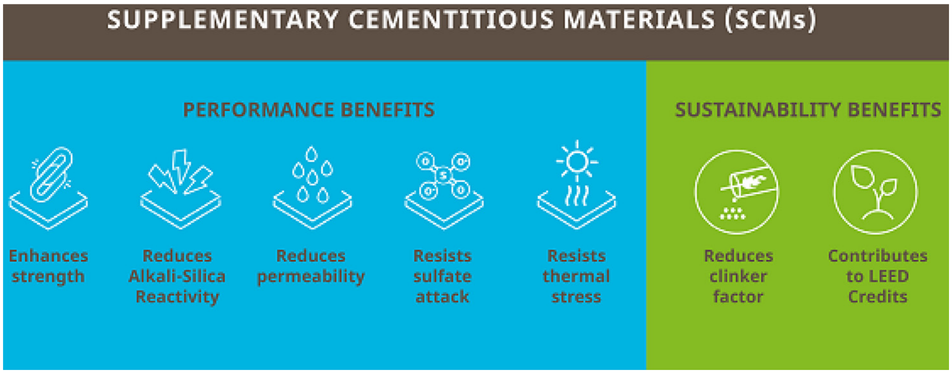

Fig. 2. Some benefits of using SCMs in concrete (Diedrick, 2019).

Table 1
Rheological properties of SCC incorporating FA.

Reference	Replacement ratio of FA (%)	Mineral admixture other than FA	Chemical admixtures	Key findings
Puthipad et al. (2018)	FA (107, 267, 267) kg	–	Air entraining agent (0.047 – 3.162)	FA can potentially enhance the self-compatibility of fresh concrete by enhancing the flowability of the concrete and encouraging the pozzolanic reaction.it reduces the friction between mortar and coarse aggregate.
Ryan and O'Connor (2016)	PFA (111 and 131 kg)	GGBS (252 and 298 kg)	Pozzolith 320 N (2.3& 2.7 kg) and Glenium 51 (1.2–3.0 L)	Replacement of cement by PFA increased the viscosity of SCC.
Jalal et al. (2015)	FA 20%, 40%, 60%	SF (40%, 50%)	SP (2.5 and 3.12) and VMA (2,2.5)	Workability and rheological properties of fresh SCC improved with FA due to its ball bearing-shaped particles, whereas TiO_2 nanoparticle reduced flowability due to high viscosity
Gholhaki et al. (2018)	FA 10% and 20%	SF, MK and RHA 10% and 20%	Carboxylate-based HRWR (2.11–7.48 kg/m^3)	All pozzolanic materials improved the self-compatibility of SCC in term of flowability and viscosity
Bani Ardalan et al. (2017)	Class F fly ash 0%, 10%, 20%, 30%, 40%, 50%	Volcanic pumice, slag 0–50% @ 10% and SF (5 and 10%)	Polycarboxylate ether-based SP	PP had a better slump for retention than other mixes. PP required high dosages of FA. Binary mixtures satisfied the requirements for U-box and V-funnel test while ternary mixtures gave satisfactory results in all test
Xin *et. al* (Wang et al., 2014)	40%	15% metakaolin, 1% nanolimestone (nanoLS)	HRWR and AEA	SCC mix achieved a slump flow of 692 mm. SCC mixture with 40% FA replacement displayed good workability. mixture with 40% FA and 15% MK replacement displayed good flowability and shape-holding ability.
Kurt et al., (2015)	20%, 30% and 40%	–	PC-based hyper-plasticizer 11 kg/m^3 and AEA 1 kg/m^3	FA decreased loss of workability. V-funnel time increased with an increase in lightweight aggregates
Güneyisi et al. (2015)	0%, 25%, 50%, 75%	Nano-silica 0%, 2%, 4% and 6%	PCE type SP. 1.71–21.38 kg/m^3	NS increased slump flow and V-funnel flow times, L-box flow time, shear thickening and Torque value, but FA decreased it.

hardened properties. It undergoes pozzolanic and hydration reactions in the same way as cement does, which improves workability and resistance to thermal cracking, prevents alkali-aggregate reactions and improves strength and durability (Dhir et al., 1988; Tangtermsirikul, 2003). The effects of FA on the fresh and hardened properties of SCC have been extensively studied. Table 1 summarizes the various research work done by different researchers on FA in SCC.

Wattanalamlerd and Ouchi (2005) investigated the influence of FA on the flowability of SCC in terms of mortar flow area and funnel speed. They concluded that FA acts as a form of lubricant due to its spherical shape. Moreover, owing to the spherical shape of its particles, FA also enhances the flowability of the fresh concrete. Consequently, FA is a widely used ingredient in SCC due to its low cost and good performance as a cement replacement (Güneyisi et al., 2013). It can also prevent the formation of agglomerate cement particle lumps. This advocates that the potential of FA to enhance the self-compatibility of fresh concrete is high. According to Jalal et al. (2015), rheological properties of fresh SCC were improved with FA due to its ball-bearing-shaped particles. Whereas Slump flow, V-funnel flow times T20, and T40 L-box flow times, torque value, and shear thickening is known to decrease by FA (Güneyisi et al., 2015). Furthermore, Naik et al. (2012) reported on research in which cement was replaced with FA in SCC. They suggested that the spherical particles of FA have a ball-bearing effect that reduces friction between paste and aggregate particles. This can considerably reduce the dosage of superplasticizer and cement required in SCC. Therefore, according to these findings, with a high volume of FA, a high-strength yet cost-effective SCC can be developed (Naik et al., 2012).

In the recent studies of Puthipad et al., 2018), FA was found to reduce the friction between mortar and coarse aggregate. This may be attributable to the spherical shape of FA particles, which contributes to the ball-bearing effect and reduction in the contact area between other solid particles. The addition of FA is found to enable the use of a higher fine aggregate content in SCC. So they concluded that FA can potentially enhance the self-compatibility of fresh concrete by enhancing the flowability of the concrete and encouraging the pozzolanic reaction, FA is useful as a replacement for cement in SCC. The ball-bearing effect of FA on the self-compatibility of fresh concrete has also been clarified, allowing a higher fine aggregate content to be used in SCC. However, FA was found to increase the amount of large entrained air bubbles (Puthipad et al., 2016). Furthermore, it was noted that the spherical shape of FA causes the unification and escape of entrained air bubbles. This is known to reduce the stability of entrained air content in SCC (Puthipad et al., 2016; Puthipad et al., 2017).

Mahure et al. (2014) had studied the fresh and hardened properties of SCC using FA as a partial replacement of cement in different percentages. The fresh properties have been determined by figuring the slump value, V-funnel value, and L-box value. It is observed that the fresh properties of concrete show an acceptable value of up to 30% replacement of FA. Loss of workability decreased with the increase in FA content. V-funnel time of SCC increased with the increase in lightweight aggregates (KURT et al., 2015). Replacement of cement by pulverized fuel ash and GGBS increased the viscosity of SCC (Ryan and O'Connor, 2016). SCC mixtures containing pumice powder had better slump flow retention in comparison with other mixes. SCC with PP had reasonable flowability, passing ability, and segregation resistance. Pumice powder increased the SP dosages. Pumice powder required high dosages of SP in comparison with that of FA. Binary mixtures satisfied the limit of the U-box and V-funnel test, while most of them did not satisfy EFNARC recommendation for the J-ring test while ternary mixtures gave satisfactory results in all tests (Bani Ardalan et al., 2017). Self-compating mortar mix with FA had better fresh properties than SF and control mix. The increase in Class C, FA decreased relative slump values because FA reduced friction between particles by dispersing cement particles (Benli et al., 2017).

Silica fume (SF)

The ferrosilicon industry produces silica fume (SF), also known as condensed silica fume, as a by-product of the manufacture of elementary silicon or silicon-containing alloys in electric arc furnaces. It is a highly reactive pozzolans, also known as micro silica, that's derived from silicon steel processing. (Ofuyatan et al., 2021). The American Society for Testing and Materials (ASTM) has designated SF as a pozzolanic material and established a standard for its use in cementitious mixtures (ASTM C1240). Because of its high amorphous silica content, SF has an unrestricted potential for use in traditional cement concrete and geo-polymer concrete (Amran et al., 2020). As a result, some researchers have used SF in SCC. Table 2 summarizes the various research work done by different researchers on SF in SCC.

SF nanoparticles reduced flowability but increased stability, according to Jalal et al. (2015). Slump flow diameter increased as FA increased, but V-funnel flow time decreased. The use of nanoparticles in conjunction with SF resulted in less bleeding and segregation. Workability was unaffected by nano-silica up to 2% (Jalal et al., 2015). Because of the reduced fluidity of concrete, carbon fiber had an impact on segregation resistance, filling, and passing capacity. Since carbon fiber made SCC more viscous, which slowed the flow of concrete, T50 slump flow time increased with carbon fiber material (Yakhlaf et al., 2013). FA in a self-compating mortar mix outperformed SF and the control mix in terms of fresh properties. Because of the high surface area and finer particle size, the workability of SCC with SF was reduced. The viscosity of SF was also reduced, while the viscosity of FA was increased (Benli et al., 2017).

Ground-granulated blast-furnace slag (GGBFS)

Ground-granulated blast-furnace slag (GGBFS) is a non-metallic product consisting of silicate and aluminates of calcium and other bases (SONG and SARASWATHY, 2006). GGBFS is obtained from molten iron slag produced from a blast furnace in water or steam, to produce a glassy and granular product that is dried and ground into a fine powder. GGBFS in combination with OPC or other pozzolanic material gives durable concrete (Zhao et al., 2015). It improved workability, durability to thermal cracking, resistance to sulfate and chloride attack, lowered heat of hydration, water demand, and permeability, and increased long-term strength. GGBFS can be used in ready-mixed concrete, precast concrete, mortar, grout, etc. The various investigations done by the different researchers to study the fresh properties of SCC with GGBFS are recorded in Table 3.

In the research work of Beycioğlu and Yılmaz Aruntaş (2014) GBFS improved flowability and passing ability, but reduced viscosity. Flow time decreased with an increase in Micronized calcite content (Beycioğlu and Yılmaz Aruntaş, 2014). Similarly, Güneyisi et al. (2010) studied the effect of GGBFS on rheological properties of SCC and concluded that lump flow diameter was 670–730 mm, T50 value was less than 7 s, V-funnel flow time was 6.3–37 s, and H2/H1 ratio was 0.704–0.976 (Güneyisi et al., 2010). And also Ternary use of GGBFS and MP decreased viscosity. The binary and ternary blend of PC, MP, and GGBFS delayed setting time (Güneyisi et al., 2010). MK and GGBS increased SP dosages, while FA decreased SP dosages. All SCC mixes satisfied EFNARC requirements (Dadsetan and Bai, 2017).

Rice husk ash (RHA)

Rice husk ash (RHA), a highly pozzolanic agricultural waste, is widely used in rice-producing countries. RHA is made by burning rice husk in a regulated atmosphere (Zadeh et al., 2021). Owing to its toxic effects on land and nearby areas as a result of direct dumping, it has become a potential environmental danger. RHA, a very fine pozzolanic material, is the most flexible eco-friendly supplementary cementitious material for concrete when combined with cement. Reduced heat of hydration, improved strength, reduced permeability at higher dosages, increased chloride and sulfate resistance/mild acids, reduced materials

Table 2
Rheological properties of SCC incorporating SF.

Reference	Replacement ratio of SF in %	Mineral admixture other than SF	Chemical admixtures	Key findings
Jalal et al. (2015)	10	Silica nanoparticles (NS) 2, combination of (10 SF + 2 NS) and FAC 5, 10 , 15	PCE-based SP 2.5 and 3.12 kg/m^{3}and VMA 2 and 2.5 kg/m3	SF and NS decreased flow ability, but improved consistency, whereas FA had opposite behavior
Benli et al. (2017)	6, 9, 12 and 15	FA (10, 20 and 30) and combination FA (10%) + SF (6, 9, 12 and 15%) and FA (20%) + SF (6 and 9%)	Modified PC-based polymer type SP (8 kg/m^3)	All SCM mixes gave satisfactory results in terms of fresh properties. But the increase in SF content decreased viscosity
Granata (2015)	35.4 kg per m^3 SCC	Calcareous powder (CP) 100 kg/m^3 and pumice powder (PP) 20 and 38.5%	PCE-based SP HRWR 6488, 5913, 6914 and 5000 g/m^3 and VMA 3244, 3548, 3457 kg/m^3	SCC with PP had good flowability, passing ability, and segregation resistance
Yakhlaf et al. (2013)	10	Pitch-based carbon fiber (CF) was 0, 0.25, 0.5, 0.75, 1%	HRWR 1.5–8.0% and 1.0–7.0%	HRWR enhanced filling and passing ability, but reduced blocking index. CF increased filling ability and blocking index, but decreased stability index and fluidity

Table 3
Rheological properties of SCC with GGBFS.

References	Replacement ratio of GGBFS in %	Mineral admixture other than GGBFS	Chemical admixtures	Key findings
Beycioğlu and Yılmaz Aruntaş (2014)	20–60	Micronized calcite 5 and 10. Low lime FA 20–60	PC-based HRWR 6.5 kg/m^3	Low lime fly ash reduced water demand, viscosity, but enhanced passing and filling ability
Güneyisi et al. (2010)	20, 40 and 60	FA (20,40, and 60), SF and MK (5, 10, and 15 each)	PCE-based SP 2.8–12 kg/m^3	Slump flow diameter 670–730 mm, T50 value was less than 7 s, V-funnel flow time was 6.3–37 s and H2/H1 ratio was 0.704–0.976
Güneyisi et al. (2009)	20, 40 and 60	MP 5, 10, 15 and 20 and (GGBFS + MP) was 20, 40 and 60	PCE-based SP was 4.31–7.34 kg/m^3	MP increased SP demand, viscosity and V-funnel flow time, while GGBFS reduced it.MP + GGBFS increased setting time
Dadsetan and Bai (2017)	0, 20 and 30	MK (10% and 20%), Class F FA (10%, 20% and 30%) and LS (89.4 and 121.6 kg/m^3)	HRWR (2.3–10.4 kg/m^3	MK and GGBS increased SP dosages and FA decreased SP dosages. All mixes satisfied EFNARC requirements for SCC

Table 4
Fresh properties of SCC produced from RHA.

References	Replacement ratio of RHA in %	W/C	Chemical admixtures	Key findings
Chopra and Siddique (Chopra et al., 2015)	10%, 15%,20%	0.41	Super plasticizer 1%	V-funnel flow time was within 6–12 s which in the range of EFNARC specification. And also the slump flow ranged between 600 and 730 mm for all the RHA-SCC mixtures.
Kannan and Ganesan (Kannan and Ganesan, 2014)	5%, 10%, 15%, 20%, 25%, 30%	0.55	Super plasticizer 2%	The slump flow of SCC with RHA (0–30%) showed gradual decrement but it's within the range of EFNARC specification. slump flow decreased primarily due to higher reactivity and high surface area of RHA. The V funnel test result of 5,10, and 15% replacement did not fulfil EFNARC specification in contrast the replacement of 20,25,30 is within the range of the standard which is 6–12
Safiuddin *et. al* (Safiuddin et al., 2012)	5%, 10%, 15%, 20%, 25%, 30%	0.35	Super plasticizer 0.70, 0.87, 1.05, 1.40, 1.75, 2.10, 2.45 (in %)	All the mixes exhibited slump in the range of 265–280 mm. Though the slump increased by only 5 mm in 30% RHA compared to 0% RHA (270 mm) at a 0.35 w/c ratio, the deformability of concrete was significantly improved. V-funnel flow time was within 8–12 s when SCC was made with RHA content less than 25%. With increasing RHA content the V-funnel flow time increased due to increased viscosity
Sua-iam and Makul (Sua-iam and Makul, 2014)	25%, 50%, 75%, 100%	0.54,0.90, 1.46, 1.89 respectively	Super plasticizer 1.2%	Mixes containing 10 and 20% RHA showed acceptable flow times of 9 and 11 s, respectively, whereas increasing RHA content (40, 60, 80, and 100%) increased the flow time as RHA particles absorbed the water, resulting in the viscous mix and reduced bleeding

costs due to cement savings, and environmental benefits related to waste disposal and reduced carbon dioxide emissions are just a few of the advantages of using RHA as a pozzolanic material in cement and concrete (Karim et al., 2012). Table 4 summarizes different fresh properties of SCC produced with RHA as binding material.

Extensive studies have suggested that RHA can enhance the self-compatibility of SCC. A study conducted by Chopra and Siddique (Chopra et al., 2015) revealed that V-funnel flow time and slump flow was within 6–12 s and 600–730 mm in line with EFNARC specification for all the RHA-SCC mixtures. Similar findings were also observed by Sua-iam and Makul (2014) in SCC mixtures containing RHA as a replacement to fine aggregate. Mixes containing 10 and 20% RHA showed acceptable flow times of 9 and 11 s, respectively, whereas increasing RHA content increased the flow time as RHA particles absorbed the water, resulting in the viscous mix and reduced bleeding. Safiuddin et al. (2012) adopted a similar method to examine the effect of partially replacing cement with RHA on the properties of SCC. All the mixes exhibited slump in the range of 265–280 mm. Though the slump flow only increased slightly, the deformability of concrete was significantly improved.

When SCC was rendered with less than 25% RHA material, studies found that the V-funnel flow time was within 8–12 s. The V-funnel flow time increased with increasing RHA content due to increased viscosity, which was enhanced by incorporating fly ash particles (Safiuddin et al., 2012). Besides, a study conducted by Kannan and Ganesan (2014) reported that the slump flow of SCC with RHA (0–30%) were within EFNARC recommended guidelines. except for the 30% RHA-SCC mix. It was concluded that with an increase in RHA content, slump flow decreased primarily due to higher reactivity and high surface area of RHA. Similarly, Pai et al. (2014) reported a suitable range of V-funnel flow value (9 s) for SCC containing RHA (331.3 kg/m^3) in addition to cement (200 kg/m^3).

Pozzolanic and filler effect of SCMs

Though this review focuses on the fresh properties of SCC, it is also important to discuss the pozzolanic and filler effect that SCMs will have on SCC. In this section, we present a general discussion of the pozzolanic and filler effect of SCMs in light of recent observations. Pozzolans are materials rich in silicon and aluminum (>70% total content) which in the form of fine particles can react with calcium hydroxide to yield products with cementitious properties (Cao et al., 2021). The various kinds of natural and artificial pozzolans are specified in ASTM C618 and ASTM C1240. It has been verified that SCMs (fly ash, blast furnace slag and silica fume in this case) has a pozzolanic effect on SCC (Nedunuri et al., 2020). Based on the amount of calcium hydroxide consumed for the formation of C-S-H, the pozzolanic potential of the SCMs were SF > FA > GGBFS (Nedunuri et al., 2020). A maximum replacement level of ordinary Portland cement with FA, SF and GGBFS was observed as 17%, 13%, and 21% respectively.

Concrete design, in its simplest conceptualization, is based on cement paste filling the void space between the aggregate. Ideally the aggregate gradation would be such to yield the densest packing, but in everyday practice this is not practicable nor desirable since some excess paste is needed for lubrication/workability. Thus addition of “fillers” such as fine aggregate component can reduce the overall cement paste quantity needed and generally improve workability characteristics (Cordeiro et al., 2008). SCMs can serve as fillers. When the SCMs are much finer than cement, they can pack between the larger cement particles, and help to achieve higher packing density. Also, the densities of most SCMs are lower than cement (Park et al., 2021), the equal-weight replacement always result in a lower initial capillary porosity.

Recommendations and future perspectives

Based on the observations of this review, we herein discuss the future potentials of the research areas and proffer some recommendations regarding the self-compatibility of SCC as regards fresh properties. It was observed that the physico-chemical nature of the SCMs significantly affects the workability of the SCC. Researchers could investigate ways for chemical or thermal treatment of SCMs to help achieve better workability for the SCC. As the SCMs supply more nucleation sites for cement hydrates, the early hydration of cement can be accelerated, just as the SCMs have not been activated. This early hydration process, when indexed by heat releasing or strength can be retarded. Development of admixture blends can also be explored. The chemical activity of admixtures in cement is dependent essentially on their lime, silica and alumina contents which are the main essential compounds needed for cement hydration for strength development (Meko et al., 2021). ASTM C-618 specification gives a threshold of 70% for pozzolanic materials. Researchers could explore ways to develop admixture blends that can meet this target and hence obtain better quality SCC. It must be noted that increasing SCMs in concrete has a deleterious effect on the hardened properties of the SCC. So as the fresh properties are being considered and optimized, special care must be taken to ensure regulatory thresholds for hardened properties are not violated. This calls for the need for multi-objective optimisation techniques. Researchers can employ statistical tools like response surface methodology (RSM) and intelligent systems like artificial neural networks to achieve this aim. Intelligent systems are the new paradigm of modelling and optimisation in engineering research (Ighalo et al., 2020; Ighalo et al., 2020). These systems are now being used even in concrete development (Koneru and Ghorpade, 2020; Ramkumar et al., 2020; Henigal, 2020).

Conclusion

Because of its high fluidity and segregation-resisting strength, SCC may integrate a variety of minerals and chemical admixtures, ensuring that the self-consolidating concrete's homogeneity and uniformity are unaffected by worker ability or the shape and bar arrangement of structural elements. As a result, the SCC uses a variety of minerals to improve its properties, including fly ash, silica fume, ground-granulated blast-furnace slag, rice husk ash, and chemical admixtures. This review paper drew the following conclusion from the recent research findings conducted to enhance the self-compatibility of SCC.

- Entraining suitable air bubbles has the potential to enhance the self-compatibility of fresh concrete while also being very beneficial in reducing the cement content of SCC.
- Workability and rheological properties of fresh SCC enhanced with FA. FA was found to reduce the friction between mortar and coarse aggregate. This is due to the spherical shape of fly ash particles, which contributes to the ball-bearing effect and reduction in the contact area between other solid particles.
- GGBFS improved workability, but it decreased V-funnel flow time, viscosity and superplasticizer demand,
- The workability of SCC with SF was decreased due to high surface area and finer particle size. And also the increase in silica fume content decreased viscosity.
- Increased content of RHA and lower water–binder ratio increased filling and passing ability, slump cone flow times and AEA dosages.

Declaration of Competing Interest

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

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