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Application of Superabsorbent Polymer as Self-Healing Agent in Self-Consolidating Concrete for Mitigating Pre-Cracking phenomenon at the rebar-concrete interface

Seyed Sina Mousavi *[1], Lotfi Guizani [2], Chandrasekhar Bhojaraju [3], and
Claudiane M. Ouellet-Plamondon [4]

Abstract

Improved autogenous healing capacity of concrete is used in the present study, using superabsorbent polymers (SAP), to present an efficient approach for mitigating damages between steel rebar and self-consolidating concrete (SCC). Additionally, a comparison study is conducted between the results for normal concrete (NC) and those for SCC mixtures. Two SAPs with different particle sizes and chemical compositions are considered in the experimental program. Results show that despite the higher reduction effect of SAP with smaller particle size on compressive strength, SCC containing this type of SAP has the highest bond strength in uncracked specimens, as compared to SAP with larger particle size, for both SAP-modified NC and SCC mixtures. Moreover, regarding the healed specimens, results show that SCC and NC containing SAP considerably have higher healing improvement factors for large crack widths ($w \geq 0.30$ mm) as compared to mixtures without polymers so that almost 46%, 30%, and 24% healing

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[1] PhD Candidate, Dept. of Construction Engineering, Univ. of Quebec, École de technologie supérieure (ÉTS), 1100 Notre-Dame West, Montreal, QC, H3C 1K3, Canada. Corresponding author (Seyed Sina Mousavi), E-mail address: seyedsina.m@gmail.com & seyed-sina.mousavi-ojarestaghi.1@ens.etsmtl.ca

[2] Associate Professor, Dept. of Construction Engineering, Univ. of Quebec, École de technologie supérieure (ÉTS), 1100 Notre-Dame West, Montreal, QC, H3C 1K3, Canada. E-mail address: lotfi.guizani@etsmtl.ca

[3] Postdoctoral Researcher, Dept. of Construction Engineering, Univ. of Quebec, École de technologie supérieure (ÉTS), 1100 Notre-Dame West, Montreal, QC, H3C 1K3, Canada. E-mail address: Chandra.Sekhar@etsmtl.ca

[4] Associate Professor, Dept. of Construction Engineering, Univ. of Quebec, École de technologie supérieure (ÉTS), 1100 Notre-Dame West, Montreal, QC, H3C 1K3, Canada. E-mail address: claudiane.ouellet-plamondon@etsmtl.ca (ASCE member)

improvement factors are obtained for average bond stress, bond strength, and residual bond stress of SAP-contained concrete mixtures respectively. Also, complete strength recovery (100% healing improvement factor) is obtained for SCC mixture with $w = 0.10$ mm, exposed to 28 days healing period.

Keywords*:* bond strength; superabsorbent polymer (SAP); self-consolidating concrete; self-healing

1 Introduction

Propagating cracks parallel to reinforcing bar (rebar) direction causes a considerable reduction in bond strength of steel rebar embedded in normal concrete (NC), denoted as the "pre-cracking phenomenon" (Brantschen et al. 2016; Mousavi et al. 2020; Mousavi et al. 2019). Only a few studies proposed a practical solution, such as the self-healing method, to mitigate internal damage due to the pre-cracking phenomenon (Mousavi et al. 2020; Mousavi 2019). Further hydration of unhydrated cement particles inside concrete mixtures along with precipitation of calcium carbonate is the main healing products used to seal and heal cracks in hardened concrete. Unhydrated cement particles and internal reservoir of water inside concrete mixtures are needed to provide appropriate conditions for the self-healing method. Different healing agents were used in concrete mixtures to provide water resources necessary to activate the self-healing method such as lightweight aggregates and polymers. Among them, superabsorbent polymer (SAP), as a hydrogel material, was found effective that has an excellent ability to absorb and retain a large amount of water, as compared to its mass. The hygroscopic materials are categorized into two main groups based on the water absorption mechanism including (a) chemical and (b) physical absorptions (Zohourian and Kabiri 2008). Chemical absorbers, such as metal hydrides, catch water by chemical reactions changing their whole structure, while physical absorbers maintain water by different mechanisms of reversible modifications of their crystal structure and physical entrapment of water through capillary forces in their macro-porous structure (Zohourian and Kabiri 2008). SAP is categorized in the physical absorber as an organic material with the enormous capability of water absorption, as compared to their own mass. Common hydrogels can absorb water or aqueous solution not more than 1 g/g, while the absorption capacity of ultrahigh absorbing materials (such as SAP) is around 10-1000 g/g. This is the reason to use the term “super” for this type of hydrogel with extraordinary water absorbency (wt%). For instance, as reported by Zohourian and Kabiri (2008), water absorptions (wt%) of Whatman No. 3 filter paper, facial tissue paper, soft polyurethane sponge, wood pulp fluff, and cotton ball are 180, 400, 1050, 1200, and 1890, respectively. They reported the value of 20200 (wt%) for an agricultural SAP, which is significantly greater than the common absorbent materials. Additionally, unlike the traditional absorbent materials, the swollen SAP gradually releases the absorbed water into the matrix as relative humidity in concrete mixture decreases due to cement hydration. This water absorption/water release cycle by SAP particles is efficient to improve self-healing (or autogenous healing) of concrete. In this field, Mousavi et al. (2020) (Mousavi et al. 2020) used superabsorbent polymers (SAP) in NC mixtures, as a healing agent. They obtained promising results for healing cracks at the steel rebar–concrete interface after exposure to the pre-cracking phenomenon. Bond properties of the pre-cracked specimens were partly recovered (regained) after wet-dry healing cycles. However, only NC was considered in their researches and there is no specific study on the effect of the pre-cracking phenomenon in different types of concrete mixtures such as self-consolidating concrete (SCC). Hence, the present study intends to study the effect of the pre-cracking phenomenon in SCC mixtures as compared to NC.

Regarding SCC mixture containing SAP, most of the previous researches only focused on autogenous shrinkage (Han et al. 2014; Shi et al. 2016), drying shrinkage (Han et al. 2014), fresh properties and passing ability (AzariJafari et al. 2016), tensile strength (Al-Hubboubi et al. 2018), compressive strength (Al-Hubboubi et al. 2018; AzariJafari et al. 2016), chloride ion permeability (Shi et al. 2016), and self-sealing and –healing cracks (Van Tittelboom et al. 2016). However, there is no specific research on the effect of SAP on interfacial properties between steel rebar and uncracked SCC specimens. As compressive strength is a crucial parameter in the bond-slip phenomenon, previous results of compressive strength of SCC mixtures containing SAP can be interesting and considerable. Generally, quantifying the effect of SAP on the concrete compressive strength is still challenging for researchers as different types of SAP were used in previous studies. SAP has two main influences on the microstructure of concrete mixtures including (1) it develops the hydration reaction by internal curing, which causes strength improvement, and (2) it generates macro voids (pores) in the mixtures causing a considerable increase of porosity and reduction in strength respectively. Chemical composition and particle size of SAP along with the initial water-to-cement ratio of concrete mixture determine the dominant mechanism. Several studies reported a reduction in the compressive strength of SAP concrete as compared to NC (Mechtcherine et al. 2017; Mousavi et al. 2020; Mousavi 2019; Van Tittelboom et al. 2016; Wyrzykowski et al. 2012), which was attributed to the existence of macro pores of SAP particles after hardening. In these studies, internal curing effect of SAP particles (first mechanism) could not compensate the strength reduction due to the second mechanism. However, some studies showed that the strength of SAP concrete is equal to or only slightly lower than that of the NC without polymer (Bentz et al. 2002; Geiker et al. 2004; Lura et al. 2006; Schröfl et al. 2012).

Most previous studies on SAP-contained SCC mixtures (SCCSAP) show that the existence of macro voids generated by SAP particles is the main reason for the strength reduction. To compensate for the formation of macro pores with SAP adding, Mechtcherine et al. (2006) (Mechtcherine et al. 2006) reported that using 0.40% SAP (by mass weight of cement) with a particle size of 200 μm in high-performance concrete (HPC), with a water-to-cement ratio of 0.24, causes 12.8%, 18.8%, and 25.0% strength reduction in compressive strength, tensile strength, and flexural strength respectively. Experimental results conducted by Han et al. (2014) (Han et al. 2014) showed that addition of 4.0% SAP (by mass weight of cementitious materials) with particle size ranging from 180 μm to 420 μm results in 7.1% and 11.1% reduction in the compressive strength and elastic modulus of high strength SCC mixtures ($f'_c > 100\ MPa$) with a water-to-binder ratio of 0.20. AzariJafari et al. (2016) (AzariJafari et al. 2016) studied the characteristics of lightweight SCC mixtures containing 1.5% pre-soaked SAP (by mass weight of binder). They found strength reduction in SCCSAP mixtures ranging from 27% to 53% in mixtures with water-to-binder ratios of 0.36 and 0.39 respectively. Van Tittelboom et al. (2016) (Van Tittelboom et al. 2016) reported that addition of 0.50% SAP (particle sizes below 600 μm) in SCC mixtures causes 18.3% strength reduction in a water-to-powder ratio of 0.30. However, contrary to these studies, Al-Hubboubi et al. (2018) (Al-Hubboubi et al. 2018) reported that addition of 0.50% SAP (by weight of cement) causes comparable and/or higher compressive strength as compared with reference SCC mixture so that 1.7% strength reduction, 5.2% strength improvement, and 6.5% strength improvement were obtained for water curing, moist curing, and air curing methods respectively. A slight increase in the mechanical properties due to the SAP addition in the SCC mixture was also reported by literature (Alex 2019). Generally, experimental observations of the previous studies indicate that the chemical composition of SAP, the particle size of SAP, and the initial water-to-cement ratio of the mixture have significant effects on the probability of strength reduction or improvement in SCCSAP mixtures.

Only a few studies determined the autogenous healing capacity of SCC mixtures with and without any polymer. Sahmaran et al. (2008) (Şahmaran et al. 2008) studied the effect of the self-healing method in SCC mixtures incorporating high volumes of fly ash (35% and 55%). After the pre-loading process, they kept specimens in water for 28 days and subsequently, the mechanical and permeation properties were measured. Promising self-healing results were observed in their results. Fly ash-based SCC had a significant content of unhydrated fly ash particles available in its microstructure which was efficient for healing the pre-existing cracks by the formation of C–S–H gels. In this field, Ramadana and Haddadb (2015) (Ramadan and Haddad 2017) investigated the potential of the self-healing method and strength recovery in SCC pavement. Their results showed that re-curing (healing) in water is more efficient as compared to only air curing to heal cracks so that damaged SCC specimens recovered compressive strength by 58% (Ramadan and Haddad 2017). Takagi et al. (2015) (Takagi et al. 2015) reported that the mechanical strength recovery is higher in SCC mixtures containing blast furnace slag cement (up to 55%) as compared to other Brazilian types of cement. They also recommended that the wet-dry cycle is more efficient than only wet conditions for the self-healing method in SCC. Thankachan and Sasi (2018) (Thankachan and Sasi 2018) investigated the effect of sodium silicate (Na_2SiO_3) and polyurethane on the self-healing capacity in SCC inserted by a pharmaceutical capsule and cementitious hollow tubes. They found that the self-healing ability of SCC can be effectively improved by using self-healing agents such as sodium silicate and polyurethane by the optimum dosage of about 4.0%. However, a limited number of previous efforts worked on the self-healing methods in SCC using SAP. In this context, Van Tittelboom et al. (2016) (Van Tittelboom et al. 2016) used encapsulated polyurethane and SAP in SCC mixtures to achieve self-healing concrete by monitoring the crack-sealing of RC beams. Their results show that the crack closing ratio, difference in crack width before and after healing period divided by the initial crack width, for the SCC mixture containing SAP particles is significantly higher as compared to mixtures with encapsulated polyurethane. However, there is no specific study for determining the effect of SAP on strength recovery after exposure of initial damages.

As reviewed until now, there are research gaps in the context of SAP studies in a reinforced concrete member. The present study thus intends to fill these gaps by answering the following objectives:

- How does the bond behavior between steel rebar and SAP-contained SCC compare to that of NC in uncracked specimens?
- How can the SAP type (chemistry or particle size) affect the bond behavior of steel rebar embedded in uncracked SCC?
- How much does the SAP affect the crack-sealing and -healing at the rebar-concrete interface, after exposure to the pre-cracking phenomenon?
- How can the SAP type (chemistry or particle size) have an influence on the crack-sealing and -healing at the rebar-concrete interface?

To address these unanswered questions, an extensive experimental program is performed. A number of 94 pull-out specimens are prepared and tested in three different statuses of uncracked, pre-cracked, and healed specimens. A comparison study is performed between NC and SCC mixtures. Wet-dry healing period, initial crack width, SAP type (chemical composition and particle size), and concrete composition are the crucial parameters studied in the present study.

2 Experimental program

2.1 Material properties

Three different concrete mixtures of SCC, SCCSAP1, and SCCSAP2 were considered for this study to determine the effect of SAP on bond characteristics in three statuses of uncracked, pre-cracked, and healed specimens. To compare the results of SCC with normal concrete (NC), reference concrete mixtures used in the recently published paper by authors (Mousavi et al. 2020) are also used in the present study, as mentioned in Table 1. However, a new analyzing procedure is used in the present study for uncracked and healed specimens. Hence, the current paper intends to report the results of a total of six concrete mixtures. Initial water-to-cement ratios of 0.41 and 0.51 were considered for reference NC and SCC respectively, while a constant initial water-to-powder ratio of 0.41 was considered for both mixtures. Ordinary Portland cement (CSA A3001 type GU or ASTM C150 type I) was used for all mixtures with a density of 3.15 g/cm^3 and maximum particle size about 70 μm, and a Blaine fineness of 383 m^2/kg. Contents of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), magnesium oxide (MgO), iron oxide (Fe_2O_3), and sulphur trioxide (SO_3) in the cement were 62.7%, 19.5%, 5.0%, 2.5%, 3.1%, and 3.9%, respectively. Limestone powder was used as a filler with a relative density of 2.68 and a maximum particle size of about 200 μm. The particle size distribution of the cement and limestone powder is illustrated in Fig. 1. Natural sand with a maximum grain size of 1.25 mm and a specific gravity of 2.68 and gravel with a nominal maximum diameter of 20 mm and a particular gravity of 2.68 were considered for mixtures. As reported in Mousavi et al. (2020) (Mousavi et al. 2020), SAP type has considerable effect on bond properties of uncracked, pre-cracked, and healed NC specimens. Hence, two types of SAP were also considered for SCC mixtures of the present experimental program including (1) SAP1: a cross-linked copolymer of acrylamide and potassium acrylate with a maximum particle size of 500 µm. SAP1 had water absorption capacities of 249 g/g (gram water per gram of SAP) and 25 g/g in deionized water and pore solution, respectively; (2) SAP2: a cross-linked anionic polyacrylamide with a maximum particle size of 150 µm. SAP2 had water absorption capacities of 170 g/g and 25 g/g in deionized water and pore solution, respectively. These SAPs were produced through the bulk polymerization technique, in which blocks of polymers were pulverized into irregular shaped powder. More details of these polymers were provided the recently published paper by authors (Mousavi et al. 2020). The SAPs were added by 0.25 wt.% of cement. Particle size distributions of SAP samples are illustrated in Fig. 1. As comprehensively explained in the recently published paper (Mousavi et al. 2020), the water absorption capacity of SAP was measured by three methods including (1) the tea bag method; (2) the slump test method; and (3) the water desorption method (the absorption of a centrifuged cement pore solution). Finally, the value of 25 gram water per dry gram of SAP was obtained and used to adjust the slump flow (workability) of mixtures. As recommended by previous research (Mousavi et al. 2020; Van Tittelboom et al. 2016), additional water was considered to compensate the free water absorbed by SAP particles to maintain the same slump flow (workability), as was suggested by Schröfl et al. (2012) (Schröfl et al. 2012). Regarding NC mixtures, slump of 100 ± 10 mm was considered as a design parameter so that different values of superplasticizer were used (Mousavi et al. 2020). The superplasticizer admixture used for this research was a type F (high-range water-reducing) admixture based on ASTM C 494/C 494M requirements (ASTM 2019). To adjust the flowability of SCC mixtures, additional water (based on 25 g/g water absorption of SAP) was also used in the present study. Moreover, viscosity-modifying admixture (VMA) was used to maintain the stability of SCC mixtures, which was a type S admixture recommended by ASTM C

494/C 494M (ASTM 2019). Contrary to NC mixtures, a constant proportion of superplasticizer was used for SCC mixtures to keep the slump flow above the 500 mm value, as recommended by the Japan Society of Civil Engineers (JSCE) (JSCE 1998; Kodeboyina 2018) and ASTM C1611 (ASTM 2009). Although additional water and different values of superplasticizer were considered for SCC mixtures, slightly reduction of slump flow was obtained, which may be attributed to the higher content of fine aggregate as compared to NC mixtures. Similar issue was reported in previous research (Van Tittelboom et al. 2016). The concrete composition of mixtures along with the fresh properties are illustrated in Table 1. SCC mixtures containing 0.25% of SAP1 and 0.25% of SAP2 are identified by SCCSAP1 and SCCSAP2, respectively, throughout the paper. Similar mix identification was also considered for NC mixtures (Mousavi et al. 2020), which is mentioned in Table 1.

2.2 Test set-up and analyzing procedure

Cylindrical specimens with dimensions of 150 mm × 113 mm were considered for pull-out specimens (Fig. 2) with a concrete cover of 75 mm. Small cylinders with a diameter of 100 mm and height of 200 mm were used for measuring compressive strength. Steel rebars were positioned at the centre of cylinders for all specimens with a nominal diameter of 10 mm, average rib–face angle of 55 degrees, rib height of 1.89 mm, rib spacing of 13.22 mm, and rib spacing-to-rib height ratio of 7.0. Specified yield strength and ultimate tensile strength of steel rebars were 432 and 620 MPa respectively. Specimens were kept in moisture room for 28 days curing at 97.3% RH and at 23 ° C. Pre-cracking simulation was applied after initially 28 days-curing to the specimens by controlled splitting tests. Based on empirical observations, the displacement rate of 0.11-0.15 mm/min was considered for splitting tests. Experimental test set-ups are shown in Fig. 2. Crack gauges were installed to control the crack width. However, due to the brittle behavior of concrete, direct measurement of crack width was considered instantly after finishing the splitting test. Then direct pull-out tests, with a displacement rate of 0.50 mm/min, were conducted after three stages of uncracked (without splitting test), pre-cracked, and healed (after 14- and 28-days re-curing) specimens.

For healing specimens, two period sets of 14 days and 28 days wet-dry cycles in the curing tank were considered at 20 °C and 60% RH. One wet-dry cycle means 24 h in water followed by 24 h in dry condition so that 7 and 14 cycles took 14 and 28 days of wet-dry curing, respectively. To prevent corrosion influences for 28 days healing period, the heat-shrinkable tube was used along the rebar at both end sides of the specimens. To analyze the results of SCC and compare them with NC, different bond parameters were considered, as shown in Fig. 3, including bond strength (τ_u), average bond stress (τ_m), residual bond stress (τ_r), and bond energy which is the area under bond-slip curve till rebar slippage of 10 mm (E). Average bond stress (τ_m) is recommended by RILEM (Recommendation RC 6, append to RILEM TC 1994 (TC 1994)) as the arithmetic mean of bond stresses of $\tau_{0.01}$, $\tau_{0.10}$, and $\tau_{1.00}$ corresponding to slips of 0.01 mm, 0.10 mm, 1.00 mm respectively, which is illustrated in Fig. 3.

3 Results and discussions

3.1 Uncracked specimens

Results of uncracked, pre-cracked, and healed SCC are summarized in Table 2. Regarding NC, a different approach is considered in the present study, as compared with the recently published paper by authors (Mousavi et al. 2020) to compare to the results with SCC mixtures. Crack width

(w), compressive strength (f'_c), average bond stress (τ_m), maximum bond stress (bond strength, τ_u), residual bond stress (τ_r), bond energy (E), number of specimens (n), and failure modes are mentioned in Table 2. A total number of 94 pull-out specimens are tested and considered in the present study. As shown in Fig. 4(a), results show that pull-out failure mode is observed for uncracked specimens. The concrete cover-to-rebar diameter ratio of around 7.5 and rib spacing-to-rib height ratio of 7.0 provide enough confinement surrounding the steel rebar preventing splitting failure mode.

Bond-slip curves of uncracked specimens for NC and SCC mixtures are illustrated in Fig. 5. In the case of NC mixtures, although similar bond-slip curves are obtained for NCSAP mixtures, SAP1 and SAP2 cause an initial reduction in ascending branches of the bond-slip curve after 10 MPa and 5 MPa bond stress respectively (Fig. 5(a)). This corresponds to the mechanical interlocking effect before the maximum bond stress (bond strength), as schematically shown in Fig. 3. This is the stage of first cracking where rebar lugs induce large bearing stresses in the surrounding concrete and transverse micro-cracks originate at the tips of the lugs allowing the rebar to slip. Observation shows the higher impact of SAP2 on initial bond reduction as compared to SAP1. However, as shown in Fig. 5(b), contrary to NC, SAP2 does not affect the initial stiffness of the ascending part, while SAP1 causes a considerable reduction in the initial stiffness of the ascending part. These observations indicate that the type of SAP can affect bond stiffness in different concrete compositions. Moreover, Fig. 5 shows that this effect initiates at specific bond stress ranging from 5 MPa to 10 MPa.

Compressive strength of mixtures is shown in Fig. 6(a). Results show that SCC mixture has lower compressive strength as compared to NC with the same water-to-powder ratio. This can be attributed to different factors including (1) higher content of fine aggregates in SCC mixtures as compared to NC ones (Aslani and Nejadi 2012; Felekoğlu et al. 2007; Schiessl and Zilch 2001) (Nikbin et al. 2014); (2) different cement efficiency factors of SCC and NC mixtures (Domone 2007); and (3) type and content of limestone powder used in SCC mixtures (Domone 2007). Similarly, some previous studies reported that the SCC mixture has lower mechanical properties (such as the modulus of elasticity and stiffness) as compared to NC mixture (Felekoğlu et al. 2007; Klug and Holschemacher 2003; Makishima et al. 2001). Results indicate that mixtures containing SAP1 have comparable and slightly higher compressive strength as compared to reference mixtures, while SAP2 causes a considerable reduction in compressive strength. This reduction effect is more crucial for NC mixtures (20.4% reduction) than SCC mixtures (8.3% reduction). This may be attributed to the smaller particle size of SAP2 as compared to SAP1, which produces more macro-voids in the bulk matrix. In this field, Mousavi et al. (2020) (Mousavi et al. 2020) found that although sizes of macro voids generated by smaller SAP are smaller than those of SAP with bigger particle size, addition of a small SAP particle size leads to a high number of voids around the aggregate particles in the matrix. Accordingly, this phenomenon increases the porosity of the interfacial transition zone (ITZ) surrounding the aggregate and thus reduces the compressive strength. Regarding compressive strength reduction due to SAP particles, comparable results were reported by previous studies, as reviewed in Table 3. They confirmed that this phenomenon is inevitable in the context of SAP-based concrete. SAP particle size, SAP chemistry (water absorption capacity), and the initial water-to-cement ratio of the concrete mixture can diminish this strength reduction phenomenon. Different advantages of using SAP in the concrete mixture may compensate this phenomenon including promoting self-healing capacity of concrete (Snoeck and De Belie 2015), having more plastic and uniform concrete mixture (Al-Nasra 2013; Al-Nasra and Daoud 2013), reducing water permeability of mixture (Snoeck and De Belie 2013), a considerable decrease in autogenous shrinkage (Mechtcherine et al. 2014), and an increase the freeze-thaw resistance of concrete mixtures (Craeye et al. 2018; Mönnig and Lura 2007).

Bond parameters of uncracked specimens are extracted from bond-slip curves, shown in Fig. 6(b). Average bond stress, bond strength, and residual bond stress of mixtures are extracted from bond-slip curves. Also, bond stress corresponds to the slip of 0.01 ($\tau_{0.01}$) is obtained to show the primary stiffness of the curves before the initial stiffness explained in Fig. 5. Results show that SCC has lower primary bond stress ($\tau_{0.01}$) and average bond stress (τ_m), while comparable and higher bond strength (τ_u) and residual bond stress (τ_r) are obtained for SCC respectively. Higher bond strength of SCC than NC was reported by literature (Mousavi et al. 2017; Mousavi et al. 2016). As shown in Fig. 6(b), even though SAP1 and SAP2 cause similar bond strength of mixtures to the reference mixtures, SAP2 is more efficient by having higher bond strength, average bond stress, and primary bond stress as compared to SAP1. However, there is no clear trend for the residual bond stress of mixtures. Results show that SAP causes higher residual bond stress in NC mixtures while it has a contradictory impact on SCC mixtures. By comparing Figs. 5 and 6(a)-(b) it can be deduced that although SAP2 produces more macro-voids in the bulk matrix of both NC and SCC mixtures resulting in lower compressive strength while providing a better interface between steel rebar and surrounding concrete. For explaining this phenomenon, normalized bond properties are shown in Fig. 6(c) with the square root of compressive strength. Previous researches along with concrete design codes used normalized value of bond strength to rather concentrate on the rebar-concrete interface than on the bulk matrix (Wu and Zhao 2012).

Generally, normalized results indicate that SCC mixtures have higher normalized bond properties as compared to NCC mixtures, especially SAP2, so that SCCSAP2 is the optimum mixture among all concrete mixtures of the present study. This can be attributed to the filling and passing abilities of SCC mixtures with high workability, which reduces the porosity at the rebar-concrete interface. Using lower content of coarse aggregate and higher content of filler material can affect this phenomenon in SCC mixtures. In the case of normalized bond strength ($\tau_u{}^* = \tau_u/\sqrt{f'_c}$), results show that SAP2 is considerably more efficient as compared to SAP1. NCSAP1 and SCCSAP1 mixtures have comparable normalized bond strength as compared with reference mixtures. To study the adhesive bond of mixtures, primary bond stress ($\tau_{0.01}$) is defined in the present study. This can be deduced from bond-slip curves of mixtures until the slip of 0.05 mm (Fig. 7). This low bond stress at a low slip range corresponds to chemical adhesion between the rough steel surface and the surrounding concrete. Highly localized stress exists close to lug tips (elastic behavior) at the end of this stage. Regarding primary normalized bond stress in NC ($\tau_{0.01}{}^* = \tau_{0.01}/\sqrt{f'_c}$), Fig. 6(c) shows that both NCSAP1 and NCSAP2 have lower bond stress as compared with NC, which continues until the slip corresponds to the maximum bond stress (Fig. 5(a)). Although NCSAP2 has higher primary bond stress as compared to NCSAP1 (Fig. 7(a)), lower initial stiffness at the ascending branch of the bond-slip curve is observed in Fig. 5(a). Changing interfacial behavior happens from the chemical adhesive bond stage to the mechanical interlocking bond stage. In the case of SCC mixtures, SAP1 causes reduction in the initial stiffness in ascending branches (Fig. 5(b)), while has no effect on primary bond stress (chemical adhesive bond, Fig. 7(b)).

The area under bond-slip curves of uncracked specimens, denoted as “absorbed energy by bond mechanism”, is illustrated in Fig. 8. Results show that the SCC reference mixture has higher absorbed energy (the average value of 176.2 N/mm) as compared to the NC reference mixture. The maximum value of 180.6 N/mm is recorded for SCC samples. In the case of NC mixtures, SAP has no considerable impact on absorbed energy so that NCSAP1 and NCSAP2 mixtures have comparable and slightly higher absorbed energy respectively as compared to NC reference mixture. However, in the case of SCC mixtures, SAP1 and SAP2 cause 5.6% and 28.5% reduction in absorbed energy (Fig. 8). Regarding energy absorption in cementitious materials containing SAP, only Snoeck et al. (2018) (Snoeck et al. 2018) conducted experimental tests on the self-healing characteristics under impact loads using a drop-weight machine. They found that specimens containing SAP have a more ductile behavior, as compared to the reference mixture. However, the bond energy absorption mechanism is different from the impact behavior. The results of the present study indicate that a lower area under the bond-slip curve represents lower bond ductility, resulting in a brittle and sudden bond drop after the maximum bond stress (bond strength). This leads to lower residual bond stress, which is shown in Fig. 5(b) for SCCSAP2 mixture. High bond strength of SCCSAP2 mixtures along with the low-absorbed energy by this mixture results in a challenging issue on designing concrete mixtures containing SAP particles. It is worth emphasizing that more experimental tests are needed for future studies to figure out the effect of SAP types (particle size and chemical composition) on mechanical strength and microstructure (bulk matrix and rebar-concrete interface) of concrete mixtures.

3.2 Pre-cracked specimens

As shown in Table 2 and Fig. 4(b), cracked specimens with $w = 0.10$ mm failed by a pull-out failure mode while splitting failure modes are observed for larger crack widths (Fig. 4(c)). Bond strengths of steel rebar embedded in cracked specimens concerning the initial crack width are shown in Fig. 9. Results show that small crack width has no considerable impact on bond strength so that only 5.7% bond reduction is observed for SCCC0.1 specimen. However, large crack width causes significant reduction in bond strength insofar as crack widths of 0.15, 0.20, 0.30, 0.40, and 0.50 mm cause around 36-52%, 21-33%, 40-84%, 59-84%, and 90% bond strength reduction respectively. Generally, results show that SCC mixtures are less sensitive to the pre-cracking phenomenon than NC mixtures so that SCC and SCCSAP2 mixtures have higher bond strength for different crack widths as compared to NC and NCSAP2 mixtures respectively. However, NCSAP1 and SCCSAP1 mixtures have similar behavior regarding cracked samples so that similar trend lines are obtained for them for bond strength as a function of crack width (Fig. 9). Moreover, initial crack width has considerable influence on the absorbed energy so that a minimum value of 1.14 N/mm is recorded for NC mixture with 0.40 crack width (NCC0.4, the average value of 2.56 N/mm for two repetitions). More details of the results presented in Fig. 9 for NC and SCC mixtures without SAP can be found in the recently published paper of authors (Mousavi et al. 2020). Fracture mechanic allowed to analyse the crack-opening after the initial crack width at the rebar-concrete interface.

3.3 Healed specimens

As illustrated in Fig. 4(c), healed specimens with $w > 0.10$ mm failed by splitting of surrounding concrete. However, as mentioned in Table 2, pull-out failure is observed for the healed specimen of SCC/28H0.1 after 28 days healing period. A healing improvement factor (IF) is defined in the present study, shown in Eq. (1), to determine the efficiency of concrete mixtures for healing cracks passing the steel rebar, and mitigating damages. As IF increases, the healing efficiency of the mixture increases. Zero value of IF corresponds to the specimens with lower or comparable bond properties than the cracked specimen with constant crack width ($\tau_{Healed} \leq \tau_{Precracked}$), while $IF > 0$ represents healed specimens with higher bond properties as compared to those of pre-cracked specimens ($\tau_{Healed} > \tau_{Precracked}$). As different crack widths are obtained by splitting tests due to the brittle nature of concrete in tension, bond reduction-crack width curves are used in few cases to predict bond properties of cracked specimens. These predicted values are used for measuring the IF.

$$IF_{heal} = \left[\frac{\tau_{Healed} - \tau_{Precracked}}{\tau_{Uncracked} - \tau_{Precracked}}\right] \times 100 \qquad (1)$$

Average healing improvement factors (IF) for all mixtures (with different repetitions) and crack widths are shown in Fig. 10 in which IF_m, IF_u, and IF_r are healing efficiency of the average bond stress, the bond strength, and the residual bond stress, respectively. These values are summarized in Table 2. As illustrated in Fig. 10(a), in the case of the average bond stress (τ_m), the maximum value of $IF_m = 45.5\%$ is obtained for SCCSAP2/28H0.3 (the average value of 35.1% for 5 repetitions). In the case of the bond strength (τ_u), the maximum value of $IF_u = 100.0\%$ is obtained for SCC/28H0.1 (Fig. 10(b)). High healing performance for SCC/28H0.1 corresponds to the small crack width of 0.10 mm, which makes it easy to entirely regain bond strength. NCSAP1/14H0.3 mixture has the highest healing $IF_r = 18.15\%$ of residual bond stress (the average value of 12.12% for 2 repetitions) among the mixtures containing SAP, while NC/28H0.4 shows the highest $IF_r = 24.14\%$ among the all mixtures (Fig. 10(c)). Generally, results show that SAP has a significant influence on increasing the healing performance of the bond strength in large initial crack widths ($w > 0.10$ mm) so that the average maximum $IF_u = 29.7\%$ is obtained for SCCSAP2/28H0.3, while the maximum value of 5.7% is recorded for mixtures without SAP (Fig. 10(b)). Similarly, in the case of the average bond stress, the maximum average value of $IF_m = 35.1\%$ is obtained for SCCSAP2/28H0.3. Moreover, the results presented in Fig. 10 show that SCC mixtures containing SAP particles are more efficient for healing damages (and/or bond strength regaining) as compared to NC mixtures containing SAP particles. This may be attributed to the existence of a slightly higher content of cement in SCC mixtures as compared to NC mixtures so that more unhydrated cement grains remain in the hardened SCC samples (Table 2). Moreover, limestone in SCC mixtures affects the cement hydration rate at early-age (Pera et al. 1999), while has no impact on long-term hydration rate (Kadri et al. 2010). Additionally, the reaction between $CaCO_3$ from limestone and C_3A from cement produce calcium carboaluminate in the matrix (Trezza and Ferraiuelo 2003). These conditions provided a better situation for SCC healing damages in both the bulk matrix and the rebar-concrete interface (Fig. 10). Additionally, results show that 14 days healing period is not enough to heal crack especially for regaining bond strength, while promising results are obtained for 28 days healing period. Moreover, Fig. 10 indicates that healing of large crack width ($w > 0.40$ mm) is totally difficult so that $IF_u < 10.0\%$ is observed for bond strength of healed samples with 0.40 mm initial crack width. Besides, results show that SAP2 is slightly more efficient than SAP1 for improving healing IF, especially in SCC mixtures.

Generally, results show that smaller crack widths are more effective to be healed for regaining the bond stiffness as compared to wider ones, which was similarly reported by previous studies for the crack-sealing phenomenon (Snoeck et al. 2014; Van Tittelboom et al. 2016). For instance, as shown in Fig. 10(a), results indicate that healing improvement factors of the average bond stress for NC/28H0.3 specimens are higher than NC/28H0.4. A similar trend was obtained for specimens with $0.30\,mm$ crack width as compared to $w = 0.40\,mm,$ including NCSAP1/14H, NCSAP1/28H, SCCSAP1/14H, SCCSAP1/28H, and SCCSAP2/14H mixtures. Regarding the improvement factor of the bond strength (Fig. 10(b)), similar trend was observed for mixtures of SCC/28H0.1 > SCC/28H0.25 > SCC/28H0.4, NCSAP1/14H0.3 > NCSAP1/14H0.4, NCSAP1/28H0.3 > NCSAP1/28H0.4, SCCSAP1/14H0.3 > SCCSAP1/14H0.4, SCCSAP1/28H0.3 > SCCSAP1/28H0.4, and SCCSAP2/14H0.3 > SCCSAP2/14H0.4. However, a few cases show another trend such as NC/28H0.3 < NC/28H0.4 and NCSAP2/28H0.3 < NCSAP2/28H0.35. This may be attributed to the internal damages in these specimens during the generation of the initial crack width, which could not be monitored by the automatic and the manual measurements after the splitting tests. For the residual bond stress (Fig. 10(c)), many cases show that as crack width increases, healing improvement factor decreases such as SCC/28H0.25 > SCC/28H0.4, NCSAP1/14H0.3 > NCSAP1/14H0.4, NCSAP1/28H0.3 > NCSAP1/28H0.4, and SCCSAP2/14H0.3 > SCCSAP2/14H0.4. However, a conflicting result was observed for NC/28H0.4 > NC/28H0.3.

To determine the effect of SAP type on self-healing performance at the rebar-concrete interface, specimens with similar initial crack widths are compared with each other. Regarding NC mixtures, results show that SAP1 is more efficient, as compared to SAP2, to regain bond properties. For instance, in the case of the bond strength (Fig. 10(b)), NCSAP1/14H0.3 mixture (12.9%) has more healing improvement factor than NCSAP2/14H0.3 mixture (6.9%). For 28 days curing period, NCSAP1/28H0.3 mixture (16.2%) also has a higher healing improvement factor as compared to NCSAP2/28H0.3 (11.4%). A similar trend was obtained for the average and the residual bond stresses. However, results indicate that SAP2 is more efficient in SCC mixtures to regain bond stiffness, as compared to SAP1 (Fig. 10). As an example, SCCSAP1/28H0.3 has an 18.6% healing improvement factor of the bond strength, while 29.7% was obtained for SCCSAP2/28H0.3. This may be attributed to the smaller particle size of SAP2, as compared to SAP1, which makes it easy to distribute more homogeneously in the SCC mixture than NC mixture. However, there is no clear explanation in the literature regarding the effect of the SAP type on crack-healing performance. Previous studies only reported that using different types of SAP (particle size, chemical composition, and water absorption) causes different influences on the mechanical properties and self-healing (and sealing) capacity of concrete mixtures (Mechtcherine et al. 2018; Snoeck et al. 2014; Zhu et al. 2015).

Bond-slip curves of the healed specimens are shown in Fig. 11. Regarding w=0.10 mm for SCC mixture, results indicate that even though maximum bond stress (bond strength) is completely recovered (regained) after healing periods, residual bond stress and bond energy are still significantly degraded (Fig. 11(a)). The pull-out failure mode is observed for this small crack (SCC/28H0.1) after 28 days of healing periods (Table 2). Results also show that splitting failures, sudden drops in bond-slip curves after reaching maximum bond stress, are observed for all healed specimens ($w > 0.10$ mm). As shown before in Fig. 10, the presence of SAP particles near rebar and at the crack path leads to higher healing improvement factors for both NCSAP and SCCSAP. This was confirmed by Snoeck et al. (Snoeck et al. 2014; Van Tittelboom et al. 2016) for crack-sealing located in the matrix bulk. However, crack-healing phenomenon, confirmed by the present study, is more complicated and difficult as compared to crack-sealing results obtained by literature. As reported in Figs. 10 and 11, SAP-containing mixtures have higher healing IF as compared with reference mixtures. There is a strong hypothesis for explaining this phenomenon. The reaction between calcium ions (Ca^{2+}), available in the matrix, and bicarbonates (HCO_3^-) and carbonates (CO_3^{2-}), available due to water ingress in the crack surface along with carbon dioxide in the air, generate calcite (Mousavi et al. 2020; Snoeck et al. 2014). These precipitates increase the ability of concrete to seal and heal the cracks (Aliko-Benítez et al. 2015). Hence, the content of calcite precipitates can directly affect the strength- and stiffness recovery. Due to the heterogeneity at the rebar-concrete interface, a transition zone exists by a physical barrier of calcium hydroxide. Enhanced quantity of calcium hydroxide at the rebar-concrete interface, as compared to the matrix, have been confirmed in the literature (Horne et al. 2007). Due to the internal shear force, cement grains tend to separate from the matrix, causing a thin area around the rebar with fewer cement particles and more water, where calcium ions can diffuse from outside the interface zone to form areas filled by calcium hydroxide (Goudar et al. 2019). Results of the present study confirm that the presence of this calcite rich layer around the rebar is useful to partly/entirely heal cracks and regain bond strength. The existence of SAP particles in the mixtures increases the possible consumption of calcite for sealing/healing cracks. Moreover, macro-voids generated by SAP particles provide a condition in which the crack path passes through the SAP particle locations. This improves the performance of the self-healing method. Even in the case of concrete without polymers, almost 5.7% healing improvement factor is obtained for large crack width (Fig. 10). However, due to the complicated pattern and distribution of healing products at the rebar-concrete interface, a sudden jump is observed in some bond-slip curves, indicating different efforts made between surfaces of rebar and healed surrounding concrete, called "strength regain" (Fig. 12). A similar observation is shown in Fig. 11(e) for SCCSAP1/28H0.4 mixture. A large quantity of stalactites is observed in the external surface of mixtures containing SAP after 28 days healing period (Fig. 13). Snoeck et al. (2014) (Snoeck et al. 2014) reported that the stalactites consist of a significant amount of $CaCO_3$ and washed out hydration products (Snoeck et al. 2014). Crystallization starts from the closer parts of crack tips and then propagates to the interior parts of the crack to provide a bridge between the crack lips.

It is worth emphasizing that the crack-healing phenomenon is different from the crack-sealing phenomenon. Crack-sealing phenomenon corresponds to the closure of the crack by hydration products, while crack-healing phenomenon shows an increase in the mechanical strength (regain in stiffness) after the healing period. Generally, crack closure percentage is higher than the healing improvement factor (Eq. (1)). To highlight this fact, crack-sealing monitoring of concrete samples after one month healing period was considered in the present study by using a Nikon XTH 225 micro-computed tomography (μ-CT) system with a 225 kV reflection X-Ray source (Fig. 14). A voxel size of 7 μm, a beam energy of 200 Kv, a current of 50 mA, and a 0.5 mm-thick copper sheet filter were used to scan the specimens (acquisition step). Then, the images were reconstructed by using Nikon CT Pro 3D software, along with the post-treatment procedure conducted by the Dragonfly image processing software (Object Research Systems (ORS)). Finally, crack width measurement was performed in the images taken before and after the healing period. To simulate the pre-cracking phenomenon, splitting test was also considered for the crack-sealing monitoring. However, to monitor crack closing by micro-CT scanning, larger cracked widths ($w > 0.50$ mm) were considered as compared to the pull-out specimens (Fig. 15). As shown in Fig. 10, SAP2 shows good healing performance. Hence, NCSAP2 mixture was used for samples of micro-CT scanning. Different locations were considered in the concrete sections to compare the crack widths before and after the healing periods. Similar to pull-out specimens, wet-dry cycles were used to seal the cracks. As shown in Fig. 15, crack widths provided by splitting tests are not constant along the crack pass. The average value is considered for this section. This can explain some high standard deviations that existed in Fig. 10 for different crack widths in the pull-out specimens. Sealing improvement factors (IF_{seal}) of crack widths at different locations (A, B, C, D, and E) are illustrated inside Fig. 15, which is defined as follows:

$$IF_{seal} = \left[\frac{w_{before} - w_{after}}{w_{before}}\right] \times 100 \qquad (2)$$

where w_{before} is crack width at different locations of concrete section before exposing to wet–dry cycles and w_{after} is crack width measured after the healing period.

Results show that SAP2 causes a maximum of 50.4% sealing IF for the average crack width of $w = 1.20$ mm (Fig. 15(a)), while a maximum of 62.7% sealing IF is obtained for the average crack width of $w = 0.95$ mm (Fig. 14(b)). Similar to the crack-healing IF (Fig. 10), SAP2 is efficient for sealing cracks. However, the range of sealing even for so large crack widths is significantly higher than the maximum crack-healing IF_u (29.7% for SAP2). Different mechanisms can help for closing (sealing) cracks including hydration of unhydrated particles and precipitation of calcium carbonate. The strength of sealed products to maintain similar mechanical properties of uncracked specimens is a challenging issue. Healing IF (bond strength recovery) should be lower than sealing IF. Comparing the results presented in Figs. 10 and 15 confirm this fact. Due to the continuous hydration in the bulk matrix of mixtures throughout the wet-dry cycles, transparency of images of micro-CT scanning after healing periods is lower than the first stage.

4 Conclusions

This paper determines the effect of SAP on the self-healing of bond damages in NC and SCC mixtures. An experimental program is carried out in three separate statuses of uncracked, pre-cracked, and healed specimens. Moreover, as there is no specific study on SAP-modified SCC mixtures, a comprehensive discussion is performed in the present study on uncracked mixtures. A comparison study is also performed on the results of NC and SCC mixtures. From the experimental results, the following main conclusions can be drawn:

- It is found that crack width smaller than 0.15 mm in SCC has no impact on the failure mode so that pull-out failure is observed for pre-cracked specimens with $w = 0.10$ mm.
- Mixtures containing SAP1 have comparable and also slightly higher compressive strength as compared to the reference NC and SCC mixtures respectively, while SAP2 causes a

considerable reduction in the compressive strength. This reduction effect is more crucial for NC mixtures (20.4% reduction) than SCC mixtures (8.3% reduction).

- Generally, results show that the bond strengths of steel rebar embedded in NC and SCC mixtures are not affected by a lower dosage of SAP (0.25%). Although SAP2 (smaller particle size) causes a considerable reduction in compressive strength, higher bond properties are obtained for this type of SAP as compared to SAP-1 with larger particle size in both NC and SCC mixtures. This clearly shows that the chemical composition of SAP plays a major role in the mechanical characteristics. More experimental studies are needed for the future to comprehensively clarify this important finding.
- Regarding the cracked specimens, SCC mixtures are less sensitive to the pre-cracking phenomenon as compared to NC mixtures.
- Promising healing results are obtained for NC and SCC mixture containing SAP particles as compared to the reference mixtures so that 29.7% bond strength recovery is obtained for SAP-contained concrete mixtures. Results also show that SAP particles are more efficient in SCC mixtures as compared to NC mixtures to heal cracks at the rebar-concrete interface.
- Results show that the self-healing performance of small crack widths is higher than large ones so that entire bond recovery is obtained for a damaged specimen with 0.10 mm crack width after 28 days healing period.

Conflict of Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

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List of Tables:

Table 1. Mix proportions of concrete mixtures

Constituent	Quantity (kg/m^3)					
	SCC	SCCSAP1	SCCSAP2	NC	NCSAP1	NCSAP2
Water (w)	215	215	215	165	165	165
Cement (GU) (c)	420	420	420	395	395	395
Limestone powder	105	105	105	-	-	-
Total powder	525	525	525	395	395	395
Superabsorbent polymer [1]	-	1.31	1.31	-	0.99	0.99
Fine aggregate	940	940	940	788	788	788
Coarse aggregate (5-10 mm)	352	352	352	822	822	822
Coarse aggregate (10-14 mm)	219	219	219	258	258	258
Coarse aggregate (14-20 mm)	270	270	270	-	-	-
Superplasticizer	5.0	5.0	5.0	2.34	3.5	3.3
Additional water	-	32.8	32.8	-	24.8	24.8
VMA	2.5	2.5	2.5	-	-	-
Total w/c	0.51	0.59	0.59	0.41	0.48	0.48
Total w/p [2]	0.41	0.47	0.47	0.41	0.48	0.48
Slump (mm)	709	618	675	97	104	109
T_{50} (s)	2.37	3.80	2.30	-	-	-
Hardened density (kg/m^3)	2375.7	2330.6	2346.0	2453.8	2416.8	2419.2

[1] 0.25% wt. of powders used; [2] p=weight of powder (cement+limestone).

Table 2 Experimental results and failure modes (“P” and “S” indicate pull-out and splitting)

Specimen	w	f'_c	τ_m	τ_u	τ_r	E	IF_m	IF_u	IF_r	n	Failure mode
	(mm)	(MPa)	(MPa)	(MPa)	(MPa)	(N/mm)	%	%	%		
SCC	0.00	40.34 (0.72)	15.32 (0.63)	24.61 (0.61)	12.21 (0.72)	176.18 (4.69)	-	-	-	3	P, P, P
SCCC0.1	0.10		16.38 (-)	23.20 (-)	4.97 (-)	107.96 (-)	-	-	-	1	P
SCCC0.2	0.20		6.79 (1.64)	18.31 (1.43)	0.69 (0.86)	25.24 (21.12)	-	-	-	3	S, S, S
SCCC0.3	0.30		5.37 (3.57)	14.72 (0.55)	0.22 (0.19)	11.66 (8.08)	-	-	-	2	S, S
SCCC0.4	0.40		5.14 (0.57)	10.11 (0.29)	0.17 (0.09)	9.78 (2.92)	-	-	-	2	S, S
SCC/14H0.3	0.30		4.65 (1.76)	9.12 (4.33)	0.13 (0.06)	7.40 (7.38)	+2.61 (3.70)	0	0	2	S, S
SCC/28H0.1	0.10		13.17 (-)	25.32 (-)	2.41 (-)	49.70 (-)	0	+100 (-)	0	1	P
SCC/28H0.25	0.25		8.99 (-)	16.80 (-)	0.36 (-)	18.86 (-)	+17.09 (-)	+0.91 (-)	+1.22 (-)	1	S
SCC/28H0.4	0.40		1.71 (-)	6.60 (-)	0.13 (-)	2.60 (-)	0	0	0	1	S
SCCSAP1	0.00	43.63 (0.54)	13.21 (0.69)	24.50 (1.19)	11.02 (0.17)	166.36 (7.19)	-	-	-	2	P, P
SCCSAP1C0.3	0.30		4.29 (0.04)	10.44 (2.65)	0.33 (0.02)	12.41 (2.64)	-	-	-	2	S, S
SCCSAP1C0.4	0.40		2.07 (0.13)	4.39 (0.54)	0.42 (0.02)	8.33 (2.27)	-	-	-	2	S, S
SCCSAP1/14H0.3	0.30		5.44 (0.42)	11.08 (1.82)	0.18 (0.03)	9.32 (0.55)	+12.93 (4.67)	+7.14 (9.61)	0	3	S, S, S
SCCSAP1/14H0.4	0.40		1.46 (0.40)	3.27 (0.59)	0.10 (0.06)	2.15 (0.69)	0	0	0	2	S, S
SCCSAP1/28H0.3	0.30		5.0 (1.89)	13.05 (3.43)	0.30 (0.04)	11.39 (4.67)	+11.55 (17.87)	+18.55 (24.41)	+0.047 (0.09)	4	S, S, S, S
SCCSAP1/28H0.4	0.40		2.89 (-)	7.33 (-)	0.10 (-)	5.89 (-)	+7.36 (-)	+14.62 (-)	0	1	S
SCCSAP2	0.00	37.24 (0.46)	16.45 (1.87)	25.20 (0.56)	6.75 (1.50)	125.91 (13.59)	-	-	-	3	P, P, P
SCCSAP2C0.3	0.30		6.23 (0.86)	13.40 (0.52)	0.095 (0.01)	9.46 (2.99)	-	-	-	2	S, S
SCCSAP2C0.4	0.40		4.13 (0.40)	8.12 (0.21)	0.11 (0.08)	5.18 (0.91)	-	-	-	2	S, S
SCCSAP2/14H0.3	0.30		8.40 (1.00)	16.75 (2.35)	0.64 (0.45)	17.67 (7.47)	+21.23 (9.83)	+28.56 (19.60)	+8.19 (6.75)	4	S, S, S, S
SCCSAP2/14H0.4	0.40		3.65 (-)	7.39 (-)	0.17 (-)	4.35 (-)	0	0	0.90 (-)	1	S
SCCSAP2/28H0.3	0.30		9.81 (2.82)	16.90 (2.63)	0.35 (0.25)	17.10 (8.29)	+35.07 (2.82)	+29.66 (22.22)	+3.97 (3.64)	5	S, S, S, S, S
NC	0.00	58.82 (1.39)	17.40 (2.07)	25.79 (1.15)	6.50 (1.46)	152.51 (9.66)	-	-	-	3	P, P, P
NCC0.2	0.20		7.35 (-)	18.05 (-)	0.043 (-)	12.57 (-)	-	-	-	1	S
NCC0.3	0.30		3.72 (0.19)	11.64 (1.74)	0.33 (0.46)	8.92 (0.19)	-	-	-	2	S, S
NCC0.4	0.40		1.68 (0.35)	4.61 (0.14)	0.087 (0.12)	2.56 (2.02)	-	-	-	2	S, S
NC/14H0.3	0.30		2.98 (0.97)	9.35 (2.77)	0.83 (0.43)	4.70 (1.31)	+0.91 (1.58)	0	+8.07 (6.90)	3	S, S, S
NC/28H0.3	0.30		6.73 (1.78)	11.84 (0.60)	0.80 (0.82)	20.96 (23.81)	+22.02 (13.01)	+2.14 (3.50)	+8.87 (11.58)	3	S, S, S
NC/28H0.4	0.40		3.0 (-)	5.82 (-)	1.64 (-)	3.77 (-)	+8.40 (-)	+5.69 (-)	+24.14 (-)	1	S
NCSAP1	0.00	54.36 (1.20)	12.57 (0.80)	24.37 (0.31)	8.11 (0.65)	148.66 (13.97)	-	-	-	3	P, P, P
NCSAP1C0.3	0.30		3.29 (0.09)	9.85 (0.19)	0.32 (0.07)	7.10 (3.35)	-	-	-	2	S, S
NCSAP1C0.4	0.40		3.20 (0.42)	5.56 (0.03)	1.46 (1.08)	17.85 (4.45)	-	-	-	2	S, S
NCSAP1C0.5	0.50		0.83 (-)	2.58 (-)	0.40 (-)	7.25 (-)	-	-	-	1	S
NCSAP1/14H0.3	0.30		3.04 (0.65)	10.44 (4.46)	1.26 (0.66)	5.49 (1.86)	+1.149 (1.63)	+12.89 (18.22)	+12.12 (8.53)	2	S, S
NCSAP1/14H0.4	0.40		2.05 (0.04)	4.26 (0.73)	0.44 (0.03)	2.62 (0.22)	0	0	0	2	S, S
NCSAP1/28H0.3	0.30		3.73	12.20	1.24	8.14	+7.73	+16.20	11.78	3	S, S, S

			(1.20)	(2.08)	(0.27)	(0.34)	(8.58)	(14.33)	(3.45)		
NCSAP1/28H0.4	0.40		1.73 (-)	7.06 (-)	1.13 (-)	5.06 (-)	0	+7.97 (-)	0	1	S
NCSAP2	0.00	46.83 (0.17)	12.61 (0.79)	25.02 (0.15)	9.08 (1.13)	154.60 (20.31)	-	-	-	3	P, P, P
NCSAP2C0.15	0.15		5.04 (1.43)	13.97 (2.80)	1.76 (1.29)	13.22 (1.46)	-	-	-	2	S, S
NCSAP2C0.3	0.30		2.57 (0.12)	5.69 (2.37)	1.66 (0.12)	4.90 (3.21)	-	-	-	2	S, S
NCSAP2/14H0.2	0.20		3.34 (1.16)	7.98 (1.06)	1.03 (0.92)	4.70 (0.58)	+0.11 (0.16)	0	0	2	S, S
NCSAP2/14H0.3	0.30		2.39 (0.38)	7.03 (0.01)	0.67 (0.45)	4.35 (1.03)	+0.47 (0.66)	+6.91 (0.05)	0	2	S, S
NCSAP2/28H0.3	0.30		1.95 (0.88)	7.89 (0.01)	0.47 (0.28)	6.07 (1.27)	+0.033 (0.047)	+11.37 (0.07)	0	2	S, S
NCSAP2/28H0.35	0.35		0.82 (-)	6.58 (-)	0 (-)	2.92 (-)	0	+20.60 (-)	0	1	S
Range of parameter	$0.10 \leq w \leq 0.50$		0.8-19.5	2.6-27.1	0.0-14.5	1.1-180.6	0.0 to +45.50	0.0 to +100.0	0.0 to +24.14	All specimens $n = 94$	

* data inside the parentheses denote the standard deviation.

Table 3 Review of the effect of SAP on concrete compressive strength in literature

References	SAP (%)	w/c	w_e/c	w_T/c	Reduction range of f'_c (%)
Lam and Hooton (2005)	0.3, 0.6	0.35	0, 0.10	0.35, 0.45	20.46-32.48
Igarashi and Watanabe (2006)	0.35, 0.7	0.25	0, 0.04, 0.09	0.25-0.34	3.29-22.36
Piérard et al. (2006)	0.3, 0.6	0.35	0, 0.02, 0.04	0.35-0.39	7.48-21.65
Lura et al. (2006)	0.40	0.31, 0.32	0, 0.05	0.31-0.37	2.76-8.62
Mechtcherine et al. (2006)	0.40	0.25	0, 0.04	0.25, 0.29	2.27
Esteves et al. (2007)	0.20	0.25-0.35	0, 0.05	0.25-0.40	7.0-19.26
Dudziak and Mechtcherine (2008)	0.40	0.24, 0.25	0.03, 0.05	0.28, 0.29	2.27-12.79
Craeye and De Schutter (2008)	0.04, 0.06, 0.08	0.32	0-0.10	0.32-0.42	16.0-31.0
Dudziak and Mechtcherine (2009)	0.3, 0.4	0.22, 0.27	0-0.07	0.22-0.31	1.57-25.19
Wang et al. (2009)	0.3, 0.5, 0.7	0.3, 0.34	0-0.06	0.30-0.38	3.41-12.38
Hasholt et al. (2010)	0-0.6	0.35-0.50	0-0.07	0.35-0.57	0.97-17.12
Craeye et al. (2011)	0-0.42	0.32	0-0.19	0.32-0.51	13.25-28.02
Schröfl et al. (2012)	0.1, 0.2, 0.3	0.30	0-0.26	0.30-0.56	2.66-50.37
Olawuyi and Boshoff (2013)	0-0.6	0.25	0-0.19	0.25-0.44	7.83-44.84
Mechtcherine et al. (2014)	0, 0.3	0.30	0, 0.03, 0.04	0.30-0.34	6.61-8.53
Laustsen et al. (2015)	0.07, 0.15, 0.3	0.45	0-0.13	0.45-0.58	9.52-31.75
Wang et al. (2013)	0-0.60	0.35	0	0.35	8.46-19.58
Snoeck et al. (2014)	0.5, 1.0	0.50	0-0.3	0.50-0.80	1.72-53.49
Justs et al. (2015)	0.21, 0.31	0.15, 0.2	0, 0.03	0.15-0.20	8.88-19.52
Kong et al. (2015)	0.20, 0.40	0.29	0, 0.05, 0.1	0.29-0.39	4.69-53.39
Van Tittelboom et al. (2016)	1.0	0.27	0, 0.07	0.27, 0.34	18.32
Shen et al. (2016)	0.05, 0.15, 0.26	0.33	0-0.05	0.33-0.38	2.34-10.47
Mechtcherine et al. (2017)	0-0.60	0.45	0, 0.05, 0.07	0.42-0.50	0.27-23.68

Note: w/c= initial water-to-cement ratio; w_e/c= additional water-to-cement ratio; w_T/c= total water-to-cement ratio.