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EFFECT OF DOSE AND TYPES OF THE WATER REDUCING ADMIXTURES AND SUPERPLASTICIZERS ON CONCRETE STRENGTH AND DURABILITY BEHAVIOUR: A REVIEW

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Abstract. As one of the concrete admixtures, water reducing admixtures and superplasticizers are usually used to reduce the mixing water volume and improve the performance of the harden concrete while maintaining better workability of the fresh concrete. However, the concrete strength and durability properties are affected differently by different types and dosages of the water reducing admixtures and superplasticizers. Based on the published literatures, this paper comprehensively reviews and analyzes this problem. Different types of the concretes, including ordinary Portland cement concrete, ordinary Portland cement concrete containing pozzolan, fly ash and ground granulated blast furnace slag, calcium sulfoaluminate cement concrete, ferrite aluminate cement concrete, recycled aggregates concrete, lightweight aggregate concrete, self-compacting concrete and ultra-high performance concrete, are considered to discuss the influence of types and dosages of the water reducing admixtures and superplasticizers on their strengths. Water absorption, frost resistance and permeability resistance of the concrete are mainly reviewed to discuss this influence on the durability properties of the concrete. Then, some suggestions on the application of the water reducing admixtures and superplasticizers in reinforced concrete structures and projects are proposed.

Keywords: type of the water reducing admixtures and superplasticizers, dosages of the water reducing admixtures and superplasticizers, concrete strength, durability property.

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1. Introduction

Due to the development of the modern projects, new requirements for the durability and construction technology of the reinforced concrete (RC) structural members are constantly put forward. To meet this demand, adding chemical admixtures in concrete is one of the most commonly method (Plank & Ilg, 2019; Yaphary et al., 2017). In the modern advanced concrete, about 80% of the produced concrete contains different kind of the admixtures (Plank & Ilg, 2019). Among them, the widely used admixtures in the fresh concrete are water-reducing admixtures and high water-reducing admixtures (superplasticizers). At present, according to the capacity of reducing water, water reducing agents are usually divided into ordinary water reducing agents represented by lignosulfonate, high range water reducing agents represented by naphthalene series, aliphatic series, etc., and high-performance water reducing agents represented by polycarboxylic acid series. According to their functions, they are divided into early strength type, standard type and retarding type, and the water reducing rate is generally more than 5% (Collepardi, 1996). By adding the water reducing admixtures in the fresh concrete, high strength concrete without losing the workability can be obtained (Papayianni et al., 2005; Aicha, 2020).

For the fresh concrete, the flocculation cement particles are deflocculated by the addition of the water reducing admixtures and superplasticizers and open network voids are formed, see Figure 1 (Bjömström & Chandra, 2003). The added water reducing admixtures are adsorbed on the hydrating cement particles, see Figure 2a. For the previous generation of the water reducing admixtures such as lignosulfonate, the electrostatic repulsion shown in Figure 2b is the dominant cement dispersion mechanism. For the new generation of the high-performance water reducing agents such as polyacrylates, polycarboxylates, and polyethylenebased copolymers, inhibition of reactive sites (see Figure 2d) through dispersion becomes the dominating mechanism (Mehta & Monteiro, 2017), where HMW and LMW indicate high and low molecular weight, respectively. For all types of the water reducing admixtures, the steric repulsion shown in Figure 2c creates short-range physical barriers between the cement particles.

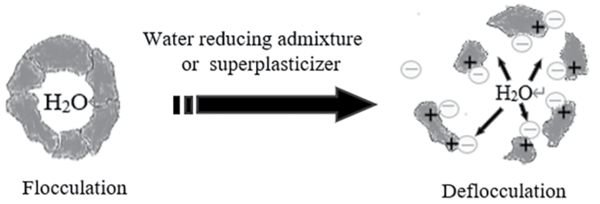


Figure 1. Flocculation of cement particles by the water reducing admixtures and superplasticizers (Bjömström & Chandra, 2003)

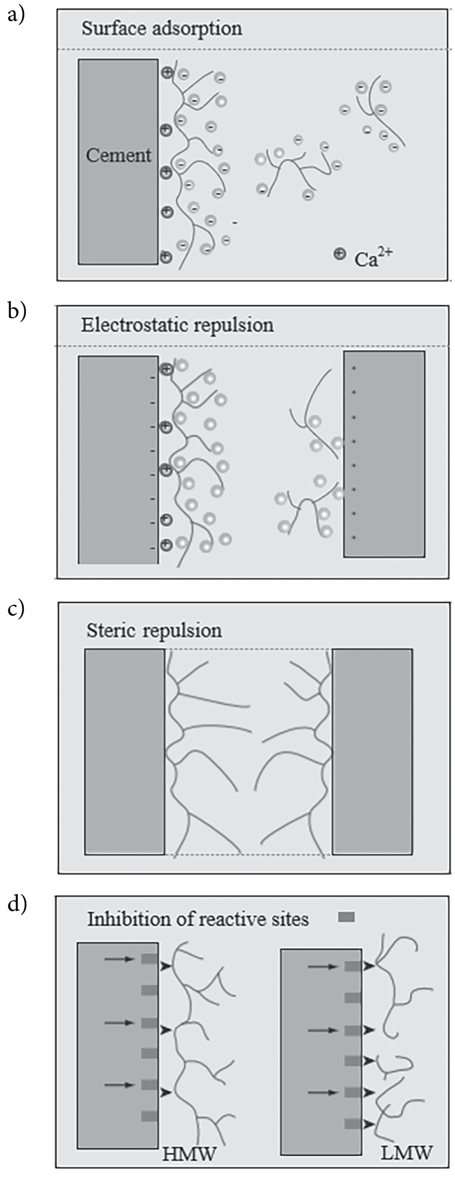


Figure 2. Diagrammatic illustration of the dispersion mechanisms of the water reducing admixtures and superplasticizers (Mehta & Monteiro, 2017)

However, due to the distinct cement, different doses and types of the water reducing admixtures and superplasticizers, it is a complex task to understand and quantify their effects in the fresh concrete (Boukendakdji et al., 2012). It is still uncertain how the concrete strength and durability behaviour are influenced by the different dosages and types of the water reducing admixtures and superplasticizers? In the present paper, a comparatively review has been carried out to discuss the influence of varying dosages and different types of water reducing agents and superplasticizers on concrete strength and durability behaviour. Basing on the literature review, some suggestions for the application of water reducing agents and superplasticizers in the preparation of structural concrete in practical projects are proposed.

2. Effect of different dosages and types of the water reducing admixtures and superplasticizers on the concrete strength

Usually, the compatibility or incompatibility of cement and admixtures can have unpredictable effects on cement hydration; for the same water reducing agent and superplasticizer, this effect may vary when the concrete type is different (John et al., 2019; Marchon & Flatt, 2016). In this section, the influence of varying dosages and different types of superplasticizers on concrete strength will be reviewed, considering different types of concretes containing different cementitious materials and aggregates.

2.1. Ordinary Portland cement concrete

Three types of the superplasticizers (Jhatial et al., 2018) – BASF Rheobuild 850, 561 and 858, were used to M15 concrete with a water-to-cement ratio (W/C) of 0.5, where the superplasticizer dosages ranged from 0.5%~2.5% with an increment of 0.5%. Ordinary Portland cement (OPC) was used as the cementitious material. The results showed (see Figure 3) that, the lower superplasticizer dosages addition effectively improved the 28-day compressive and flexural strengths of the concrete. For the 28-day compressive strength of the concrete, those lower superplasticizer dosages were equal and less than 1.0%, 1.5% and 2.0% for BASF Rheobuild 561, 858, and 850, respectively; for the flexural strength of the concrete, those lower superplasticizer dosages were equal and less than 1.5%, 1.5% and 2.0% for BASF Rheobuild 561, 858, and 850, respectively. Then, for each superplasticizer, when the superplasticizer dosage was larger than the above-stated corresponding dosage, both compressive and flexural strengths of the concrete decreased with the increased superplasticizer dosages. It can be seen from Figure 3 that, the concrete with 1.0% addition of BASF Rheobuild 561 had the maximum increase in compressive strength while for the flexural strength, 2.0% BASF Rheobuild 850 resulted in a maximum increase.

Similar results were also observed by Antoni et al. (2017), where five superplasticizers – CC, SV, AS, BA and BS, were used to OPC mortars with W/C of 0.3. The 7-day and 28-day compressive strength of the mortar increased and then decreased with increasing dosage of the superplasticizers (see Figure 4).

Except for AS, the optimum dosage for the other four superplasticizers was about 0.4% to 0.5%, resulting in an increased mortar strength about 20 MPa. It is worth noting that, when the dose of AS was larger than 0.5%, the mortar compressive strength declined more significantly. After the dosage of AS reached 0.8%, the compressive strength had been below the strength of mortar without superplasticizer, which was due to the segregation of the fresh mortar with excessive superplasticizer, meanwhile there were more significant decrease in the 7-day harden mortar compressive strength. Obviously, the addition of excess superplasticizer maybe has greater adverse influence on early strength of the mortar, thus higher early strength was observed in OPC concrete without water reducing agent (Ramachandran et al., 2017). For OPC mortars with 0.25 and 0.35 water-to-cement ratios (W/C), the change of the compressive strength of the 28-cured mortar with the varying doses of the superplasticizers CC, SV, AS, BA and BS is shown in Figure 5.

Compared to the same mortar without the superplasticizer, for OPC mortars with lower W/C (see Figure 5a), the 28-day compressive strength was comparatively larger increasing with the varying dosages of CC, SV and BA superplasticizers; and the optimum dosages of CC, SV and BA superplasticizers range from 0.2% to 0.5%. For OPC mortars with larger W/C and the varying dosages of AS and BS superplasticizers (see Figure 5b), comparatively obvious increment in 28-day compressive strength was observed. Thus, it seems that, for the same OPC mortar and concrete, the optimum dosage is depending on the superplasticizer type. In addition, due to the different superplasticizer type and optimum dosage, the increment in the concrete/mortar compressive strength is also different.

Apparently, Table 1 summarizes the optimum dosages of different water reducing agents and superplasticizers applied to OPC concrete from other experimental studies. It also clearly shows that, for different superplasticizer type, the increment in compressive strength and the optimal dosage of OPC mortar and concrete with the same coarse or fine aggregate type is different.

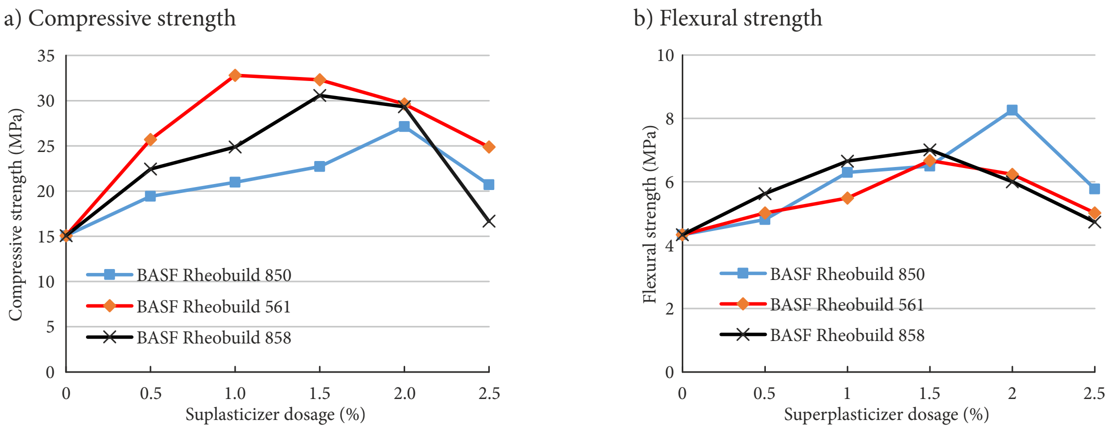


Figure 3. Variation of the 28-day compressive and flexural strength of the ordinary Portland cement concretes with varying dosages of three different superplasticizers (data from Jhatial et al., 2018)

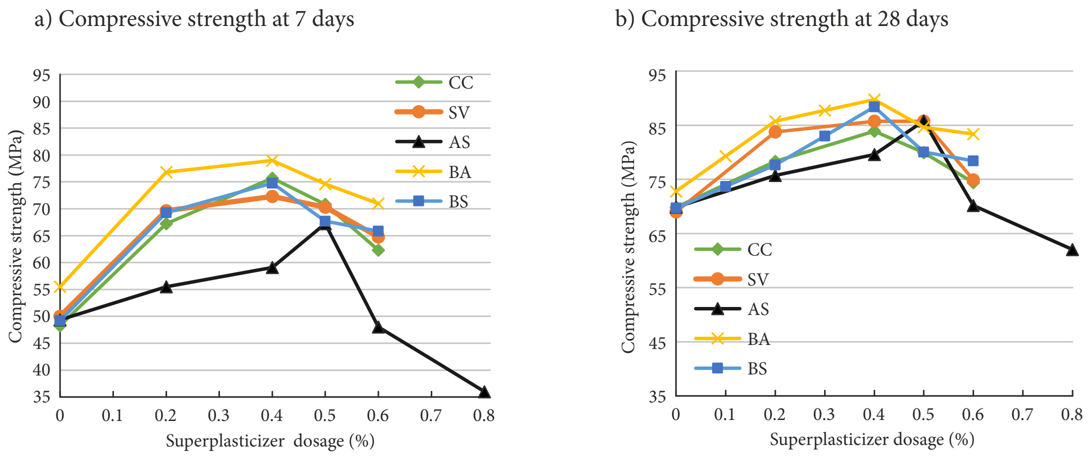


Figure 4. Variation of the 7-day and 28-day compressive strength of the ordinary Portland cement mortars with varying dosages of five superplasticizers (data from Antoni et al., 2017)

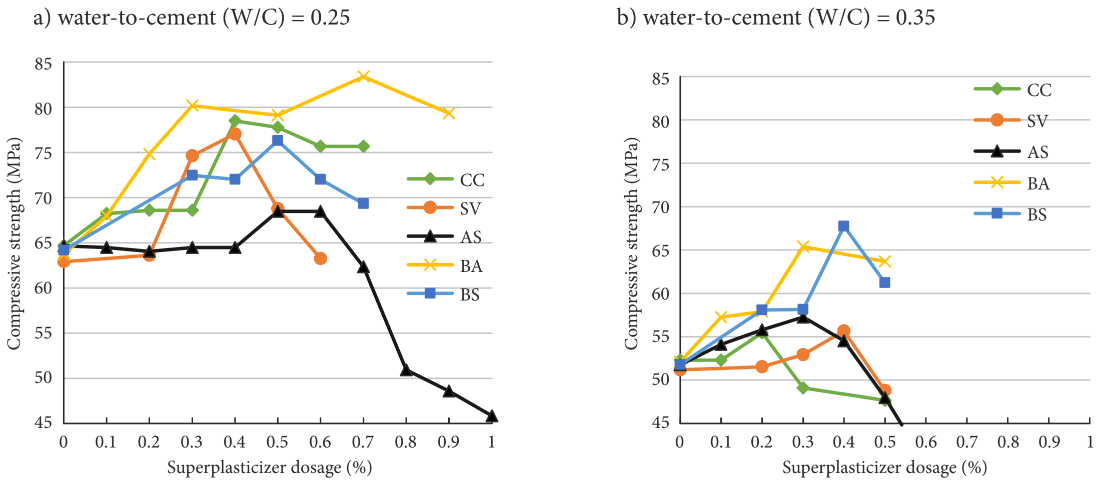


Figure 5. Variation of the 28-day compressive strength of the ordinary Portland cement mortars with different water-to-cement ratios with varying dosages of five superplasticizers (data from Antoni et al., 2017)

Table 1. The optimal dosage of different superplasticizers in OPC concrete or mortar

Compressive strength class	Superplasticizer	Optimum dosage / %	Type of coarse aggregate	Type of fine aggregate	Water-to-binder ratio (W/B)	Increased compressive strength at 28d /%	References
M15	BASF Rheobuild 850	2.0%	Crashed stones with a maximum size of 20 mm	Crushed stones with a maximum size of 4.75 mm	0.5	80.1%	Jhatial et al. (2018)
M15	BASF Rheobuild 561	1.0%	Crashed stones with a maximum size of 20 mm	Crushed stones with a maximum size of 4.75 mm	0.5	117.7%	Jhatial et al. (2018)
M15	BASF Rheobuild 858	1.0%	Crushed stones with a maximum size of 20 mm	Crushed stones with a maximum size of 4.75mm	0.5	102.9%	Jhatial et al. (2018)
M20	Type A, and F, anionic melamine polycondensate non-toxic superplasticizer	0.5%	Crushed stones with a maximum size of 20 mm	Ordinary sand	0.48	40.2%	Shah et al. (2014)
M30	Liboment-FF	1.8%	Crushed granite with a maximum size of 20 mm	Sea sand	/	12.8%	Alsadey (2013)
M30	Glenium	0.8%	Crushed granite with a maximum size of 20 mm	River sand with a maximum size of 5 mm	0.66	10.8%	Salem et al. (2016)
M35	Sikament@R2002	1%	Crushed granite with a maximum size of 20 mm	Sylhet sand	/	29.5%	Muhit et al. (2013)

2.2. Portland pozzolan cement concrete

Strength variation of Portland pozzolan cement (PPC) mortars with the dosage of five different superplasticizers – CC, SV, AS, BA and BS was also studied by Antoni et al. (2017), see Figure 6. Similar to the trend shown in Figure 4, the 7-day and 28-day PPC mortar compressive strength increased and then decreased with excess superplasticizer. Even so, compared with the OPC mortars with the same W/C in their experimental study, the optimum dosages relevant to the maximum increment in compressive strength was relatively low, ranging from 0.2% to 0.5%. This is mainly due to the reduction of the inter-particle attraction force by the volcanic ash, and thus reducing the amount of water required in the fresh concrete mix. The optimum dosages of the five superplasticizers, namely CC, SV, AS, BA and BS for the maximum increment in compressive strength varied greatly when they were compared to the mortar without the superplasticizer. For instance, compared to the same mortar without superplasticizers, the maximum increment in 28-day compressive strength of PPC mortar by the addition of superplasticizers CC, SV, AS, BA and BS were 5.8%, 31.7%, 23.3%, 25.1% and 28.2%, respectively. The maximum and minimum increment in mortar strength corresponds to the 0.5% addition of SV and 0.2% addition of CC superplasticizers, respectively.

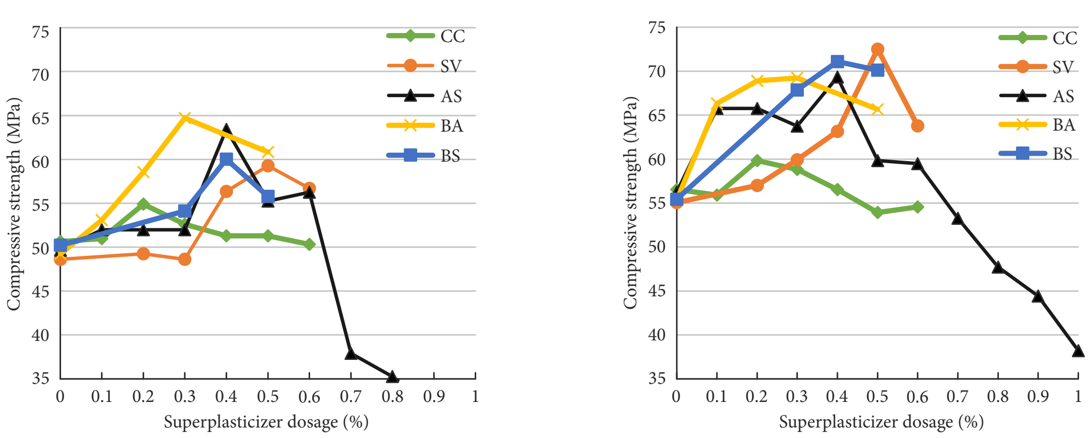
Considering the strength variations of ordinary Portland cement mortars and Portland pozzolan cement (PPC) mortars with the dosage of five different superplasticizers – CC, SV, AS, BA and BS shown in Figure 4 and Figure 6, it can be concluded that, for the same type of the mortar and concrete, the increment in mortar and concrete strength resulting from the addition of the different superplasticizers is different; for the same type of the water-reducing agent, the optimum dosages relevant to the maximum increment in compressive strength of two types of the mortar and concrete is different. Those different effects clearly show the compatible or incompatible problems between binders and superplasticizers.

2.3. Ordinary Portland cement concrete containing fly ash

It is universally known that fly ash is a solid particle dross produced by the combustion of coal, consisting mostly of SiO_2, Al_2O_3, Fe_2O_3, CaO and other impureness. Fly ash exhibits pozzolanic properties when the CaO content is low, and exhibits cementitious properties when fly ash contains up to 20% CaO (Oner et al., 2005). At ambient temperatures, fly ash can serve as partial substitute of cement or as mineral additive. The resulting product through the pozzolanic effect fills the pores inside concrete to increase the compressive strength and impermeability (Ahmaruzzaman, 2010). However, changes in W/C and the content of fly ash will affect the concrete strength (Law et al., 2015), and these adverse effects can be reduced by adding water reducing agents and superplasticizers.

Stuart et al. (1980) investigated the optimal amount of two superplasticizers, i.e., melamine-based admixture and naphthalene-based admixture, on the strengths of Portland cement mortars containing 0%, 20%, 40% and 60 % by volume fly ash replacements. Test results showed that the trend of water reduction rate and the strength were consistent for the concrete with melamine-based admixture. Its optimum dosage was a little more than the maximum recommended dosage when the W/C of mortar was 0.63. While for the naphthalene-based admixture, the variation of water reduction rate and strength had multi-peak characteristics due to the ability to further deflocculate the grains at high dosages and the optimum dosage of the superplasticizers was the same as the maximum recommended dosage.

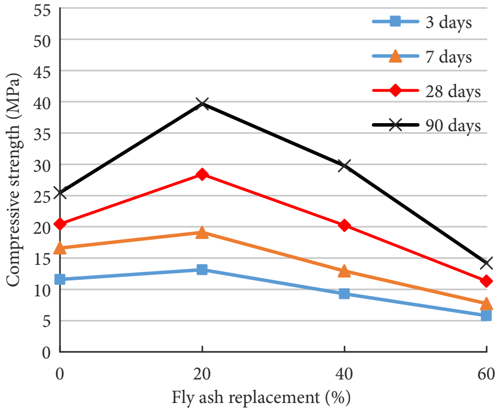
In addition, owing to the high-efficiency water reducing agents attached onto cement particles, the optimal dose which was on account of the content of the Portland cement in concrete was not affected by fly ash replacements (Stuart et al., 1980). For fly ash concrete without super water reducer, when the fly ash replacements varied from 20% to 60%, the maximum strength of the fly ash concrete at 3, 7, 28 and 90 days were observed at 20% fly ash replacement, see Figure 7a. For fly ash concrete mixed with the water reducing agents, the concrete strength decreased with the increased fly ash replacements from 0% to 60% (see Figures 7b and 7c). It was appeared that the strength-producing properties of the fly ash and its replacement percentage were important factors (Stuart et al., 1980). However, the strength of concrete mixed with melamine-based admixture was higher at 0% fly ash replacement, see Figure 7b. For the same target slump (50 mm~90 mm) of the fresh concrete containing fly ash, when the water reducing agents added were the maximum dose, 1.5 times the maximum dose or 2 times the maximum dose, the increased admixture dosage led to increased concrete strength (Alaka & Oyedele, 2016). That because the water reducing agent reduced the W/C required to achieve the set target slump, and the corresponding W/C at each dose ranged from 0.35 to 0.38, 0.31 to 0.34 and 0.28 to 0.32.


a) Compressive strength at 7 days

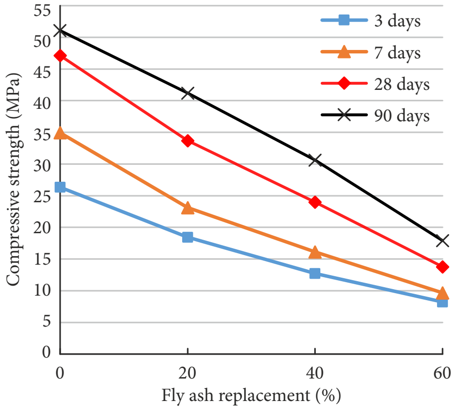
b) Compressive strength at 28 days

Figure 6. Variation of the 7-day and 28-day compressive strength of the Portland pozzolan cement mortars with varying dosages of five superplasticizers (data from Antoni et al., 2017)

a) Compressive strength of mortar without super water reducer



b) Compressive strength of mortar with melamine-based admixture



c) Compressive strength of mortar with naphthalene-based admixture

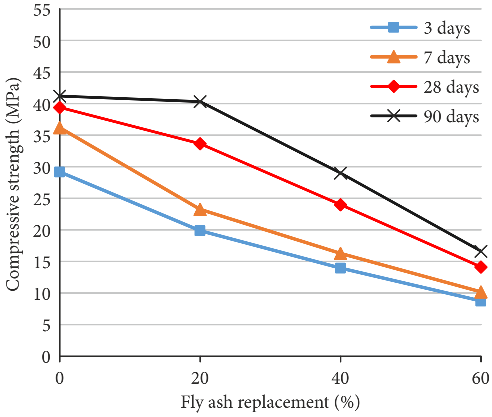


Figure 7. The effect of two types super water-reducing admixtures on concrete incorporating fly ash and varied dosages at 3, 7, 28, 90 days (data from Stuart et al., 1980)

So, from this perspective, for concrete with high volume fly ash, the excess water reducing agent is beneficial to its strength. It is worth noting, however, that the high range water reducers contain a certain percentage of water content (Stuart et al., 1980; Alaka & Oyedele, 2016), which means that very large doses may lead to a corresponding increase in the W/C.

2.4. Ordinary Portland cement concrete containing GGBFS

Ground granulated blast furnace slag (GGBFS) is a by-product of the ironmaking, and consists of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, etc. (Raut et al., 2015; Özbay et al., 2016). The strength of the OPC concrete containing GGBFS was also influenced by the different water reducing agent dosages. For instance, 0.25% by the weight of cement of three superplasticizers, namely Na-styrene sulphonate, Na-β-naphthol and Na-phenol sulphonate formaldehyde condensates, were added to the slag cement slurry with an initial W/C of 0.25, respectively. The compressive strength of the slag cement pastes with the superplasticizer was enlarged to some extent, mainly because the addition of superplasticizer meliorated the pore structure of the slurry hardening and made the structure denser (El-Hosiny et al., 2002).

Memon et al. (2007) prepared mortars with three mix ratios (1:2, 1:2.5 and 1:3, respectively) firstly and then investigated the compressive strength of the mortars at 0%, 50% and 60% GGBFS replacements and superplasticizer dosage in the range of 0% to 0.5% by the mass of blast furnace slag and OPC, where superplasticizer of trade named SIKAMENT NN was used. Test results showed that (see Figure 8), for mortar with 0% GGBFS, the increase in water reducing agent dosage increased the compressive strength (see Figure 8a). For mortars with 50% and 60% GGBFS replacements, the increase of water reducing agent dosage was beneficial to the compressive strength, but the increase trend gradually slowed down when the dosage exceeded 0.2%, then the compressive strength tended to be stable when the dosage was in the range of 0.3% to 0.4% (see Figures 8b and 8c). For mortar with mix ratio 1:2.5 and 50% GGBFS replacements, the compressive strength was reduced when the water reducing agent dose reached 0.5% (see Figure 8b). The same trend was also observed for mortar with mix ratio 1:3 and 60% GGBFS replacements (see Figure 8c). That is because the tardy hydration process resulting from the superplasticizers in high dose (Fujii et al., 2015), which meant that, from view of both cost and engineering requirements, the better dosage of the superplasticizer SIKAMENT NN was 0.2% by the weight of total binder.

2.5. Calcium sulfoaluminate cement concrete and ferrite aluminate cement concrete

Calcium sulfoaluminate cement (CSC) concrete is prepared with CSC and mixed with sodium nitrite admixture, which is characterized by high early strength, better frost resistance and corrosion resistance as well as low shrinkage (García-Maté et al., 2013; Qin et al., 2018), and is widely used in the RC structures. In practical projects, water reducing agents and superplasticizers in the CSC concrete can improve the strength and enhance the workability.

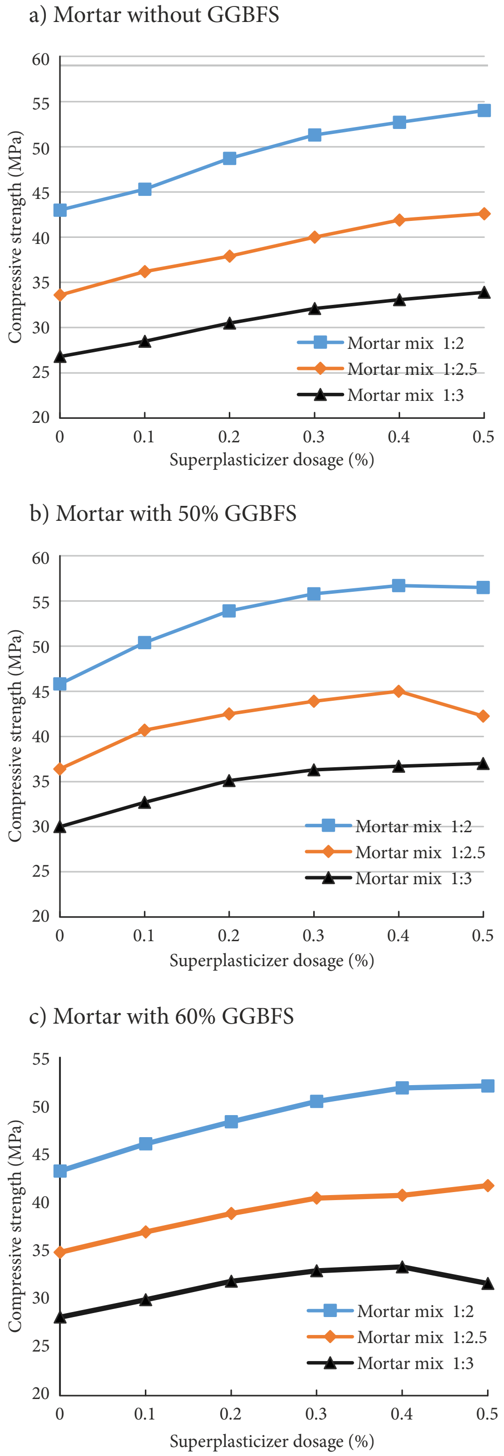


Figure 8. Effect of different superplasticizer dosages on the 28-day compressive strength of the mortars incorporating GGBFS and varied dosages (data from Memon et al., 2007)

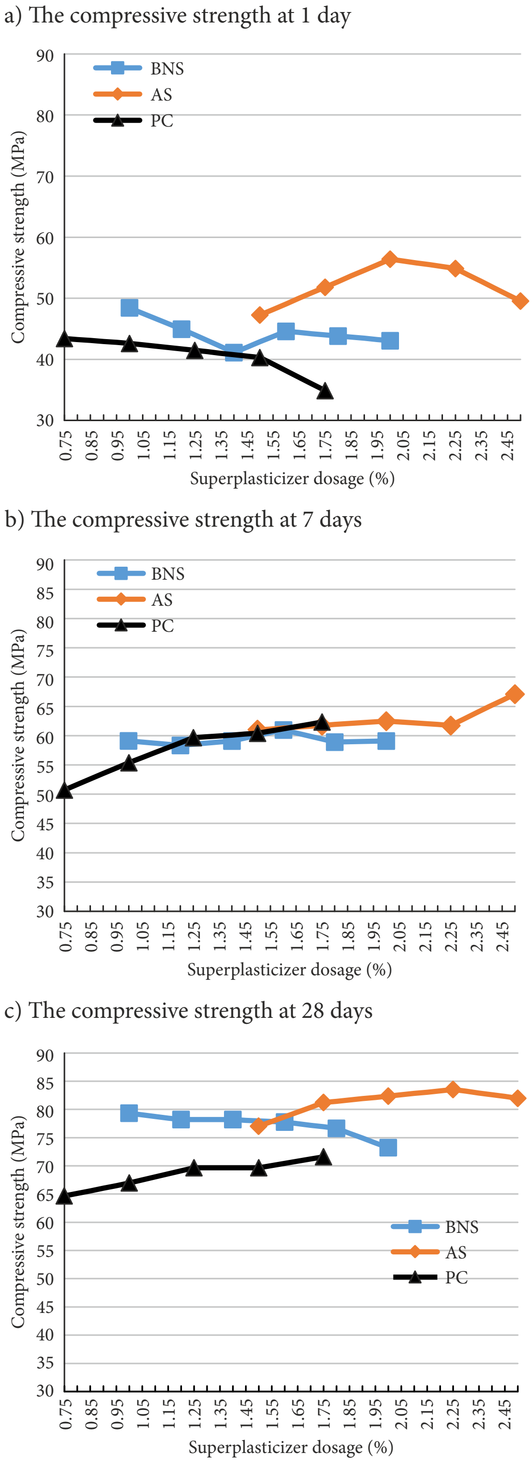


Figure 9. Effects of superplasticizer dosage on compressive strength of the calcium sulfoaluminate cement mortars (data from Zhang et al., 2016)

For CSC mortar with W/C of 0.35 (Zhang et al., 2016), the effect of different type and doses of superplasticizer on mortar strength were investigated, where β-naphthalenelfonic acid-based superplasticizer (BNS), aminosulfonic acid-based superplasticizer (AS), polycarboxylate acid-based superplasticizer (PC) were used. Five different dosages were selected for BNS, AS and PC, see Figure 9. The 1-day compressive strength of samples containing BNS first decreased and then tended to level off. For the mortar containing AS, the strength first rose and then started to decrease when the amount of AS exceeds 2%. For the mortar containing PC, the strength decreased from the beginning, and the change was most obvious at the dose of 1.75%, and the compressive strength was about 10 MPa lower than those of the other two types of the mortar with superplasticizers BNS and AS (see Figure 9a).

The 7-day and 28-day compressive strengths of mortar samples obviously increased compared to the 1-day compressive strength of the corresponding mortars with the same superplasticizer, see Figure 9b and Figure 9c. For mortar samples with BNS, AS and PC, in the corresponding dosage ranges – 1.0%~2.0% for BNS, 1.5%~2.5% for AS and 0.75%~1.75% for PC, respectively, the variations in 7-day compressive strength were 0~3.2%, 0~10% and 0~22.9%, respectively, indicating the 7-day compressive strength of mortar samples was less affected by BNS and increased slightly with increasing AS and PC dosages (see Figure 9b). For the 28-day compressive strength of mortar samples, different strength variation trends were observed, see Figure 9c: compressive strength of mortar samples with PC increased from 64.7MPa to 71.6 MPa with the increased superplasticizer dosages from 0.75%~1.75%; compressive strength of mortar samples with BNS decreased from 79 MPa to 73.2 MPa with the increased superplasticizer dosages from 1.0% to 2.0%; the strength of mortar samples with AS increased with the increased superplasticizer dosages from 1.5% to 2.25% and then began to decrease in the dosage range 2.25%~2.5%.

The above-mentioned phenomena may be related to the fact that the presence of superplasticizer slows the cement hydration down, in the meantime, the reduction in early compressive strength of mortar specimens is associated with the retardation effect for the formation of ettringite (Hekal & Kishar, 1999). Similar conclusions were also obtained in an experimental study by Wu et al. (2021), where two types of superplasticizers, namely BNS and PC, were added to CSC mortar with W/C of 0.35. Test results showed that, with BNS in the range of 0.8% to 2%, the compressive strength of the CSC mortar was gradually increased at 2 hours, 7 days and 28 days. As for superplasticizer PC, the strength increased insignificantly in the dose range of 0.08%~0.17%, and even gradually decreased in 7 days. The 2 h compressive strength decreased by 36%, when the dose amount came up to 0.20%. The scanning electron microscopy (SEM) study on the 2h-mortar showed that, the addition of the BNS in the mortar can promote the generation of the ettringite, thus improving its early compressive strength; while the addition of PC resulting in the morphology of ettringite changed from rod-like to flake-like, causing a decrease in compressive strength.

Although the CSC has the increasing performance advantages, its large-scale application is limited resulting from the scarcity of alumina raw materials (Huang et al., 2020), for which the use of ferrite materials to partially replace aluminum materials in calcium sulphate aluminate cement to make ferrite aluminate cement (FAC) an attempt to solve this problem (Bullerjahn et al., 2014). Huang et al. (2021) investigated the effects of the superplasticizers on workability of FAC pastes. As the experimental study showed, in the FAC pastes with W/C of 0.29, when the fluidity was 180 mm, 240 mm and 270 mm, the required dosage of polycarboxylate acid-based water reducing agent (PC) was lower than that of the melamine-based water reducing agent (MA) and aliphatic-based water reducing agent (AP), which indicated that the PC had slow setting effect and better dispersion capacity in comparison. Similar to CSC concrete, the addition of PC in the concrete retarded the hydration process and had an effect on the hydration product of ettringite (Hekal & Kishar, 1999). During the preparation of FAC paste, the dose of PC should be controlled, which can ensure the strength from the perspective of reducing the W/C.

For the above-mentioned different types of cementitious materials concrete, water reducing agents and superplasticizers added to concrete/mortar can improve the workability and reduce the W/C. The strength of the concrete/mortar can also be improved when the dose of the superplasticizer is in a certain range. But when the dosage of superplasticizer exceeds the optimum, the compressive strength will generally decrease with the increased dosage. This may be caused by the segregation or bleeding caused by excessive superplasticizer, such as the segregation in OPC concrete. The reduction in strength of the concrete containing GGBFS or fly ash may result from the superplasticizer-delayed hydration reaction. The strength of CSC and FAC concrete with water reducing agents is also affected by the quantity and formation of the hydration products. In any case, it is not reasonable that the addition of water reducing agents or superplasticizers exceed the optimal dose. However, in some special cases, excessive water-reducing agents and superplasticizers can be added to make concrete reach the target slump and reduce the W/C as much as possible, such as in the high-volume fly ash concrete.

2.6. Recycled aggregates concrete

For the aim of meeting the challenges in the continuous exploitation of building raw materials and environmental protection, recycled aggregate (RA) will be a greater substitution for natural aggregate (NA). RA can be divided into coarse and fine RA, respectively. Concrete made from RA tends to have poor performance (Olorunsogo & Padayachee, 2002; Zaharieva et al., 2003), and minor addition of water-reducing agents and superplasticizers can improve the RA concrete properties. In the study of Pereira et al. (2012a, 2012b), the fine RA replaced NA at four substitution rates of 0%, 10%, 30%, 50% and 100%. At each substitution rate, for the superplasticizer content of 1% of the cement mass, the addition of lignosulfonate-based regular superplasticizer and modified polycarboxylates high-performance superplasticizer to the concrete increased the 28-day compressive strength. This is due to the adding superplasticizers to ensure the optimal workability of concrete and reduce W/C. The 28-day compressive strength of fine RA concrete without superplasticizer or with modified polycarboxylates superplasticizer was basically not affected by the change of the replacement rate of fine RA while this strength of fine RA concrete with lignosulfonate superplasticizer decreased with the increase of fine RA replacement.

The dispersion mechanism of modified polycarboxylate superplasticizer is mainly due to the so-called steric hindrance effect (Yoshioka et al., 1997; Collepardi, 1998) or steric repulsion shown in Figure 2c, while the dispersion mechanism of lignosulfonate superplasticizer is mainly due to electrostatic repulsion shown in Figure 2b. As fine recycled aggregate had a higher specific surface area, superplasticizer can be adsorbed in the stirring process, thus reducing the effect of ligninsulfonate superplasticizer. The increase of fine RA made an increase of the effective W/C of concrete with the addition of ligninsulfonate superplasticizer greater. Similarly, the increase of the replacement rate of fine RA will also reduce the splitting tensile strength of concrete (Pereira et al., 2012a, 2012b), which can be weakened by the addition of ligninsulfonate superplasticizer or modified polycarboxylates superplasticizer. For coarse RA concrete (Matias et al., 2013a), at the replacement rate of 25%, 50% and 100% coarse RA, similar results were also obtained by adding lignosulfonate superplasticizer and modified polycar-boxylate superplasticizer, respectively. The addition of superplasticizer can reduce the adverse effects brought by the addition of coarse RA. It can be predicted the higher the water reducing capacity of the superplasticizer, the better this effect. On the premise of maintaining a constant effective water-to-binder ratio (W/B), with the increase of the replacement rate of coarse aggregate by coarse RA, the dosage of lignosulfonate superplasticizer did not change while the dosages of the modified polycarboxylate superplasticizer increased from 0.42% to 0.48%, which was always smaller than the dosage of lignosulfonate superplasticizer, indicating the different dispersion mechanism of each superplasticizer, as mentioned above and shown in Figure 2.

2.7. Lightweight aggregate concrete

Light aggregate concrete is made of cement, water, light coarse and fine aggregates. It has the advantages of light, advanced soundproof, heat-insulating, better freezing and fire resistance (Ke et al., 2010). The high-efficiency superplasticizers can usually be added to improve the slump and enhance the concrete strength to prepare high-performance light aggregate concrete (Ramachandran & Malhotra, 1996; Mehta, 1999).

Lightweight fine and coarse aggregates (LWAC), made by Portland cement and fly ash in a certain proportion, were used to prepare concrete (Gesoğlu et al., 2014). Under the condition of constant W/B of 0.32, the appropriate amount of polycarboxylic ether type superplasticizer was added to ensure the target slump of LWAC. The dosage of the superplasticizer was reduced with the increasing utilization rate of light aggregate. The dosage of the superplasticizer was reduced to 0.7% of cement content, when both the replacement rates of coarse and fine aggregate by LWAC of 100%. Due to the brittleness of lightweight aggregate itself, the strength will also decrease with the increased amount of lightweight aggregate (Kim et al., 2010; Khaleel et al., 2011). Experimental results showed that, the increased dosage of the polycarboxylic ether type superplasticizer can reduce the W/B of LWAC while ensuring the target slump, and thus improve the concrete strength (Gesoğlu et al., 2014). This is consistent with the conclusion of Wilson and Malhotra (1998).

2.8. Self-compacting concrete

Self-compacting concrete (SCC) is characterized by the filling capability and evenly through its own fluidity under the action of gravity without the need for manual vibration. Compared with ordinary concrete, self-compacting concrete has lower aggregate content, lower W/C and higher dosage of highly effective superplasticizer (De Schutter et al., 2008; Łaźniewska-Piekarczyk & Szwabowski, 2012; Esen & Orhan, 2016). Because of its better self-compactness, it is more convenient for the construction process, thus saving the cost and reducing the pollution caused by vibration. When self-compacting concrete is prepared, the type and dosage of the superplasticizer have a great influence on its performance.

In the experimental study of Benaicha et al. (2019), water-reducing agent named ViscoCrete Krono 20 with 0.3%~1.0% dosages of the increment of 0.1% were added to self-compacting concrete with W/B of 0.37. When the superplasticizer dose was 0.3%, see Figure 10, the concrete compressive strength at different ages reached the maximum; although the strength decreased with the increased superplasticizer dosages in the range of 0.3% to 0.7%, it was always higher than the concrete strength without superplasticizer. When the superplasticizer dosages were within 0.8%~1%, the addition of superplasticizers reduced

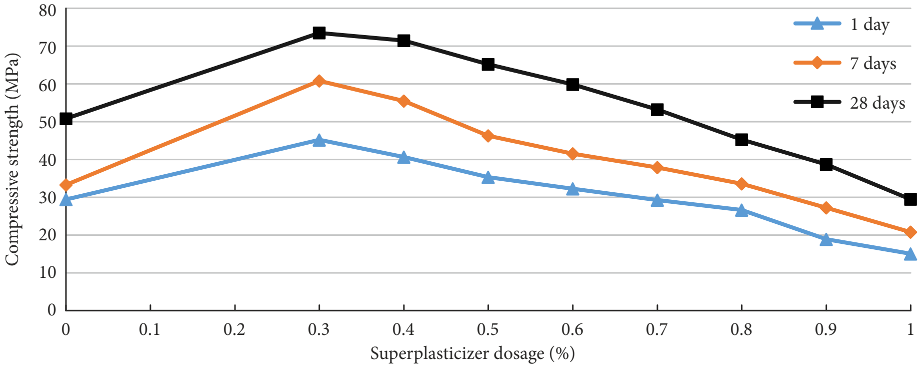


Figure 10. Effects of superplasticizer dosage on strength of self-compacting concrete (data from Benaicha et al., 2019)

the strength to lower than the same age strength of the specimens without superplasticizers (see Figure 10).

The above-stated reduced concrete strength with the increased superplasticizer dosages is related to the segregation and bleeding of the fresh concrete. In SCC, the effectiveness of high-efficiency superplasticizer would not continue to exceed the saturation dosage (Manomi et al., 2018; Oualit et al., 2018), i.e., when the dose exceeded the saturated point, continuously adding high-efficiency superplasticizer would not improve the fluidity of cement paste or fresh concrete but delay the setting time of cement (Aicha, 2020) and lead to segregation and bleeding of fresh SCC (Mazloom et al., 2018). For the Self-compacting concrete S9W45SF0, S11W45SF0, S13W45SF0 and S15W45SF0 with the same water-to-cement ratio 0.45 and the corresponding superplasticizer dosages 0.4%, 0.8%, 1.2% and 1.6%, respectively, no bleeding was observed in S9W45SF0 and S11W45SF0 fresh concrete, while bleeding tendency was shown in S13W45SF0 fresh concrete and segregation, bleeding tendency was observed in S15W45SF0 fresh concrete. The 28-day compressive strength of the harden S9W45SF0, S11W45SF0, S13W45SF0 and S15W45SF0 concrete specimens were 47 MPa, 42 MPa, 40 MPa and 37 MPa, respectively (Mazloom et al., 2018). Compared to the S9W45SF0 specimen with 0.4% superplasticizer dosage, the excessive 1.2% superplasticizer dosage in S15W45SF0 concrete specimen made the 28-day compressive strength 27% reduction. Obviously, when the superplasticizer dosages exceed the saturation dosage, both the workability of the fresh concrete and the strength of the harden concrete are greatly affected.

2.9. Ultra-high performance concrete

Ultra-high performance concrete (UHPC), related to high toughness, ultra-high strength and better durability, is a new type of composite material mainly composed of high-strength matrix and fiber and its W/B is about 0.2 (Yoo & Banthia, 2016; Zhou et al., 2021). Applying the superplasticizer appropriate in preparing UHPC is very important. Adding the superplasticizers to concrete can not only promote its the workability, resulting in the uniform fiber distribution, but also improve the pore structure of the harden concrete. Both two aspects are beneficial for the concrete strengths.

In the experimental study of Wang et al. (2017), for UHPC with fiber volume fraction of 1%, 2% and 3%, the optimal yield stresses of fresh concrete with 1%, 2% and 3% fiber were 900–1000 Pa, 700–900 Pa and 400–800 Pa, respectively. The yield stress was affected by superplasticizer slightly while the superplasticizer reduced W/B down to 0.18. In the fresh concrete, the superplasticizer dosage should be within a relatively suitable range to provide a uniform distribution of fibers. In addition, in cement paste with polypropylene fibers, due to the electrostatic repulsion and steric hindrance effects of polycarboxylate, the dispersibility of polycarboxylate superplasticizer increased with increasing length and dosage of the fiber (Zhang et al., 2019). The microstructure of UHPC is also affected by the superplasticizer dosage. For UHPC containing rushed quartz (Courtial et al., 2013), with the superplasticizer in the range of 0.5% to 1.8%, the microstructure was not changed visibly when there was no crushed quartz; however, the superplasticizer in the range of 1.8% to 2% caused a big impact on the microstructure when there was crushed quartz in concrete.

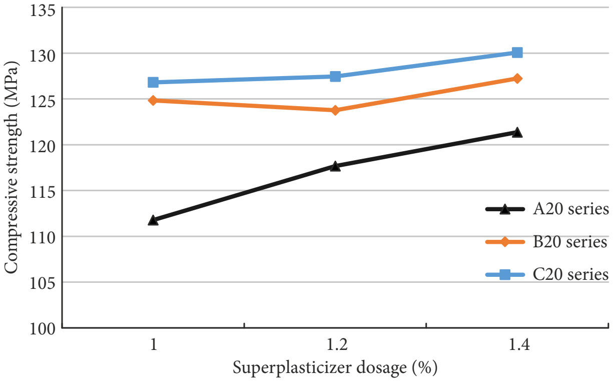


Figure 11. Effects of superplasticizer dosage on 28-day strength of ultra-high-performance concrete (Sadrmomtazi et al., 2018)

The strength of UHPC is also affected by the superplasticizer dosage. Sadrmomtazi et al. (2018) investigated the effect of three superplasticizer contents, i.e., 1%, 1.2%, 1.4%, on the compressive strength of UHPC with a W/B of 0.20 (see Figure 11), where in Figure 11, concrete specimens with the dimension of 50×50×50 mm were prepared. A20, B20 and C20 series specimens shown in Figure 11 all had the W/B of 0.20 while the binder contents in these three series specimens were 800, 900 and 1000 kg/m^3, respectively. Figure 11 shows that, with the increase of the superplasticizer dosage from 1.0% to 1.4%, for A series UHPC with a relatively lower binder contents, the compressive strength increased from 111 MPa to 121 MPa by about 9% increment. While for C series UHPC with the largest binder content, the increase of the concrete compressive strength was not significant.

In conclusion, for ordinary concrete and SCC, the addition of superplasticizers can reduce the W/B as far as possible under the condition of achieving the target slump, and there has a relatively optimal dosage. For UHPC, besides the similar effect of that in ordinary concrete and SCC, the effect of the superplasticizer addition and dosage on the concrete fiber distribution and microstructure should also be considered.

3. Effect of different dosages and types of the water reducing admixtures and superplasticizers on concrete durability behaviour

Durability is defined as the capability of the concrete to resist aggressive environment attacks such as weathering action, chemical attack, abrasion etc. to maintain the integrity of its original structure, quality and serviceability for a long time (Tang et al., 2015). In the following section, the effect of the doses and types of the superplasticizers on the main durability indexes, namely water absorption, frost resistance and permeability resistance of the concrete will be mainly reviewed.

3.1. Water absorption

Water absorption of the concrete can give useful information of the pore structure, permeation and durability behavior of the concrete. As such, water absorption is a vital element for quantifying the durability of concrete (Parrott, 1992; Henkensiefken et al., 2009; Castro et al., 2011). Water absorption rate in unsaturated hydraulic concretes is often determined by the ASTM C1585 (ASTM International, 2004). Since the concrete water absorption is vastly affected by its microstructure, such as pore size, pore structure, pore connection, etc., the influence of the adding superplasticizers on the hydration of the Portland cement and the following microstructure development of the concrete was investigated. Results showed that the two aspects of concrete were affected by the superplasticizers in high doses (Gu et al., 1994). The addition of superplasticizer (1.2% by mass of cement) in OPC paste led to reduced total pore volume and refined pore structures (Khatib & Mangat, 1999). As a result, for the concrete prepared by OPC and NA, the water absorption of the concrete with superplasticizer was reduced by the melamine superplasticizer in 2.2% of cement, leading to 26% lower than that of the concrete without superplasticizer (Grabiec, 1999).

In order to explore the effect of the adding superplasticizer on the durability of concrete made with fine recycled concrete aggregate (RCA), Cartuxo et al. (2016) prepared the concrete with volume replacement rates of NA by fine RCA of 0%, 10%, 30%, 50% and 100%, respectively. Two commercially available superplasticizers, i.e., SikaPlast 898 and Sikament 400 plus were selected, where the amount was 1% by weight of cement. Test results indicated that, the water absorption by immersion and the adverse effects caused by the addition of fine RCA were reduced with the use of the superplasticizers. For the regular superplasticizer Sikament 400 plus, the water absorption by immersion of the concrete containing fine RCA decreased up to 28% while this value up to 43% for the SikaPlast 898 high performance superplasticizer (see Figure 12a). The 72-hour capillary absorption test on three cylindrical specimens made from fine RCA also showed reduction up to 48% and 66% for the Sikament 400 plus and SikaPlast 898, respectively, see Figure 12b. However, for the concrete containing coarse RA (Matias et al., 2013b), due to all coarse RA concrete mixtures absorb about 17% of water, it seems that adding superplasticizer will not affect the water absorption by immersion. Since the coarse RA had the high-porosity mortar portion, the water absorption by capillarity of the coarse RA concrete risen by adding the superplasticizers were almost identical, irrespective of the type of superplasticizer.

3.2. Frost resistance

Frost-induced durability problem of the concrete is mainly related to two factors, i.e., the internal cracking resulting from the freezing-thawing cycles and surface scaling due to the presence of deicer salts. The laboratory data and field experience have clearly showed that, in properly air-entrained concretes, there are hardly any internal cracking due to frost. On the occasion of deicing salts, scaling due to freezing becomes the further complicated trouble linked to the concrete surface microstructure (Pigeon et al., 1996). Besides the entrainment of air in concrete, the W/B is also related to the porosity and pore structure of the concrete. It was reported that the deicer salt scaling resistance increased with the decreased W/B from most field and laboratory data (Pigeon et al., 1996). Some experimental results even showed that for some concrete with very low W/B, it is not necessary to entrain air (Pigeon et al., 1996; Gagne et al., 1991); and properly air-entrained concretes and low W/B can be achieved by adding water reducing agents and superplasticizers.

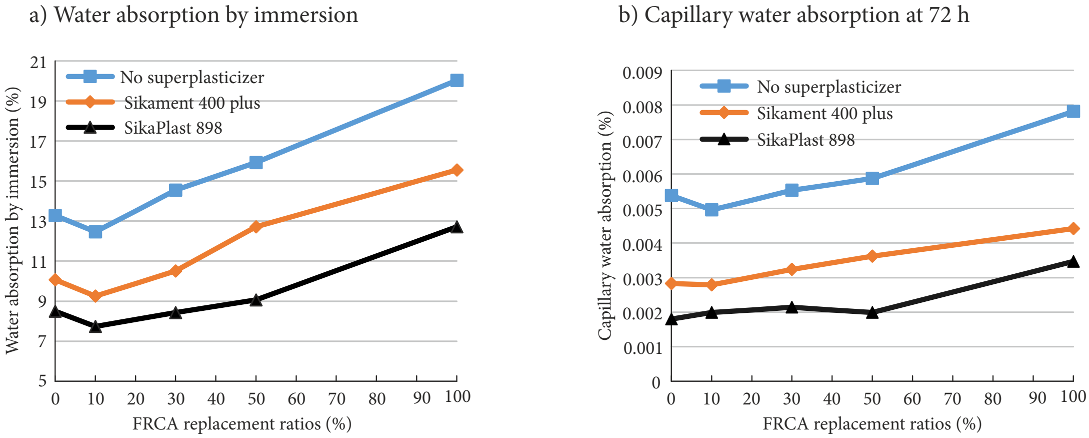


Figure 12. Effects of different type superplasticizers on water absorption of concrete made with fine recycled concrete aggregate (Cartuxo et al., 2016)

Grabiec (1999) studied the influence of melamine superplasticizer with a content of 2.2% by cement weight on the frost durability of concrete. For the fresh concrete having the same slump, the W/B of concrete without superplasticizer was 0.43, and that of concrete with superplasticizer was 0.35. For concrete samples subjected to 200 cycles of freezing and thawing, compared to the control samples kept in water, 18.5% and 7.7% reductions in frost resistance expressed by the compressive strength were reported for the series of concrete without and with superplasticizer, respectively. In addition, different types of the superplasticizers had different influences on the frost durability of concrete. For SCC, the values of frost-resistance and air-voids parameters were affected by the type of superplasticizer obviously. Due to the "air entraining" side effect of superplasticizer SP1 acting, it can be guaranteed that the frost resistance of the SCC would be better. The SCC made of "not air-entraining" superplasticizer SP2 (without entraining side effect) is not frost-resistant (Łaźniewska-Piekarczyk, 2012). For concrete having the identical structure, W/B and fluidity, application of a dosage of 1% polycarboxylate superplasticizer, in comparison to the 1.1% naphthalene-formaldehyde one, facilitated the increased frost resistance from F2300 to F2400 (Shuldyakov et al., 2016). It can be concluded that, the type of the superplasticizer and the superplasticizer with and without air entraining side effect are very vital factors to improve the frost resistance of the concrete.

3.3. Permeability resistance

The durability of concrete is also affected by its permeability resistance. Obviously, improving the permeability resistance is beneficial for the service life extension of the RC structures. The pore structure of concrete is an important aspect for the performance (Zhang & Li, 2011) and the macro porosity of concrete can be reduced by the addition of superplasticizer (Wang et al., 2015). In order to explore the superplasticizer and Portland pozzolana cement interaction in chloride ion penetration resistance (Sathyan & Anand, 2019), the superplasticizers, namely sulphonated melamine formaldehyde (SMF), lignosulphates (LS), sulphonated naphthalene formaldehyde (SNF) and polycarboxylic ether (PCE), were used. Except for SMF-based mixture, reduction in charge passing was shown in Portland pozzolana cement incorporated mixes. In the test study of the Zhang and Kong (2014), a self-synthesized polycarboxylate superplasticizer was incorporated into the mortar with a W/B of 0.29, and the dosage was 0%, 0.1%, 0.3% and 0.5% of the cement content. Test results showed that, pore volume, average pore size and inkbottle pores volume in the hardened cement pastes decreased with the increasing dosage of superplasticizer. With the growth in curing ages from 7 days to 28 days, the pores were filled with more hydrates, resulting in a significantly lower porosity and average pore size of the 28-days hardened cement pastes than that of the pastes cured for 7 days (see Figure 13).

On the other hand, for reactive powder concrete (Tam et al., 2012), adding insufficient superplasticizer dosage may make concrete not dense enough, resulting in high porosity and connectivity between pores. This porous concrete can be used in the pavement structures, making them multifunctional, environmental, and sustainable, having hydraulic, mechanical, skid resistance, sound absorption, temperature regulation and air quality improvement characteristics (Elizondo-Martínez et al., 2020). Excessive use of the superplasticizer could also result in chemical incompatibility problem and segregation, which reduces the permeability of the concrete. Therefore, there is an optimal dosage of superplasticizer, which is helpful to disperse the material particles, so as to obtain more compacted paste with low porosity.

In conclusion, the durability indexes of the concrete, namely water absorption, frost resistance and permeability resistance, are all affected by the concrete porosity. In most cases, adding superplasticizers to the concrete can improve the durability of concrete by densifying the concrete microstructure. It is obvious that, the superplasticizer type, the optimal superplasticizer dosage, the hydration reaction of superplasticizer to binders and air entraining side effect of the superplasticizer are the main concerns in selecting the superplasticizers.

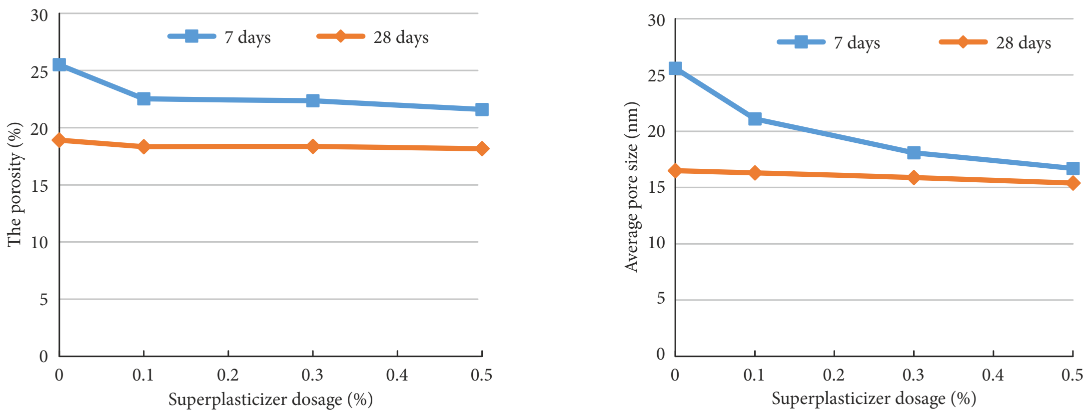


Figure 13. Effects of superplasticizer dosage on the porosity and average pore size in the hardened cement pastes (data from Zhang & Kong, 2014)

4. Conclusions

This paper comprehensively reviews the effect of the different types and dosages of the superplasticizers on the concrete strength and durability properties. The main conclusions are as follows:

1) The action mechanism of various water-reducing agents and superplasticizers is different, and there are compatible or incompatible problems between binders and superplasticizer, leading to different effects;
2) For the different types of the concrete, the addition of the appropriate dosage of the water-reducing agents and superplasticizers can densify the microstructure of the concrete, thus improving the strength and durability of the concrete;
3) The superplasticizer type, the superplasticizer dosage, the hydration reaction of superplasticizer to binders and air entraining side effect of the superplasticizer play important roles in reducing the water absorption of the concrete as well as improving the frost and permeability resistances of the concrete.

Therefore, in the RC structural engineering, the type of cementing material, the performance requirements of the concrete, the aggregate characteristics and other factors should be comprehensively considered to select the appropriate type of water-reducing agents and superplasticizers. Meanwhile, for the selected water-reducing agent or superplasticizer, the optimal dosage should be tested so as to guarantees that the hardened concrete can obtain a better pore microstructure and improve the concrete strength and durability properties.

Disclosure statement

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Author contributions

Xiao-Hui Wang: Funding acquisition, Supervision, Methodology, Writing, Data curation; Zhi-Chao Fang: Data curation, Writing; Li Zheng: Writing – review & editing.

References

Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in Energy and Combustion Science*, *36*(3), 327–363. https://doi.org/10.1016/j.pecs.2009.11.003

Aicha, M. B. (2020). 8 – The superplasticizer effect on the rheological and mechanical properties of self-compacting concrete. In P. Samui, D. Kim, N. R. Iyer, & S. Chaudhary (Eds.), *New materials in civil engineering* (pp. 315–331). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-818961-0.00008-9

Alaka, H. A., & Oyedele, L. O. (2016). High volume fly ash concrete: The practical impact of using superabundant dose of high range water reducer. *Journal of Building Engineering*, *8*, 81–90. https://doi.org/10.1016/j.jobe.2016.09.008

Alsadey, S. (2013). Effects of super plasticizing and retarding admixtures on properties of concrete. In *International Conference on Innovations in Engineering and Technology* (pp. 25–26), Bangkok, Thailand.

Antoni, H. J. G., Kusuma, O. C., & Hardjito, D. (2017). Optimizing polycarboxylate based superplasticizer dosage with different cement type. *Procedia Engineering*, *171*, 752–759. https://doi.org/10.1016/j.proeng.2017.01.442

ASTM International. (2004). *Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes* (ASTM C1585-04). West Conshohocken, PA, USA.

Benaicha, M., Alaoui, A. H., & Jalbaud, O. (2019). Dosage effect of superplasticizer on self-compacting concrete: correlation between rheology and strength. *Journal of Materials Research and Technology*, *8*(2), 2063–2069. https://doi.org/10.1016/j.jmrt.2019.01.015

Bjömström, J., & Chandra, S. (2003). Effect of superplasticizers on the rheological properties of Cements. *Materials and Structures*, *36*, 685–692. https://doi.org/10.1007/BF02479503

Boukendakdji, O., Kadri, E.-H., & Kenai, S. (2012). Effects of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete. *Cement and Concrete Composites*, *34*(4), 583–590. https://doi.org/10.1016/j.cemconcomp.2011.08.013

Bullerjahn, F., Schmitt, D., & Haha, M. B. (2014). Effect of raw mix design and of clinkering process on the formation and mineralogical composition of (ternesite) belite calcium sulphoaluminate ferrite clinker. *Cement and Concrete Research*, *59*, 87–95. https://doi.org/10.1016/j.cemconres.2014.02.004

Cartuxo, F., De Brito, J., & Evangelista, L. (2016). Increased durability of concrete made with fine recycled concrete aggregates using superplasticizers. *Materials*, *9*(2), Article 98. https://doi.org/10.3390/ma9020098

Castro, J., Bentz, D., & Weiss, J. (2011). Effect of sample conditioning on the water absorption of concrete. *Cement and Concrete Composites*, *33*(8), 805–813. https://doi.org/10.1016/j.cemconcomp.2011.05.007

Collepardi, M. M. (1996). Water reducers/retarders. In V. S. Ramachandran (Ed.), *Concrete admixtures handbook* (pp. 286–409). William Andrew Publishing. https://doi.org/10.1016/B978-081551373-5.50010-6

Collepardi, M. (1998). Admixtures used to enhance placing characteristics of concrete. *Cement and Concrete Composites*, *20*(2–3), 103–112. https://doi.org/10.1016/S0958-9465(98)00071-7

Courtial, M., de Noirfontaine, M. N., & Dunstetter, F. (2013). Effect of polycarboxylate and crushed quartz in UHPC: Microstructural investigation. *Construction and Building Materials*, *44*, 699–705. https://doi.org/10.1016/j.conbuildmat.2013.03.077

De Schutter, G., Bartos, P. J. M., & Domone, P. (2008). *Self-compacting concrete*. Whittles Publishing, CRC Press LLC, Taylor and Francis Group, USA.

Hekal, E. E., & Kishar, E. A. (1999). Effect of sodium salt of naphthalene-formaldehyde polycondensate on ettringite formation. *Cement and Concrete Research*, *29*(10), 1535–1540. https://doi.org/10.1016/S0008-8846(99)00110-6

El-Hosiny, F. I. (2002). Hydration and pore structure characteristic of superplasticized hardened slag cement pastes. *Ceramics-Silikáty*, *46*(2), 63–67.

Elizondo-Martínez, E.-J., Andrés-Valeri, V.-C., Jato-Espino, D., & Rodriguez-Hernandez, J. (2020). Review of porous concrete as multifunctional and sustainable pavement. *Journal of Building Engineering*, *27*, Article 100967. https://doi.org/10.1016/j.jobe.2019.100967

Esen, Y., & Orhan, E. (2016). Investigation of the effect on the physical and mechanical properties of the dosage of additive in self-consolidating concrete. *KSCE Journal of Civil Engineering*, *20*, 2849–2858. https://doi.org/10.1007/s12205-016-0258-2

Fujii, A. L., dos Reis Torres D., de Oliveira Romano, R. C., Cincotto, M. A., & Pileggi, R. G. (2015) Impact of superplasticizer on the hardening of slag Portland cement blended with red mud. *Construction and Building Materials*, *101*, 432–439. https://doi.org/10.1016/j.conbuildmat.2015.10.057

Gagne, R., Pigeon, M., & Aitcin, P. C. (1991). Deicer salt scaling resistance of high strength concretes made with different cements. *ACI Special Publication*, *126*, 185–200.

García-Maté, M., De la Torre A. G., León-Reina, L., Aranda, M. A. G., & Santacruz, I. (2013). Hydration studies of calcium sulfoaluminate cements blended with fly ash. *Cement and Concrete Research*, *54*, 12–20. https://doi.org/10.1016/j.cemconres.2013.07.010

Gesoğlu, M., Güneyisi, E., & Özturan, T. (2014). Self-consolidating characteristics of concrete composites including rounded fine and coarse fly ash lightweight aggregates. *Composites Part B: Engineering*, *60*, 757–763.
https://doi.org/10.1016/j.compositesb.2014.01.008

Grabiec, A. M. (1999). Contribution to the knowledge of melamine superplasticizer effect on some characteristics of concrete after long periods of hardening. *Cement and Concrete Research*, *29*(5), 699–704. https://doi.org/10.1016/S0008-8846(99)00024-1

Gu, P., Xie, P., Beaudoin, J. J., & Jolicoeur, C. (1994). Investigation of the retarding effect of superplasticizers on cement hydration by impedance spectroscopy and other methods. *Cement and Concrete Research*, *24*(3), 433–442. https://doi.org/10.1016/0008-8846(94)90130-9

Henkensiefken, R., Castro, J., & Bentz, D. (2009). Water absorption in internally cured mortar made with water-filled lightweight aggregate. *Cement and Concrete Research*, *39*(10), 883–892. https://doi.org/10.1016/j.cemconres.2009.06.009

Huang, Y., Pei, Y., & Qian, J. (2020). Bauxite free iron rich calcium sulfoaluminate cement: Preparation, hydration and properties. *Construction and Building Materials*, *249*, Article 118774. https://doi.org/10.1016/j.conbuildmat.2020.118774

Huang, C., Cheng, Z., Zhao, J., Wang, Y., & Pang, J. (2021). The influence of water reducing agents on early hydration property of ferrite aluminate cement paste. *Crystals*, *11*, Article 731. https://doi.org/10.3390/cryst11070731

Jhatial, A. A., Sohu, S., & Lakhiar, M. T. (2018). Effectiveness of locally available superplasticizers on the workability and strength of concrete. *Civil Engineering Journal*, *4*(12), 2919–2925. https://doi.org/10.28991/cej-03091208

John, V. M., Quattrone, M., & Abrao, P. C. R. A. (2019). Rethinking cement standards: Opportunities for a better future. *Cement and Concrete Research*, *124*, Article 105832. https://doi.org/10.1016/j.cemconres.2019.105832

Ke, Y., Ortola, S., & Beaucour, A. L. (2010). Identification of microstructural characteristics in lightweight aggregate concretes by micromechanical modelling including the interfacial transition zone (ITZ). *Cement and Concrete Research*, *40*(11), 1590–1600. https://doi.org/10.1016/j.cemconres.2010.07.001

Khaleel, O. R., Al-Mishhadani, S. A., & Razak, H. A. (2011). The effect of coarse aggregate on fresh and hardened properties of self-compacting concrete (SCC). *Procedia Engineering*, *14*, 805–813. https://doi.org/10.1016/j.proeng.2011.07.102

Khatib, J. M., & Mangat, P. S. (1999). Influence of superplasticizer and curing on porosity and pore structure of cement paste. *Cement and Concrete Composites*, *21*(5–6), 431–437. https://doi.org/10.1016/s0958-9465(99)00031-1

Kim, Y. J., Choi, Y. W., & Lachemi, M. (2010). Characteristics of self-consolidating concrete using two types of lightweight coarse aggregates. *Construction and Building Materials*, *24*(1), 11–16. https://doi.org/10.1016/j.conbuildmat.2009.08.004

Law, D. W., Adam, A. A., & Molyneaux, T. K. (2015). Long term durability properties of class F fly ash geopolymer concrete. *Materials and Structures*, *48*(3), 721–731. https://doi.org/10.1617/s11527-014-0268-9

Łaźniewska-Piekarczyk, B. (2012). The influence of selected new generation admixtures on the workability, air-voids parameters and frost-resistance of self compacting concrete. *Construction and Building Materials*, *31*, 310–319. https://doi.org/10.1016/j.conbuildmat.2011.12.107

Łaźniewska-Piekarczyk, B., & Szwabowski, J. (2012). The influence of the type of anti-foaming admixture and superplasticizer on the properties of self-compacting mortar and concrete. *Journal of Civil Engineering and Management*, *18*(3), 408–415. https://doi.org/10.3846/13923730.2012.698908

Manomi, N., Sathyan, D., & Anand, K. B. (2018). Coupled effect of superplasticizer dosage and fly ash content on strength and durability of concrete. *Materials Today: Proceedings*, *5*(11), 24033–24042. https://doi.org/10.1016/j.matpr.2018.10.196

Marchon, D., & Flatt, R. J. (2016). Impact of chemical admixtures on cement hydration. In P.-C. Aïtcin, & R. J. Flatt (Eds.), *Science and technology of concrete admixtures* (pp. 279–304). Woodhead Publishing. https://doi.org/10.016/B978-0-08-100693-1.00012-6

Matias, D., de Brito, J., & Rosa, A. (2013a). Mechanical properties of concrete produced with recycled coarse aggregates – Influence of the use of superplasticizers. *Construction and Building Materials*, *44*, 101–109. https://doi.org/10.1016/j.conbuildmat.2013.03.011

Matias, D., de Brito, J., Rosa, A., & Pedro, D. (2013b). Durability of concrete with recycled coarse aggregates: Influence of superplasticizers. *Journal of Materials in Civil Engineering*, *26*(7), 06014011. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000961

Mazloom, M., Soltani, A., & Karamloo, M. (2018). Effects of silica fume, superplasticizer dosage and type of superplasticizer on the properties of normal and self-compacting concrete. *Advances in Materials Research*, *7*(1), 45–72. https://doi.org/10.12989/amr.2018.7.1.045

Mehta, P. K. (1999). Advancements in concrete technology. *Concrete International*, *21*(6), 69–76.

Mehta, P. K., & Monteiro, P. J. M. (2017). *Concrete microstructure, properties and materials* (3rd ed.). McGraw-Hill.

Memon, N. A., Sumadi, S. R., & Ramli, M. (2007). Performance of high workability slag-cement mortar for ferrocement. *Building and Environment*, *42*(7), 2710–2717. https://doi.org/10.1016/j.buildenv.2006.07.015

Muhit, I. B. (2013). Dosage limit determination of superplasticizing admixture and effect evaluation on properties of concrete.

International Journal of Scientific & Engineering Research, *4*(3), 1–4.

Olorunsogo, F. T., & Padayachee, N. (2002). Performance of recycled aggregate concrete monitored by durability indexes. *Cement and Concrete Research*, *32*(2), 179–185. https://doi.org/10.1016/S0008-8846(01)00653-6

Oner, A., Akyuz, S., & Yildiz, R. (2005). An experimental study on strength development of concrete containing fly ash and optimum usage of fly ash in concrete. *Cement and Concrete Research*, *35*(6), 1165–1171. https://doi.org/10.1016/j.cemconres.2004.09.031

Oualit, M., Irekti, A., & Melinge, Y. (2018). Saturation point of superplasticizers determined by rheological tests for self compacting concrete. *Periodica Polytechnica Civil Engineering*, *62*(2), 346–352. https://doi.org/10.3311/PPci.11247

Özbay, E., Erdemir, M., & Durmuş, H. İ. (2016). Utilization and efficiency of ground granulated blast furnace slag on concrete properties – A review. *Construction and Building Materials*, *105*, 423–434.
https://doi.org/10.1016/j.conbuildmat.2015.12.153

Papayianni, I., Tsohos, G., Oikonomou, N., & Mavria, P. (2005). Influence of superplasticizer type and mix design parameters on the performance of them in concrete mixtures. *Cement and Concrete Composites*, *27*, 217–222. https://doi.org/10.1016/j.cemconcomp.2004.02.010

Parrott, L. J. (1992). Water absorption in cover concrete. *Materials and Structures*, *25*(5), 284–292. https://doi.org/10.1007/BF02472669

Pereira, P., Evangelista, L., & de Brito, J. (2012a). The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates. *Construction and Building Materials*, *28*(1), 722–729. https://doi.org/10.1016/j.conbuildmat.2011.10.050

Pereira, P., Evangelista, L., & de Brito, J. (2012b). The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, *34*(9), 1044–1052. https://doi.org/10.1016/j.cemconcomp.2012.06.009

Pigeon, M., Marchand, J., & Pleau, R. (1996). Frost resistant concrete. *Construction and Building Materials*, *10*(5), 339–348. https://doi.org/10.1016/0950-0618(95)00067-4

Plank, J., & Ilg, M. (2019). The role of chemical admixtures in the formulation of modern advanced concrete. In W. Boshoff, R. Combrinck, V., Mechtcherine, & M. Wyrzykowski (Eds.), *3rd International Conference on the Application of Superabsorbent Polymers* (*SAP*) *and Other New Admixtures Towards Smart Concrete*. SAP 2019. RILEM Bookseries (Vol. 24, pp. 143–157). Springer, Cham. https://doi.org/10.1007/978-3-030-33342-3_16

Qin, L., Gao, X., & Zhang, A. (2018). Potential application of Portland cement-calcium sulfoaluminate cement blends to avoid early age frost damage. *Construction and Building Materials*, *190*, 363–372. https://doi.org/10.1016/j.conbuildmat.2018.09.136

Ramachandran, V. S., & Malhotra, V. M. (1996). Superplasticizers. In V. S. Ramachandran (Ed.), *Concrete admixtures handbook* (pp. 410–517). William Andrew Publishing. https://doi.org/10.1016/B978-081551373-5.50011-8

Ramachandran, D., George, R. P., & Vishwakarma, V. (2017). Strength and durability studies of fly ash concrete in sea water environments compared with normal and superplasticizer concrete. *KSCE Journal of Civil Engineering*, *21*(4), 1282–1290. https://doi.org/10.1007/s12205-016-0272-4

Raut, S. R., Saklecha, P. P., & Kedar, R. S. (2015). Review on ground granulated blast-furnace slag as a supplementary cementitious material. *International Journal of Computer Applications*, *975*, Article 8887.

Sadrmomtazi, A., Tajasosi, S., & Tahmouresi, B. (2018). Effect of materials proportion on rheology and mechanical strength and microstructure of ultra-high performance concrete (UHPC). *Construction and Building Materials*, *187*, 1103–1112. https://doi.org/10.1016/j.conbuildmat.2018.08.070

Salem, M., Alsadey, S., & Johari, M. (2016). Effect of superplasticizer dosage on workability and strength characteristics of concrete. *IOSR Journal of Mechanical and Civil Engineering*, *13*(4), 153–158. https://doi.org/10.9790/1684-130407153158

Sathyan, D., & Anand, K. B. (2019). Influence of superplasticizer family on the durability characteristics of fly ash incorporated cement concrete. *Construction and Building Materials*, *204*, 864–874. https://doi.org/10.1016/j.conbuildmat.2019.01.171

Shah, S. N. R., Aslam, M., & Shah, S. A. (2014). Behaviour of normal concrete using superplasticizer under different curing regimes. *Pakistan Journal of Engineering and Applied Sciences*, *15*, 87–94.

Shuldyakov, K., Kramar, L., & Trofimov, B. (2016). Superplasticizer effect on cement paste structure and concrete freeze-thaw resistance. *AIP Conference Proceedings*, *1698*, Article 070011. https://doi.org/10.1063/1.4937881

Stuart, K. D., Anderson, D. A., & Cady, P. D. (1980). Compressive strength studies on Portland cement mortars containing fly ash and superplasticizer. *Cement and Concrete Research*, *10*(6), 823–832. https://doi.org/10.1016/0008-8846(80)90010-1

Tam, C. M., Tam, V. W. Y., & Ng, K. M. (2012). Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong. *Construction and Building Materials*, *26*(1), 79–89. https://doi.org/10.1016/j.conbuildmat.2011.05.006

Tang, S. W., Yao, Y., & Andrade, C. (2015). Recent durability studies on concrete structure. *Cement and Concrete Research*, *78*, 143–154. https://doi.org/10.1016/j.cemconres.2015.05.021

Wang, D., Shi, C., & Wu, Z. (2015). A review on ultra high performance concrete: Part II. Hydration, microstructure and properties. *Construction and Building Materials*, *96*, 368–377. https://doi.org/10.1016/j.conbuildmat.2015.08.095

Wang, R., Gao, X., & Huang, H. (2017). Influence of rheological properties of cement mortar on steel fiber distribution in UHPC. *Construction and Building Materials*, *144*, 65–73. https://doi.org/10.1016/j.conbuildmat.2017.03.173

Wilson, H. S., & Malhotra, V. M. (1988). Development of high strength lightweight concrete for structural applications. *International Journal of Cement Composites and Lightweight Concrete*, *10*(2), 79–90. https://doi.org/10.1016/0262-5075(88)90034-6

Wu, Y., Li, Q., Li, G., Tang, S., Niu, M., & Wu, Y. (2021). Effect of naphthalene-based superplasticizer and polycarboxylic acid superplasticizer on the properties of sulfoaluminate cement. *Materials*, *14*, 662. https://doi.org/10.3390/ma14030662

Yaphary, Y. L., Lam, R. H. W., & Lau, D. (2017). Chemical technologies for modern concrete production. *Procedia Engineering*, *172*, 1270–1277. https://doi.org/10.1016/j.proeng.2017.02.150

Yoo, D. Y., & Banthia, N. (2016). Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review. *Cement and Concrete Composites*, *73*, 267–280. https://doi.org/10.1016/j.cemconcomp.2016.08.001

Yoshioka, K., Sakai, E., & Daimon, M. (1997). Role of steric hindrance in the performance of superplasticizers for concrete. *Journal of the American Ceramic Society*, *80*(10), 2667–2671. https://doi.org/10.1111/j.1151-2916.1997.tb03169.x

Zaharieva, R., Buyle-Bodin, F., & Skoczylas, F. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement and Concrete Composites*, *25*(2), 223–232. https://doi.org/10.1016/S0958-9465(02)00010-0

Zhang, M., & Li, H. (2011). Pore structure and chloride permeability of concrete containing nano-particles for pavement. *Construction and Building Materials*, *25*(2), 608–616. https://doi.org/10.1016/j.conbuildmat.2010.07.032

Zhang, Y., & Kong, X. (2014). Influences of superplasticizer, polymer latexes and asphalt emulsions on the pore structure and impermeability of hardened cementitious materials. *Construction and Building Materials*, *53*, 392–402. https://doi.org/10.1016/j.conbuildmat.2013.11.104

Zhang, G., Li, G., & Li, Y. (2016). Effects of superplasticizers and retarders on the fluidity and strength of sulphoaluminate cement. *Construction and Building Materials*, *126*, 44–54. https://doi.org/10.1016/j.conbuildmat.2016.09.019

Zhang, K., Pan, L., & Li, J. (2019). How does adsorption behavior of polycarboxylate superplasticizer effect rheology and flowability of cement paste with polypropylene fiber. *Cement and Concrete Composites*, *95*, 228–236. https://doi.org/10.1016/j.cemconcomp.2018.11.003

Zhou, M., Wu, Z., & Ouyang, X. (2021). Mixture design methods for ultra-high-performance concrete-a review. *Cement and Concrete Composites*, *124*, Article 104242. https://doi.org/10.1016/j.cemconcomp.2021.104242