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EFFECT OF SUPERABSORBENT POLYMER ON MITIGATING DAMAGES AT STEEL BAR-CONCRETE INTERFACE

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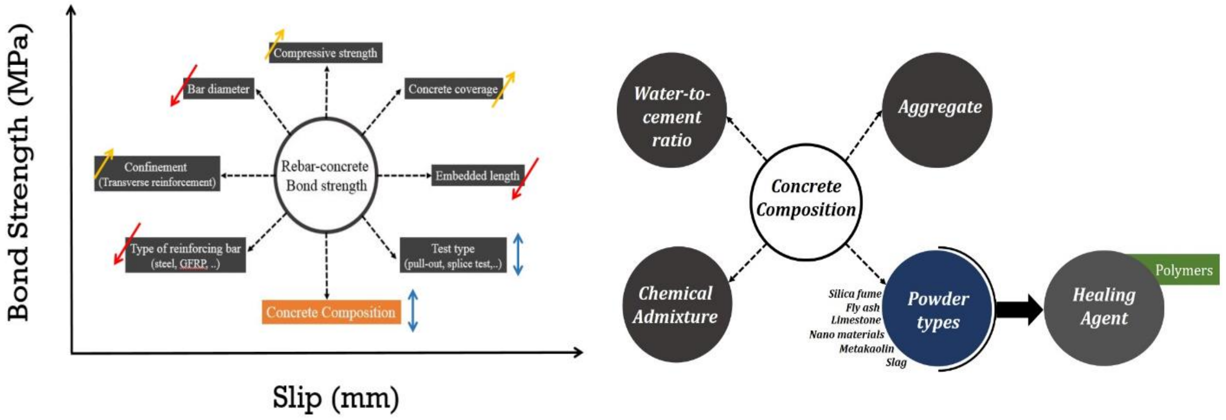
Abstract: Autogenous healing capacity of concrete has been considered in the last decades for mitigating internal damages in concrete structures. However, there is no specific research for healing cracks at rebar-concrete interfaces. Superabsorbent polymer (SAP) is used in this study to produce SAP concrete as a smart generation of concrete for autogenously healing cracks perpendicular to the rebar direction. An experimental program was conducted to check the performance of SAP as a healing agent in comparison with the reference mix. Two types of SAP particle sizes were considered and tested in this program with 0.25 %wt. of cement. Controlled displacement loading with the rate of 0.15 mm/min was applied to prevent unexpected splitting failure during pre-cracking process. Two period of 14 and 28 days were considered for healing internal damages. Although bond strength is relatively lower in SAP-based concrete compared to the normal concrete because of macro pores at SAP locations, results show a good healing effect for maximum bond strength within the cracks of cracked SAP-based concrete subjected to wet-dry recurring cycles. Also the position and non-uniform shape of SAP voids has a big effect on crack path so that provide an appropriate condition for healing. Generally, findings evidently support the hypothesis that concrete composition could be a key parameter for controlling cracks at rebar-concrete interfacial surfaces. Obtained results show that concrete with SAP shows higher healing capacity compared to the concrete without SAP.

1 INTRODUCTION

Concrete composition as a key parameter in bond behavior (Mousavi, Dehestani, and Mousavi 2017, Mousavi, Dehestani, and Mousavi 2016) can be used to control the damages at rebar-concrete interface. Minimum concrete cover for reinforcing bar (rebar), rebar diameter, characteristic strength of concrete, embedded length of rebar, area of stirrups, and spacing of stirrup are the important factors considered in existing equations for bond strength. Characteristic strength of concrete is the only parameter, which is directly related to the concrete composition (Guizani, Chaallal, and Mousavi 2017, Mousavi, Dehestani, and Mousavi 2017, Mousavi, Dehestani, and Mousavi 2016). However, results reported by the literature show different trend in which powder types and content, aggregate types and contents and also admixture can significantly change the bond properties (Martí-Vargas et al. 2012). Concrete composition is defined by four important parameters including admixtures, aggregate, water to cementitious material ratio, and powder. Changing every of these factors in both field of the quality and the quantity can significantly affect the bond properties (Mousavi, Dehestani, and Mousavi 2017, Sfikas and Trezos 2013). Effect of powder (types and dosage) directly on bond strength can be a good option for changing the structure of rebar-concrete interfacial behavior and improving the damaged layers around the rebar caused by pre-cracked phenomenon (Mousavi, Guizani, and Ouellet-Plamondon 2019). No specific research has been concentrated on healing cracks at rebar-concrete interaction after initial damages. Hence, this study aims to begin to address the problem of pre-cracking by using self-healing ability of concrete. The major hypothesis of this study is depicted in Figure 1.



a) b)

Figure 1: Concrete composition as a key parameter in bond-slip phenomenon

Self-healing or autogenous healing ability of concrete is a promising solution to alleviate internal damages. However, there is no research available using self-healing method in internal damages at rebar-concrete interaction. Self-healing can be mainly attributed to two mechanisms: (1) hydration of unhydrated cement particles and (2) dissolution and subsequent carbonation of $Ca(OH)_2$. There is a limitation of crack width for using autogenous healing of concrete without any healing agents inside the mixture. In order to accelerate this autogenous healing and increase the ability for healing larger crack widths, superabsorbent polymer (SAP) is used in this study (Figure 2). As water is always needed for autogenous healing to occur, different types of water supply has been used to accelerate the healing process such as superabsorbent polymer. Hydrogels, or superabsorbent polymers (SAPs), have the ability to absorb a significant amount of water from the surrounding environment and to retain the water within their structure without dissolving. SAP particles promote self-healing by providing water on crack formation, which results in more visual crack closure and more regain in mechanical properties. Cracks up to 30 µm are able to heal completely by SAP at the crack mouth and up to 150 µm heal partly when specimens are subjected to wet-dry cycles (Snoeck and De Belie 2015). Lee, Wong, and Buenfeld (2016) have shown that in the case of 0.3 mm crack width, peak flowrate and total flow can be reduced up to 85 and 98 % respectively by SAP particles. In this field, results of experimental tests reported by Snoeck et al. (2012) show that cracks up to 0.13 mm in SAP-based concrete can be closed completely in wet-dry cycles due to the precipitation of calcium carbonate.

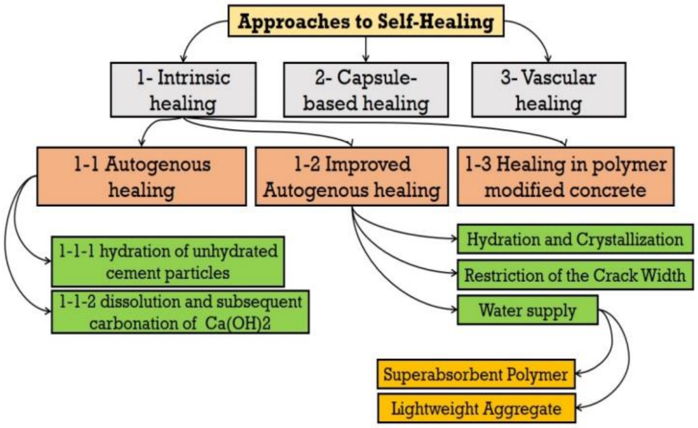


Figure 2: Superabsorbent polymer (SAP) as a water supply agent for self-healing

2 EXPERIMENTAL PROGRAM

Three main states of specimen were considered in the experimental program including uncracked, cracked and healed specimens. Splitting test (Brazilian test) was used to simulate pre-cracking. After pre-cracking, the specimens were exposed to wetting and drying cycles for two periods of 14 and 28 days.

2.1 Materials

Concrete composition is shown in Table 1. General use cement is used with density of 3.15 t/m^3. Water to cement ratio of 0.41 was considered for concrete mixture. The aggregates are a natural sand with a maximum grain size of 1.25 mm and specific gravity of 2.68 and a gravel with maximum grain size of 14 mm. Rebar with diameter (d_b) of 10 mm was considered for experimental program. Yield and tensile strength of rebar were 432 and 620 MPa respectively.

Table 1: Concrete composition (kg/m^3)

Sample	Water	Cement	Sand	Coarse aggregate 5/10	Coarse aggregate 10/14	SAP	Internal curing water *	f_c [MPa] (SD)
NC	162	395	788	822	258	-	-	58.82 (1.39)
NC-S1	162	395	788	822	258	0.99	24.75	54.36 (1.20)
NC-S2	162	395	788	822	258	0.99	24.75	46.83 (0.17)

*water absorption of 25 (g water/g of SAP) is considered for 0.25% SAP.

Normal concrete with 0.25% SAP (by weight percentage of cement) was considered for experimental tests. Mixtures with S1 and S2 correspond to SAPs with max particle size of 0.5 and 0.15 mm respectively. Water adsorption of SAP particles inside the concrete mixture is different from pure water due to the pH (12 for concrete) and ion exchange. In order to determine the amount of additional water for SAP particles, specific amount of water and cement were first mixed together. Then the water from cement paste (pH=13.47) was extracted by centrifuge. Specific amount of SAP was added to this water for about one hour. After weighting, mixture of water and SAP was putted into an oven at 105 °C. After 24 h, difference between the weights of before and after heating showed the water absorption. Finally, the amount of 25 gr_{water}/gr_{SAP} was obtained for both SAP sizes so that workability of concrete maintained in an acceptable range. More details of SAPs used in experimental tests are summarised in Table 2.

Table 2: Properties of superabsorbent polymers (SAP) provided for tests.

Items	SAP-1	SAP-2
Chemical name	Cross-linked copolymer of acrylamide and potassium acrylate	Cross-linked anionic polyacrylamide
Company	SNF	BASF
Particle size (µm)	< 500	< 150
d10	92	13
d50	260	47
d90	450	92
Mean absorption and desorption of SAP (g fluid/g SAP)		
deionised water, pH=6.5 (Teabag method)	249	170
pore solution, pH=13.5 (Teabag method)	26.7	25.4
desorption, pH=13.5	26.1	25.0
Specific gravity	1.51	1.49
Bulk density	0.82	0.84

2.2 Test setup

Total number of 33 cylindrical molds with dimension of 150×100 mm^2 were used for preparing specimens including 3 uncracked specimens and 9 cracked specimens with different healing periods. Direct pull-out test was used to determine maximum bond strength of steel rebar in SAP concrete. Ratio of concrete cover-to-bar diameter of 7.5 was considered for specimens to provide pull-out failure modes in uncracked concrete. Embedded length of $5d_b$ was also considered for measuring average bond strength. Different approaches have been used for simulating initial cracks at rebar-concrete interface. In this study, controlled pre-loading approach introduced by Desnerck, Lees, and Morley (2015) was used so as to induce initial crack prior to conducting pull-out test. Displacement-controlled loadings with a rate of 0.5 and 0.15 mm/min were applied for pull-out and splitting tests respectively to impede unexpected splitting failure during the pre-cracking loading. Crack widths were manually measured just after stopping the pre-cracking test. Also in order to visualise the crack healing, disk-shaped cylinders were cutted and polished for monitoring by microscope.

3 RESULTS

Overall results are summarized in Table 3. Maximum bond strength at different statue of uncracked, pre-cracked, and healed were measured. Crack width of 0.3 mm was considered for simulating pre-cracking phenomenon.

Table 3: Maximum bond strength of specimens (crack width of 0.3 mm)

Sample	τ_{max} [MPa] / (SD)*			
	uncracked	pre-cracked	healed	
			14d	28d
NC	25.79 (1.14)	11.64 (1.74)	9.35 (2.77)	11.84 (0.60)
NC-S1	24.37 (0.31)	9.85 (0.18)	10.44 (4.46)	12.20 (2.08)
NC-S2	25.02 (0.15)	5.70 (2.37)	7.03 (0.01)	7.89 (0.01)

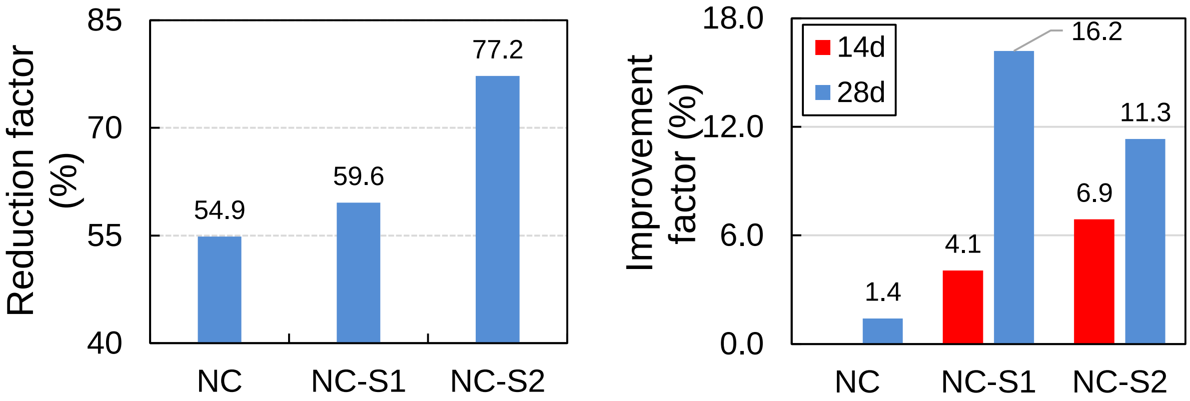
*SD=standard deviation.

General results show that 0.25 % SAP has no significant effect on maximum bond strength of SAP concrete. Regarding to the particle size of SAP, mixture containing large SAP particle (NC-S1) shows lower maximum bond strength compared to the small size one (NC-S2). In order to determine the effect of SAP on crack healing, two parameters of reduction factor (RF) and improvement factor (IF) are defined as follows:

$$[1] \quad \mathrm{RF} = \left[1 - \left(\frac{\tau_{Precracked}}{\tau_{Uncracked}}\right)\right] \times 100$$

$$[2] \quad \mathrm{IF} = \left[\frac{\tau_{Healed} - \tau_{Precracked}}{\tau_{Uncracked} - \tau_{Precracked}}\right] \times 100$$

where $\tau_{Precracked}$ and $\tau_{Uncracked}$ are the maximum bond strength of pre-cracked and uncracked concrete respectively. Similar to results reported for normal concrete (Mousavi, Guizani, and Ouellet-Plamondon 2019), pre-cracking has significant impact on maximum bond strength at crack width of 0.3 mm. Despite the large particle size, SAP with small particle size is more sensitive to pre-cracking phenomenon (Figure 3(a)). Overall results indicate that SAP particle has significant effect on healing cracks so that mixtures of NC-S1 and NC-S2 have 16.2 and 11.3 improvement factor respectively after 28 days wet-dry cycles (Figure 3(b)). As improvement factor increases, potential of mixture increases to heal cracks at rebar-concrete interfaces. Results also reveal that period of healing is efficient for improving the healing capacity of SAP concrete.



a) b)

Figure 3: Overall Results: (a) reduction factor for pre-cracking phenomenon; (b) improvement factor for self-healing capacity

General finding, illustrated in Figure 3(b), shows that large particle size of SAP is more efficient compared to the small size so that concrete containing S1 is less sensitive to pre-cracking phenomenon and more efficient for accelerating self-healing capacity of concrete. It can be attributed to the higher specific weight of SAP-2 compared to SAP-1, which increases the number of SAP particles in the same volume and same water absorption. That is to say, as SAP particle size decreases, strength reduction in SAP concrete increases, which has been reported by some studies (Snoeck et al. 2014, Schröfl, Mechtcherine, and Gorges 2012, Mechtcherine et al. 2017). Results also show that concrete without SAP particles can heal cracks at rebar-concrete interfaces after 28 days wet-dry cycles with IF of about 1.4 %. However, SAP concrete significantly accelerate this rate. As SAP particle is needed at the crack surface for increasing the possibility of crack healing process, cracks pathing the location in which SAP provide water resource for producing healing products. Figure 4 shows that the position and non-uniform shape of SAP voids has a big effect on crack path so that provide an appropriate condition for healing. In the other hand, cracks are more propagating from the location of SAP particles instead of air voids.

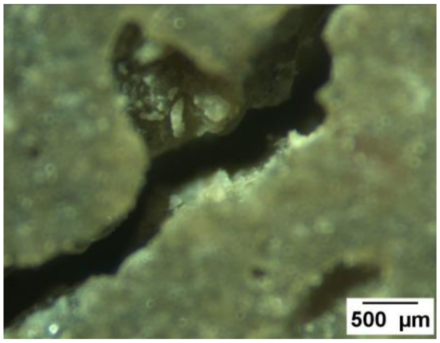


Figure 4: Effect of SAP location on the crack paths on the surfaces of concrete

In order to visually evaluate of the crack healing, disk-shaped layer of concrete cylinders after healing periods were cutted. Cyclic exposure of cracked concrete cylinders causes the production of some autogenous healing at crack surface, which can be detected by white precipitates (Figure 5). Visual observations show that crack paths after healing periods consist of two main categories of partly and completely healed cracks. As shown in Figure 3(b), similar to the completely healed cracks, partly healed crack can significantly affect the bond properties. This can be explained by particle interlock around the rebar or along the crack surface, which can change the bond-slip curves after providing partly healed cracks. The evolution of healing process shown in Figure 5 indicate that a long healing period (more than 28 days) is necessary to heal completely the cracks in concrete containing 0.25% SAP.

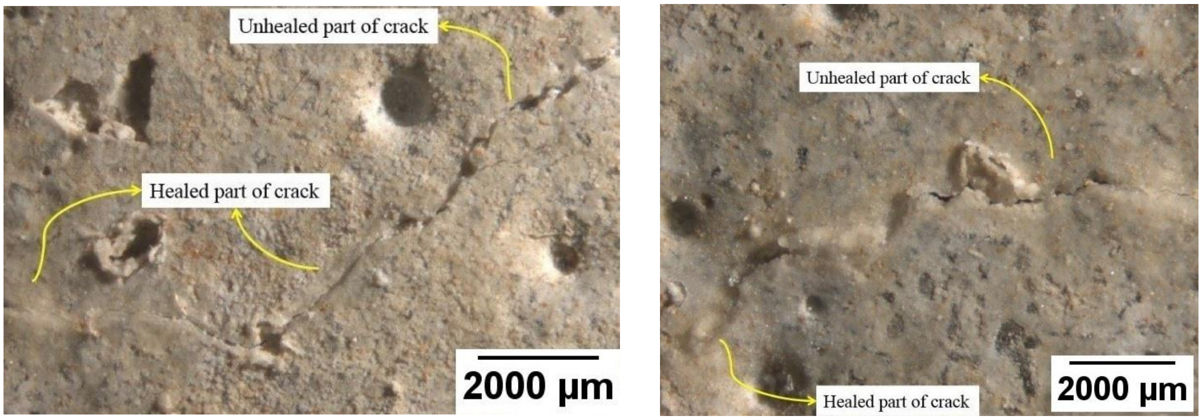


Figure 5: Self-healing products on crack surface after wet-dry cycles

4 CONCLUSION

This study evaluates the possibility of crack healing at rebar-concrete interface by using concrete composition as a key parameter in bond-slip phenomenon. Superabsorbent polymer (SAP) has been used to accelerate the healing process in wet-dry cycles. The following important concluding remarks were drawn eventually. The findings indicate that the addition of SAP-based concrete accelerates the healing process so that the reduction factor of maximum bond strength is significantly reduced. Regarding the improvement factor (IF), accelerated self-healing capacity of SAP concrete improves the maximum bond strength with IF of 16.2 %.

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