Interaction of Superabsorbent Polymers and Admixtures on The Properties Of Engineered Cementitious Composites

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ABSTRACT: The addition of Superabsorbent Polymers (SAP) as additives can strongly affect the mechanical characteristics and enhance the water content for internal curing of Engineered Cementitious Composite (ECC). ECC is a special type of ductile concrete with high tensile strain hardening and micro-cracking characteristics due to the presence of Polyvinyl Alcohol Fibers (PVA). This paper presents the results of a research conducted to investigate the effect of different types and sizes of SAP's and different chemical admixtures on the fresh and mechanical properties of ECC mixtures when both W/C ratio and dosages of superplasticizers are adjusted. Different mixing procedures are also produced to get the optimum self-consolidating characteristics of ECC's when mixed with SAP's. In addition, test results revealed that the use of SAP particles in ECC mixture can help to stimulate self-healing property of ECC mixture in order to produce sustainable ECC concrete for construction applications.

1 Introduction

Civil infrastructure such as buildings, bridges, tunnels, dams and roadways may subject to different types of damages all over the world. Cracks are one type of those damages that can affect significantly the service life of structural element. Despite the presence of extensive research in concrete material development, still it is difficult to protect structural element from such concrete deteriorations. In North America alone, $5.2 billion is estimated as an average annual maintenance cost only for bridges while the cost of reconstruction for bridges was estimated between $20 and $200 billion (Ahn & Kishi, 2010). Once the structural element ages, the damage in concrete structure progressively increases and the cost of repairs and maintenance increases as well. Accordingly, with decreasing annual budget allocations for infrastructure maintenance, the need for greater durability is apparent. Many experimental studies and practical experiences have confirmed that concrete has a natural ability to heal the inherent cracks by itself which commonly occur due to lower concrete tensile property. Therefore, the healed cracks will reduce the ingress of aggressive ions throughout the cracks leading to lowering the chances of concrete deteriorations and getting more sustainable civil infrastructures. Autogenous Self-healing in concrete cracks is a phenomenon that has been discovered by the French Academy of Science in 1836, which concluded that self-healing property is occurred when calcium hydroxide ($Ca(OH)_2$) leached out from hydrated cement pastes to form precipitated calcium carbonate ($CaCO_3$) when concrete exposes to the atmosphere (Mihashi & Nishiwaki, 2012). Among other factors, this phenomenon was emphasized by (Edvardsen, 1999) who revealed that the precipitation of $CaCO_3$ was the main reason of autogenous crack healing.

In order to prevent the early-age cracking in concrete due to autogenous shrinkage, the conventional external curing methods have been widely used in concrete structures. External curing is very important especially at early ages in order to ensure the maximum amount of early hydration since Calcium Silicate Hydrates (C-S-H) layers will start to coat progressively the un-hydrated cementitious particles leading to cease further hydrations. Theoretically, the concrete can be hydrated completely without external curing when W/C ratio is equal to 0.42 or greater. If less than 0.42, all the available water will be consumed during hydration to replace the capillary pores by gel and leaving behind empty spaces of pores filled by un-hydrated cementitious particles. This can cause self-desiccation for concrete and consequently and as soon as the moisture in concrete has lost, Relative Humidity (RH) will drop below 80%. Therefore, hydration will stop and strength development will be ceased as well. As a result, appropriate external curing is essential to ensure the maximum hydration (Mindess, Young, & Darwin, 2003). Unfortunately, in the case of bulk mass of concrete, Ultra High Performance Concrete (UHPC) or ECC which featured with very low W/C ratios, the conventional curing methods are not effective anymore which may cause high impermeable matrices and internal self-desiccation as well. Accordingly, different curing strategies have been developed to overcome the concern of autogenous shrinkage in such kind of cement based materials. Among others and despite the fact that the replacement of normal aggregates by Light Weight Aggregates (LWA) reduced the concrete strength as in the case of high strength concrete, still the replacement of standard aggregates in ECC by LWA considering them as an internal water reservoirs was giving the hope to provide additional internal moisture for ECC composites (Şahmaran, Lachemi, Hossain, & Li, 2009). In addition, the use of SAP as concrete additives is another promising strategy that can be used as water internal curing to reduce autogenous shrinkage and self-desiccation. Recently and in addition to curing function, SAP was added to ECC mixtures in order to stimulate their self-healing phenomenon due to the ability of storing large amounts of water and serve as water internal curing. Although SAP may affect the strength of concrete due to their expansive behavior, still limited amounts of SAP in ECC mixtures can serve the precipitation of $CaCO_3$ crystals and hence promote self-healing property (Snoeck, Tittelboom, et al. 2012).

SAP has the ability to absorb large amount of liquids from the surrounding environment which has estimated as 500 times more than its own weight leading to considerable swelling capacity and keeps the liquid inside its structure without dissolving as well. Once SAP exposes to the surrounding water during mixing process, it will start to absorb water from fresh concrete and swell rapidly forming water pockets inside the matrix. After the concrete hardens and for further cement hydration, SAP starts to discharge the absorbed water gradually from its structure and then shrinks leaving behind empty pores instead of formed water pockets. Therefore, the released water from SAP will act as internal water curing and facilitate for further hydration. Once the cracks generate in concrete, crack propagation through those empty pores is favored because they are the weakest zones in the matrix. Obviously, crack formation allows moisture to enter throughout the cracks leading SAP to absorb the moisture and swell again inside the empty pores. The re-swilling state of SAP may block the crack walls and seal them physically allowing the water stored for the second time inside SAP to contribute and stimulate the crack self-healing phenomenon (Snoeck, Steuperaert, et al. 2012; Snoeck, Tittelboom, et al. 2012; Van Tittelboom & De Belie 2013).

The discovery of new ductile materials, such as ECC, has been giving the hope to construct non-brittle structures with smaller crack widths that promotes the structural elements to resist the ingress of different aggressive agents and therefore, reduces corrosion and spalling phenomenon in concrete structures. Accordingly, the use of ECC in this research as a control material is very important due to its ability to undergo tensile strain-hardening capacity over 300 to 500 times than normal concrete accompanied with multiple crack formation and generate tight crack width less than 60μm even under ultimate strength loadings. The tight crack property in ECCs is considered to be one of the most important factors for stimulating both moisture internal curing and autogenous crack healing in concrete structures that may help to fill the microcracks and smaller empty pores by C-S-H products quickly (Na et al., 2012)

The demand of water for concrete structures is a big concern because internal and external curing is not always available during the life time of concrete structures. To overcome this problem, since SAP particles can work as internal water reservoirs while ECC matrix can provide tight crack width, an effective combination between SAP particles and ECC mixtures could be successfully used in this research in order to promote both moisture internal curing and self-healing phenomena in ECC mixtures.

This research is a preliminary study to the use of SAP particles in ECC technology at Ryerson University. In order to develop new SAP-ECC technology in Canada, wide range of research should be conducted related to short/long-term mechanical/durability properties of SAP-ECC system. The main objective of the current research is to explore the effect of SAP particles incorporating different types of chemical admixtures and different W/C ratios on SAP-ECC mixtures and analyze their mechanical properties such as compressive and flexural strengths, and ultrasonic pulse velocity. In addition, self-healing phenomenon was examined as well in order to produce sustainable ECC concrete for construction applications.

2 Experimental Programs

2.1 ECC Materials

The material used in the production of standard ECC mixtures were Portland cement (C) Type I general use (GU) with calcium content 61.40%; Class-F fly ash (FA) with calcium content 5.57%; micro-silica sand (SS) with an average and maximum grain size of 0.30 and 0.40 mm, respectively; polyvinyl alcohol (PVA) fibers; water; and a polycarboxylic-ether (ADVA Cast 575) from Grace Construction Products and Polycarboxylate superplasticiser (Glenium 7700) from BASF Chemical Company; both are types high-range water-reducing admixture (HRWRA). Two types of SAPs from M² Polymer Technologies, Inc. (Illinois, United States) were used. These include SAP type Na, Sodium Polyacrylate, Cross-linked (particle size ranges between 200-800μm), and SAP type K, Acrylamide/Potassium Acrylate Copolymer, Cross-linked (particle size ranges between 500-1200μm). SAP was expressed as mass% (m%) of cement weight. 1 m% of SAP was selected to obtain better results after (Snoeck, Tittelboom, et al., 2012). PVA used in this research characterised with a diameter of 39 μm, length of 8 mm, tensile strength (1620) MPa, elastic modulus (42.8 GPa), and maximum elongation (6.0%) to meet the requirements of strain-hardening performance of ECC material (Li, Wu, Wang, & Ogawa, 2002).

2.2 ECC Mixture Proportions

To investigate the influence of SAP particles employed in the production of ECC mixtures, two different types of SAP particles were used with two different types of Superplasticiser (SP) as well. In this research, 14 different samples were prepared under 3 different groups. The first group was composed of two standard ECC mixtures produced by using Class-F FA with cement replacement at ratio of 1.2 (55%), silica sand and W/C=0.27 ratio but one produced by using SP type GL and the other one produced by SP type GR as controls. The second group composed of SAP-ECC mixtures produced by using SAP type K, SP (type GL & GR) with different amounts, namely 4x, 7x and 10x which means 4, 7 or 10 times more than the standard amount of SP used in the production of standard ECCs and finally 3 W/C ratios, namely 0.27, 0.23 and 0.19. The third group composed of same second SAP-ECC group but produced by using SAP type Na. Mixture proportions and designations for all ECC groups are given in Table 1.

Table 1: SAP-ECC mixture proportions

Groups	Mixture ID	Ingredients per 1 part of Cement							W/B	FA /C
		Water	C	FA	SS	PVA	HRWRA or SP	SAP		
1	Control-GL	0.60	1	1.2	0.80	0.045	0.0044	0.01	0.27	1.2
	Control-GR	0.60	1	1.2	0.80	0.045	0.0044	0.01	0.27	1.2
2	K-0.27-4X-GL	0.60	1	1.2	0.80	0.045	0.018	0.01	0.27	1.2
	K-0.27-4x-GR	0.60	1	1.2	0.80	0.045	0.018	0.01	0.27	1.2
	K-0.23-7X-GL	0.51	1	1.2	0.80	0.045	0.031	0.01	0.23	1.2
	K-0.23-7X-GR	0.51	1	1.2	0.80	0.045	0.031	0.01	0.23	1.2
	K-0.19-10X-GL	0.42	1	1.2	0.80	0.045	0.044	0.01	0.19	1.2
	K-0.19-10X-GR	0.42	1	1.2	0.80	0.045	0.044	0.01	0.19	1.2
3	NA-0.27-4X-GL	0.60	1	1.2	0.80	0.045	0.018	0.01	0.27	1.2
	NA-0.27-4X-GR	0.60	1	1.2	0.80	0.045	0.018	0.01	0.27	1.2
	NA-0.23-7X-GL	0.51	1	1.2	0.80	0.045	0.031	0.01	0.23	1.2
	NA-0.23-7X-GR	0.51	1	1.2	0.80	0.045	0.031	0.01	0.23	1.2
	NA-0.19-10X-GL	0.42	1	1.2	0.80	0.045	0.044	0.01	0.19	1.2
	NA-0.19-10X-GR	0.42	1	1.2	0.80	0.045	0.044	0.01	0.19	1.2

C: Cement, FA: Class-F fly ash, SS: Silica sand, HRWRA: High range water reducing admixture, SP: Superplasticiser, SAP: Superabsorbent polymers, W/B: water to binder ratio (binder = C+FA)

As shown in Table 1, SAP-ECC mixtures are recognized from their Mixture IDs. The first letters stands for Type K or Na SAP particles. The first number after the letter stands for W/C ratio. The second number after the letter stands for SP amount and the last letters stand for SP type (GL or GR).

2.3 Testing and Specimen Preparation

Two mechanical tests were carried out in order to investigate the performance of SAP-ECC mixtures in this research. The first test was compressive strength test and the second was Ultrasonic Pulse Velocity (UPV) test applied on flexural strength prismatic samples for all SAP-ECC groups. The experimental tests were conducted at 28 and 56 days for every kind of tests.

Three specimens of each SAP-ECC mixture were tested under each type of loading. 50-mm cubic specimens were prepared for the compressive strength test at the age of 28 and 56 days. 355×50×76 mm prism specimens were prepared for four-point bending test to examine the UPV property based on flexural strength performance at the age of 28 days. All specimens were demolded after 24 hours and moisture cured in plastic bags at 95 ± 5% relative humidity (RH), 23 ± 2 °C. The specimens were kept in the curing room until the day of testing. In addition, after cracking the prismatic samples, the samples soaked for another 28 days to study the self-healing performance for SAP-ECC mixtures by collecting the UPV readings again.

2.4 Test Procedure

The performance of SAP-ECC mixtures was assessed by measuring compressive strength at ages 28 and 56 days. Cubic samples (at least 3 specimens for each age) of 50 mm were cast from each SAP-ECC mixture. The compression test was carried out on the cubic specimens by using a compression testing machine with a capacity of 400,000 lbs. Medium failure load; range 3 (up to 80,000lbs) was used for all cubes in accordance with (ASTM C39, 2012).

In order to measure the UPV test of SAP-ECC specimens based on flexural strength performance (Modulus of rupture), three prismatic samples of 355x50x76 mm were prepared for the ages of 28 days in accordance with (ASTM C 78, 2010). External loads were applied on the short side direction of the SAP-ECC specimen to balance the applied load for consistent crack propagation through the sample. The test was applied under the displacement control at the loading rate of 0.005 mm/sec on a closed-loop controlled servo-hydraulic material test system. The span length was 304.8 mm with a 101.6 mm center to center span length. Load-displacement curve was recorded during the flexural tests through automatic data acquisition system

2.5 Mixing Procedure

In this research, several trial mixes were prepared to find out best mixing method for SAP particles when used in the production of ECC mixtures. Initially, it was difficult to incorporated SAP particles in ECC mixture because ECCs characterized by lower W/C ratios. Moreover, it is well known that SAP particles have the ability to absorb water immediately once it touches them. Therefore, the solid materials except PVA fiber including cement, FA, SS and SAP particles in solid state were thrown into the mixer for the dry mix. Hobart type mixer of 20-liter capacity was used to prepare all SAP-ECC mixes. All the materials were weighed individually before starting the mixing. Mixing procedure is shown in Figure 1 as follows:

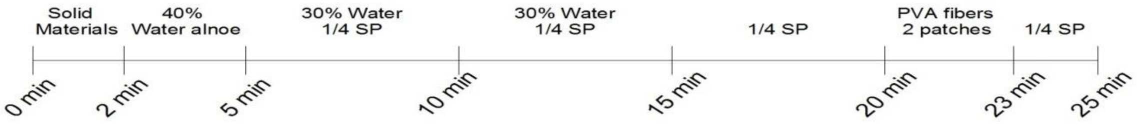


Figure 1: Best mixing procedure for ECC mixtures incorporating SAP particles.

Figure 2 shows the flowability of SAP-ECC mixtures. Slump test was conducted for the best SAP-ECC mixture. The slump flow value was around 660mm.

Figure 2: Best mixing procedure for ECC mixtures incorporating SAP particles.

It should be noted that best SAP-ECC mixture means the mixture that made of both SAP types (K and NA) with W/C ratio of 0.27 and SP amount of 4 times more than the standard SP amounts used in standard ECC mixtures.

3 Results and Discussions

3.1 Compressive Strength

The compressive strength test results of ECC mixtures incorporating different SAP types (K and Na), different types and quantities of SP (GL and GR) and different W/C ratios (0.27, 0.24 and 0.19) are presented in Table 2.

Sample ID.	W/C ratio / SP amount		
	0.27/4x	0.24/7x	0.19/10x
K-GL-28 days	44	50	53
K-GL-56 days	62	60	43
K-GR-28 days	49	44	52
K-GR-56 days	59	54	48
Na-GL-28 days	57	62	63
Na-GL-56 days	65	66	63
Na-GR-28 days	51	63	66
Na-GR-56 days	68	61	58

Table 2: Compressive strength results at 28 and 56 days of SAP-ECCs

Three cubic specimens (50 mm) were tested for every sample at the ages of 28 and 56 days in order to explore the compressive strength performance of SAP-ECC mixtures as a function of time. As shown in both Table 2 and Figure 3, the compressive strength values of both type K and Na SAP-ECC mixtures were increased at the age of 28 days when W/C ratio decreased from 0.27 to 0.19 and the amount of chemical admixtures increased up to 10 times more than the standard amounts. It is well known that the optimum amount of W/C ratio used at standard ECC mixtures is around 0.28 (Kamada & Li, 2000). Reducing W/C ratio down to 0.19 will affect negatively the PVA fiber dispersion. In addition to that, the presence of SAP particles made the mixing process more difficult due to high absorption capacity of SAP particles for the mixing water leaving behind a very low moistened mix with water as shown in Figure 4. Therefore, failing to reach full fiber dispersibility will lead to severe deterioration in such kind of concrete. In order to compensate the big lack in water, extra dosages of SP were used in order to provide better driving force in matrix flowing, resulting in well fiber dispersion. It was agreed that compressive strength values may increase by 25% of the controls when the SP increases and not from the decrease in W/C ratios alone. By increasing the dosage of SP, compressive strength values will be improved due to two reasons. Firstly, the cement efficiency will increase which means every cement particle will dissolve easily and completely in water and secondly, uniform microstructure with lower void content will improve greatly due to well cement and fiber dispersibility (Mindess et al., 2003). This may be attributed to the increase in the compressive strength values at 28 days when SP increased up to 10 times of standard value as shown in Table 3 and Figure 3.

Unlike the results at 28 days, the compressive strength values of both type K and Na SAP-ECC mixtures were increased at the age of 56 days when the optimum W/C ratio of ECC mixtures was used (W/C=0.27) compared to W/C=0.19; and when the amount of SP increased up to 4 times only more than the standard amounts compared to 10 times, see Table 3 and Figure 3. The slight increase in SP was done only to support the effective water used in mixing process and to compensate the mixing water that has been absorbed by the SAP particles. It is well known that ECC's characterized by very low porosity and high resistance to shrinkage due to the presence of low W/C ratios and to the presence of PVA fibers, respectively. Therefore, full hydration of cementitious materials in ECCs cannot be reached and stops early due to the lack of free water and to the lack of free space in microstructure pores as well. It was revealed by (Termkhajornkit, Nawa, Nakai, & Saito, 2005) that when 50% cement replacement of fly ash was used, as in the case of this study, around 25-30% of fly ash did not participate in the hydration process and acted as fillers. This means that the pores of ECCs are fully packed with fly ash particles along with PVA fibers. In order to enhance the hydration, SAP particles were added and acted as internal water reservoirs. However, SAP particles would help at the first stages of concrete sitting to provide small amount of water and help to enhance the hydration slightly but not completely due to fully packed pores by un-hydrated cementitious particles along with PVA fibers. It is known that SAP has the ability to absorb large quantities of water (500 times more than its own weight). After concrete hardens, SAP particles start to release free water from their own structures and leave behind free spaces designated by big empty voids and going back to its original state. In general, generating empty voids may work in two different cases; either allowing more spaces for more hydration to occur and in addition to that, the released free water definitely will enhance the RH of microstructure and reactivate the hydration again of the surrounded un-hydrated cementitious particles, or impacting negatively the mechanical properties at later ages due to the presence of big voids which may weaken the microstructure. As a confirmation to the first case, the compressive strength values in this study at 56 days were increased more than 28 days when optimum W/C ratio of 27% was used. Consequently, no influence observed on the compressive strength values as in the case of 28 days when the SP amount increased 10 times more at W/C=0.19. As a justification for the second case, the generation of the big voids after SAP particles started to release the free water may occur in some locations that surrounded by lots of un-hydrated cementitious particles and this may help to compensate more hydration products in these free spaces and therefore enhances the compressive strength at 56 days as well. It should be noted that the values of compressive strength of SAP-ECC mixtures at the age of 56 days were higher than the values of same ECC mixtures without SAP particles even at the age of 90 days (Sherir, Hossain, & Lachemi, 2014).

Figure 4: Harsh mix with low moistened after adding SAP particles.

As shown in Figure 5, it was observed that SAP-ECC mixtures type Na have higher compressive strength values than SAP-ECC mixtures type K in both ages at 28 and 56 days. This may be attributed to the big difference in size between the two types of SAP particles as shown in Figure 6. The SAP-ECCs made of big particle size of SAP type K created bigger empty voids after releasing the free water which made it weaker than SAP-ECCs made of SAP type Na. Moreover, higher surface area for SAP type Na provided more quantities of free water which may enhance the concrete microstructure and stimulate more hydration.

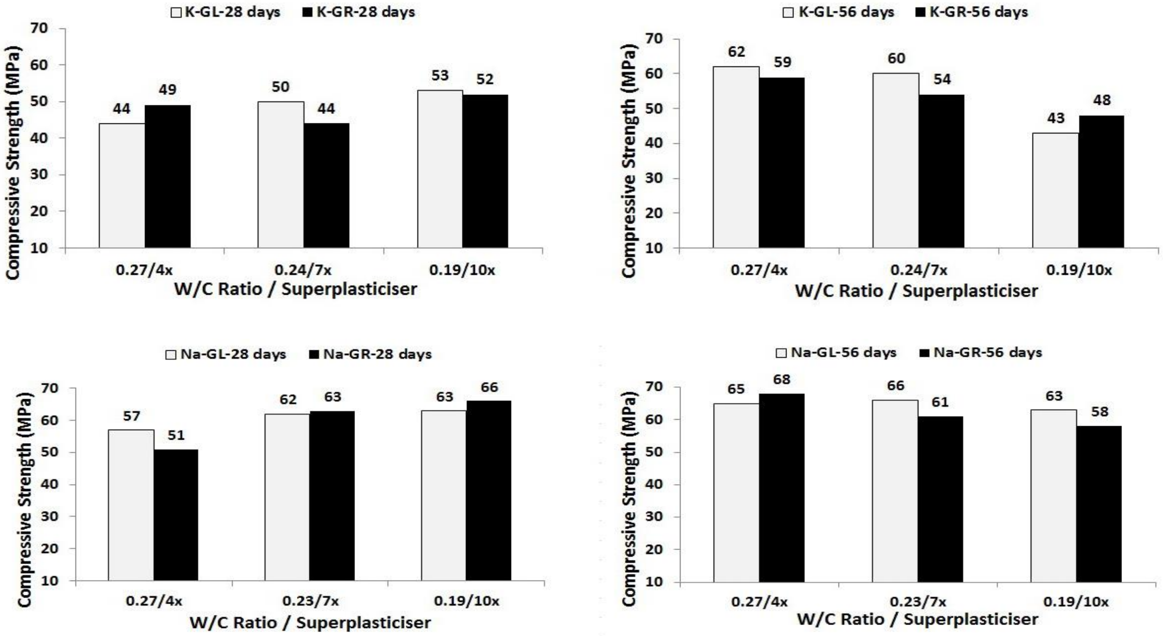


Figure 3: Compressive strength values of SAP-ECCs incorporating different SAPs (K and Na), different SP (GL and GR) and different W/C ratios (0.27, 0.24 and 0.19) at the ages of 28 and 56 days.

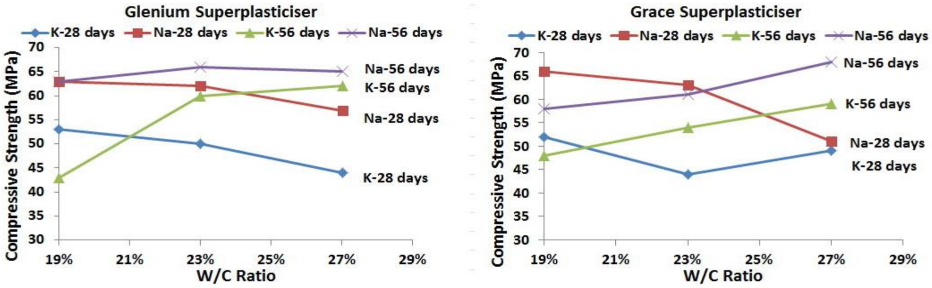


Figure 5: SAP-ECCs type-Na has higher compressive strength values than type-K at 28 and 56 days.

3.2 Size Effect on SAP-ECC Mixtures

According to the difference between the sizes of the two type pf SAP particles as shown in Figure 6, the author preferred to crush the two types of SAPs down to < 300µm in order to apply a consistent differentiation between them. Mortar and pestle was used to crush the two types of SAP particles. After the crushing, both samples were sieved through sieve size 300µm and the retained on sieve 200µm was taken. All samples were mixed by using SP type Grace at same W/C=0.27 ratio and tested at 56 days. As shown in Figure 7, compressive strength results revealed that both SAP-ECC mixtures made of SAP particles < 300µm particle size and the regular size particles were higher than the control. In addition, the results of SAP-ECC mixtures with size < 300µm were higher than the regular sizes for both types of SAP particles (Na and K). It should be noted that the percentage of the increase in compressive strength values between the same SAP types was almost the same for both of them (type Na and K). For instance, for SAP type-K, the % increase of compressive strength values of SAP-ECCs made of K < 300µm was 8.47% more than SAP-ECCs made of regular size particles. Moreover, at the same size, the percentage of the increase in compressive strength values between SAP type K and Na was almost the same as well for both sizes (< 300µm and regular size). For instance, for SAP size < 300µm, the % increase of compressive strength values of SAP-ECCs made of Na < 300µm was 14.06% more than SAP-ECCs made of K < 300µm.

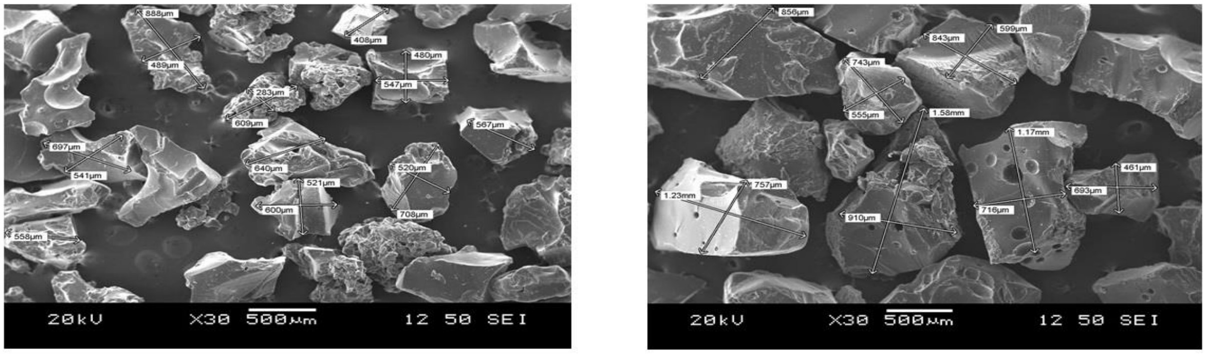
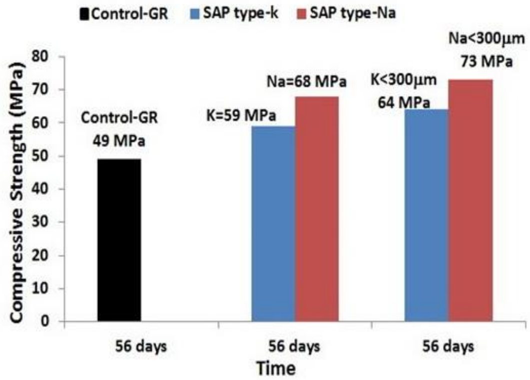
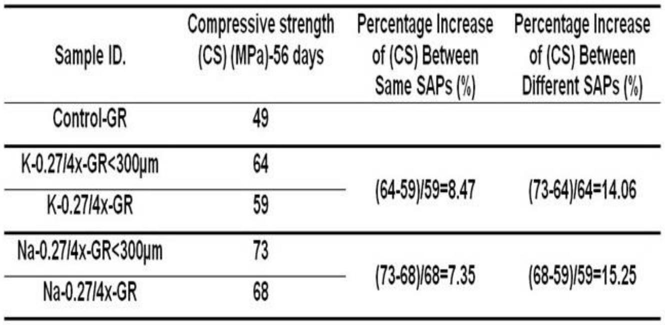


Figure 6: SEM micrograph of SAPs size; left: type-Na (200-800μm) and right: type-K (500-1200μm).





Sample ID.	Compressive strength (CS) (MPa)-56 days	Percentage Increase of (CS) Between Same SAPs (%)	Percentage Increase of (CS) Between Different SAPs (%)
Control-GR	49		
K-0.27/4x-GR<300µm	64	(64-59)/59=8.47	(73-64)/64=14.06
K-0.27/4x-GR	59		
Na-0.27/4x-GR<300µm	73	(73-68)/68=7.35	(68-59)/59=15.25
Na-0.27/4x-GR	68		

Figure 7: Size effect of SAP particle size for both types (Na and K) compared to the control.

3.3 Self-healing Property for SAP-ECC Mixtures

The self-healing property was examined at the age of 28 days based on Ultrasonic Pulse Velocity readings of SAP-ECCs incorporating different SAP types (K & Na), different SP (GL and GR) and different W/C ratios (0.27, 0.24 and 0.19) as shown in Table 4 & Figure 8.

Three prismatic samples were tested at the age of 28 days for each SAP-ECC mixture in order to explore the UPV performance of SAP-ECC mixtures. The UPV readings were taken for the samples at the age of 28 days before and after cracking and before and after curing as well. For consistent comparison purposes, the damage percentages were measured based on pre and post cracking UPV readings for every sample then the damage percentage of every sample was connected to the related control sample. For instance, the UPV damage calculation for K-0.27-4X-GL sample is as follows: ((108.2-98)/108.2=9.43%); then the UPV damage for the same sample was related to the control as follows: ((9.43%-8.11%)/8.11%=116.27%). For recovery calculation, the samples were soaking inside the water for another 28 days then UPV reading were taken again in order to calculate the recovery percentages.

The goal of studying the damage and recovery properties for SAP-ECC mixtures is to find out which type of SP is better to be used with SAP-ECCs and to study the performance of SAP particles under the flexural strength property of ECC mixtures at the age of 28 days before and after cracking. As shown in Figure 8 and as in the case of compressive strength values at the age of 28 days, the SP effect was the dominant part not W/C ratio in increasing the UPV damage and recovery readings at W/C=0.19 ratio.

Sample ID.	UPV at 28 D[*a]	UPV at 28+0 D[*b]	UPV Damage %[*c]	UPV Damage % Due to Control[*d]	UPV at 28+28 D[*e]	UPV Recovery %[*f]	UPV Recovery % Due to Control[*g]
Control-GL	102	111	8.11	100.00	92.8	19.61	100.00
Control-GR	96.3	103.4	6.87	100.00	88.7	16.57	100.00
K-0.27-4X-GL	98	108.2	9.43	116.27	91.6	18.12	92.40
K-0.27-4x-GR	94.6	110.4	9.99	123.22	90.9	20.25	103.26
K-0.23-7X-GL	93	110.3	10.06	124.05	88.3	20.65	105.31
K-0.23-7X-GR	94.8	109.7	6.14	75.71	87.6	15.83	80.69
K-0.19-10X-GL	93.6	103.4	7.78	95.99	85.7	17.21	87.73
K-0.19-10X-GR	93.7	106.8	9.38	115.70	86.5	18.85	96.12
NA-0.27-4X-GL	97	101	12.14	176.77	87.2	21.45	129.44
NA-0.27-4X-GR	94.2	102.9	12.04	175.41	87.6	22.82	137.70
NA-0.23-7X-GL	93	101.5	12.92	188.18	86.6	23.47	141.61
NA-0.23-7X-GR	96	99.9	6.71	97.66	85.2	17.47	105.39
NA-0.19-10X-GL	92.6	103.4	7.31	106.42	87	17.25	104.11
NA-0.19-10X-GR	95	103.2	7.95	115.72	85.3	20.98	126.62

Table 4: Ultrasonic Pulse Velocity readings for SAP-ECCs; [*a] pre-cracking at (28days); [*b] post-cracking immediately at (28+0days); [*c] UPV damage % between [*a &*b]; [*d] UPV damage % between [*c] based on controls (Control-GL/Control-GR); [*e] UPV post-curing for 28 days in water (28+28days); [*f] UPV recovery % between [*b &*e]; and [*g] UPV recovery % between [*f] based on controls (Control-GL/Control-GR)

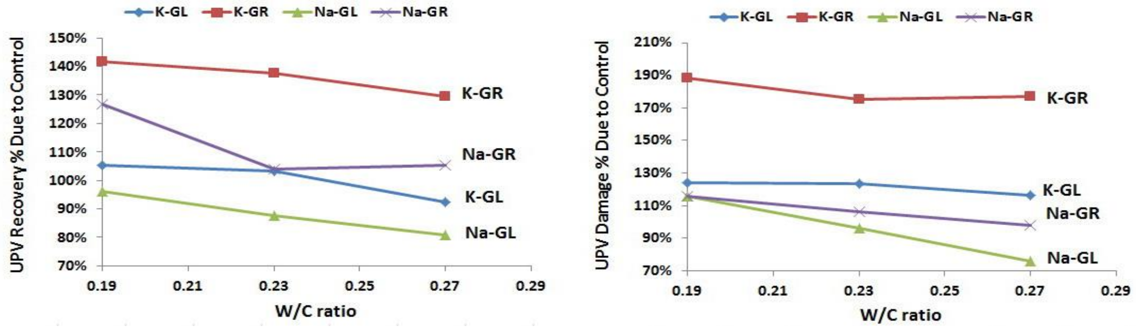


Figure 8: UPV recovery/damage readings for SAP-ECC mixtures at the age of 28 days.

From the Figure 8, it was observed that SAP-ECC mixtures made of SAP type K developed more UPV recovery readings than SAP-ECC mixtures made of SAP type Na. There are two explanations for the superior self-healing performance of SAP particles type K; firstly and after exploring the chemical composition for SAP particles type K, it was found that more than 50% of its composition made of carbon CO$_2$. The plenty of carbon inside the structure of SAP type K may stimulate the self-healing property by diffusing easily more calcium ions Ca^{2+} within the concrete cracked walls leading to more precipitations of CaCO$_3$ crystals (Edvardsen, 1999). Moreover, the big particle size of SAP type K allowed them to release plenty amount of water that is fully saturated with CO$_2$ stored inside their structures. The availability of carbon will allow to consume the available Ca^{2+} ions from the deepest portions of hardened cement pastes and then precipitate more CaCO3 as well (Edvardsen, 1999; Snoeck, Tittelboom, et al., 2012).

From the Figure 8, it is shown clearly that SAP-ECC mixtures made of SP type GR developed more UPV damage and recovery percentages than same mixtures made of SP type GL at the age of 28 days. Referring to Figure 8, it was observed that SAP-ECC mixtures made of SAP particles type K developed more UPV damage percentages than SAP-ECCs made of SAP particles type Na. This result was totally opposed to the compressive strength finding which revealed that SAP-ECCs type Na developed better compressive strength values than type K. It is well known that the mechanism of compressive strength testing is totally different than the flexural strength testing. Therefore, the behavior of the two tests within this study does not necessary to be also the same especially with the presence of SAP particles. For complete understanding of the mechanical performance of ECCs containing SAP particles, further research will be needed to determine the mechanical characteristics of SAP-ECC mixtures.

4 Conclusions

The mechanical performance of SAP-ECC mixtures made of SAP particles type (NA and K) and different SP type (GL and GR) at different W/C ratios is described in this paper. Compressive strength and ultrasonic pulse velocity tests were carried out to study the performance of SAP-ECC mixtures. The following conclusions were drawn from the study:

- The dominant part of increasing both the compressive strength values of SAP-ECCs and the UPV damage/recovery readings at the age of 28 days was the SP effect not W/C ratio especially when W/C ratio of 19% and 10 times extra of SP was used
- At 56 days, compressive strength values of SAP-ECCs were increased when the optimum W/C ratio of ECCs was used (W/C=0.27) and 4 times extra of SP as well.
- SAP-ECCs made of SAPs type K developed more UPV damage percentages than those made of SAP type Na. This is opposed to the finding of compressive strength readings which revealed that SAP-ECCs made of SAP type Na developed better values than type K.
- SAP-ECCs made of SAP particles < 300µm particle size had higher compressive strength values than SAPs made of regular size particles and the control as well.
- SAP-ECCs type K developed more recovery readings than SAP-ECC type Na.
- SP type GR developed more UPV damage and recovery percentages than same mixtures made of SP type GL at the age of 28 days

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