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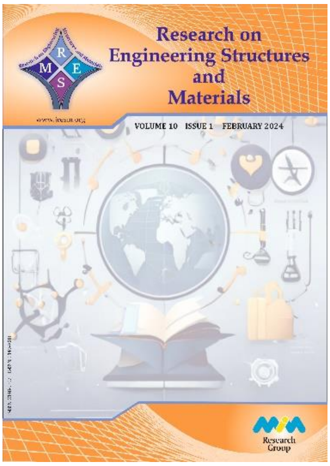

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Research Article

Impact of superabsorbent polymer on self-compacting concrete's workability, strength, carbonation and freezing-thawing

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Abstract

Superabsorbent Polymer, an internal curing material, is a significant development in concrete technology. Self-compacting concrete is popular due to high flowability or pumpability. However, the higher quantity of cementitious materials required higher moisture consumption to complete the hydration. Further moisture unavailability leads to shrinkage increment. External curing cannot give proper moisture to cementitious material at higher depth. Hence, internal curing with super absorbent polymer is an economical solution for this problem. This study examines the impact of super absorbent polymer on the mechanical and durability properties of concrete. Laboratory tests were conducted to evaluate the workability, mechanical characteristics of the concrete, such as compressive strength and flexural strength. In addition, freezing-thawing tests and carbonation tests were conducted to investigate the durability performance of concrete. Scanning electron microscopy images were also used to observe the concrete's microstructure after freezing-thawing cycles. The findings demonstrate that Compressive strength and flexural strength values decreased in water curing while in air curing, those were increased. Additionally, it was discovered that the freezing-thawing cycles decreased the compressive strength of reference concrete in standard water curing. However, compressive strength increased after freezing-thawing cycles in air-curing super absorbent polymer mixes. Scanning electron microscopy images have confirmed that the microstructure of air-curing super absorbent polymer mixes was improved.

1. Introduction

There are drawbacks to the external concrete curing method, including time requirements, resource waste, and subpar curing results. As a result, internally cured concrete technology is being developed gradually (1). Super absorbent polymer (SAP) is a macromolecular substance with strong water retention and super water absorption capabilities. It can effectively increase the volume stability of concrete and prevent issues like micro-cracks and shrinkage. The effect of SAP on the operating performance, mechanical performance, volume stability, and durability of concrete was investigated under low water-cement (w/c) ratio circumstances (2) (3). It was also feasible to ascertain how the SAP and curing age affected the distribution of concrete pores using 3D volume analysis (4). The evolution law was also studied, along with the effects of time-varying damage brought on by various internal curing agents, on concrete's macro and micro characteristics. Zhutovsky et al. (5) demonstrated about the same compressive strength (for 0.33 w/c) with pumice and a 10% drop in compressive strength for w/b of 0.21,0.25 concretes for low water binder concretes. Moreover, SAP reduces compressive strength during the early stages but

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increases it later in life. As SAP content increases, compressive strength falls. This is the result of the breakdown of SAP leaving behind huge holes (6)–(7). In contrast, SAP has been shown in other experiments to progressively increase compressive strength above the control mix at 28 days (8). The compressive strength of SAP mixture samples is greater than that of the control mix even at later ages (9)(10). Due to the lengthier hydration of the higher cementitious material by SAP's entrained water, this benefit is likely greater in SCC. As mentioned earlier, the research has revealed that there is debate regarding the impact of SAP on concrete strength (11,12) and that SAP can significantly increase the durability (13)(14)(15). Aggressive ions are transported via the micro gaps that SAP creates, yet internal curing effect produces a denser microstructure and increases durability (1). Reinhardt et al. (3) also show that SAP enhances the resistance to water penetration and oxygen permeability. By increasing SAP dosage up to 0.6%, Benshausen et al. (13) verified that SAP can reduce carbonation depth and chloride ion penetration depth. Other researchers also noted that the increased hydration of the binder by SAP-released water resulted in a reduction of the carbonation depth and chloride penetration (1). To better understand how SAP affects concrete performance, the morphology of the hydrated product, pore structure, and mineral composition were considered.

Additionally, it was investigated (16–18) how the concrete's pore parameters affected the antifreeze performance. From a micro perspective, it was explained that SAP could increase the concrete's durability and resistance to frost (4) (17). When vapor-filled pores are created, the internal relative humidity of a sealed system decreases, a process known as self-desiccation (5). SAP enhances flexural joints' performance by preventing this self-desiccation (19).

Flowability of SCC has decreased by SAP in dry condition (20)(21). The impact of SAP depends on absorption of SAP, size of SAP, dosage of SAP on properties of self-compacting concrete (SCC). Nevertheless, further clarification is required because it is still being determined. Additionally, there have been few quantitative studies on how much SAP has improved the durability of concrete. It is also necessary to conduct more research on how SAP affects the flexural strength of concrete. More investigation is necessary to ascertain the extent and mechanism of the micro-pore features of SAP-influence concrete on compressive strength. More research is required on how freezing-thawing affects the internally cured concrete with SAP regarding mass loss and compressive strength loss. It also required to study how internally cured concrete affects the carbonation depth and microstructural changes, which caused the change in durability and strength.

This paper investigated the effect of SAP on Workability, freezing-thawing performance, carbonation depth, flexural strength, and compressive strength of SCC with three different curing regimes on internally cured SCC mixtures. Also, microstructural analysis was conducted on SCC samples which were collected after freezing-thawing testing. In addition, the internal curing effect of SAP on SCC made up of Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC) was studied.

The Novelty of the research is an attempt to solve inadequate curing problems in India's hot climate and improve the strength, durability, and microstructural properties of self-compacting concrete. This parametric study is to meet the shrinkage reduction, durability, compressive strength and flexural strength by SAP as an internal curing agent. A literature review has been done to search for suitable and effective internal curing agents for reducing the shrinkage problem of Self compacting concrete in high-temperature climates. The super absorbent polymer can give a solution to the reduction of shrinkage in self-compacting concrete and improper curing in hot weather conditions.

2. Experimental Program

2.1. Materials

The experimental study used PPC and PSC with specific gravities of 2.90 and 2.98, respectively. Table 1 displays the PPC and PSC's chemical compositions. The coarse aggregate was consisted of crushed granite with a maximum particle size of 10 mm and a specific gravity of 2.7. Sand from the Kharun River, with a specific gravity of 2.62, served as the fine aggregate. Concrete mixtures were mixed with tap water. The Superplasticizer Master Glenium 8632, manufactured by BASF, is based on polycarboxylate ether and contains a viscosity-modifying ingredient. It can ensure the workability of reference concrete with a 650 mm to 750 mm slump flow diameter by flow table test. The Superplasticizer has a specific gravity of 1.08. The chemical compositions of superabsorbent polymer (SAP, Innovative Agro India) were shown in Table 1. The bulk density of SAP is 0.65-0.80 g/cm^3. SAP before and after water absorption is shown in Figure 1. Commercially available Sodium based Poly acrylate was used as super absorbent polymer. Water absorption capacities of SAP is 36g/g and 170g/g in cement solutions (prepared solution with w/c=5.0) and tap water respectively calculated by Tea bag method which was given by Schröfl et al. (18). Higher ionic concentration of Ca^{+2}, Na^{+} present in cement solution may decrease the water absorption of SAP. Hence SAP won’t affect the concrete properties directly because it absorbs and desorb the water based on humidity conditions. Based on Bentz formula dosage of SAP calculated in the previous work (22). Theoretically, the amount of SAP required to achieve full hydration for 533.33 kg/m^3 cement is 0.219 kg/m^3. Due to this the dosage of SAP starts from 0.05% cement which 0.27 kg/m^3 as shown in the Table 2.

Table 1. Chemical composition of PPC, PSC, and SAP

Components	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O + K_2O	Na	O_2	C
PPC	50.00	26.33	11.45	1.75	8.97	-	1.41	-	-	-
PSC	56.64	22.15	10.23	2.65	6.37	1.95	-	-	-	-
SAP	-	-	-	-	-	-	-	33.03	55.78	11.19

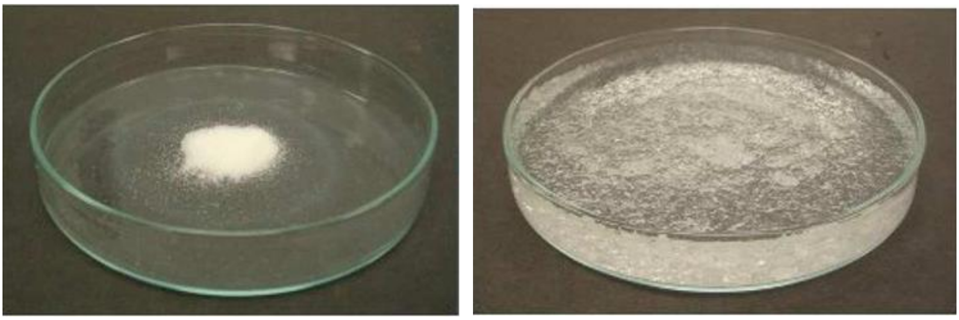

Fig. 1. Image of SAP before and after swelling by water absorption

2.2. Mix Proportion and Specimen Preparation

According to the IS 10262:2019 (23), the mix proportions of SCC were designed with PPC and PSC cement. PPC and PSC mix proportions are shown in Table 2 and Table 3, respectively. The w/c ratio of the reference concrete mixture varied from 0.30 to 0.40. P30, P35, and P40 are PPC mixes with 0.30, 0.35, and 0.40 w/c ratios, respectively. S30, S35, and S40 are the PSC mixes with 0.30, 0.35, and 0.40 w/c ratios, respectively. S0, S5, S10, and S15 are the dosages of SAP at 0%, 0.05%, 0.10%, and 0.15% of cementitious materials, respectively.

Table 2. Mix proportions of PPC in kg/m³

Mixes	Cement	W/B	Water	Sand	Coarse aggregate	SAP	SP
P30-S0	533.33	0.3	160	863.33	821.26	0	8
P30-S5	533.33	0.3	160	863.33	821.26	0.27	8
P30-S10	533.33	0.3	160	863.33	821.26	0.53	8
P30-S15	533.33	0.3	160	863.33	821.26	0.8	8
P35-S0	471.43	0.35	165	886.77	843.55	0	7.1
P35-S5	471.43	0.35	165	886.77	843.55	0.24	7.1
P35-S10	471.43	0.35	165	886.77	843.55	0.47	7.1
P35-S15	471.43	0.35	165	886.77	843.55	0.71	7.1
P40-S0	425	0.4	170	902.65	858.66	0	6.4
P40-S5	425	0.4	170	902.65	858.66	0.21	6.4
P40-S10	425	0.4	170	902.65	858.66	0.43	6.4
P40-S15	425	0.4	170	902.65	858.66	0.64	6.4

Table 3. Mix proportions of PSC in kg/m³

Mixes	Cement	W/B	Water	Sand	Coarse aggregate	SAP	SP
S30-S0	533.33	0.3	160	870.06	827.65	0	8
S30-S5	533.33	0.3	160	870.06	827.65	0.27	8
S30-S10	533.33	0.3	160	870.06	827.56	0.53	8
S30-S15	533.33	0.3	160	870.06	827.56	0.8	8
S35-S0	471.43	0.35	165	892.72	849.21	0	7.1
S35-S5	471.43	0.35	165	892.72	849.21	0.24	7.1
S35-S10	471.43	0.35	165	892.72	849.21	0.47	7.1
S35-S15	471.43	0.35	165	892.72	849.21	0.71	7.1
S40-S0	425	0.4	170	908.01	863.76	0	6.4
S40-S5	425	0.4	170	908.01	863.76	0.21	6.4
S40-S10	425	0.4	170	908.01	863.76	0.43	6.4
S40-S10	425	0.4	170	908.01	863.76	0.64	6.4

Each specimen was cast, held indoors for 24 hours, and then molded with a number. Reference concrete and internal curing concrete specimens were cured using room air, Gunny bags, and normal water. Concrete specimens that were air-curing in the room were set up in the lab setting. In the process of gunny bag curing, specimens were covered entirely in wet gunny bags, and water was applied twice daily. The water-curing ponds held the conventional water-curing concrete examples.

2.3. Testing Methods

2.3.1 Workability

One of the physical characteristics of concrete that affects strength is workability. Concrete is transportable, installable, and compactable when done correctly, without bleeding or isolation. Slump flow, the V-funnel test, the L-box test, and the sieve segregation test can all be used to gauge workability. In this article discussion of workability done based on Slump flow test (Slump flow time and Slump Flow diameter), V-Funnel test. These tests performed according to IS: 10262-2019 (23). Figure 2 shows the slump flow diameter of SCC.

Fig. 2. Slump flow diameter of fresh SCC

2.3.2 Compressive Strength Test

The Compressive strength was measured by applying a Compressive load on 100mm*100mm*100mm concrete cubes with a Compressive strength testing machine (CTM). Cube specimens' compressive strength was studied on 28 days after casting and curing in three curing regimes. The cube specimens are tested on a CTM machine per IS: 516-2018 (24). The highest load applied to the specimen during the test is recorded once the load is increased until the specimen fails. The figures 4 and 5 shows test set up of compressive strength and tested cubes respectively.

Fig. 3. Compressive strength testing machine apparatus

Fig. 4. SCC specimens after compressive strength testing

2.3.3 Flexural Strength Test

On concrete beams that were 500mm*100mm*100mm, a four-point bending test was used to determine flexural strength. In three different curing regimes, the flexural strength of beam specimens was examined 28 days after casting. According to IS: 516-2018(24), the beam specimens were evaluated using a flexural strength testing apparatus. The peak load applied on the specimen is recorded during flexural testing. Figure 5 shows SCC specimens after Flexural strength testing.

Fig. 5. SCC specimens after Flexural strength testing

2.3.4 Carbonation Test

The carbonation resistance test was performed following the IS 516-2018 (24) standard test procedure for ordinary concrete's long-term performance and durability. For each batch, three specimens measuring 100 mm cubes were evaluated. The specimens underwent a 28-day curing process under the appropriate curing conditions. The specimens were left for 48 hours to dry before the test. The specimen's top and bottom surfaces were sealed to ensure horizontal CO_2 diffusion that could occur. The specimens were positioned in an accelerated carbonation chamber which was set at (20 ± 2)°C of temperature , (70 ± 5)% of relative humidity and (20 ± 3)% of CO_2. After that break the specimens into two parts and applied phenolphthalein indicator on the broken surfaces. Further measure the depth of non-colored length from the surface of cube.

2.3.5 Freezing-Thawing Test

According to ASTM C666-08 (25) , each mixture's quick freezing-thawing durability was evaluated. Three samples measuring 150 mm*150 mm*150mm cubes were cast for each mixture to examine the resistance to quick freezing-thawing. The specimens were removed from the molds after 24 ± 2 hours and cured for 28 days at three different curing regimes. Then specimens were taken out and kept in water to achieve the target internal thaw temperature (+4^{0}C) for testing. After taking initial measurements, the specimens were put in a water-filled pan so that all faces were completely covered at all times of water during the freezing-thawing cycles. The water-filled pans and the concrete samples were then put in a chamber that underwent freeze-thaw cycling, which involves gradually dropping the temperature of the samples from +4°C to -18°C throughout 4 to 5 hours and then gradually raising it back to -18°C to +4°C. At the desired thaw temperature, samples were taken out and evaluated until they had undergone 100 cycles.

2.3.6 Scanning Electron Microscopy

Scanning Electron microscopy (SEM) Analysis can be used for qualitative purposes but not for quantitative assessment. Both reference concrete and internal curing concrete underwent SEM analysis. Utilizing SEM, the precipitates in the concrete cube's cracks were also examined. After being tested for compressive strength, the broken piece of a 28-day-cured concrete cube specimen was used for this analysis. Acetone was applied to these cubes to stop the process of further hydration. Before being examined, the samples were coated with carbon using sputter coating Emitech K575.

3. Results and Discussions

3.1 Workability

Test methods used to study the attributes of fresh concrete include the Slump flow test and V-funnel test. These tests were led to decide the filling capacity, and passing capacity and resistance to the isolation of the SCC mix. All SCC mixtures were produced with PPC and PSC with w/c ratios of 0.30, 0.35, and 0.40. For three Water cement ratios, every mix exhibits a slump flow diameter range from 600mm to 760mm, which shows workability varying from class SF1 to SF3 as per IS 10262:2019. When mixing and casting cubes, neither bleeding nor segregation are seen in the SCC mixes. For a more thorough study and comprehension of the workability and rheology of SCC, the tests carried out are the slump flow test, V-funnel test, L-Box test, sieve segregation test and rheometer test.

3.1.1. Slump Flow Time (T500) Test

The slump flow time values of PPC and PSC mixes were observed in the medium range of workability. Figure 6 show the variations of T500 values of PPC and PSC mixes of 0.3, 0.35 and 0.4 w/c ratio. It is observed that the 5%, 8%, and 12% increment in T500 values with the addition of SAP of 0.05%, 0.1%, and 0.15% of the mass of cement as compared to control SCC of 0.3 w/c ratio PPC mixes. Similarly, in 0.35 w/c ratio PPC mixes, the increment observed was 4%, 7% and 10%. In 0.4 w/c ratio PPC mixes, this increment was 5.3%, 8.7%, and 12.7% as compared to control SCC.

While in 0.3 w/c ratio PSC mixes, the increment was 4.5%, 7.5% and 11.5% as compared to control SCC. Similarly, in 0.35 w/c ratio PSC mixes, the increment observed was 3.5%, 6.5% and 9.5%. In 0.4 w/c ratio PSC mixes, this increment was 4.9%, 8.2%, and 12.2% as compared to control SCC.

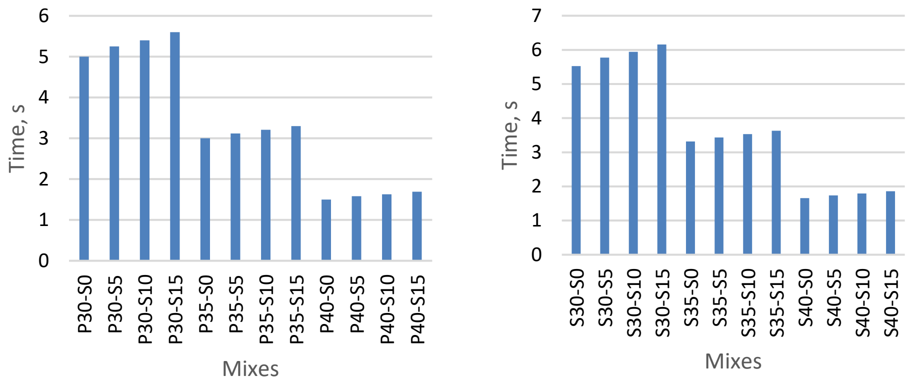

Fig. 6. T500 values of PPC and PSC mixes

3.1.2 Slump Flow Diameter Test

The slump flow diameter values of PPC and PSC mixes were observed in the medium range of workability. Figure 7 show the variations of slump flow diameters of PPC and PSC mixes of 0.3, 0.35 and 0.4 w/c ratio. It is observed that the 2.9%, 5.9%, and 8.8%reductionin slump flow diameters with addition of SAP of 0.05%, 0.1%, and 0.15% of mass of cement as compared to control SCC of 0.3 w/c ratio PPC mixes. Similarly, in 0.35 w/c ratio PPC mixes, the reduction observed was 2%, 4.7% and 6.8%. In 0.4 w/c ratio PPC mixes, this reduction was 2.6%, 5.3%, and 7.9% as compared to control SCC. While in 0.3 w/c ratio PSC mixes, the reduction was 3.1%, 6.2% and 9.2% as compared to control SCC. Similarly, in 0.35 w/c ratio PSC mixes, the reduction observed was 1.4%, 4.3% and 5.7%. In 0.4 w/c ratio PSC mixes, this reduction was 2.8%, 5.6%, and 6.9% as compared to control SCC.

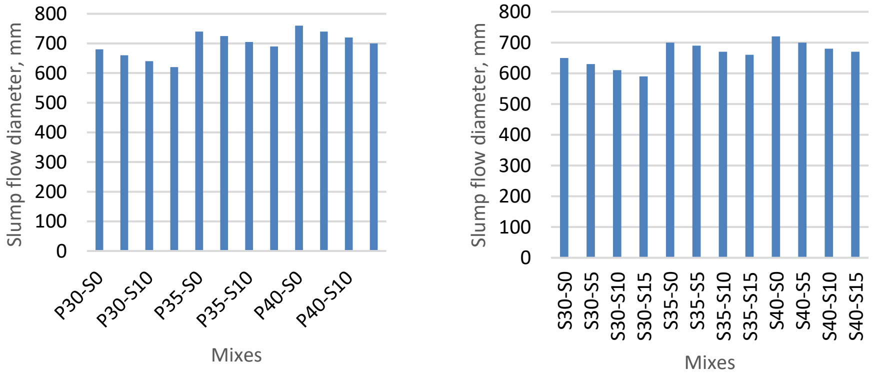

Fig. 7. Slump flow diameters of PPC and PSC mixes

3.1.3 V-funnel Test

The V-Funnel time values of PPC and PSC mixes were observed in the medium range of workability. Figure 8 shows the variations of V-Funnel values of PPC and PSC mixes of 0.3, 0.35 and 0.4 w/c ratios. It is observed that the 7%, 12.8%, and 19.8%incrementinV-Funnel values with addition of SAP of 0.05%, 0.1%, and 0.15%of mass of cement as compared to control SCC of 0.3 w/c ratio PPC mixes. Similarly, in 0.35 w/c ratio PPC mixes, the increment observed was 6.6%, 14.5% and 22.4%. In 0.4 w/c ratio PPC mixes, this increment was 7.7%, 15.4%, and 23.1% as compared to control SCC. While in 0.3 w/c ratio PSC mixes, the increment was 6%, 11.8% and 18.7% as compared to control SCC. Similarly, in 0.35 w/c ratio PSC mixes, the increment observed was 5.6%, 14.5% and 22.4%. In 0.4 w/c ratio PSC mixes, this increment was 8.7%, 16.4%, and 24.2% as compared to control SCC.

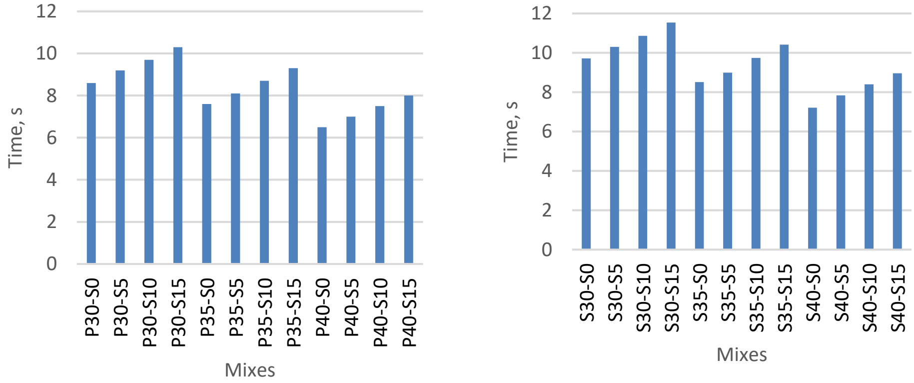

Fig. 8. V-Funnel times of PPC and PSC mixes

From the figures 6 and 8, it is clear that the Slump flow times and V-funnel times of SAP concrete have increased. After observing above workability tests SAP decreases the flowability of SCC. However, this may be due to the absorption of water from the mix by dry SAP. At a time, segregation and bleeding were decreased if additional water is not added which is in accordance with previous researchers(26).

3.2 Compressive Strength

Figure 9 shows the results of the compressive strength tests of the control SCC and internal curing mixes with additions of SAP at 0.05%, 0.10%, and 0.15% with PPC and PSC, respectively. Experimentation was conducted on w/c ratios of 0.30, 0.35, and 0.40 and curing regimes of water, air, and gunny bag for 28 days of curing period.

Compressive strength of PPC mixes of 0.3 w/c ratio in water curing was decreased by 2.6%, 5.2% 7.8% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While compressive strength in air curing was increased by 17.7%, 33.9%, 24.6% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 6.25%, 16.67%, and 12.5% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Compressive strength of PPC mixes of 0.35 w/c ratio in water curing was decreased by 2.3%, 4.7% 7.0% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While compressive strength in air curing was increased by 16.7%, 30.6%, 22.2% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 5.0%, 9.1%, and 6.6% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Compressive strength of PPC mixes of 0.40 w/c ratio in water curing was decreased by 2.8%, 5.6% 8.3% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While compressive strength in air curing was increased by 16.3%, 38.4%, 23.2% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 6%, 14%, and 8% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

It can be observed that the compressive strength of all mixtures in the water curing regime decreased with SAP. Whereas compressive strength in air curing and gunny bag curing regimes increased with SAP. The reduction in compressive strength in the water curing regime can be attributed to several macro voids in the microstructure due to SAP hydrogel not being utilized by 100% relative humidity in curing ponds. The humidity meter was arranged in air curing chamber and gunny bag curing chamber to check the humidity percentage variation. In air curing regime, the compressive strength has enhanced from 43.33 MPa for control concrete to 58 MPa for best SAP mix. Here best SAP mix means the strength properties were high at this dosage. The enhancement in compressive strength in the air curing regime can be attributed to the absence of macro voids in the microstructure due to SAP hydrogel being utilized by having less than 60% relative humidity in the surrounding air. In the Gunny bag curing regime, the compressive strength has increased from 48 MPa to 60 MPa for SAP 0% to SAP 0.1%. It may be due to the relative humidity in gunny bag curing varying between 60% and 90%. Hence SAP has yet to release water from SAP hydrogels to the full extent.

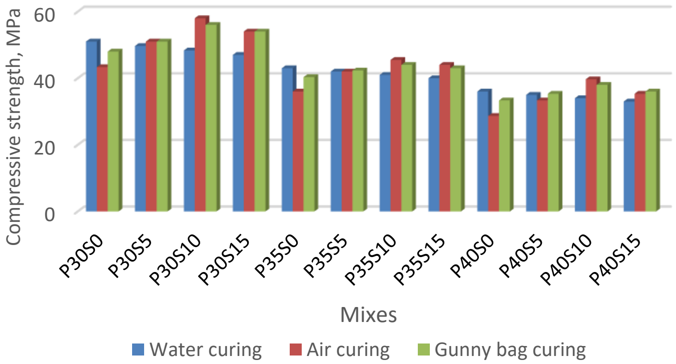

Figure 9. Compressive strength of PPC-based SCC mixes with and without super absorbent polymer in different curing regimes

The compressive strength results of PSC-based reference and internally cured mixtures with 0.30, 0.35, and 0.40 w/c ratios are shown in Figure 10. Compressive strength of PSC mixes of 0.3 w/c ratio in water curing was decreased by 3%, 7.2% 9.6% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While compressive strength in air curing was increased by 9.7%, 26.2%, 17.9% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 6.2%, 8.1%, and 7.1% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Compressive strength of PSC mixes of 0.35 w/c ratio in water curing was decreased by 2.8%, 6.9% 9.4% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While compressive strength in air curing was increased by 17.2%, 28.9 %, 21.9% for the SAP dosage of 0.05%, 0.10%, and 0.15%

respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 6.8%, 15.9%, and 13.6% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Compressive strength of PSC mixes of 0.40 w/c ratio in water curing was decreased by 2.4%, 4.9% 8.1% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While compressive strength in air curing was increased by 21.2%, 48.5%, 36.4% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 16.2%, 25%, and 19.8% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

The results of PSC mixtures followed the pattern of PPC-based mixtures. In water curing, the compressive strength has decreased from 55.33 MPa to 50MPa for SAP 0% to SAP 0.15%, and the reduction is around 10%. In air curing, the compressive strength has increased from 48 MPa to 61 MPa, and in gunny bag curing, strength has increased from 53 MPa to 59 MPa. These increments are up to SAP 0.10% which is best SAP dosage. The compressive strength in PPC and PSC mixtures increased with best SAP dosage in air curing in the range of 10% to 15% as compared to control mixes in water curing. This improvement most probably higher in SCC because of the longer hydration of higher cementitious material by entrained water of SAP. Previous studies (27)(28)(29) also confirms that the increment of compressive strength in concrete by adding SAP to the concrete mix.

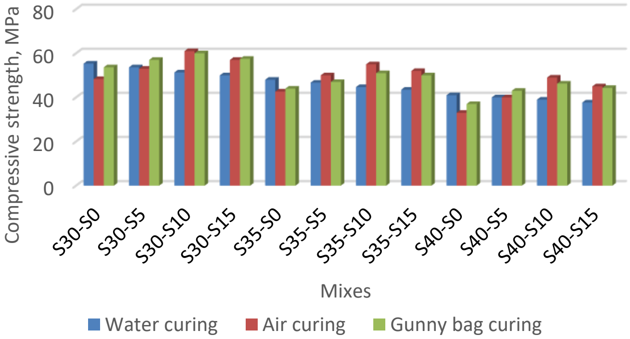

Fig.10. Compressive strength of PSC-based SCC mixes with and without super absorbent polymer in different curing regimes

3.3 Flexural strength

The material is under the most significant stress when it is about to give, which is represented by flexural strength. The flexural strength results of SCC mixtures with varying SAP dosages in three curing regimes with w/c ratios of 0.30, 0.35, and 0.40 were shown in Figures 11 and 12 for PPC and PSC-based mixes, respectively.

Flexural strength of PPC mixes of 0.3 w/c ratio in water curing was decreased by 2.2%, 3.3% 5.5% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While flexural strength in air curing was increased by 6.8%, 18.2%, 11.4 % for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 4.5%, 12.4%, and 6.7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Flexural strength of PPC mixes of 0.35 w/c ratio in water curing was decreased by 3%, 6.1% 9.1% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While flexural strength in air curing was increased by 19.4%, 27.4 %, 22.6% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 7.9%, 20.6%, and 14.3% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Flexural strength of PPC mixes of 0.40 w/c ratio in water curing was decreased by 1.8%, 3.5% 7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While flexural strength in air curing was increased by 9.1%, 18.2%, 12.7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 5.4%, 10.7%, and 8.9% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

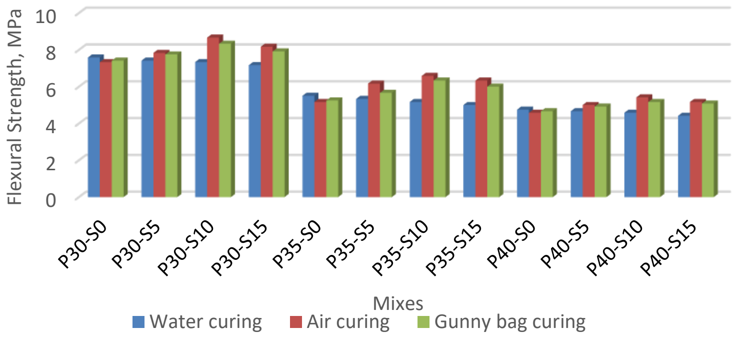

Fig. 11. Flexural strength of PPC-based SCC mixes with and without super absorbent polymer in different curing regimes

Flexural strength of PSC mixes of 0.3 w/c ratio in water curing was decreased by 2.7%, 4.2 % 7.3% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While flexural strength in air curing was increased by 6.3%, 17.1 %, 9.3 % for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 3.5%, 7.4%, and 10.4% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Flexural strength of PSC mixes of 0.35 w/c ratio in water curing was decreased by 3.5%, 6.4% 10.4% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While flexural strength in air curing was increased by 18.8%, 24.7 %, 19.7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by 7.4%, 19.5%, and 12.7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

Flexural strength of PSC mixes of 0.40 w/c ratio in water curing was decreased by 2.2%, 4.4% 8.7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the water curing. While flexural strength in air curing was increased by 8.6%, 17.1%, 10.7% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the air curing. In the gunny bag curing it was increased by

4.9%, 9.7%, and 7.4% for the SAP dosage of 0.05%, 0.10%, and 0.15% respectively with respect to control concrete in the gunny bag curing.

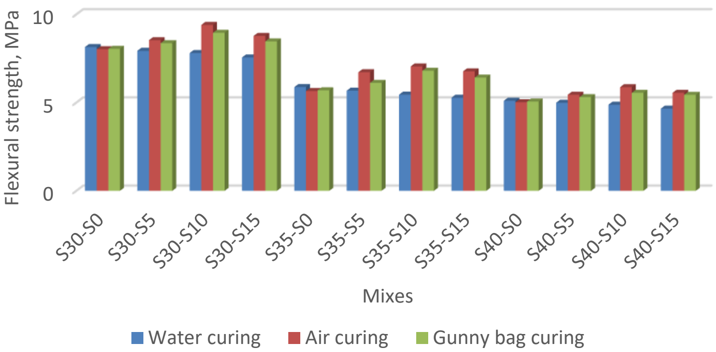

Fig. 12. Flexural strength of PSC-based SCC mixes with and without super absorbent polymer in different curing regimes

It can be observed that the flexural strength of all mixtures in the water curing regime decreased. In comparison, flexural strength in air and gunny bag curing regimes has increased. The flexural strength in air and gunny bag curing increased to SAP with 0.1% SAP dosage which is best. The flexural strength in PPC and PSC mixtures has been increased with best SAP dosage in air curing in the range of 14% to 20% as compared to control mixes in water curing. Previous researchers (30)(31) also confirms that the increment of flexural strength in concrete by adding SAP to the concrete mix. The bending strength is lower in water-curing SAP combinations than in air-curing and gunny-curing SAP mixtures because these mixtures contain more air voids and macropores. Previous research (1) investigated the effect of the total air voids and macro pores in the tensile plane's cross-sectional area on the composite's bending strength. The macro pores will result in a localized loss of strength, possibly reducing the strength in the water curing regime.

3.4 Carbonation Depth

Concrete is an alkaline substance with a higher pH. Concrete's pH value decreases due to carbonation, making it easier for the reinforcement to corrode in reinforced concrete. Therefore, concrete carbonation testing is crucial in determining the concrete's endurance. The carbonation test is conducted on PPC and PSC mixtures for w/c ratios of 0.30, 0.35, and 0.40. In addition, for each curing regime 100 mm cubes were casted and cured in respective regime for 28 days. The concrete carbonation test results for each of the three w/c ratios are shown in Figures 13 and 14. The depth of carbonation of reference concrete in air and gunny bag curing regimes increased compared to the water curing regime. However, an air curing regime with best SAP dosage of internal curing mixtures was shown the reduction of carbonation depth as compared to reference concrete. This may be due to denser interfacial transition zone (ITZ) formed in the internal curing mixtures. Concrete's carbonation resistance is correlated with the matrix's degree of compactness (29)(32). The water from the SAP was released into the environment when the concrete hardened, promoting further hydration of the cement matrix and enhancing the compactness of the concrete. These results aligned with compressive strength and flexural strength results. Depth of carbonation decreased by 4-8% in best SAP mixes in air curing compared to control mix in water curing. Other studies (29)(13)(17)(33) also confirm that decrement in the carbonation by adding the SAP to concrete mix.

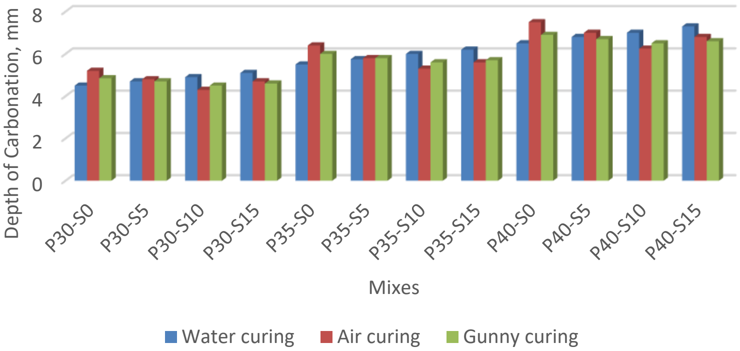

Fig. 13. Carbonation depth of PPC-based SCC mixes with and without super absorbent polymer in different curing regimes

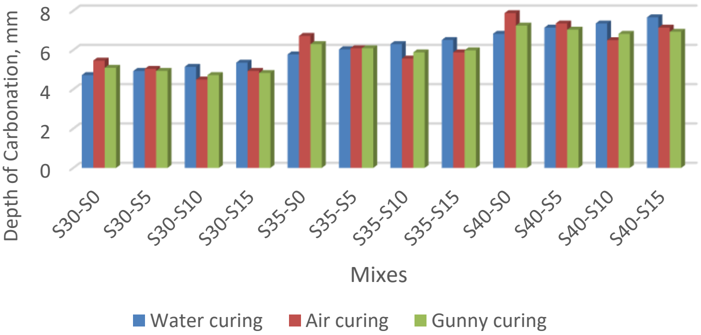

Fig. 14. Carbonation depth of PSC-based SCC mixes with and without super absorbent polymer in different curing regimes

3.5 Freezing-Thawing

Mass loss or gain of SCC specimens can be observed in Figures 15 and 16. In reference mixtures, for instance, P30-S0 and S30-S0, the mass has been lost by to 0.38% and 0.24%, respectively. It may be due to the weakening of ITZ. In the case of internal curing mixtures: water-curing mixtures showed a mass loss, but air-curing and gunny mixtures showed a mass gain. It may be due to water-curing mixtures of SAP hydrogel causing macro cracks. In the case of air and gunny bag mixtures, SAP hydrogel released the total water before the freeze-thaw experiment and thickened the ITZ. However, Nanosized SAP particles again absorb the water up to 1% of the mass. This mass is not high because denser ITZ will not allow an increment of the size of the hydrogel. Other studies (34)(35) also aligned with the same phenomenon. Mass loss has been observed in reference concrete and internally cured concrete with water curing. However, in air curing and gunny bag curing, it has been observed that mass has gained after 100 freezing-thawing cycles. The mass loss in water curing mixtures around 0.25% to 0.5%. However, in best SAP mixtures in air curing, the mass has gained 0.4 % to 0.9%.

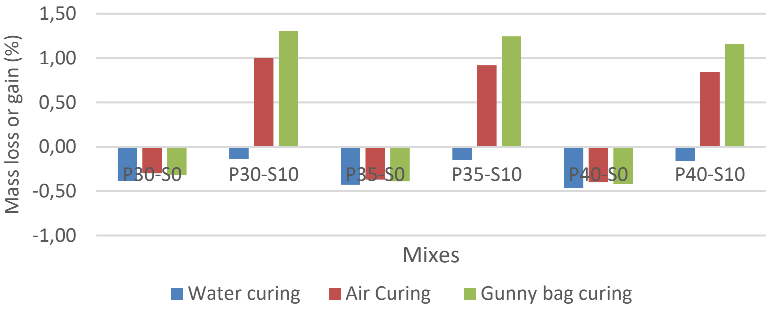

Fig. 15. Mass loss or gain of PPC-based SCC mixes with and without super absorbent polymer at different curing regimes

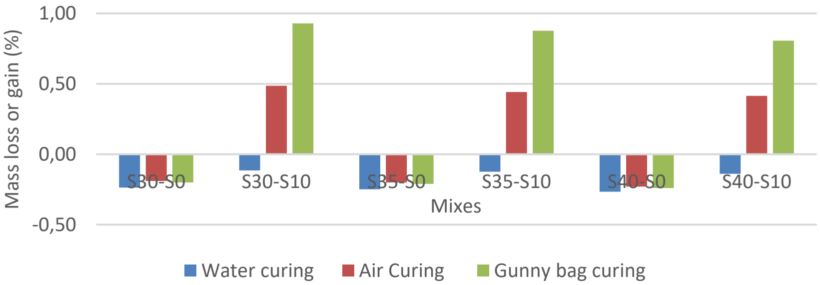

Fig. 16. Mass loss or gain of PSC-based SCC mixes with and without super absorbent polymer in different curing regimes

In Figures 17 and 18, the results of the compressive strength test without freeze-thaw and with freeze-thaw for PPC and PSC mixtures, respectively. In the legends of figures 17 and 18, of "w/o" stands for "without". Compressive strength in the water curing regime with and without SAP was decreased.

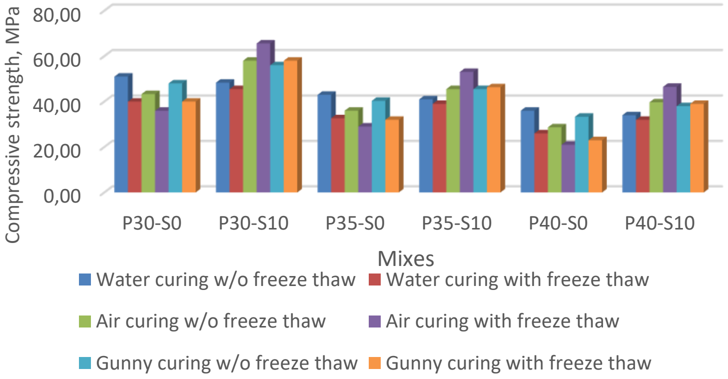

Fig. 17. Compressive strength of PPC-based SCC mixes with and without freeze-thaw effect in different curing regimes

However, in the air curing and gunny bag curing regimes with freeze and thaw cycles, specimens were shown to increase compressive strength results, which may be due to the full redemption of water from SAP particles and improved ITZ throughout the specimen. In the case of water curing, SAP particles have not released the water and become macro void and weaken the ITZ. In the case of reference, freeze-thaw cycles damaged the concrete microstructure and led to lower strength than those without freeze-thaw cycles. Previous research (36)(37) also concluded the same analogy for freeze-thaw cycle experiments on internally cured mixtures with SAP. Regarding Mass change previous studies (38)(35)(37)approve that SAP Mass has lost in water curing regime and mass has increased in the air curing and intermittent curing regimes. And increment of compressive strength after freezing and thawing was also observed in other studies with air curing due to lowest air voids and lesser water content present in those mixtures (39)(40)(41).

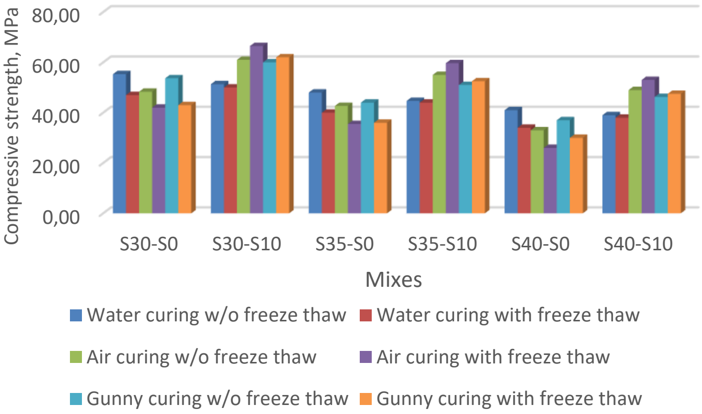

Fig. 18. Compressive strength of PSC-based SCC mixes with and without freeze-thaw effect in different curing regimes

3.6 Scanning Electron Microscopy

SEM photographs of a few chosen mixes were obtained to determine the impact of freeze-thaw cycles' impact on the concrete microstructure. Figures 19 and 21 show the cracks in the microstructure of reference concrete mixtures (P35-S0, S35-S0). These cracks were responsible for the reduction of compressive strength after freezing-thawing. However, the internal curing mixtures (P35-S10, S35-S10) with best SAP dosage of 0.1% showed denser ITZ in their microstructure. This can be observed in Figures 20 and 22 for PPC and PSC mixtures, respectively. Consequently, the freezing-thawing exposures specimens shown increased compressive strength values. These results aligned with the results freeze-thaw cycle test. Hence internal curing with SAP in air and gunny bag curing enhances durability, especially against freeze-thaw conditions. Other studies (42) also confirms that microstructure of concrete improved by hydration of cementitious materials to full extent.

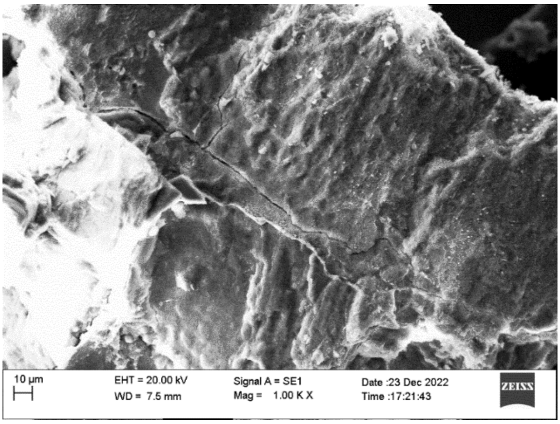

Fig. 19. SEM image of P35S0 mix in standard water curing after freeze and thaw

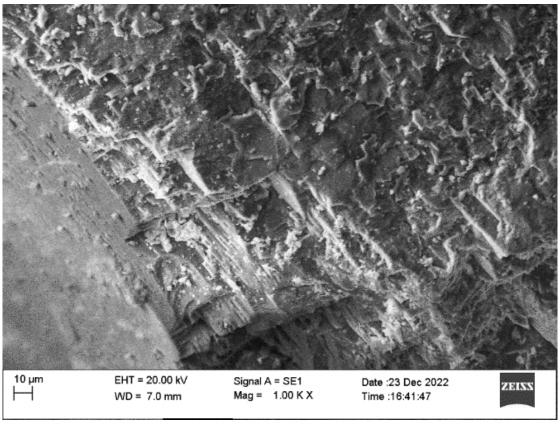

Fig. 20. SEM image of P35S10 mix in air curing regime after freeze and thaw

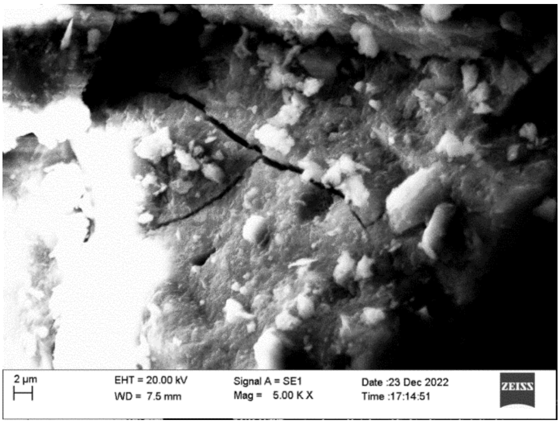

Fig. 21. SEM image of S35S0 mix in standard water curing regime after freeze and thaw

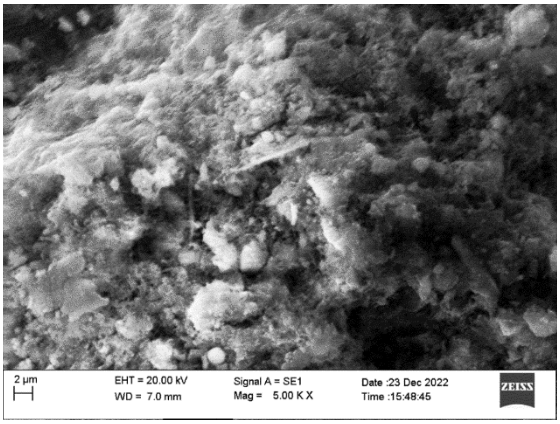

Fig.22. SEM image of S35S10 mix in air curing regime after freeze and thaw

4. Conclusions

From the above experimental investigation following conclusions could be drawn.

- T500 values of optimum SAP mixes were increased by 7-8% compared to the reference mix. The slump flow diameter of SAP mixes was decreased by around 4.9-5.7% compared to the reference concrete mix.
- The v-funnel time of SAP mixes was increased by 12.5% to 15.5% compared to the reference concrete mix.
- Fresh concrete test results reveal that the workability has decreased with adding SAP into the mix. It is due to dry SAP absorbing the water from the mix initially. However, all the workability results are within the limits of standard specifications.
- Super absorbent polymer has shown enhanced strength results in air curing regime especially. The compressive strength in PPC and PSC mixtures increased with best SAP dosage in air curing in the range of 10% to 15% as compared to control mixes in water curing. Compressive strength and flexural strength increased with SAP dosage up to 0.1% in air curing and gunny bag curing.
- The flexural strength in PPC and PSC mixtures has been increased with best SAP dosage in air curing in the range of 14% to 20% as compared to control mixes in water curing.
- Carbonation depth has decreased in air curing and gunny bag curing in SAP mixes. Depth of carbonation decreased by 4-8% in best SAP mixes in air curing compared to control mix in water curing.
- Mass loss has been observed in reference concrete and internally cured concrete with water curing. However, in air curing and gunny bag curing, it has been observed that mass has gained after 100 freezing-thawing cycles. The mass loss in water curing mixtures around 0.25% to 0.5%. However, in best SAP mixtures in air curing, the mass has gained 0.4 % to 0.9%.
- Compressive strength has been decreased after freezing-thawing cycles in the water curing regime. On the other hand, for cubes with air curing compressive strength has been enhanced.
- Scanning electron microscope images also revealed that cracks had been developed in reference concrete in water curing. SAP mix with air curing regimes shows that denser microstructure.

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