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Technical Note

Development of high-performance self curing concrete using super absorbent polymer and silica fume additives

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Abstract

Curing plays a vital role in determining the mechanical properties of hardened concrete. The use of Super Absorbent polymer (SAP) has been found to be highly effective in reducing the water requirement for curing. Silica Fume (SF) is commonly used as a mineral admixture in High Performance Concrete (HPC) to improve mechanical and durability properties. But when silica fume was incorporated in SAPs, contradictory results with respect to strength after curing has been reported and this study aims to evaluate the effect of altering dosage of SAP and SF to maximize the strength and to reduce the water requirements in HPC. Concrete tested include traditional HPC and specimens of HPC with SAP, HPC with SF and HPC with combined dosage of SAP and SF. Compressive strength test, Split Tensile test and Sulphate attack test were conducted as per relevant Indian Standards. The dosage of SAP and SF were individually varied in the initial stage and from the experimental results, optimal dosage of SAP and SF was determined. The combined specimen with the optimal dosage of SAP and SF was tested in the final stage. The results showed that self-curing effect of SAP and the filler effect of SF maximize the compressive and tensile strength of hardened concrete. The optimal dosage was derived as 0.35% (by weight of cement) for SAP and 10% (by weight of cement) for SF and higher SAP or SF content in HPC was found to be detrimental with respect to strength.

1. Introduction

As concrete is one of the most widely used construction materials, ensuring its' optimum performance is of prime importance. Curing of concrete play a major role in determining the final microstructure of concrete and proper curing ensures its durability and performance. However, in practice good curing is not easy to achieve all the time owing to water shortage. In such a scenario, self-curing or internal-curing is desirable, where some curing agents are introduced in order to reduce the evaporation of water from concrete, thereby increasing the water retention capacity of the concrete.

The control of properties of cement-based materials in different stages of hardening can be achieved using chemical admixtures. Among the various chemical admixtures available, Super Absorbent Polymer (SAP) possess several desirable properties and the use of water-soluble polymers as self-curing agents in concrete has found several applications recently [1]. SAP is a polymer-based material that can absorb a considerable quantity of water from the surroundings, resulting in the swelling of the polymer matrix and thus retain water without dissolving. It can take up water during the mixing process, enabling it to be used as a dry concrete admixture.

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The pioneering studies with respect to the application of SAP in self-curing were done by Tsuji et al. [2] and Jensen et al. [3]. The water uptake capacity of SAP was reported to be more than 100 times its weight [3] and hence, sometimes, it is referred to as hydrogels. SAP can be used as an alternative to low density aggregate for self-curing. In addition to self-curing, studies have shown that SAPs can influence the properties of fresh and hardened concrete [3]. The process of bulk polymerization is employed for the preparation of majority of SAPs and the resultant product consists of crosslinked bulk of randomly composed copolymers with irregular shape [4]. Inverse suspension polymerization involving dispersion of reaction mixture with water droplets in oil phase can be used to produce SAPs of regular shapes, like spherical ones. However, this process is more complicated and use of a surfactant is necessary to stabilize water droplets. Such additions can badly affect the cement chemistry as reported by Laustan et al. [5].

The physico-chemical mechanism of sorption in SAPs was investigated by Toyoicki Tanaka [6] and he concluded that the favorable interactions between water and the polymer network depends on electronegativity of atoms in the network. The positively charged atoms like Na^+, K^+ were found to be having higher affinity towards water. The driving force of sorption can be described based on net osmotic pressure across the semipermeable polymer network. Most of SAPs are prepared from natural or synthetic monomers and commercially available SAPs are mostly acrylate-based. The mechanism of sorption in acrylic acid-based SAPs was studied by Zhu et al. [7]. They reported that SAP compositions that contained higher concentrations of acrylic acid had large swelling capacities. They also found that such SAPs were very sensitive to the presence of cations in the salt solution, especially, Ca^{2+}, Al^{3+}, etc. which can reduce sorption due to ion exchange. Lee et al. [8] reported that higher alkalinity inhibits ion exchange and hence by increasing the concentrations of Na^+ and K^+, resultant SAPs can retain more water for a longer period.

Several researchers have incorporated mineral and chemical admixtures to modify the SAP sorption properties. Silica Fume (SF) admixture is commonly used in HPC as it has an amorphous state and it has extreme fineness as compared to other mineral admixtures which improves mechanical and durability properties of HPC. A study conducted by Smarzewski et al. [9] concluded that SF can be used as an effective replacement of cement and significant improvement in strength was reported by adding up to 10% (by weight of cement) SF in HPC. However, when silica fume was incorporated with SAPs, contradictory results with respect to strength after curing was reported. The study by Bose et al. [10] reported an increase in mechanical properties while another study reported a decrease of the same [11]. The control of dosage of silica fume plays a dominant role in the development of superior mechanical properties in HPC.

The possibility of developing a HPC mix with combined addition of SAP and SF, to achieve the twin objectives of improving mechanical properties and simultaneously minimizing the water requirement for curing is yet to be explored in detail. The purpose of this study is to experimentally determine the effects of different proportions of SF, SAP and their combined form (SF+SAP) as a partial replacement of cement on the various properties of fresh and hardened concrete. In the present study, the mechanical properties of HPC were investigated with the addition of SAP and silica fume in two stages. In the initial stage, the SAP and SF dosage in HPC were individually varied to derive an optimal dosage of both and a specimen with both SAP and SF in their respective optimal dosage was prepared for the final stage of testing. To this end, a systematic experimental plan was formulated; starting with material characteristic test followed by mix design for HPC. Mechanical properties tests including compressive strength, tensile strength tests were carried out and to assess the durability, Sulphate attack test was also carried out for various concentrations of SAP and SF mineral admixture.

2. Materials

This section deals with the materials used and properties of the material tested. The study involves the use of OPC cement, coarse and fine aggregates, SF and SAP for making concrete mixes.

2.1 Ordinary Portland Cement

Ordinary Portland Cement of OPC 53 grade as per IS 269-2015 [12] was used along with SAP and silica fume. The laboratory tests conducted on OPC were Specific gravity test, Initial and Final setting time test and Standard consistency test. The physical properties of cement determined in this study are given in Table 1.

Table 1. Properties of cement

Test	Result	Permissible limit as per IS 269-2015
Standard consistency	32%	22-33 %
Specific gravity	3.19	3.13-3.19
Initial setting time	26 min	Should not be greater than 30 minutes
Final setting time	590 min	Should not be greater than 600 minutes

2.2 Coarse and Fine Aggregates

Coarse aggregate used in the present work was crushed aggregate with a maximum nominal size of 20 mm. Material properties of coarse aggerate was determined using specific gravity, sieve analysis and water absorption tests. M-sand was used as fine aggregate with aggregate size less than 4.75 mm. Sieve Analysis of Fine aggregate is presented in Table 2 and from the percentage weight retention, Fineness Modulus was calculated. The consolidated properties of aggregates are shown in Table 3.

Table 2. Sieve analysis of fine aggregate

Sieve size(mm)	Weight retained(g)	Percentage weight retained	Percentage Cumulative weight
4.75	11.2	1.1	1.1
2.36	25.5	2.507	3.607
1.18	18.5	1.819	5.426
600	53.9	5.3	10.726
300	248.4	24.42	35.146
150	266.9	26.24	61.386
75	339.4	33.37	94.756
Pan	53.2	5.231	100

Table 3. Properties of coarse and fine aggregate

Test	Result	
	Coarse Aggregate	Fine Aggregate
Specific gravity	2.74	2.67
Fineness modulus	6.15	3.17
Water Absorption	0.49%	0.61%

2.3 Silica Fume Admixture and SAP

Silica Fume (SF) was added in the present study as mineral admixture and SAP was used for internal curing. The specific density of silica fume was estimated as 1.91 g/cm^3. SAP used is Acryl amide/acrylic acid-based copolymer and the average size of SAP particles used was approximately 1 mm.

3. Mix Design and Specimen Details

A total of 8 combinations were considered for the study using HPC grade including the control specimen of traditional HPC. SF content used were 0%, 5%, 10%, 15% (by weight of cement) and SAP content used in the present study were 0.3%, 0.35% and 0.4% (by weight of cement). HPC grade was prepared by setting the Water to Cement ratio as 0.35. The total cementitious material used was 448 kg/m^3 and amount of Fine Aggregate as percentage of total Aggregate was selected as 33% (by weight of cement).

The required quantity of cement, SAP, m-sand, coarse aggregate and water were measured and kept aside prior to the mixing for each mix proportion. The raw materials were weighed after oven drying to eliminate the error introduced by moisture content. Mixing of all materials was done manually. Care was taken to ensure uniform mixing and to prevent the formation of lumps and dehydration of the mix. The concrete mix was transferred to prefabricated moulds of size 15x15x15 cm for cubes and 15 cm diameter and 30 cm height for cylinder for testing as per Indian Standard code IS 516:2000 [13]. The moulds were oiled prior to transferring of the mix. The transferred mix was compacted manually using the trowel and kept aside for a day. The specimen was removed from the mould after 24 hours and was transferred to a water basin for the curing. The water used for curing conforms to standard IS 156:2000. The HPC with SAP content was cured in air itself i.e self-curing was allowed. After the curing period the specimens were taken out from the water basin and were tested. Three specimens of each mix were made and tested for repeatability. Specimens with optimal SAP and SF content were selected for self-curing study. A total of 96 cubes and 48-cylinder specimens were casted for this work.

4. Experimental Procedure

The procedures for conducting the experiments are detailed in this section. In the study, compressive strength test, split tensile strength test, sulphate attack test were conducted to ascertain the mechanical and durability properties of concrete.

4.1 Compressive Strength and Split tensile Strength

Cube specimens with side of 150 mm were produced and stored immediately after mixing in a climate room. The compressive strength of the specimen was evaluated at 7, 14 and 28-days as per IS 516:2000. The test setup used is shown in Figure 1. For split tensile strength, cylindrical concrete specimens were used and the testing procedure was in accordance with IS 5816:1999 [14]. The split tensile strength was tested after 7 days and 28 days using the test setup shown in Figure 2.

4.2 Sulphate Attack Test

Magnesium sulphates and sodium sulphate solutions were used in Sulphate attack test. The cubical specimens after proper curing of 28 days were immersed in water containing 5% sodium sulphate and magnesium sulphate separately for 14 days. The degree of sulphate attack was then evaluated by testing the compressive strength of specimen using compression testing machine.

Fig. 1 Test setup for compressive strength

Fig. 2 Test setup for split tensile strength

5. Results and Discussion

5.1 Compressive Strength

The results of compressive strength test are detailed in Table 4. Specimen IDs from 1 to 8 were given for identifying different mixes of concrete used. The curing medium used and compressive strength of concrete obtained after 7,14 and 28 days are detailed in Table 4. The average strength of three specimens in each mix is reported in Table 4.

5.2 Split Tensile Strength

The results of split tensile strength test are detailed in Table 5. The curing medium used and average compressive strength of three specimens of concrete obtained after 7 and 28 days are shown in Table 5.

Table 4. Compressive strength results

Specimen Id	Mix	Curing Medium	7thday Strength N/mm²	14thday Strength N/mm²	28thday Strength N/mm²
1	HPC	Water	45.11	47.33	55.33
2	SAP (0.3%)	Air	37.50	45.11	54.44
3	SAP (0.35%)	Air	43.77	50.02	58.22
4	SAP (0.4%)	Air	37.11	44.66	55.22
5	SF (5%)	Water	45.54	48.54	56.45
6	SF (10%)	Water	46.11	49.51	57.14
7	SF (15%)	Water	45.73	48.78	56.82
8	SAP (0.35%) + SF (10%)	Air	44.98	49.82	59.13

Table 5. Split Tensile strength results

Specimen Id	Mix	Curing Medium	7thday Strength N/mm²	28thday Strength N/mm²
1	HPC	Water	2.55	3.22
2	SAP (0.3%)	Air	2.19	2.97
3	SAP (0.35%)	Air	2.66	3.34
4	SAP (0.4%)	Air	2.21	3.11
5	SF (5%)	Water	2.59	3.26
6	SF (10%)	Water	2.62	3.30
7	SF (15%)	Water	2.48	2.98
8	SAP (0.35%) + SF (10%)	Air	2.59	3.33

5.3 Sulphate attack Test

The results of sulphate attack test are detailed in Table 6. The specimen 28-day compressive strength after the sulphate attack is presented. The average percentage loss in compressive strength of the three specimens used in the study is calculated by using the test results of sulphate treated and untreated specimens and the results are shown in Table 6.

5.4 Comparison of results

The results in Figure 3 shows the comparison of properties between specimens used in the experimental study. It can be found that addition of SAP led to increase in compressive strength when compared to control specimen of HPC (Specimen 1). However, the increase was noted till 0.35% SAP addition (Specimen 2, 3) and further increase in SAP content (Specimen 4) did not improve the compressive strength. It can be postulated that at 0.3% SAP content, there was insufficient water release for self-curing. However, at 0.4% SAP content, there was reduction in compressive strength due to large voids in concrete due to excess release of water. It was confirmed by measuring the density of the specimens 1, 2, 3, 4. Specimen 4 (0.4% SAP) reported nearly 7 % reduction in density over the specimen 3 (0.35% SAP). The maximum improvement in compressive strength over control specimen that was obtained with SAP addition was 5.22%. Similar trend in compressive strength of HPC with SAP addition was reported by other researchers [15,16].

Table 6. Compressive strength of cubes after sulphate attack

Specimen Id	Mix	28^{th} Day Strength N/mm^2	Loss In Compressive Strength (%)
1	HPC	43.87	20.7
2	SAP (0.3%)	46.00	15.5
3	SAP (0.35%)	50.51	12.9
4	SAP (0.4%)	47.21	14.5
5	SF (5%)	45.83	18.8
6	SF (10%)	47.37	17.1
7	SF (15%)	47.79	15.9
8	SAP (0.35%) + SF (10%)	50.26	15.1

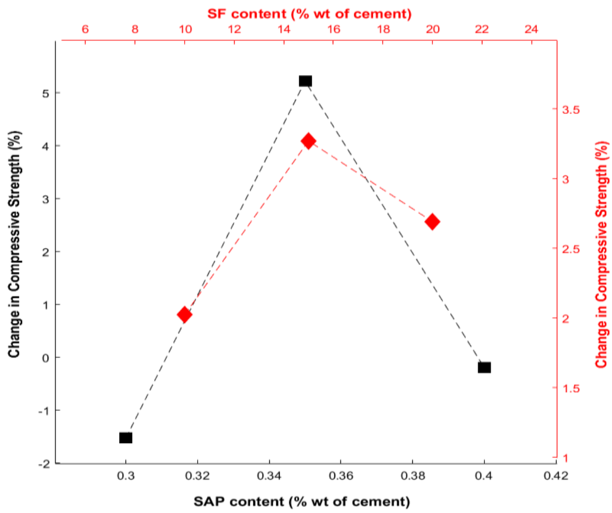

Fig. 3 Comparison of compressive strength

From Figure 3, it is also clear that the specimens 5,6,7 with SF content show higher compressive strength compared to control specimen no. 1. It can be attributed to the pozzolanic effect and filler effect provided by SF. Similar results were reported by Mazloom et al. [17] and Onuaguluchi and Panesar [18]. However, it can be found that with SF content above 10% does not improve compressive strength. This can be attributed to the reduction in C_3S and C_2S amount in the cementitious material, which lowers the concrete strength. Similar trends were reported in [19]. A specimen with 0.35% SAP and 10% SF gives the best compressive strength (6.87% increase over HPC) without water curing owing to advantageous properties of SAP and SF. The filler effect and proper amount of water released ensured proper curing and development of 28-day compressive strength.

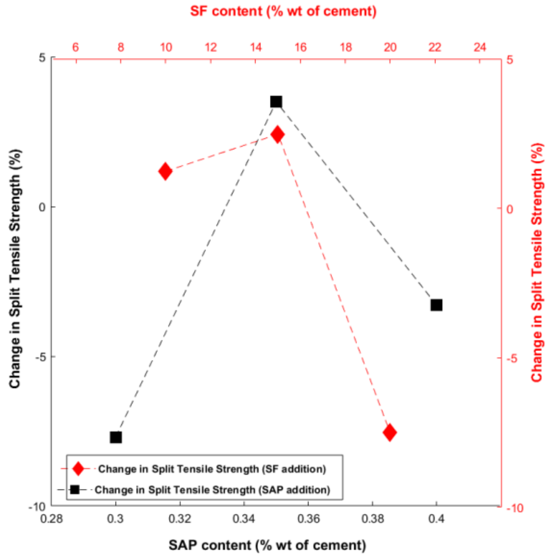

Fig. 4 Comparison of split tensile strength

From Figure 4, it can be found that addition of SAP leads to increase in split tensile strength. It can be noted that the improvement over control specimen is highest with 0.35 % SAP composition (specimen 3) and the maximum increase was 3.73%. The effect of SAP and SF addition on split tensile strength was found to show similar trend as the compressive strength, strength increased with addition till an optimal value and then starting to reduce. In this study, the replacement of the cement with SF significantly increased the splitting-tensile strength till 10% of SF (specimens 5,6). However, beyond 10% SF, it can be postulated that cement paste was not getting hardened due to loss of cementitious materials with increase in silica fume content, making it weaker in tension [20]. The combined specimen with 10% SF and 0.35% SAP gave almost same split tensile strength as specimen with 0.35% SAP which highlighted the minor influence of SF on split tensile strength.

The comparison of various specimen with respect to loss of compressive strength on sulphate attack test, is shown in Figure 5. It is clearly visible that self-curing concrete with SAP and SF can retain compressive strength in adverse conditions compared to HPC. The loss of compressive strength is only 12.9% with SAP content of 0.4% compared to 20.7% in HPC. The self-healing effect provided by SAP in specimens 2,3,4 may be the reason for reduction in loss of compressive strength in harsh environment. This effect was analyzed in [21] and various aspects of water transfer between SAP macro voids resulting in healing of cracks was explained. Similar trend was observed with SF addition even though the strength was lower than that of self-cured specimens. It is postulated that the pozzolanic reaction of SF prevents the diffusion of sulfate ions in the cement matrix, which can reduce the decalcification of hydration products thereby reducing the damage to concrete [22]. A reasonably good results of specimen 8 with respect to sulphate attack showed the importance of optimizing the SAP and SF content to maximize the performance of HPC and minimize the use of water simultaneously.

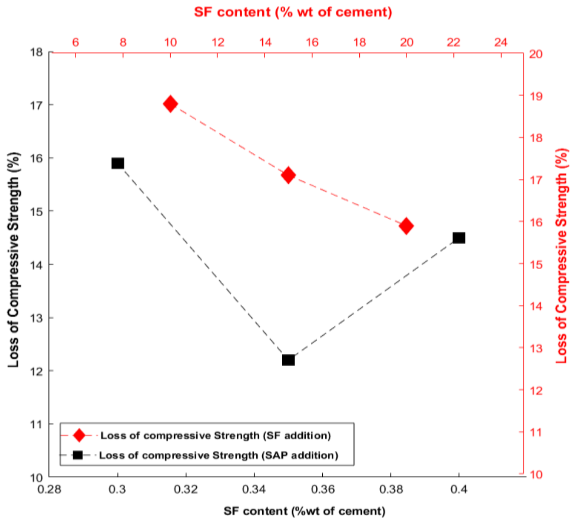

Fig. 5 Loss in compressive strength

6. Conclusions

Self-curing of concrete and its effect on mechanical properties has been a subject of research for a long period with the aim of reducing water requirements for construction. SAP offered significant potential in this area and the study highlighted the importance of the same through meticulously designed experiments. The addition of SF as filler material offered improvement in HPC compressive strength and allowed the reduction of expensive cementitious content. The combined effect of SAP and SF was also investigated in this study.

The compressive strength after 28 days with water curing on a control specimen of HPC was compared with specimens containing only SAP, only SF and a combination of SF and SAP. The optimal content of SAP for best compressive strength was found to be 0.35% with improvement of above 5% in strength over control specimen. Improvement was maximized with SF content of 10% and further addition of SF lowered the strength. Almost similar results were obtained in split tensile strength study of the specimens. A specimen with 0.35% SAP and 10% SF was selected as representative case to study combined effect of additives considering the results of individual groups. An increase in compressive strength of 6.87% over control specimen was obtained with the specimen. The sulphate attack test results also highlighted the importance of selecting the optimal concentration of SAP and SF. SAP content above 0.35% and SF content above 10% is not recommended based on the experimental results.

Even though many researchers reported beneficial results, the application of SAP and SF in the field is limited at present, primarily on account of lack of formal standards and regulations. Additional studies can be carried out in this area by replacing SAP with other self-curing agents like calcium lignosulfonates. The study of microstructure of the concrete with SAP and SF, especially after sulphate attack test, can also be taken up to gain valuable insights on the various mechanisms to better explain the results of the experimental work.

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