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PROPERTIES OF CONCRETE INCORPORATED WITH SELF-HEALING AND INTERNAL CURING AGENTS

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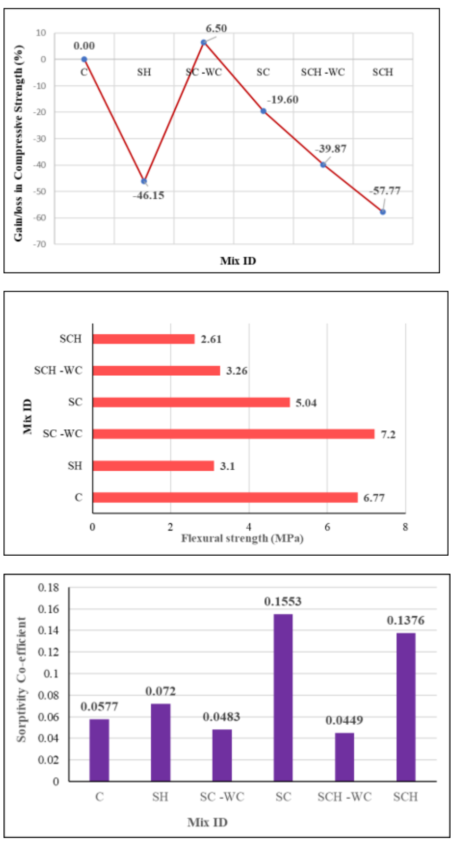
Graphical abstract



Abstract

In this study, effects of collective addition of self-healing and internal curing agents on the strength and permeation properties of concrete were determined. The internal curing agent Polyethylene Glycol (PEG 400) was added at 2% of cement based on weight and a mixture of Bentonite, Quick lime and Magnesium oxide were replaced for cement at 5% each as self-healing agent. Six mixes were investigated which includes a control mix (water curing), a mix with PEG 400 (with and without water curing), a mix with self-healing agents (water curing) and a mix integrated PEG 400 and self-healing agents. (With and without water curing) The density of concrete and strength parameters like compressive, flexural and tensile strengths were found by conducting experiments using the procedures given in testing standards. Permeation features were also studied by subjecting the concrete to water absorption and sorptivity tests. Density values lowered because of internal curing agents. The integration of internal curing and self-healing agents have adverse effects on density, strengths, water absorption and sorptivity co-efficients but there is an improvement in the mentioned properties when the specimens were cured in water.

Keywords: Self-healing, Internal curing, strength, water absorption, sorptivity

1.0 INTRODUCTION

Concrete which is a mixture of cement, aggregates and water forms a major part in the building sector. Appropriate curing is vital to maintain the necessary moisture and temperature for the hydration process to occur thereby enabling the concrete to achieve the desired and targeted strength since improper and inadequate curing can severely disturb the characteristics of concrete. Conventional methods of curing include curing by water which is the utmost effectual type of curing that could be adopted by ponding, wet coverings, sprinklings etc. The other type of curing is sheet curing which is easier to adopt in the vertical and horizontal surfaces where the polythene sheet is used to cover the surface for keeping the moisture in concrete. Membrane curing is yet another type of curing where the spraying compounds are applied on the surface. This method has the advantage over water curing and sheet curing methods because in this method, once the curing compounds are applied on the surface, further supervision is not required.

Later on, a technique called self-curing or internal curing was evolved with an aim of providing moisture in concrete for better cement hydration. Here the concrete cures itself by retaining moisture content and by reducing the evaporation of water, which also reduces shrinkage and other micro-cracks thereby reducing the permeability and increasing the strength. This concrete is more suitable when there is water insufficiency and where the water curing is not imaginable due to certain factors. Several researches demonstrated the use of self-curing agents in concrete. For M30 grade concrete, the ideal percentages of wood powder and PEG400 are found to be 6% and 1.5% for room temperature and 6% and 2.5% for outdoor temperature [1]. 15% of light weight aggregates that were pre-soaked by volume or 2% of polyethylene glycol by weight were determined to be the optimum ratio for good mechanical and physical properties compared with the other ratios investigated. 15% of silica fume increases the properties of self-curing concrete due to the enhanced pozzolanic action and its ability to hold water [2, 3, 4].

Amongst the self-curing agents namely Super Absorbent Polymer, Poly Vinyl Alcohol, PEG 4000, PEG 6000, PEG 4000 is effective for maximum compressive strength whereas for tensile and flexural strengths, PEG 6000 is better [5]. When one percent of PEG400 is added, mix is found to be the best for M20 grade of concrete without affecting the workability [6]. While analysing the individual effect of curing agents Poly Vinyl Alcohol and Polyethylene Glycol, it was noticed that, the increased content of self-curing agent resulted in strength reduction and 1% of the above said curing agents is ideal for strength not negotiating the workability [7]. 0.8% of Propylene glycol, Polyethylene glycol and Perlite are observed to be the optimal percentages for workability and strength whereas for Sodium polyacrylate and Vermiculite, 0.2% and 0.4% are the optimal dosages respectively. Out of the above curing agents, Propylene glycol and Polyethylene glycol are found to be the best agents [8]. For M30 concrete mix, 1% of the PEG-400 is the perfect quantity for maximum split tensile and compressive strengths and 0.5% is the ideal amount for maximum strength in flexure [9].

On the other side, due to huge infrastructure expansion across the world and owing to the advancement in the area of concrete thereby developing the new types of concrete and other binder materials over a period, infrastructure constructed with these new materials require intensive patch-up and upkeep during its design life due to either the formation of cracks due to weathering or due to human actions or due to the porosity nature. Recently, self-healing concrete is one where the self-healing processes are developed in autogenic or autonomous modes through self-healing agents that may be biological, polymeric or inorganic in nature that could help in the sealing of cracks and several works were reported in the literature. Concrete with healing capability has better long-term strength, efficient crack sealing capacity, better compatibility of the concrete matrix and the newly formed material due to the addition of healing agents [10]. Surface cracks could be healed effectively by the addition of bioagents like Bacillus halodurans, Bacillus pasteurii and Bacillus subtilis as they make the concrete impervious and hence resulted in the recovery of mechanical properties due to calcium carbonate crystals formation. Bioagents helps for the improvement of durability and quality of concrete in addition to the reduction of maintenance and repair expenses and could be a sealant [11, 12, 13].

Sodium silicate in capsule form when used as healing agents react with calcium hydroxide available in the concrete and forms crystals due to precipitation which arrest the cracks thereby filling the pores within it [14]. Sodium silicate when used as healing agent, improves the microstructure by forming Calcium Silicate Hydrate due to its reaction with calcium hydroxide and fills up the pores and cracks in concrete thereby making the concrete dense resulting in higher compressive strength [15]. Methyl methacrylate heals the cracks at young age and the tensile and compressive strengths could be improved by adding waste steel scraps and polyethylene fibers respectively [16]. The property of self-healing can be attained in concrete using mineral admixtures such as 12.5% of silica fume and 35% of GGBS with improved values of compressive strength. Through the openings of the cracks, the un-hydrated particles of mineral admixtures get hydrated by the moisture present in the atmosphere and forms the calcium hydroxide crystals which heals the cracks [17]. Betocrete-CP-360-WP has an encouraging self-healing ability in addition to the better resistance to chemicals despite low early age compressive strength. However, during the subsequent hardening process, strength is almost comparable with the control concrete [18].

Use of Bentonite as a healing agent supports healing process by filling the gaps in the cracks thereby lessening the width and depth of the cracks. GGBS could also support in the retrieval of flexural stiffness and tensile strength [19]. The minerals that are expansive in nature like Quick lime, Bentonite clay and Magnesium oxide have the capacity to activate healing on its own through the sealing and bridging of cracks by crystallization and hence helps in the recovery of strength [20]. Pellets of Magnesium oxide have substantial potential for self-healing ensuing the development of slurry walls with cement, slag and bentonite with additional resilience [21].

From the literatures it is realized that the addition of self-curing agents has negative effect on strength properties when it is added beyond the optimum level. Also, it could be understood that the optimum level varies for each of the grade of concrete. Moreover, few researches were on the study of the self-healing capacity of variety of polymeric, biological, and inorganic agents. Despite of extensive research that has been executed to find out the effect of internal curing and self-healing agents individually, to the best knowledge of the authors, there was no work to study the effects of these agents when adopted together in the concrete mix. Practically there are situations in which the concrete may require to use self-curing agents for the internal curing and at the same time there may be necessity to incorporate self-healing agents for the better long-term performance of any structure. So, through this experimental work, the combined effects of PEG 400 and the self-healing agents Bentonite, Quick lime and Magnesium oxide on the strength and permeation of concrete were evaluated and presented.

2.0 METHODOLOGY

2.1 Materials

The ingredients used in concrete making are in Figures 1a and 1b. Fine aggregate is M sand and after performing the sieve analysis as per IS 2386 – Part 1 1963 [22], the fineness modulus is 2.77 for M sand classified as grading Zone II by IS 383-2016 [23]. The specific density and compacted bulk density are found to be 1607 kg/m^3 and 2.61 for M sand. For coarse aggregates they are determined to be 3.03 and 1718.5 kg/m^3 respectively. The water absorption and fineness modulus are 0.6% and 7.008 correspondingly. The cement used is Portland Pozzolana Cement (43 grade) obeying IS 1489-Part 1 1991 [24] and possessing a specific density of 3.13 and soundness 1 mm. Having a 34% consistency, the initial setting time of cement is 34 minutes (IS: 4031 (Part 4 & Part 5) – 1988) [25,26]. Internal curing agent used is PEG 400 which is used as an additive during the making of concrete and it is added at 2% by weight of cement. PEG 400 is in liquid form which is viscous and colorless with a specific density of 1.12. Self-healing agents used are a mixture of Bentonite (Specific gravity 2.66), Quick lime (Specific gravity 3.3) and Magnesium Oxide (MgO) all available in the form of powder and they were added as a replacement material each at 5% by weight of cement.

2.2 Mix Design and Proportions

Design mix for M20 grade of concrete was arrived based on Indian standard code for mix proportioning [27]. Six mixes were investigated in total out which one is the control mix designated as 'C' without internal curing and self-healing agents. The second mix is with self-healing agents in which the cement is replaced by 5% each of Bentonite, Quick lime and MgO and the mix is named as 'SH'. The third mix designated as 'SC' is cast with addition of 2% internal curing agent PEG 400. The fourth mix 'SC-WC' is same as that of 'SC' except that water curing is done additionally. The fifth and sixth mixes are named as SCH and SCH-WC which refers to a mix having both self- healing and internal curing agents and without water curing and with water curing respectively. The material quantities in the six mixes are provided in Table 1. During the making of concrete, PEG 400 being a liquid is mixed with the required quantity of water arrived in the design mix and the self - healing agents are mixed along with cement as they are in powder from.

Figure 1a Cement and aggregates

Figure 1b Self-healing and self-curing agents

Table 1 Mixes and Quantities in kg/m³

Mix ID	Cement	M sand	Coarse aggregate	Water	Bentonite	Quick lime	MgO	PEG 400
C	370	658	1176	208	-	-	-	-
SH	314.5	658	1176	208	18.5	18.5	18.5	-
SC - WC	370	658	1176	208	-	-	-	7.4
SC	370	658	1176	208	-	-	-	7.4
SCH - WC	314.5	658	1176	208	18.5	18.5	18.5	7.4
SCH	314.5	658	1176	208	18.5	18.5	18.5	7.4

2.3 Preparation and Testing of Specimens

Tests were done to realize the consequence of internal curing and self-healing agents and the influence of water curing on properties like density, compressive, tensile and flexural strengths, water absorption and sorptivity. Cubes (all dimensions 150 mm) were prepared for the density, compressive strength (IS: 516 – 1959), sorptivity and water absorption tests. Prisms (500 mm long, 100 mm breadth, 100 mm depth) were prepared for testing under flexure (IS: 516 – 1959) and cylinders (100 mm diameter, 200 mm height) were prepared for split tensile strength (IS 5816:1999) [28,29]. 54 cubes, 18 prisms and 18 cylinders were made for the entire test process as displayed in Figures 2 to f. The standard ASTM C642 was implemented to study the relative porosity or permeability characteristics of concrete at 28 days [30]. The absorption was calculated from the saturated and dry masses. To assess the quality of concrete based on surface pores and to evaluate the degree of infiltration of water into the concrete pores by capillary force, sorptivity test was done. Cube samples of 150 mm size were exposed to the water by keeping it in a pan and maintaining the water level at about 5 mm above the bottom of the samples. So as to achieve the flow of water in one direction, the lower portions of the sample sides touching the inflow face were sealed with bituminous paint to avoid absorption of water into the exterior pores. At certain intervals like 1, 4, 9, 16, 25, 36, 49, 81and 100 minutes, the specimens were weighed, the amount of water adsorbed was estimated and normalized with regard to the cross-sectional area. The slope of the line drawn between Q/A and square root of time gives the sorptivity where Q is the amount of water adsorbed (mm³), A is the contact area of the specimen (mm²), t is time (minutes).

Figure 2a C Specimens

Figure 2b SH Specimens

Figure 2c SC-WC Specimens

Figure 2d SC Specimens

Figure 2e SCH-WC Specimens

Figure 2f SCH Specimens

3.0 RESULTS AND DISCUSSION

3.1 Density

Addition of PEG 400 and the partial replacement of cement by the self-healing agents Bentonite, quick lime and Magnesium oxide have a negative effect on the density which could be seen as depicted in Figure 3. The density is highest value for control concrete ‘C’ which is 2457 kg/m^3. The lowest density of 2264 kg/m^3 is for samples with both internal curing and self-healing agents without water curing. With internal curing agent, the density gets reduced by 4% when compared to ‘C’ and the same decreasing trend is reported for self-cured concrete using calcium lignosulfonate [31]. However, when the internally cured specimens are subjected to water curing, they have relatively same density as that of ‘C’ and the reduction in density is only 0.6%. With self-healing agents and water curing, there is a dip in density by 3.05%. It is exciting to note that when internal curing and self-healing agents are used in the concrete mix, reduction in density is high which is about 7.87%. But when water curing is done in SCH-WC samples, the drop in density is only about 5.54%. We can see that the density reduction is more due to the addition of internal curing agents which might be due to the development of larger voids in the concrete structure as compared to self-healing agents. Also, with water curing, it is probable to attain a relatively denser concrete that might be due to the improvement in the concrete pore structure.

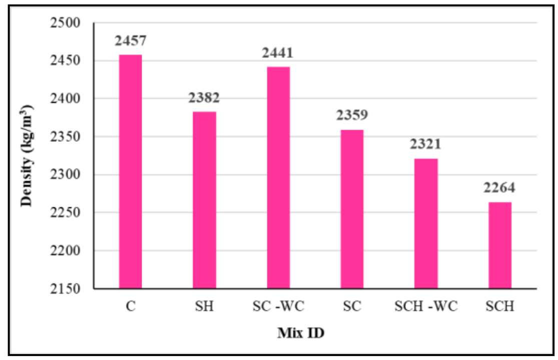


Figure 3 Density

3.2 Compressive Strength

From the Figure 4, it could be noticed that, the substitution of cement by 5% each of magnesium oxide, bentonite, quicklime has drastically decreased the compressive strength by nearly 46.15 % at 28 days. The ‘C’ mix has a strength of 33.41 MPa at 28 days. The addition of 2% of Polyethylene Glycol reduced the strength of concrete to 26.86 MPa without water curing. This might be due to the nature of the internal curing agent of absorbing more water and hence the concrete remains wet after room temperature curing. The SC-WC mix has a maximum strength of 35.58 MPa which is greater than ‘C’ mix and about 32.5% higher than the SC mix. For SCH specimens that possess internal curing and self-healing agents the compressive strength is the least with a value of 14.11 MPa without water curing. On the other hand, when water cured for 28 days the strength reduced by only 39.87%. Self-healing agents have detrimental effect as the strength reduces almost by half as the bentonite absorbs more water and also due to its smallest amount of involvement in the pozzolanic reaction of the cement added. It is also noted that additional water curing of specimens has positive influence on the strength as we could see an increase in strength as compared to that of specimens that were not subjected to water curing as revealed in Figure 5. Except SH and SCH mixes, all other mixes gave a compressive strength greater than 20 MPa.

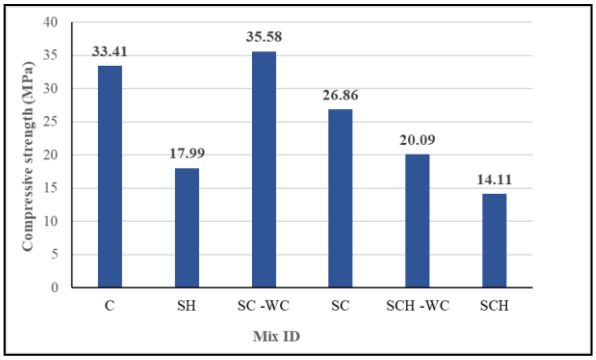


Figure 4 Compressive strength

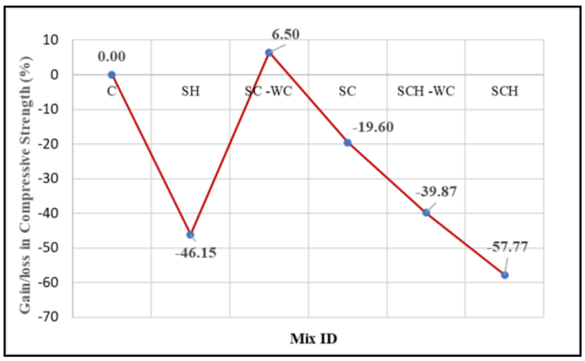


Figure 5 Effect of self-curing and self-healing agents on compressive strength

3.3 Flexural Strength

The strength at flexure at 28 days is given in Figure 6. The trend is similar to that of strength due to compression and hence they could be related. The strength of 'C' mix is 6.77 MPa at 28 days. The addition of PEG400 reduced the strength of concrete and the drop is about 25.55% without water curing. The SC-WC mix has a maximum strength which is 6.35% greater than 'C' mix and about 42.86% higher than the SC mix. For SCH specimens that possess internal curing and self-healing agents the flexural strength is the least and the decrease is about 61.45% without water curing. On the other hand, when cured in water, 28 days strength reduced by only 51.85%. Hence with PEG 400, water curing has a constructive outcome by enhancing the strength. The next least value is for SH mix where the self-healing agents alone are involved which has a strength of 3.1 MPa. Self-healing agents have worse consequence on the flexural strength also as the strength reduces by more than 50% in all the mixes where the healing agents are substituted for cement. From the experimental values, the relation between the flexural and the compressive strengths is found to be linear for all the tested ratios and it is related as $f_f = 0.98 \times \sqrt{f_{ck}}$, where f_f and f_{ck} are the flexural and compressive strengths respectively.

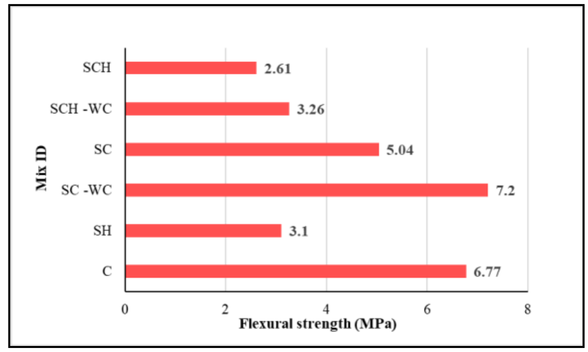


Figure 6 Flexural Strength

3.4 Split Tensile Strength

From the results given in Figure 7, we could realize that the 'C' mix has a strength of 3.11 MPa and the addition of 2% of PEG 400 with water curing gives the highest tensile strength which is 11.58% higher. But in the absence of water curing, SC samples has a strength which is 47.7% less than the SC-WC mix and 32.3% lesser than the CC mix. The average strength values are same for SC and SH mixes. For mixes having both the agents, there is a notable declination in strength compared to 'C' mix with more degradation in strength for SCH samples as compared to SCH-WC specimens. The SCH samples have a tensile strength of just 1 MPa that is 67.8% lower than 'C' whereas SCH-WC samples have a tensile strength that is 27.33% lower than 'C'. Hence water curing has helped in the strength gain. From the experimental results, the tensile strength f_t and the compressive strength f_{ck} are related as $f_t = 0.49 \times \sqrt{f_{ck}}$.

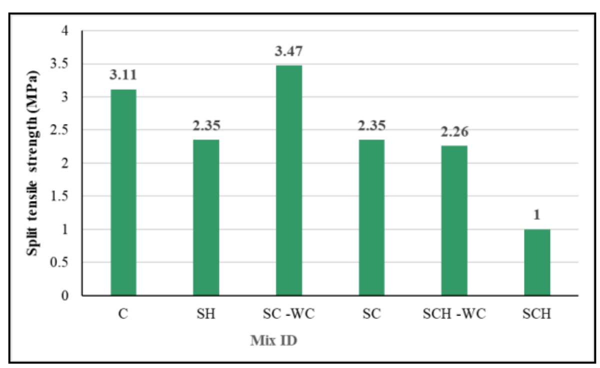


Figure 7 Split tensile Strength

3.5 Water Absorption

The absorption of water for the mixes at 28 days is listed in Table 2. SC-WC has minimum water absorption of 0.32% and as compared to SC-WC absorption is 1.38, 2.78, 6.28, 2.38 and 12.19 times higher for C, SH, SC, SCH-WC and SCH mixes respectively whereas the highest value is for SCH concrete with 3.9% of absorption. We can observe that all the water-cured samples have lower absorption than the samples that were not subjected to water curing. This indicates that curing with water has helped in the proper hydration of cement compounds, thereby reducing the pores and henceforth leads to the development of the denser microstructure of concrete. The water absorption values of SH, SC-WC, SC, SCH-WC and SCH mixes are about 2, 0.7, 4.6, 1.7 and 8.8 times the water absorption value of 'C' mix respectively. Hence the addition of PEG 400 and self-healing agents have some undesirable effect on water absorption also except for SC-WC where the water curing has brought in some positive results by reducing the water absorption.

Table 2 Initial and final weights during test

Mix ID	Specimen No.	Initial weight (kg)	Final weight (kg)	Water absorption (%)	Average percentage
C	1	7.69	7.73	0.55	0.44
	2	8.19	8.22	0.35	
	3	8.90	8.12	0.41	
SH	1	8.05	8.11	0.73	0.89
	2	7.93	7.99	0.81	
	3	7.57	7.66	1.12	
SC-WC	1	8.35	8.38	0.36	0.32
	2	8.15	8.18	0.32	
	3	8.23	8.26	0.28	
SC	1	7.97	8.13	1.98	2.01
	2	8.06	8.23	2.11	
	3	8.02	8.17	1.95	
SCH-WC	1	7.85	7.92	0.85	0.76
	2	7.90	7.95	0.67	
	3	7.82	7.88	0.77	
SCH	1	7.87	8.19	4.08	3.9
	2	7.41	7.70	3.95	
	3	7.71	7.99	3.67	

3.6 Sorptivity

The sorptivity co-efficients plotted in Figure 8 were calculated from the water absorbed at different time intervals. The collective volume of water pierced per unit area of the contact surface (Q/A) was plotted in the Y- axis and the square root of time in X- axis as shown in Figures 9a to 9f and the slope of the line provides the sorptivity values. The co-efficient is higher for SC with a value of 0.1553 and the next highest value is for SCH with a value of 0.1376. Sorptivity is least for SCH-WC having a value of 0.0449. Sorptivity co-efficient of the samples which were not cured in water, was found to be high compared to the other samples. With self-healing agents alone, sorptivity value increases by 25%. PEG 400 has increased the sorptivity by about three times as compared to the 'C' mix when the samples are not cured in water against a decrease in co-efficient by 16% when they are cured in water. Similarly for SCH samples also the sorptivity increased by about two times as compared to the 'C' mix when the samples are not cured in water against a decrease in co-efficient by 22% when they are cured in water. Hence water curing helped in the reduction of voids in concrete and hence the specimens had low water permeability.

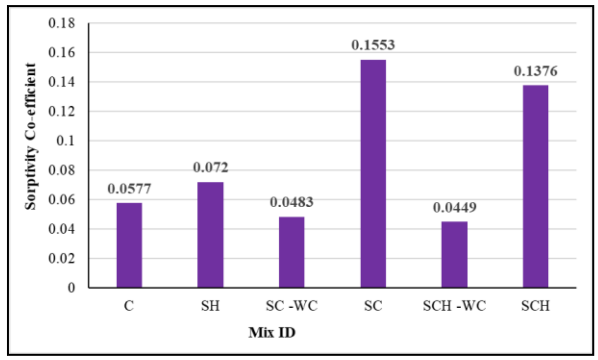


Figure 8 Sorptivity

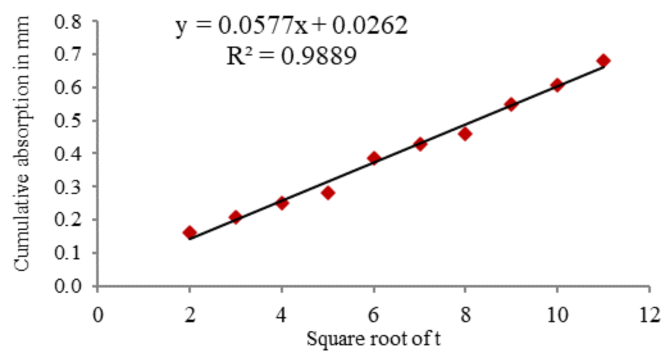


Figure 9a $\frac{Q}{A}$ Vs $\sqrt{t}$ for 'C' specimens

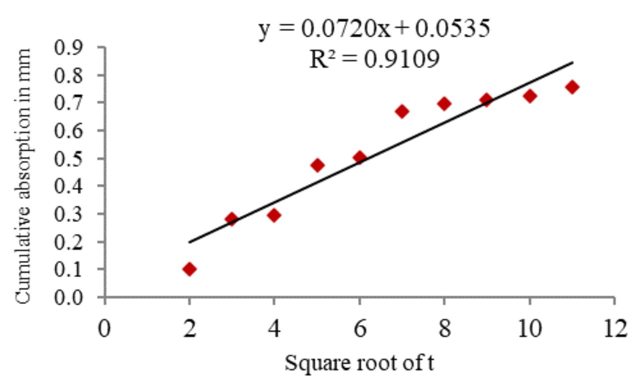


Figure 9b $\frac{Q}{A}$ Vs $\sqrt{t}$ for SH specimens

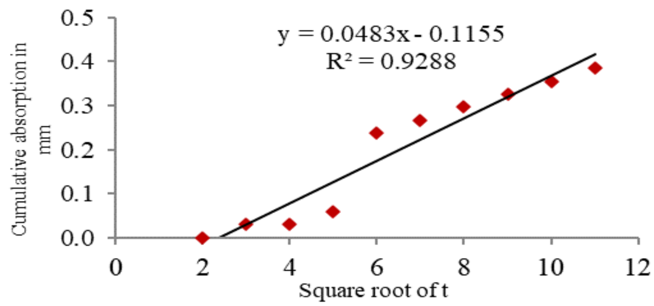


Figure 9c $\frac{Q}{A}$ Vs $\sqrt{t}$ for SC-WC specimens

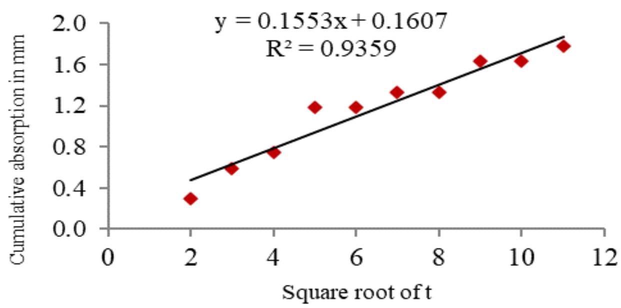


Figure 9d $\frac{Q}{A}$ Vs $\sqrt{t}$ for SC specimens

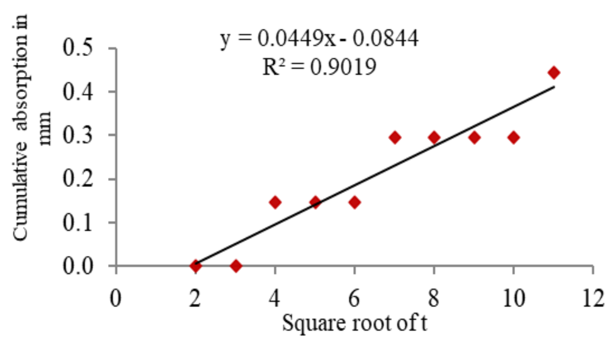


Figure 9e $\frac{Q}{A}$ Vs $\sqrt{t}$ for SCH-WC specimens

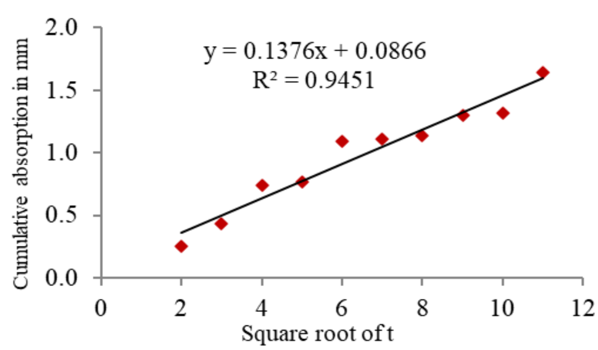


Figure 9f $\frac{Q}{A}$ Vs $\sqrt{t}$ for SCH specimens

4.0 CONCLUSION

From the experiments executed, the following points are worthy to conclude: Density reduction is observed owing to the addition of internal curing agents as compared to self-healing agents. Use of Curing agent PEG 400 with water curing aided the curing process in a more controlled manner thereby ensuring proper hydration reactions to happen and attaining a relatively denser concrete with enhanced strength properties. More investigations are required with other curing agents and water curing to find the probable applications of these materials and also to find the limitations on using these materials in practice. About 50% reduction in compressive strength is seen with self-healing agents and this might be due to the bentonite absorbing water and also due to its meagre amount of involvement in the pozzolanic reaction of the cement added. Water curing of specimens has positive impact on the strength as we could see an increase in strength as compared to that of specimens without water curing. Except SH and SCH mixes, all other mixes gave a compressive strength greater than 20 MPa. Self-healing agents have worse consequence on the flexural strength also as the strength reduces by more than 50% in all the mixes where the healing agents are substituted for cement. For mixes having both the agents, tensile strength also declines as compared to reference concrete with degradation pretty high for SCH samples. Water curing has helped in the strength gain of concrete.

Water-cured samples have lower absorption than the samples that were not subjected to water curing. PEG 400 and self-healing agents have undesirable effect on water absorption but the water curing of concrete has brought in some positive outcome by reducing the water absorption. PEG 400 has increased the sorptivity as compared to the reference concrete mix when the samples are not cured in water but there is a decrease in co-efficient by 16% when they are cured in water. Similarly, for SCH samples, the sorptivity increased when the samples are not cured in water whereas the co-efficient decreases when they are cured in water. Hence water curing helped in the reduction of voids in concrete and hence the specimens had low water permeability. More investigations are required to explore the possibilities of integrating the internal curing and self-healing agents in order to obtain their optimum contents so that the benefits of both the agents could be reaped and realized for enhancing the properties of concrete.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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