

Optimal dosage arrival of polyethylene glycol-400 in achieving self-curing concrete: An experimental strength and durability study

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Concrete has been a widely used building material that has required significant amount of water, especially for the curing purpose. Challenges such as water scarcity, inadequate potable water quality, and lack of proper curing practices have posed threats to the strength and durability of concrete structures. In order to address these issues, self-curing agents have been introduced, resulting in self-curing concrete (SCC), which has gained attention in the construction industry as a promising solution. The current study has examined the fresh, hardened, and durability properties of M_{20} grade SCC using polyethylene glycol-400 (PEG-400) as a self-curing agent in the varying concentrations (0–3% at 1% intervals) with a constant water-binder ratio of 0.45 and binder content of 410.32 kg/m^3 . Fresh properties have been assessed using the slump flow test, while mechanical properties, including compressive, split tensile, and flexural strengths, have been evaluated at 7 and 28 days of curing. Durability tests such as water absorption, sorptivity, Rapid Chloride Penetration Test (RCPT), and resistance to acid and sulfate attacks were also carried out. The results have indicated that 1% PEG-400 provides an optimal performance, enhancing strength and durability. X-ray diffraction has identified key minerals (Si, Al, Fe, and Ca) contributing to strength gains, while microstructural analysis has confirmed cohesive binder-particle interactions at 1% PEG-400. In Overall, it has been found that the PEG-400 concentration for SCC is optimal at 1% for the M_{20} concrete.

Keywords: Durability study, Fresh and mechanical properties, Microstructural study, PEG-400, Self-curing concrete

1 Introduction

The global concrete industry is growing rapidly, providing a wide range of characteristics to enhance the performance of a structure over its lifetime. Concrete is the most dominant building material; hence, researchers have focused on fulfilling the industry's demand for higher-performance concrete^{1,2}. In order to obtain the desired strength and durability of concrete, curing for a minimum period of 28 days is essential for complete hydration³. Curing maintains stable and continuous moisture content, and this creates room for the achievement of maximum hydration, hence making concrete less permeable and durable^{4,5}.

Cement hydration decreases and eventually stops when relative humidity drops below 80%⁶. Aside from this, this process is affected by relative humidity that also reduces capillary formation in inner pores⁷. The concrete surface would appear to be porous and brittle where inadequacy or improper water curing takes place, which decreases its quality and makes it vulnerable to hazardous conditions⁸. Therefore, water is essential at every stage of production and curing of

concrete, conventional curing techniques normally employ three cubic meters of water for each cubic meter of concrete. Nowadays the availability of water is very demand and challengable even it is ready to purchase also. The main limitation in the availability of water is increasingly making it difficult even when bought, specially in height-based construction projects which include vertical structures, sloping roofs, and walkways. The continuous curing in such cases seems impossible; actually, curing is hardly performed. This scenario has recently focused the attention of researchers toward self-curing concrete, though it still exists at the developmental stages⁹⁻¹².

Water retained in the concrete during mixing and setting is allowed to percolate out as a result of cement hydration, during self-curing¹³. Such is a mechanism for self-curing that solved all the issues caused by improper curing. The previous research has been conducted using various self-curing agents including calcium lignosulphonate, polyvinyl alcohol, super absorbent polymers, kerosene emulsions, hydrocarbon resins, acrylic resins, polyacrylamide and other water soluble polymers. These agents are found either retaining moisture or very slowly

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releasing it over some time during hydration which ensures internal curing. There is no universally accepted best self-curing agent, though PEG-400 has been widely used, since it efficiently retains moisture, is inexpensive, and available in the market. PEG-400 is known best for retaining water and is easy to mix with concrete, which makes it convenient for use in the self-curing applications¹⁴⁻¹⁷.

The current study aims to assess the influence of different concentrations of PEG-400 (0%, 1%, 2%, and 3%), as a self-curing agent, on the strength, durability, and microstructural properties of M20 grade concrete. The effect of various PEG-400 dosages has been examined in terms of compressive strength, tensile and flexural strength, as well as concrete qualities such as water absorption, sorptivity, RCPT, and resistance to chemical attacks. Microstructural changes caused by PEG-400 will be examined utilizing techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Analysis (EDAX), and X-ray diffraction (XRD). Overall, the optimum % concentration of PEG-400 is attempted to be identified in order to achieve maximum strength, durability, and ideal microstructure in self-curing M₂₀ grade concrete.

The specific choice of PEG-400 as a self-curing agent and the concentration levels used, which are sparingly examined in the existing researches, constitute the uniqueness of this study. Along with sophisticated microstructural investigation methods like SEM, EDAX, and XRD all of which are combined in similar studies this experimentation has included systematic examination of mechanical and durability parameters. This thorough approach offers new perspectives on PEG-400's behavior in concrete, offering a thorough comprehension of its function in enhancing the long-term durability and performance of self-curing concrete.

2 Materials and Methods

2.1 Cement

For this study, all the concrete mixes were prepared using 53 grade cement. The cement samples were tested to be free from the hard lumps and should pass the sieve test as per IS: 8112-1989 exhibiting uniform shade of gray with slightly greenish in color¹⁸. In addition to that, standard consistency of 32%, specific gravity of 3.12, an initial setting time of 38 minutes, and a final setting time of 486 minutes were also found. All the above tests were conducted in accordance with

the provision of the codes mentioned in IS: 8112-1989, which serves a standard for portland pozzolana cement. The standard further, the properties required and the test of the cement that should be considered to have qualified to be used in concrete.

2.2 Fine aggregate

M-Sand used for the entire experimental work was locally available and fulfilled all the criteria of Zone II classification as mentioned in IS: 383-1970¹⁹. The sample retained on a 4.75 mm sieve, which confirms to the grading requirement of the standard. Basic character tests were conducted to determine the properties of the M-Sand, resulting in a specific gravity of 2.64, a fineness modulus of 2.39, a bulk density of 1619 kg/m³, and a water absorption rate of 2.47%. The tests were performed according to the codal provisions of IS: 383-1970, which stipulates quality and grading guidelines for aggregates intended for use in concrete so that they comply with requirements designed for performance as well as durability in construction.

2.3 Coarse aggregate

Coarse aggregates of maximum size of 12.5 mm were used according to the specifications provided in IS: 383-1970¹⁹. The basic character tests were performed in order to understand the properties of coarse aggregate, that a specific gravity of 2.72, fineness modulus of 6.73, bulk density of 1748 kg/m³, water absorption rate of 0.48%, aggregate impact strength of 22%, and aggregate crushing value of 25%. Tests conducted on these aggregates were done based on the codal provisions prescribed under IS: 383-1970. This is the standard for coarse aggregate grades, for quality, and for other physical requirements for use in concrete.

2.4 Water

For this study, potable water was used, as mentioned in IS 456-2000 and IS 10262-2019^{20,21}. Quality of water is an essential factor for the hydration of cement and therefore should be maintained for concrete. The quality of the water to be used for concrete is brought out through the codal provisions mentioned in IS 456-2000. The IS 10262-2019 also specifies the procedures followed in mix design of concrete, which consequentially has an implication on the quality of water.

2.5 PEG-400

The self-curing agent, Polyethylene glycol-400 (PEG-400), was used in this study, as shown in

Fig. 1(a, b), where (a) represents the self-curing agent and (b) diluted dosage level of PEG 400. The PEG-400, has the general formula $H(OCH_2CH_2)_nOH$, where n is the average number of repeating oxyethylene groups, usually 4 to 180 which is in a state of polycondensate of ethylene oxide and water. Its main characteristics were water solubility, non-toxicity, odorless ness, neutrality, lubricating properties, and non-volatility²²⁻²⁴.

2.6 Mix proportion and specimens

In this research work, four different mixtures of SCC were prepared with the binder content was 410.32 kg/m^3 . The study objectives are to investigate the effect of different PEG-400 concentrations on the fresh and hardness properties of SCC. The PEG-400 concentrations were kept at 0% to 3% and the water-cement ratio (w/c) of the binder was at a constant value of 0.45. To ensure an even dispersion of the self-curing agent throughout the concrete, the liquid PEG-400 solution was progressively added to the concrete mix while water was being mixed. For 1%, 2%, and 3% concentrations, 4.1032 kg/m^3 , 8.2064 kg/m^3 , and 12.3096 kg/m^3 of liquid PEG-400 were added to the concrete mix, respectively. The mix design ratio of SCC was 1:1.5:3. According to the IS 10262-2009, the amount of water required to produce 1 m^3 of M_{20} grade concrete was 186 liters²⁰. The names of the SCC and details are mix proportion given in Table 1.

Materials as discussed in the Table 1, was proportioned accordingly and concrete was prepared

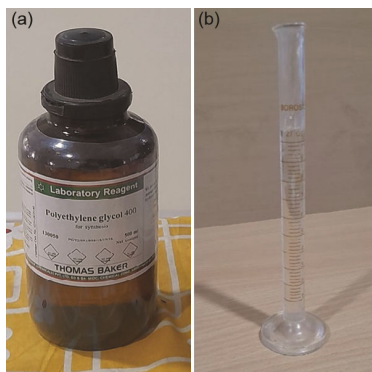


Fig. 1 — (a) PEG-400 - Self curing agent and (b) Diluted dosage level of PEG 400.

in accordance with IS 516²⁵. The cement and fine aggregate was blended thoroughly in dry state. Then coarse aggregate is added and mixed with the blended cement and fine aggregate. Slowly on three phases the calculated water has added along with the calculated quantity of self curing agent PEG-400 liquid solution. Entire mixing of concrete was take part in the pan mixture machine for around 3 minutes. The same mixing procedure was adopted for all the mixes w.r.t to varying proportions of self curing agent as described in Fig. 2. The prepared self curing concrete was filled in the moulds of cube, cylinder and prism respectively, properly compacted in three layers and allowed to dry for the period of 24 hours. The specimen size and details are discussed in the Table 2. Totally 96 specimens compares of 48 cubes, 36 cylinders and 12 prisms were taken in this experimental study.

After demoulding, the cube, cylinder and prism specimens (as shown in Fig. 3(a-c)) are dried for 7, 28, and 56 days at ambient temperature for testing, however, the control specimens are subjected to water curing.

2.7 Experimental testing

2.7.1 Fresh properties

The fresh concrete properties of various self curing concrete mixes using PEG-400 mixes are assessed through a slump flow test which is a most widely used test to assessing the accuracy of workability. The slump flow test measures the workability by evaluating the height difference between the mold height and the average sinked fresh concrete²⁶.

2.7.2 Mechanical properties

The PEG-400 SCC specimens were evaluated for their compressive strength, split tensile strength, and flexural strength after curing at ambient temperature

Table 2 — Self curing concrete specimen details.

Specimen Description	Size of the specimens	PEG-400 Concentrations			
		0%	1%	2%	3%
No. of. Cubes	$100 \times 100 \times 100 \text{ mm}$	12	12	12	12
No. of. Cylinders	$100 \times 200 \text{ mm}$	9	9	9	9
No. of. Prisms	$100 \times 100 \times 500 \text{ mm}$	6	6	6	6
No. of Cylinders	$100 \times 50 \text{ mm}$	6	6	6	6

Table 1 — SCC mix proportion based on PEG-400 concentrations.

S. No	Mix Id	PEG-400 Concentrations	Cement (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	Water (Kg/m^3)	PEG-400 (Kg/m^3)
1	SCC1	0%	410.32	619.95	1230.45	186	0
2	SCC2	1%	410.32	619.95	1230.45	186	4.1032
3	SCC3	2%	410.32	619.95	1230.45	186	8.2064
4	SCC4	3%	410.32	619.95	1230.45	186	12.3096

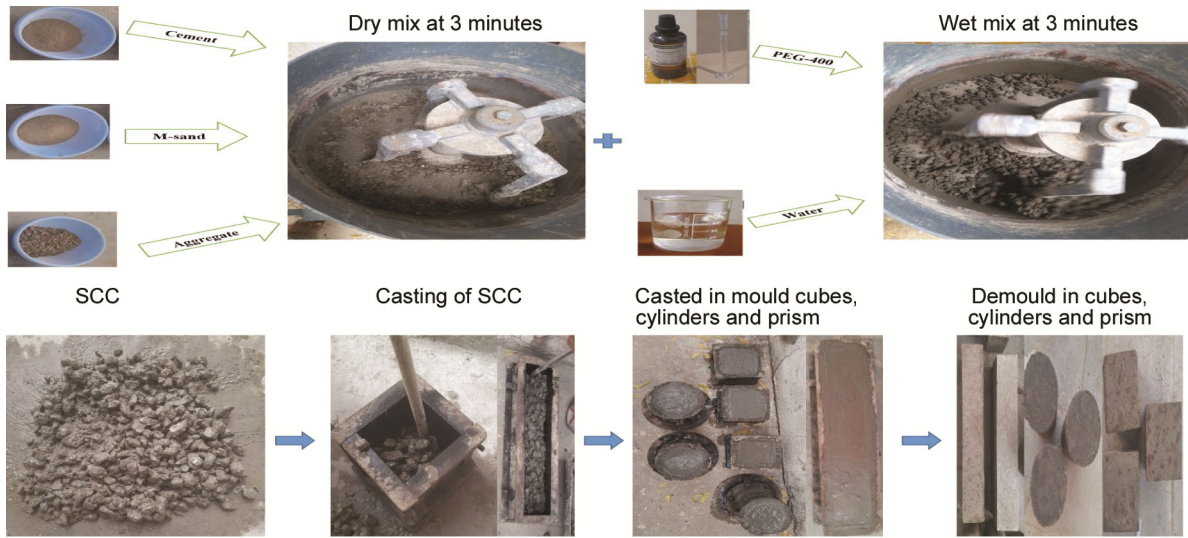


Fig. 2 — Preparation of self curing concrete specimens.

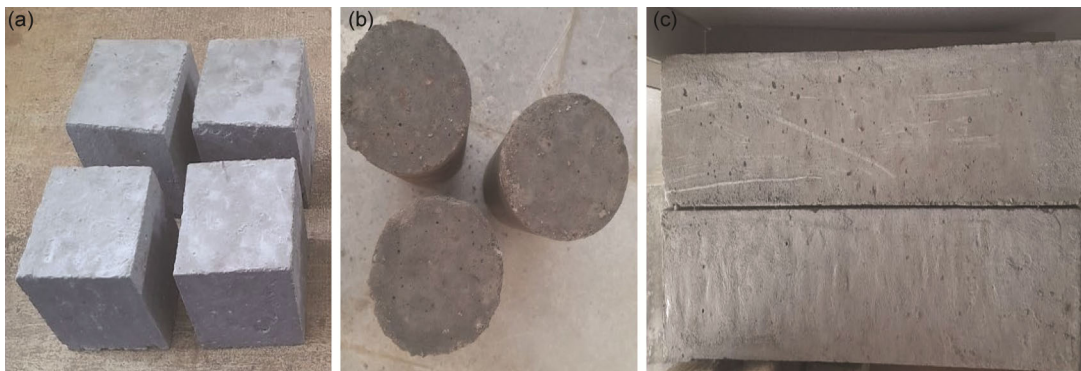


Fig. 3 — Casted SCC specimens of (a) Cubes, (b) Cylinders, and (c) Prism.

and water curing for the period of 7 and 28 days. Compression tests can help to evaluate the compressive strength and were tested on a compression testing machine (CTM). The axis of the structure is set to the centre of the load and the load is slowly increased at a constant rate until the structure reaches its resistance. At a constant rate of about 14 N/mm^2 per minute, the cube specimen in the machine's centre is subjected to tensile stress until it breaks^{5,27}. The split tensile strength is also evaluated in the CTM. The cylinder specimen was positioned horizontally in the centre of the machine and a force of 2.4 N/mm^2 per minute was applied and the separated tensile strength of a cylindrical structure is determined by dividing the weight by the corresponding geometric parameters such as the diameter and length of the structure^{28,29}.

Flexural strength test was carried in the Universal Testing Machine (UTM) with the prismatic specimens without reinforcement. The UTM has four contact points: two support points and two loading points. Two

steel cylinders with a diameter of 38 mm are to be fixed on the bed of the universal measuring machine, on which the specimen must be placed. It is recommended to place the samples at a distance of 400 mm from centre to centre for 100 mm samples³⁰⁻³².

2.7.3 Durability properties

Durability properties of concrete includes water absorption, sorptivity, acid and sulfate assaults (HCL, Na_2SO_4), and Rapid Chloride Penetration Testing (RCPT) for this experimental study. The test were briefed in a detailed manner. The Water absorption tests were performed in confirming with the standards of ASTM C 642-97. During the 24 hours period, the concrete specimens were dried in the hot air ovens to remove the complete moisture content. After taking from the oven, the specimens were weighed at W_1 (g). A minimum time of 24 hours was required for the concrete specimens to be immersed in water. After the samples were removed from the water, the final weight W_2 (g) was determined^{33,34}. Water sorptivity was

performed by observing the capillary rise and absorption rate on relatively homogeneous materials. The cylindrical specimen of size 100 mm diameter and 50 mm height in was placed in hot oven dried for the durations of 24 hours at 100 degrees and then the specimens were allowed to cool in dry conditions for another 24 hours. During the test, one circular surface of the specimen was immersed in water at a depth of 5 mm. A waterproof tape provided around the specimen which prevents the penetration of water from its peripheral surface. Using a top pan balance weighing up to 0.1 mg, the quantity of water absorbed during 180 minutes was measured in the interval of 30 minutes. During the regular intervals of 30, 60, 90, 120, 150, and 180 minutes, the capillary increases its absorption rate of water. The sorptivity of a porous material is measured by its capillary action's ability to absorb and transmit water. Water absorption per area of the inflow surface increases as time elapses^{35,36}. In RCPT, Concrete resistance to chloride ion penetration can be measured w.r.t to voltage across the concrete specimens. There are two chambers in the diffusion cell. A solution is prepared by mixing one liter of distilled water with 30 grams of NaCl salt and 12 grams of NaOH pellets. The NaCl solution is placed in one chamber while the NaOH solution is placed in the other chamber. Centrally positioned vacuum-saturated concrete specimens under 60 Volts of impressed DC voltage were forced to migrate chloride ions. Those samples are exposed to electrical current for 6 hours, and the Coulomb number, which measures the amount of charge transferred during the test, is interpreted as a measure of permeability. A concrete that is more permeable has a higher coulomb; a concrete that is less permeable has a lower coulomb^{37,38}. A good correlation has been found between the method and chloride test according to ASTM C 1202-97.

$$Q = 900 (I_0 + 2I_{30} + \dots + 2I_{330} + I_{360}) \quad \dots (1)$$

Where, Q = Coulombs of current flowing through one cell.

I_0 = Amount of the voltage applied is the current reading in amperes immediately.

I_t = Amount of the voltage applied t minutes after the current reading in amperes.

For acid resistance test, the casted cube specimens of size 100 mm × 100 mm in the water curing was taken out and allowed to dry for one day. The initial weights of the concrete cube specimens were taken. Then the cubes was immersed in the acidic water containing Hydrochloric acid (HCL) with a pH of

approximately 2 at 2% of the water weight was added in the water for the period of 56 days after 28 days curing at ambient condition. The pH was maintained throughout the immersion period. After the required immersions period, concrete cubes were taken away from the acidic water and the acid attack was determined by the percent weight loss, color change, surface cracks, voids, salt deposits, material deterioration, and percent loss of compressive strength³⁹. The sulfate attack was determined by immersing the casted concrete cubes specimens of 100 mm × 100 mm in the sulfate water containing 2% to 5% of sodium sulfate (Na_2SO_4) by weight of water. The concrete cubes of size 100 mm × 100 mm were immersed in water with 2% of Na_2SO_4 for the period of 56 days after 28 days curing at ambient condition. The concentration of sulfate water was maintained throughout the period. After 28 and 56 days of immersion period, the sulfate attack was identified by the percent weight loss, color change, surface cracking, voids, salt deposition, material deterioration, and percent loss of compressive strength of concrete cubes^{40,41}.

2.7.4 Characterization study

XRD is an effective technique for establishing the crystalline structural formation of SCC at varying PEG-400 concentrations from 0% to 3%. The dispersed X-rays generate a diffraction pattern that conveys the information about the atomic distance and arrangement in the SCC specimens. The appropriate XRD patterns were observed from 10° to 80°⁴². SEM imaging was used to analyze the surface morphological and microstructure properties of SCC with PEG-400 concentrations varying from 0% to 3%. The material properties were studied with high resolution up to 2 μm. The elemental composition of SCC has been identified by using the EDAX technique for the PEG-400 concentrations varying from 0% to 3%⁴³.

3 Results and Discussion

3.1 Slump cone test

The workability of SCC mixtures varying from 0% to 3% PEG-400 concentrations was obtained from the slump flow test as shown in Fig. 4. According to the IS 10262-2009 guidelines, SCC has a good workable capacity when the slump value is in the range of 80 mm to 150 mm. For control specimen (0% PEG-400 concentration), the slump value is 84 mm. It is observed that (in Fig. 5), the slump value is increased to the maximum of 98 mm for 1% PEG concentration. But for the further increase in the

PEG-400 concentration of 2% and 3%, the slump value is decreased to 86 mm and 81 mm respectively. The higher concentration of PEG-400 causes more particle contact, which makes the mixture difficult to flow and mostly causes the slump value to decrease. Such a combination results in a less feasible SCC.



Fig. 4 — Slump cone test.

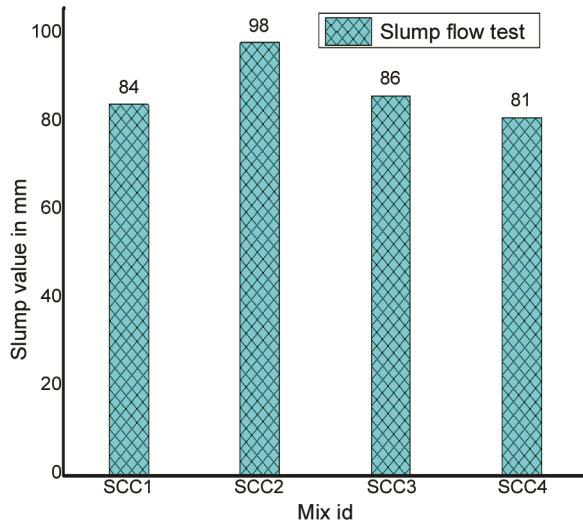


Fig. 5 — Slump values on SCC.



Fig. 6 — (a) Placing of specimen under compression loading, (b) Specimen crushing during loading and (c) Failure specimens after loading.

3.2 Compression test

Figure. 6 (a–c) shows the compression test conducted on the cast cube specimens with various PEG-400 concentrations, depicting the specimen during loading, crushing, and failure. The test results of the compressive strength against 7 days and 28 days for various PEG-400 concentrations are showed in Fig. 7. For control specimen of 28 days curing (0% PEG-400 concentration), the compressive strength is found to be 24.8 N/mm², when PEG-400 concentration of 1% introduced, the compressive strength increased to 26.2 N/mm². The percentage of compressive strength increased is around 23.60%. If the PEG-400 concentration is further increased to 2 % and 3 %, the compressive is found to be reduced to 25.95% and 37.40% respectively due to the delay of hydration rate. In 7 days curing also, the same effect is seen.

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3.3 Split tensile test

Figure. 8 (a–c) shows the split tension test conducted on the cast cylinder specimens with various PEG-400 concentrations, depicting the specimen during loading, crushing, and failure. The test results of the split tensile strength against 7 days and 28 days for various PEG-400 concentrations are showed in Fig. 9. Like compression test, split tensile strength is more and

maximum (2.13 N/mm^2) for PEG-400 concentration of 1% than conventional one. But when concentration increased to 2% and 3%, the split tensile strength is reduced to 8.45 % and 23.47 %, respectively in comparison with PEG-400 concentration of 1%. However, the split tensile strength is increased to 15.02 % and 7.18 % for 1% and 2% PEG-400 concentration respectively in comparison with conventional concrete but it is decreased to 9.94% for 3% of PEG-400 concentration.

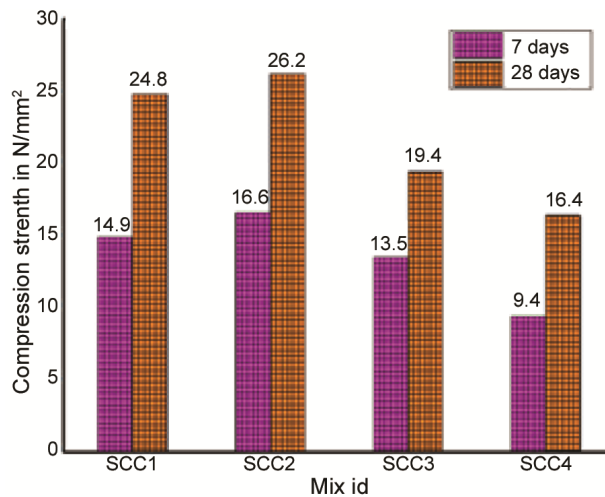


Fig. 7 — Compressive strength test results.



Fig. 8 — (a) Placing of specimen under split tension loading, (b) Specimen crushing during loading and (c) Failure specimens after loading.

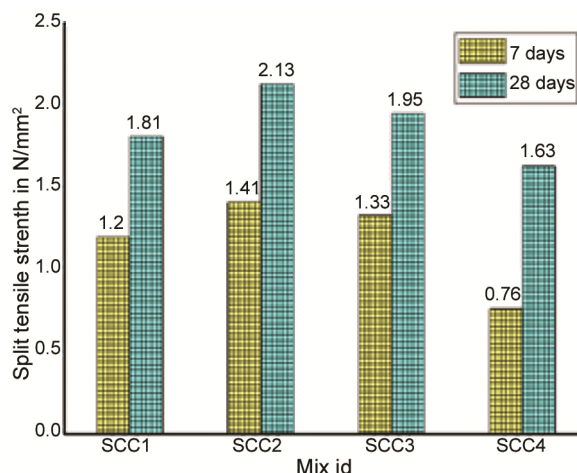


Fig. 9 — Split tensile strength test results.

3.4 Flexural test

Figure. 10 (a–c) shows the flexural test conducted on the cast prism specimens with various PEG-400 concentrations, depicting the specimen during loading, crushing, and failure. The test results of the flexural strength against 7 days and 28 days for various PEG-400 concentrations are showed in Fig. 11. Like other mechanical property test, flexural strength is more and maximum (3.6 N/mm^2) for PEG-400 concentration of 1% than conventional one. But when concentration increased to 2% and 3%, the flexural strength is reduced to 11.11 % and 16.67 %, respectively in comparison with PEG-400 concentration of 1%.

However, the flexural strength is increased to 12.5 % and 1.56 % for 1% and 2% PEG-400 concentration respectively in comparison with conventional concrete but it is decreased to 4.76 % for 3% of PEG-400 concentration. Among the results of mechanical property tests, it is found that 1% of PEG-400 concentration is highly desirable. But even when it is 2% and 3% also, the strength is not much varied for achieving the minimum strength of M_{20} concrete. The ideal dosage determined by analyzing the mechanical properties will be used as a guide for additional assessments in this research. This ideal dosage is significant since its performance characteristics are superbly matched without compromising durability. Therefore, to make these findings empirically supported and useful for self-curing concrete applications, the durability qualities will be tested on the next optimal dosage of PEG-400.

3.5 Water absorption test

The water absorption values for various PEG-400 concentrations of SCC mixes ranging from 0% to 3% for the 28 days curing are 6.18%, 5.79%, 6.23% and 7.21% respectively. There is a discernible difference in the water absorption values across the various PEG-400 concentrations of SCC mixtures; 1% of PEG-400 concentrations exhibits the lowest value (5.79%) and 3% of PEG-400 concentrations shows the highest (7.21%). 1% of PEG-400 concentrations is the combination that is most resistant to water penetration, as indicated by its lowest water absorption value among the other mixes which indicates this could be a denser concrete matrix with fewer pores and capillaries, resulting in greater resistance to water penetration by the presence of smaller PEG-400 concentrations. This combination is predicted to offer greater durability and a longer service life than the other mixtures. This performance could be

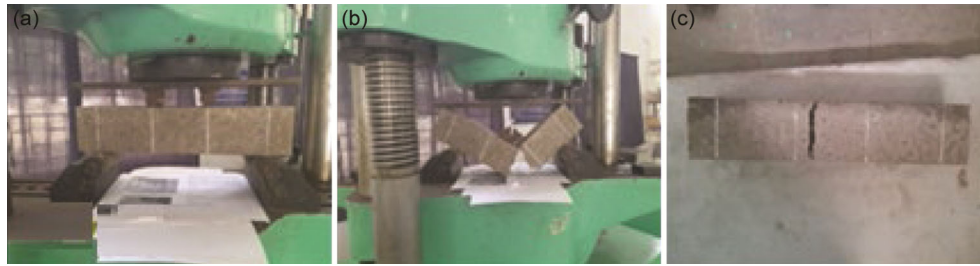


Fig. 10 — (a) Placing of specimen under flexural loading, (b) Specimen crushing during loading and (c) Failure specimens after loading.

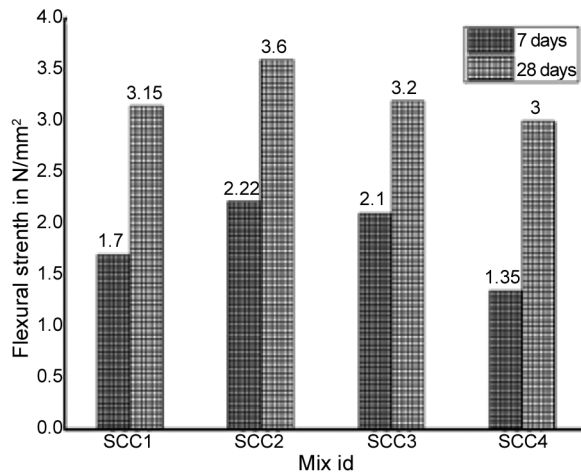


Fig. 11 — Flexural strength test results.

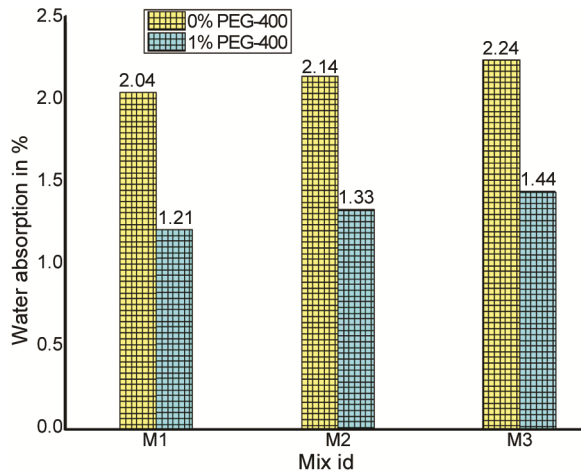


Fig. 12 — Water absorption test results.

ascribed to an optimum mix design, which may include a well-balanced water-cement ratio, effective additive application, and proper aggregate grading. The 3% of PEG-400 concentrations has the highest water absorption rate at 7.21%, which indicates this could be a more porous concrete structure, due to higher water-cement ratio, inadequate curing, or less effective use of admixtures. In terms of resistance to water absorption, conventional and 2% of PEG-400 concentrations perform similarly, as seen by their comparable water

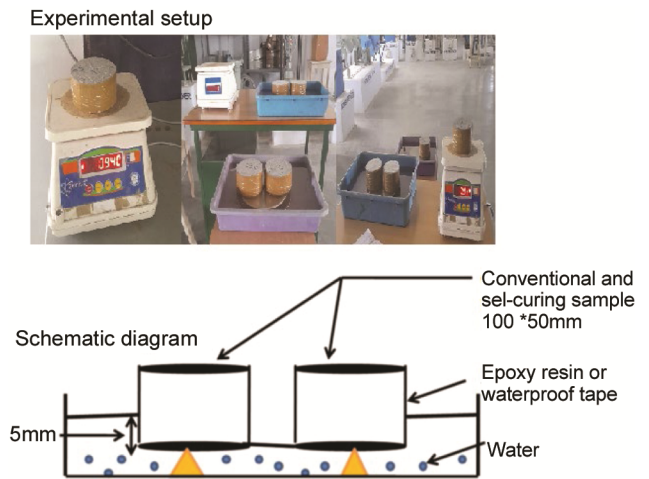


Fig. 13 — Water sorptivity test.

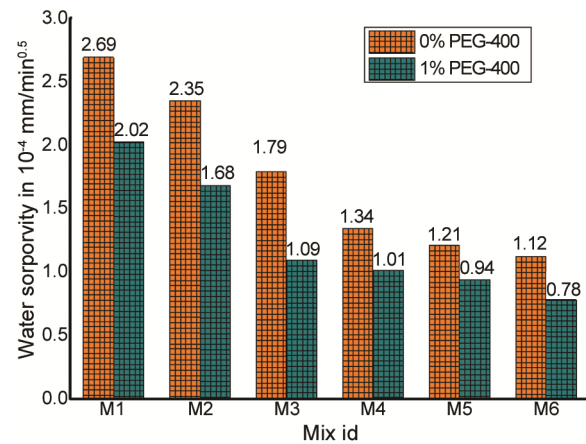


Fig. 14 — Water sorptivity test results.

absorption values (6.18% and 6.23%, respectively) as shown in Fig. 12.

3.6 Water sorptivity test

The experimental configuration for measuring water sorptivity in conventional and self-curing concrete samples of conventional and 1% PEG-400 concentration is shown in the Fig. 13. For easier comprehension, the setup includes real pictures of the experiment as well as a schematic diagram. The graph as shown in Fig. 14 shows the water sorptivity values

for the two specimens of conventional and 1% PEG-400 concentration against six different time intervals (T30 to T180) without PEG-400 (0%) and with 1% PEG-400. Water sorptivity is measured in terms of 10^{-4} mm/min^{0.5}, which is indicating the rate at which water is absorbed by effect of capillary action. The 1% PEG-400 concentration reliably lowers the sorptivity of water than the conventional in all the time intervals.

The water sorptivity was decreased by 24.90%, 28.51%, 39.10%, 24.62%, 22.31% and 30.35% in compairison with conventional specimens against the time intervals of 30, 60, 90, 120, 150 and 180 minutes. This indicates that the inclusion of PEG-400 concentration has increased the concrete's capillary action-based resistance to water absorption interms of preventing the water evaporation.

3.7 RCPT

The electrical potential between the depth of chloride penetration and time can be used to determine the chloride migration coefficient in the transient state and test set up of RCPT is shown in Fig. 15. Based on the RCPT experiments, the chloride ion penetration in



Fig. 15 — RCPT test setup.

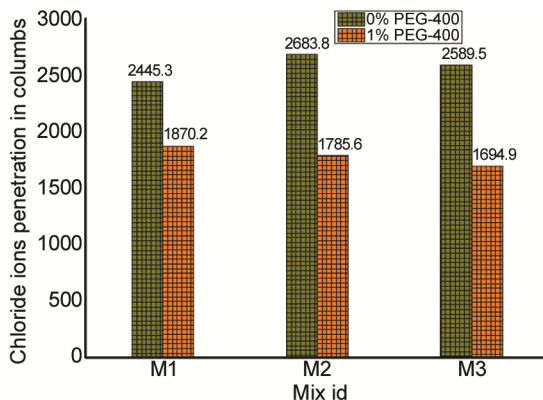


Fig. 16 — RCPT test results.

terms of coulombs on the specimens (three numbers) of conventional and 1% of PEG-400 concentration are given in Fig. 16. In this figure, the corresponding range of penetration and its level also given. It is observed that, for the conventional concrete (0% of PEG-400 concentration), the average of these three specimens are 2572.8 coulombs which lies in the range of moderate chloride penetration. But, for 1% of PEG-400 concentration the average value is 1768.57 coulombs which lies in the range of low chloride penetration. The test results indicated that, 1% of PEG-400 concentration gives good resistance to the chloride penetration because of high internal moisture content and improvement on the cement hydration in terms of gel formation which could minimize the concrete voids.

3.8 Acid resistant test

The acid resistant test was conducted by immersing the conventional and 1% of PEG-400 concentration cube specimens after 28 days of curing in the acidic water of hydrochloric acid (HCL) as shown in Fig. 17. The immersion period is taken as 28 days and 56 days. For observing the acid resistant, two factors were taken into account loss of weight and loss of compressive strength. In comparison to the 0% PEG-400 samples, the samples' weight loss is decreased with the addition of 1% PEG-400 as shown in Table 3. The 1% PEG-400 samples lost 0.93% less weight after 28 days than the 0% PEG-400 samples. At 56 days, the 1% PEG-400 samples continue to exhibit a 1.54% decrease in weight loss, continuing this trend. Similar to weight loss, the strength reduction is less noticeable in samples containing 1% PEG-400. After 28 days, the strength reduction in the 1% PEG-400 samples is 1.54% lower than in the 0% PEG-400 sample. By 56 days, the difference in

Charge (Coulombs)	Chloride permeabilit
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

strength reduction between the two sets of samples had risen to 1.97%.

The addition of 1% PEG-400 reduces acidic effects by functioning as a protective barrier mechanism. This inhibits acidic solutions' uptake, resulting in slower rate of weight and strength loss. Furthermore, PEG-400 appears to increase the initial strength of the material, implying that it improves the curing process and microstructural integrity of the concrete.

3.9 Sulfate resistance

The sulfate resistance test was conducted by immersing the conventional and 1% of PEG-400 concentration cube specimens after 28 days of curing in the sulfate solutions of sodium sulfate (Na_2SO_4) as



Fig. 17 — Immersion and appearance of specimens in acid resistant test.

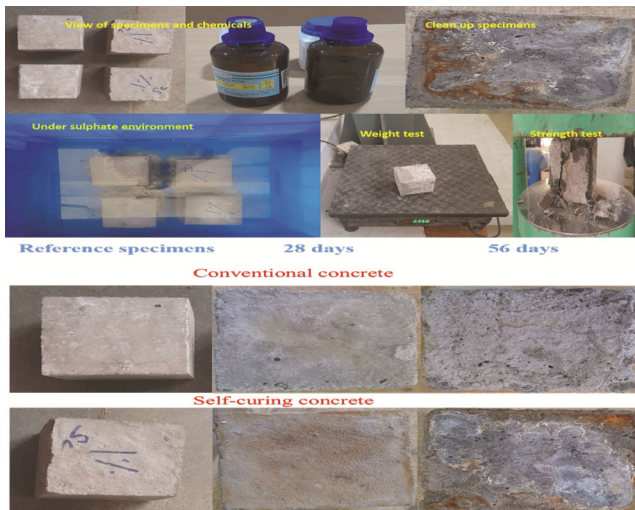


Fig. 18 — Immersion and appearance of specimens in sulfate resistance test.

shown in Fig. 18. The immersion period is taken as 28 days and 56 days. For observing the sulfate resistant, two factors were taken into account loss of weight and loss of compressive strength as like sulfate resistant.

Both samples have a gradual increase in weight loss; however, after 28 and 56 days, the sample containing 1% PEG-400 exhibits a lower percentage of weight loss in comparison to the sample containing 0% PEG-400 as shown in Table 4. The weight reduction at 28 days is 4.03% for 1% PEG-400 and 4.78% for 0% PEG-400. After 56 days, the weight reduction for 0% and 1% PEG-400, respectively, is 9.65% and 8.13%. Samples without and with 1% PEG-400 had initial compressive strengths of 23.24 N/mm² and 26.94 N/mm², respectively. After 28 day immersion of sulphate solution, strength was reduced to 22.03 N/mm² for the sample without PEG-400 (5.18 % strength loss) and 25.80 N/mm² for the sample with 1% PEG-400 (4.23 % strength loss) respectively. Similarly after 56 days immersion of sulphate solution, the strength decreased from 21.29 N/mm² (8.39% strength loss) to 25.08 N/mm² (6.89% strength loss). Chemical reactions that damage the material's integrity and structure are the primary causes of weight and strength loss in sulfate-exposed materials. PEG-400 appears to reduce these effects by providing a protective mechanism against sulfate intrusion, resulting in slower degradation rates.

Table 3 — Test results of acid resistance test.

Description	Immersion Period	0% PEG-400	1% PEG-400
Weight	0 th day	2.550 kg	2.502 kg
	28 th days	2.382 kg	2.359 kg
	56 th days	2.276 kg	2.271 kg
Loss of Weight	28 th days	6.56 %	5.63 %
	56 th days	10.72 %	9.18 %
	0 th day	22.94 N/mm ²	26.34 N/mm ²
Strength	28 th days	21.38 N/mm ²	24.95 N/mm ²
	56 th days	20.67 N/mm ²	24.27 N/mm ²
	28 th days	6.78 %	5.24 %
Loss of Strength (%)	56 th days	9.89 %	7.92 %

Table 4 — Test results of sulfate resistance.

Description	Immersion Period	0% PEG-400	1% PEG-400
Weight	0 th day	2.555 kg	2.526 kg
	28 th days	2.433 kg	2.424 kg
	56 th days	2.308 kg	2.32 kg
Loss of Weight	28 th days	4.78 %	4.03 %
	56 th days	9.65 %	8.13 %
	0 th day	23.24 N/mm ²	26.94 N/mm ²
Strength	28 th days	22.03 N/mm ²	25.80 N/mm ²
	56 th days	21.29 N/mm ²	25.08 N/mm ²
	28 th days	5.18 %	4.23 %
Loss of Strength (%)	56 th days	8.39 %	6.89 %

3.10 Microstructural analysis

The impact of the additive on the development of the crystalline phases found in the material is established by the XRD analyses of samples made with varying concentrations of PEG-400 (0%, 1%, 2%, and 3%) as shown in Fig. 19. For elements like silicon (Si), aluminum (Al), and calcium (Ca), diffractograms reveal distinct peaks, demonstrating that the structure includes certain crystalline phases, including silica, calcium silicates, and aluminates. Compared to the 1% PEG-400 sample, the 0% PEG-400 sample exhibited broad, low peaks, which typically imply reduced crystallinity. Conversely, the 1% PEG-400 sample has strong, pointed peaks that point to increased crystallinity and a well-formed structure. The intensity of the peaks, particularly the one pertaining to the silica and calcium compounds, lowers as the percentage of PEG-400 increases to 2% and 3%. This is because PEG-400 decreases the material's crystallinity by slowing down the pace at which hydration and crystallization take place. More amorphous phases are visible at higher PEG-400 percentages, indicating a greater inhibition of crystallization. This is because PEG-400, when added here, primarily limits the mobility of water and ionic molecules, which affects the overall crystallization of cement hydrates and other comparable compounds. Higher PEG-400 percentages improve the amorphous phases, as seen by the peak intensity's extreme sensitivity to PEG-400 content. Because of the tendency for a higher amorphous content, this higher proportion may alter the mix's mechanical properties. A higher crystalline calcium silicate hydrate content appears to result from the interaction of 1% PEG-400

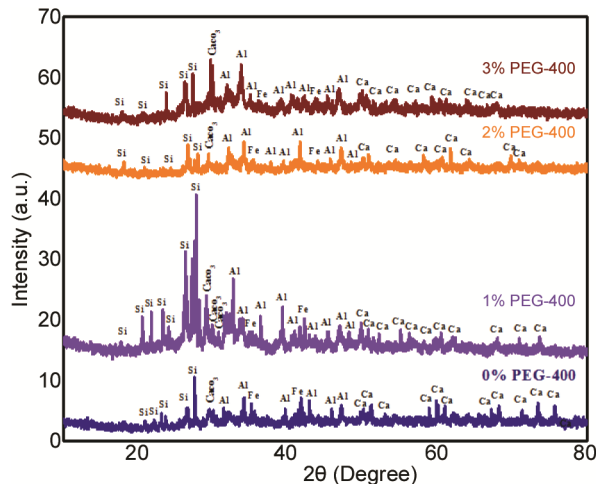


Fig. 19 — XRD analysis of PEG-400 concentration based on SCC mixes.

with the hydration process, giving the concrete more strength and durability.

After 28 days of ambient curing, SEM and EDAX were used to examine the changes in microstructural behavior and elemental composition of SCC depending on varying PEG-400 concentrations. SEM pictures of SCC mixes with PEG-400 concentrations ranging from 0% to 3% are shown in Fig. 20 (a to h) at various resolutions. The high degree of cohesiveness between the binder phase and coarse particles is indicated by the micrographs of SCC, which appear heterogeneous, compact, and dense which explains the good mechanical performance. Furthermore, the water evaporation brought on by the PEG-400 concentration increase from 0% to 3% may have caused a delay in the polymerization reaction. The reaction between the 1% denser microstructure on the aggregate surface and the PEG-400 concentration results in the formation of a robust pozzolanic-binder matrix. Moreover, the SEM images revealed the few pores that were visible in the ambient-cured specimen. The binder matrix was densely partially reacted, and the absorption source might have been these concrete pores. Silica (Si), calcium (Ca), alumina (Al), iron (Fe), and a few smaller peaks of Na and K are also visible in the majority of the EDAX spectra. These elements are the main constituents of SCC mixtures. The EDAX results for the ambient curing of SCC with varying PEG-400 concentrations are shown in Fig. 1-24. The increased mechanical strength and durability previously indicated are closely linked to the large Si, Ca, Al, and Fe peaks that are seen in the SCC specimens, especially at the concentration of 1% PEG-400. The existence of well-crystallized phases in silica, calcium silicates, aluminates, and potentially iron oxides can explain the peaks. They are important and required for concrete's stability and strength growth. The 1% PEG-400 sample's well-resolved diffraction peaks further suggest the presence of strong, dense inner matrices, which could improve compressive strength. By reducing porosity, the formation of such crystalline phases may boost durability by lowering the likelihood of chemical assault, water infiltration, and freeze-thaw cycles. Therefore, the exceptionally high and sharp peak for Si, Ca, Al, and Fe at 1% PEG-400 indicates the ideal balance that enhances SCC's mechanical characteristics and long-term performance^{30, 31}.

3.11 Cost analysis

Due to differences in labor, materials, and curing techniques, the price of self-curing concrete and

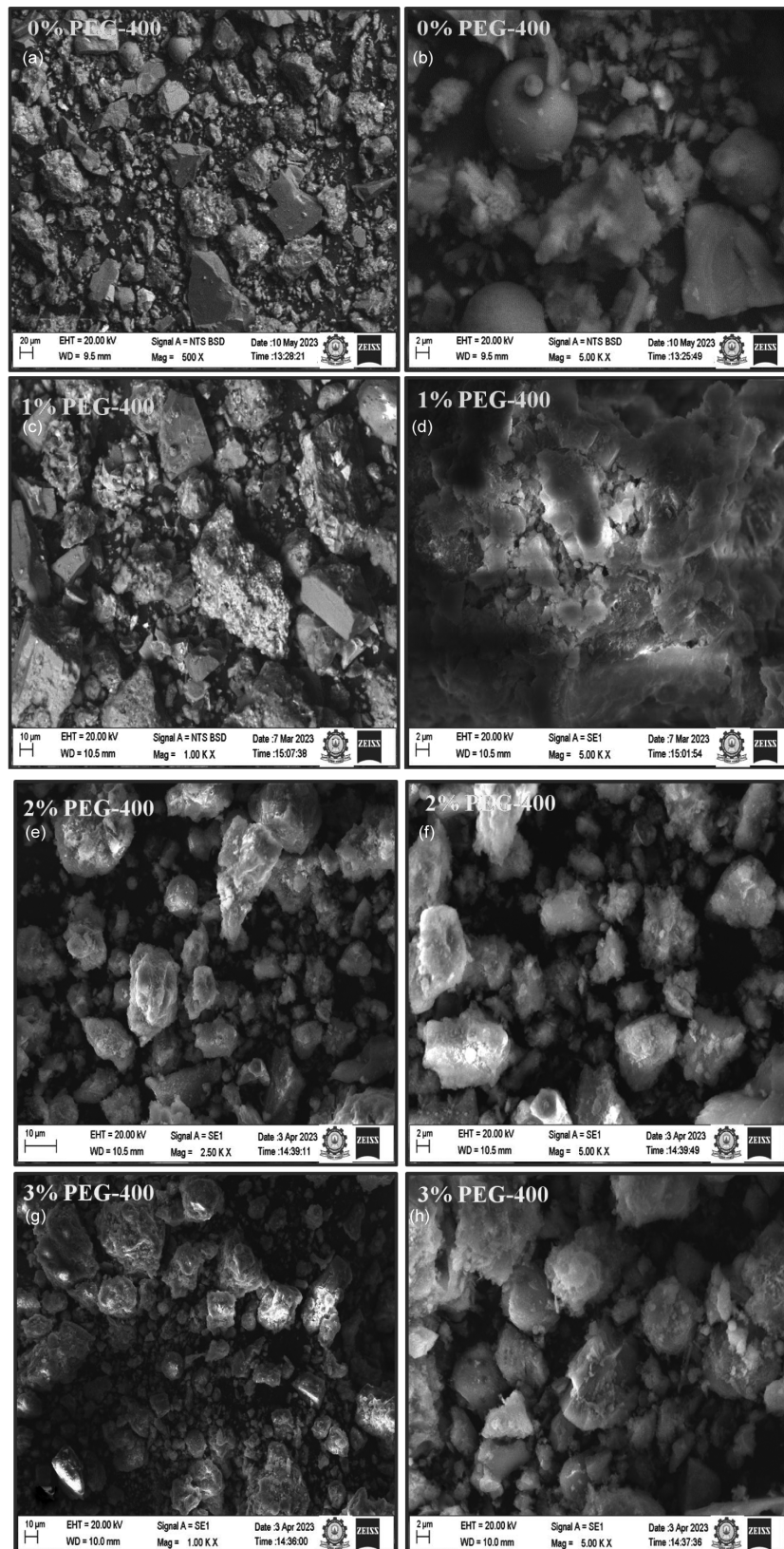


Fig. 20 — shows SEM images of PEG-400 at 0% with (a) 20 magnifications (b) 2 magnifications.

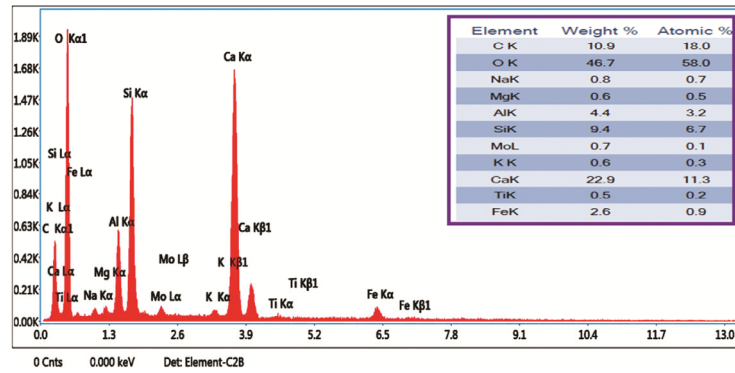


Fig. 21 — EDAX spectrum image of PEG-400 (0%).

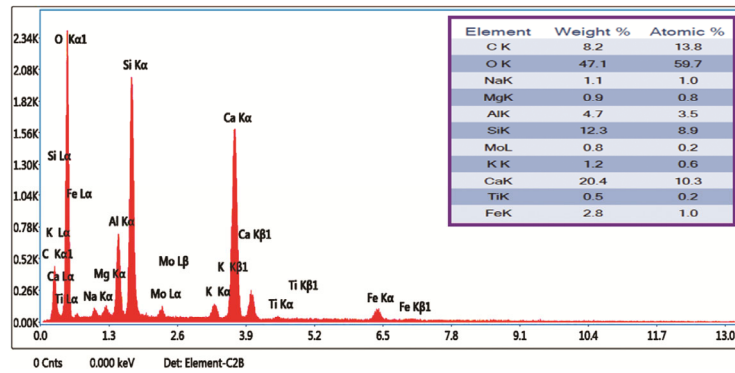


Fig. 22 — EDAX spectrum image of PEG-400 (1%).

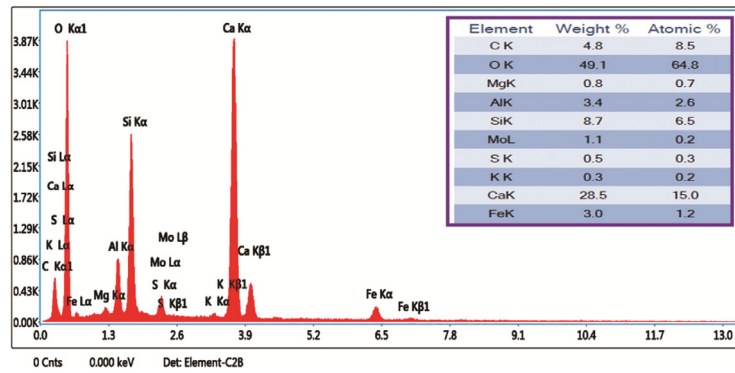


Fig. 23 — EDAX spectrum image of PEG-400 (2%).

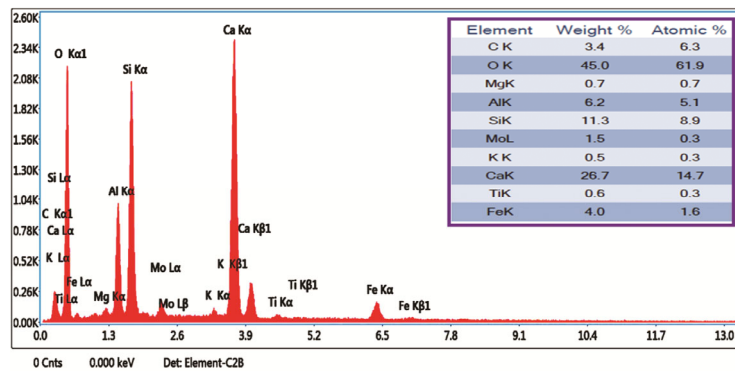


Fig. 24 — EDAX spectrum image of PEG-400 (3%).

Table 5 — Cost analysis of conventional concrete and SCC / m³.

0% PEG 400 (Conventional)		1% PEG 400 (SCC)	
Water requirement	3000 litres	Water requirement	186 litres
Water cost / litre	0.75 Rs.	Water cost / litre	0.75 Rs.
Total water cost for 28 days (A)	2250.00 Rs.	Total water cost for 28 days (A)	140.00 Rs.
Labour requirement	1 Nos.	Labour requirement	-
Labour salary / Day	100.00 Rs.	PEG 400 requirement	1.86 litres
Total labour salary for 28 days (B)	2800.00 Rs.	PEG 400 cost / litre	1040.00 Rs.
		Total PEG 400 cost for 28 days (B)	1934.00 Rs.
Total cost (A + B)	5050.00 Rs.	Total cost (A + B)	2034.00 Rs.

conventional concrete might differ significantly. The detailed cost comparison among the conventional and self curing concrete of 1% PEG-400 concentration. The cost comparison is made for the conventional concrete (0% PEG-400 concentration) and self curing concrete (1% PEG-400 concentration) and it is shown in Table. 5 for 28 days of curing per m³ of concrete. The key factors considered is the requirement of water, labour and self curing agents. Using self-curing concrete with 1% PEG-400 Rs 3016.00 per cubic meter is saved than conventional concrete. Conventional concrete, while initially it may appear as less expensive, but higher curing costs and potential long-term difficulties will be there if not properly cured. Despite the fact that PEG-400 is more expensive, the cost is mostly being reduced since less water is needed and labor-related expenses are eliminated.

4 Conclusion

The following conclusions can be drawn from the results of this experimental study,

- All the mixes are in the good workability range of 80 mm to 150 mm but however, 1% PEG-400 concentrations has the highest slump value 98 mm, which is indicating the better workability and flow of the mixtures.
- The experimental result statistics clearly shows that a 1% concentration of PEG-400 is optimal for improving concrete performance, whereas larger concentrations result in lower returns or even strength reductions. When it is compared to conventional concrete (0% PEG-400), it exhibits a 5.65% improvement in compressive strength, 17.68% in split tensile strength, and 14.29% in flexural strength.
- Adding 1% PEG-400 considerably reduces chloride ion penetration in all mixtures around 23% to 34%. This suggests that PEG-400 increases the durability and resistance to chloride ion penetration in concrete, hence improving its corrosion resistance. 1% of PEG-400 concentration specimens under acid and sulfate resistance test, resulting in

less deterioration, weight loss, and strength loss when compared to 0% PEG-400 based SCC mixes. For acid resistance and sulphate resistance, the loss of strength is 6.89% and 7.92% respectively, which is around 17%-19% reduction than the conventional concrete. In Overall, 1% PEG-400 concentration in SCC mixes demonstrates good durability aspects.

- From the evidence of microstructure analysis, it is understood that Si, Ca, Fe, Al and Mg mineral phases were present in 1% PEG-400 concentration based on SCC mixes which can be better in terms of achieving the degree of hydration, the formation of hydration products in comparison with 0% PEG-400 based on SCC mixes. The analysis has revealed better in terms of their morphology, texture, and distribution of phases, pores, aggregates, and other components compare to 0% PEG-400 based on SCC mixes. It is understood in overall, 1% PEG-400 concentration based on SCC mixes well-performance influences the microstructure and composition of the concrete matrix as observed through these analytical techniques compare to the 0% PEG-400 based on SCC mixes.

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