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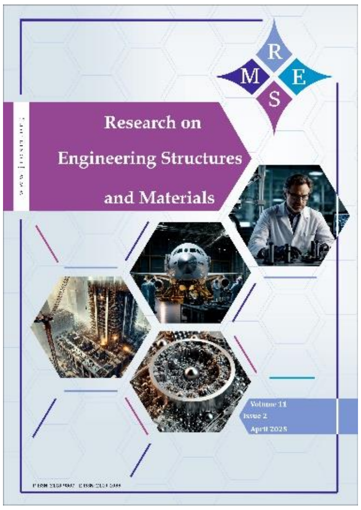

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Online Publication Date: 30 April 2026

URL: http://www.jresm.org/archive/resm2026-1520me0219rs.html
DOI: http://dx.doi.org/10.17515/resm2026-1520me0219rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Jayasankar K, Krishnaraj L, Ravichandran P T. Integrated evaluation of smart internal curing strategies in concrete: Mechanical, durability and SEM insights. *Res. Eng. Struct. Mater.*, 2026; 12(3): 1875-1897.

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Research Article

Integrated evaluation of smart internal curing strategies in concrete: Mechanical, durability and SEM insights

K Jayasankar [a], L Krishnaraj [b], P T Ravichandran [*,c]

Department of Civil Engineering, College of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu Dt, Chennai - 603203, Tamil Nadu, India

Article Info

Article History:

Received 19 Feb 2026
Accepted 26 Apr 2026

Keywords:

Self-Curing concrete;
Superabsorbent polymers;
Polyethylene glycol;
Microstructural analysis;
Durability performance

Abstract

This study investigates the influence of self-curing agents like Super Absorbent Polymers (SAPS), Polyethylene Glycol Liquid (PEGL), and Polyethylene Glycol Powder (PEGP) with various dosages on the performance of M30 grade concrete under different curing regimes like complete water, complete air, and partial air and water curing regimes. Compressive, split tensile and flexural strength Studies were evaluated alongside durability parameters such as water absorption, sorptivity, and rapid chloride permeability. Scanning electron microscopy analysis revealed enhanced hydration and densified microstructure in specimens with self-curing agents compared to Control specimens without any self-curing agent. Among the mixes, SAPS 0.3%, PEGL 1.0%, and PEGP 1.0% demonstrated optimal performance, achieving an additional strength recovery over Control Specimen without any self-curing agent under air curing regime and Water curing regime. Notably, under the 7-day air + 21-day water curing regime, SAPS 0.3% increased 28-day strength from 33.9 MPa (control) to 42.0 MPa (+24%); under 7-day air + 49-day water it increased from 41.1 MPa to 48.8 MPa (+19%). The study concludes that PEG and SAPS-based internal curing significantly recover concrete performance in terms of workability, strength and durability, especially in environments with limited access to external water curing.

1. Introduction

Curing is a critical phase in the concrete lifecycle because it governs the continuity of hydration and pore-structure refinement, thereby controlling microstructural development, mechanical performance, and the long-term durability of cementitious systems [55,56]. Traditional curing methods such as water ponding, spraying, wet gunny wrapping, and the use of curing membranes are widely adopted across civil engineering applications. These methods aim to maintain adequate moisture and temperature conditions during the early stages of cement hydration, thereby enhancing the strength and durability of concrete and mortar [1]. However, the efficacy of these methods is largely dependent on site-specific factors including climate, material availability, labor skill, size & scale of the structure and project logistics. In many developing countries, traditional wet curing practices often face operational constraints, especially in high-rise or precast structures where continuous water application is impractical [44, 45]. Inadequate curing may lead to early age cracking, shrinkage, and reduced long-term durability due to incomplete hydration and weak interfacial zones [2].

Despite their widespread use, conventional curing approaches encounter several limitations. Water curing, though effective in a controlled environment, is labor-intensive and water-consuming. In arid or water-scarce regions, maintaining saturated conditions is nearly unfeasible

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[*] Corresponding author: ravichap@srmist.edu.in

[a] orcid.org/0009-0008-8635-0496; [b] orcid.org/0000-0001-9449-9524; [c] orcid.org/0000-0002-9555-2005
DOI: http://dx.doi.org/10.17515/resm2026-1520me0219rs

[3,4]. According to [5], poor execution also causes plastic shrinkage, capillary porosity, and surface cracking. Examples of this include premature drying or inadequate wetting intervals. Due to the dense microstructures, quick hydration requirements, and moisture retention sensitivity of high-performance concrete (HPC), ultra-high-performance concrete (UHPC), and precast structural components, the curing process is more complicated in modern construction practices. Their thick microstructures make curing requirements more challenging in modern concrete applications like high-performance concrete (HPC), ultra-high-performance concrete (UHPC), and precast parts. According to [6] and [7], this density restricts internal moisture mobility, increasing the probability of self-desiccation and autogenous shrinkage even when external curing procedures are used. More dependable, internally controlled curing techniques are therefore becoming more necessary [47-54]. One potential remedy for this problem is self-curing, sometimes known as internal cure. To sustain internal relative humidity (IRH) without the use of external water sources, it entails the insertion of materials that can absorb and progressively release water throughout the hydration process [8],[9]. This technique was first used in large-scale concrete projects, where lightweight particles were used to control temperature changes and hold onto moisture [10].

Self-curing treatments are still not widely used in the field, despite encouraging lab results. The lack of defined dose methods, inconsistent performance resulting from material variability, and a lack of long-term performance data under a variety of environmental exposures are major obstacles. Although several laboratory studies propose practical dosage windows (e.g., PEG-based admixtures commonly in the range of about 0.5–1.0% by cement mass and SAPS typically around 0.2–0.4%, depending on the target property), these values are not directly transferable across projects because the “effective dose” is highly mix- and material-dependent [11]. Additionally, nothing is known about how self-curing chemicals interact with fibers, chemical admixtures, and supplemental cementitious materials (SCMs). Furthermore, the majority of current research places a higher priority on compressive strength than on tensile strength, flexural capacity, and practical durability under service conditions. Hence, the current challenge is less the absence of any reported dosages, and more the lack of a universally adopted, field-ready dosage design procedure that accounts for material variability, mixture proportions, and placement/curing conditions [12].

Lightweight aggregates (LWA), superabsorbent polymers (SAPS), and water-retaining admixtures like polyethylene glycol (PEG) are the three broad categories into which self-curing materials fall. Water is absorbed by LWAs in their porous structure and subsequently released as the internal relative humidity of concrete decreases [13] Because SAPS are made of cross-linked polymers, they have the capacity to hold 100–500 times their weight in water, which is then released after hydration due to capillary tension [14],[15].In contrast, PEG-based admixtures minimize water loss during the early stages of hydration by lowering the surface tension of water and creating a protective barrier around cement particles [16]. The goal of all self-curing agents is to maintain constant internal water availability during the hydration cycle, even though each one functions differently. Cement chemistry, water-to-cement ratio, and targeted performance measures all have a role in choosing an appropriate agent [17]. Numerous experimental investigations demonstrate how successful self-curing is. After seven days of air exposure, concrete with SAPS maintained above 90% IRH, according to [18]. This resulted in a 15–20% increase in compressive strength over specimens that were externally cured. Additionally, [19] showed improved mechanical and durability properties in mortar treated with PEG and subjected to high curing temperatures.

Conducted more research and found that the best PEG dosages ranged from 0.5% to 1.0% by cement weight, which significantly reduced shrinkage and preserved strength. Long-term durability and shrinkage resistance were greatly improved by SAPS in the 0.2–0.4% range [20, 21]. Additionally, by decreasing permeability and chloride penetration, these compounds helped improve the pore structure [22]. In mortar matrices, internal curing procedures have also been shown to enhance bond strength, reduce early-age cracking, and promote early strength growth [23].

Superabsorbent polymers (SAPS), which are often made from cross-linked sodium polyacrylate or acrylamide, have the unique capacity to swell because they contain functional groups like amide and carboxylate. SAPS, which usually take the form of white beads or granules, are very useful in internal curing systems for concrete since they can hold 500 times the weight of water. By promoting continuous hydration and reducing autogenous shrinkage, the slow release of this stored water enhances the qualities of early-age concrete. SAPS are ideal for shrinkage mitigation applications despite having low mechanical reinforcement qualities and limited thermal resilience (around 150°C) because of their low density [23].

Materials based on polyethylene glycol, such as PEGL (liquid) and PEGP (powder), also function as internal curing agents; however, their molecular weights and physical characteristics vary greatly. PEGL, a viscous liquid with a low molecular weight (200–600 g/mol), is perfect for improving workability because it is completely miscible in water and improves flow characteristics through its plasticizing impact. PEGP, on the other hand, is a solid crystalline material that has a molecular weight that is often greater than 1000 g/mol. It helps to increase internal densification and control over the rheology of mixtures. Both PEG variations have ether and hydroxyl groups that work well with cementitious systems to promote hydration and improve the microstructure. Their high thermal stability (~200°C) ensures safe incorporation under typical curing and mixing conditions. Overall, SAPS provides superior moisture retention for shrinkage control, while PEGL and PEGP contribute to workability and fluidity management, with PEGP also enhancing the packing and consistency of the fresh mix [24,25].

Although several studies have reported the use of internal curing agents in cementitious systems, most of them focus on a single material, limited dosage ranges, or only one curing condition. In addition, previous studies have shown the potential of SAPS- and PEG-based internal curing, the recent literature indicates that important issues remain unresolved, particularly dosage sensitivity, the balance between hydration enhancement and SAPS-induced void formation, and the long-term implications for durability and transport behavior. Recent reviews and studies also show that comparative experimental evidence across different self-curing agents under identical mix conditions and multiple curing regimes is still limited. Therefore, the present work fills this gap by directly comparing SAPS, PEGL, and PEGP at multiple dosages in M30 concrete under full water curing, full air curing, and alternate air–water curing. The novelty of this study lies in integrating mechanical, durability, and SEM-based microstructural assessments within a single framework to identify optimum self-curing strategies for practical applications where external curing is inadequate.

This research provides a direct and systematic comparison of three self-curing approaches—SAPS, PEGL, and PEGP—at multiple dosage levels within the same concrete grade and constant w/c ratio, thereby minimizing confounding effects and enabling an objective evaluation of agent efficiency. Unlike many studies that focus on a single agent or a single curing condition, the present work quantifies performance under complete water curing, complete air curing, and combined air–water curing, reflecting both ideal and field-limited curing scenarios. The study further links compressive-strength development (28 and 56 days) with key durability indicators (water absorption, sorptivity, and RCPT) and validates the observed trends using SEM-based microstructural evidence. Collectively, the outcomes identify optimum dosage ranges for each agent and provide practical guidance for selecting self-curing strategies where external curing is insufficient or inconsistent. The key advancement of the present study is the establishment of a consistent comparative framework for evaluating SAPS, PEGL, and PEGP under multiple curing regimes, thereby clarifying their relative performance, optimum dosage, and practical significance for internal curing of concrete.

2. Materials and Methods

2.1. Binders

The study incorporates a range of raw materials and admixtures, selected based on standards and their established use in cementitious systems. Ordinary Portland Cement (OPC) of 53-grade conforming to IS: 269-2015 was used throughout the study. The cement had a specific gravity of 3.15 and met the required fineness and standard consistency criteria. The chemical composition primarily included CaO (63.2%), SiO_2 (20.4%), Al_2O_3 (4.5%), and Fe_2O_3 (3.5%), as confirmed by XRF analysis, ensuring its suitability for structural applications. Natural river sand, confirming to

Zone II of IS:383-2016, was used as fine aggregate, with a specific gravity of 2.65 and fineness modulus of 2.78. Crushed granite aggregates of nominal size 20 mm, with a specific gravity of 2.70 and water absorption of 0.5%, were used as coarse aggregate. Both fine and coarse aggregates properties were shown in Table 1. Potable tap water, free from suspended particles, oils, and organic matter, was used for mixing and curing. The water complied with IS:456-2000 recommendations for use in concrete.

Table 1. Fine/coarse aggregate sieve analysis

Fine Aggregate			Coarse Aggregates – 20down		
IS Sieve Size	IS Limit % IS 383-2016	Sieve analysis %	IS Sieve Size	IS Limit %	Sieve analysis %
10	100	100	40	100	100
4.75	90-100	95.5	20	90-100	95
2.36	75-100	84.5	10	25-55	30
1.18	55-90	66	4.75	0-10	1
600	35-59	44			
300	8-30	20			
150 Mic	0-10	5.5			
75 Mic		2			

2.2. Self-Curing Agents (SCA)

The superabsorbent polymer used in this study (denoted as SAPS) is a cross-linked sodium polyacrylate / poly(acrylate-co-acrylamide)–based hydrogel supplied in granular form (particle size: 100–300 μm). The absorption capacity of SAPS was about 300–500 times its dry weight in distilled water. SAPS was added as a partial replacement of water at 0.1%, 0.2%, 0.3%, and 0.4% by weight of cement. SAPS acts as an internal reservoir, releasing water slowly to mitigate autogenous shrinkage and enhance hydration.

Table 2. Chemical composition and functional properties of curing agents

Property	SAPS (Super Absorbent Polymer)	PEGL (Polyethylene Glycol - Liquid)	PEGP (Polyethylene Glycol - Powder)
Chemical Nature	Cross-linked sodium polyacrylate / acrylamide	Polyethylene glycol (PEG)	Polyethylene glycol (PEG)
Chemical Formula	$-[CH_2-CH(COONa)]-$ or $-[CH_2-CH(CONH_2)]-$	$H-(O-CH_2-CH_2)\_n-OH$	$H-(O-CH_2-CH_2)\_n-OH$
Physical Form	White granular powder / beads	Clear viscous liquid	White crystalline powder
Functional Groups	Carboxylate (-COONa), Amide (-CONH$_2$)	Hydroxyl (-OH), Ether (-O-)	Hydroxyl (-OH), Ether (-O-)
pH (5% solution)	6.0–7.5	5.0–7.0	5.0–7.0
Solubility in Water	Swells 100–500 times its weight	Fully soluble	Fully soluble
Swelling Capacity	Very high (up to 300–500 g/g)	N/A	N/A
Molecular Weight (g/mol)	High (crosslinked, not fixed)	Typically 200–600	Typically >1000 (solid form)
Density	~0.4–0.8 g/cm^3 (dry)	~1.12–1.13 g/cm^3	~1.2 g/cm^3
Melting/Boiling Point	Decomposes before melting	>200°C (boiling point varies)	~60–65°C (melting point varies)
Thermal Stability	Stable up to ~150°C	Stable up to ~200°C	Stable up to ~200°C
Usage in Concrete	Internal curing, reduces autogenous shrinkage	Internal curing, plasticizer-like behavior	Internal curing, improved workability

The polymer network is produced via radical polymerization with multifunctional crosslinking to generate an insoluble, swellable structure [26, 27]. PEGs were dosed at 0.25%, 0.5%, 0.75%, 1.0%, and 1.25% by weight of cement. PEG functions as a water-retaining chemical admixture, forming a temporary film around cement grains and delaying evaporation without disrupting hydration [28,16].

The three internal curing agents—SAPS, PEGL, and PEGP—differ significantly in their chemical nature, molecular structure, and physical behavior, which in turn influences their functionality in cementitious systems are shown in Table 2.The dosage ranges of SAPS (0.1–0.4% by cement mass) and PEG-based agents (PEGL/PEGP: 0.25–1.25%) are intentionally different because these materials do not function through the same mechanism and therefore do not have the same effective dosage scale.

2.3. Concrete Mix Design and Mix Combinations

The control mix was designed for M30 grade concrete as per IS:10262-2019, targeting a characteristic compressive strength of 30 MPa at 28 days. A constant water-to-cement ratio (w/c) of 0.4 was maintained across all mixes to ensure comparability. The following proportions were used (per m^3 of concrete): Fifteen mixes were prepared likely One control mix without self-curing agents, Four mixes with SAPS (0.1%, 0.2%, 0.3%, 0.4%), Five mixes with PEG Liquid (0.25% to 1.25%), Five mixes with PEG Powder (0.25% to 1.25%) respectively.

The dosage levels of SAPS, PEGL, and PEGP were selected to cover a practical range of low, medium, and higher contents so that the effect of dosage variation on internal curing performance could be evaluated systematically. The selected ranges were guided by previous literature on self-curing materials and were intended to identify the optimum dosage for each material under identical mix and curing conditions. This approach also enabled assessment of both the beneficial effects of internal moisture retention and the possible adverse effects associated with excessive dosage. The selected dosage levels were chosen based on ranges commonly reported in previous studies and were structured to identify the optimum performance window of each self-curing material through a systematic comparative evaluation.

This research investigates the influence of self-curing agents (SCA) on the plastic, mechanical and durability properties of M30 grade concrete with varying dosage of SCA under three curing regimes. A detail of various concrete performance evaluation tests done under different curing regimes are tabulated in Table 2. Fifteen concrete mixes were prepared, including the control mix. Each mix incorporated a specified dosage of SCA expressed as a percentage of cement weight. Table 3 and 4 presents the mix designations and binder compositions.

Table 3. Details of properties of concrete evaluated

Mix ID	Binder Composition	Description
Control	OPC 53 only	Conventional reference mix
SAPS 0.1	OPC 53 + 0.1 % SAPS	Self-curing with 0.1 % SAPS
SAPS 0.2	OPC 53 + 0.2 % SAPS	Self-curing with 0.2 % SAPS
SAPS 0.3	OPC 53 + 0.3 % SAPS	Self-curing with 0.3 % SAPS
SAPS 0.4	OPC 53 + 0.4 % SAPS	Self-curing with 0.4 % SAPS
PEGL 0.25	OPC 53 + 0.25 % PEGL	Self-curing with 0.25 % PEGL
PEGL 0.5	OPC 53 + 0.5 % PEGL	Self-curing with 0.5 % PEGL
PEGL 0.75	OPC 53 + 0.75 % PEGL	Self-curing with 0.75 % PEGL
PEGL 1.0	OPC 53 + 1.0 % PEGL	Self-curing with 1.0 % PEGL
PEGL 1.25	OPC 53 + 1.25 % PEGL	Self-curing with 1.25 % PEGL
PEGP 0.25	OPC 53 + 0.25 % PEGP	Self-curing with 0.25 % PEGP
PEGP 0.5	OPC 53 + 0.5 % PEGP	Self-curing with 0.5 % PEGP
PEGP 0.75	OPC 53 + 0.75 % PEGP	Self-curing with 0.75 % PEGP
PEGP 1.0	OPC 53 + 1.0 % PEGP	Self-curing with 1.0 % PEGP
PEGP 1.25	OPC 53 + 1.25 % PEGP	Self-curing with 1.25 % PEGP

Table 4. Mix design of M30 grade of concrete

Constituent	Quantities Kg/ M^3	Remarks
Cement	360	
Fine Aggregates	740	
Coarse Aggregates	1120	50 :50 (20 mm :10 mm)
Water	160	Free water
Super Plasticizer (0.55 %)	2	
SAPS - (0.3 %)	1	Added dry – pre soaked
W/C	0.44	Free W/C

For the SAPS-modified mixture, the SAPS was incorporated in dry form with pre-soaking. The additional water required for SAPS compensation was calculated from the absorption capacity of SAPS and the mass of SAPS added to the mix. The compensation water was determined using Eq. (1,2,3);

$$Wadd=ASAPS\times MSAPS \tag{1}$$

$$Wadd=40\times 1.0 \tag{2}$$

$$Wadd=40kg/m^3\approx 40L/m^3 \tag{3}$$

Where, Wadd is the additional SAPS-compensation water, ASAPS is the SAPS absorption capacity, and MSAPS is the SAPS dosage. When SAP is incorporated in concrete, it absorbs a portion of the mixing water during batching, which reduces free water and leads to slump loss. In various trials, the slump loss test indicated that 40 L/m^3 extra water was required to bring workability back to the same level as the control mix. This additional water is not part of the effective w/b ratio; it remains stored inside the SAP particles as internal curing water. As hydration proceeds, the SAP gradually releases this water to replenish pores that would otherwise self-desiccate, mitigating autogenous shrinkage and microcracking in low w/b mixes. Because the water is initially immobilized within SAP and does not increase capillary porosity at early ages, it does not reduce compressive strength. The key is that SAP dosage and its absorption capacity are matched so the 40 L/m^3 is fully entrained for curing, not excess free water. Determined by slump loss testing, this approach follows RILEM TC 225-SAP guidance: adjust total water to maintain workability while keeping the effective w/b unchanged. Properly dosed, the internal curing water improves long-term hydration and durability without strength penalty. The experimental plan covered the evaluation of fresh, mechanical, and durability characteristics of concrete under different curing regimes. The scope of testing is summarized in Table 5.

Table 5. Experimental program of M30 blended concrete

Property Category	Test Conducted	Testing Age (days)	Curing Regimes Applied
Fresh properties	Slump test	0	—
Mechanical properties	Compressive strength	3, 7, 14, 28, 56	Water, Air, Alternate
	Split tensile strength	28, 56	Water, Air, Alternate
	Flexural strength	28, 56	Water, Air, Alternate
Durability properties	Water absorption	28	Water, Air
	Sorptivity	28	Water, Air
	RCPT	28	Water, Air

2.4. Concrete Specimens Casting and Strength Testing

Dry mixing of cement, fine, and coarse aggregates was carried out for 2 minutes in a pan mixer. SAPS was pre-saturated for 30 minutes before adding to the mix to avoid excessive water absorption during mixing. PEGs were dissolved in the mixing water prior to use. Wet mixing continued for an additional 3 minutes to ensure homogeneity. Slump tests were conducted immediately after mixing to assess workability as per IS:1199 (Part 2) - 2018. Conventional Curing:

Specimens were submerged in water for 28 days and 56 days. The internal curing agents (SAPS, PEGL, PEGP) maintained internal relative humidity throughout the hydration period. For each mix, cubes (150×150×150 mm), cylinders (150×300 mm), and beams (100×100×500 mm) were cast for various strength and durability tests. Specimens were demolded after 24 hours and subjected to respective curing conditions. The strength characteristics of concrete are primary indicators of its structural performance. Compressive Strength of the concrete was measured on 150 mm cubes at 3, 7, 14, 28, and 56 days as per IS: 516 (Part 1) (Sec 1) - 2021. Split Tensile Strength of concrete was assessed at 28-days on 150 mm diameter cylinders and flexural strength was measured at 28-days on 150 mm beams as per IS: 516 (Part 1) (Sec 1) – 2021. For each mix combination and each test condition, three specimens (n = 3) were cast and tested in accordance with the relevant code provisions. The reported results represent the average value of three specimens, and the variability of the measurements is indicated by the error bars in the corresponding figures.

2.5. Durability Tests of Concrete

Durability assessments focused on properties influencing long-term service life. Water Absorption of concrete specimens is measured as per ASTM C642, Sorptivity properties of concrete specimen were measured as per ASTM C1585, Rapid Chloride Penetration Test (RCPT) was conducted as per ASTM C1202. RCPT was performed in accordance with ASTM C1202 on 50 mm thick, 100 mm diameter concrete discs prepared from cylindrical specimens at 28 days for both curing conditions (water curing and air curing). Prior to testing, discs were conditioned using the ASTM vacuum-saturation procedure: specimens were placed under vacuum for 3 h, then saturated with de-aired water, followed by soaking for 18 ± 2 h to ensure full saturation. The test cell contained 3.0% NaCl solution on one side and 0.3 N NaOH solution on the other side, and a constant potential difference of 60 V DC was applied for a total duration of 6 h. Current readings were recorded at regular intervals (every 30 min) and the total charge passed was calculated and reported in coulombs (C). For interpretation, coulomb values were additionally related to the ASTM C1202 chloride ion penetrability categories (e.g., high, moderate, low, very low, negligible), while the tabulated results are presented primarily as total coulombs.

2.6. Microstructural Analysis of Concrete

To assess the internal structure and hydration behavior of self-cured cementitious matrices, a small number of selected specimens were examined using scanning electron microscopy (SEM). After being shattered to reveal their natural internal surfaces and exposed to ethanol exchange to cease hydration, samples were vacuum-dried after a 28-day curing period. Following their mounting on aluminum stubs using conductive carbon tape, the dried specimens were coated with a thin layer of gold-palladium to increase conductivity. SEM imaging employed accelerating voltages between 10 and 20 kV. The analysis focused on identifying calcium silicate hydrate (C-S-H) gels, calcium hydroxide (CH) crystals, unhydrated cement particles, microcracks, and pore structure, particularly near self-curing agents.

3. Results and Discussion

3.1. Physical and Chemical Properties Analysis

The physical assessment of the binder mixes revealed noticeable variations in bulk density, specific gravity, and fineness modulus due to the inclusion of internal curing agents such as Superabsorbent Polymer (SAPS), Polyethylene Glycol in liquid form (PEGL), and its powdered variant (PEGP). These parameters play a crucial role in determining the concrete’s workability, compaction quality, and strength development. Compared to the control mix (OPC with a specific gravity of 2.65), most modified mixes exhibited slightly higher specific gravity values, implying a denser and more compact matrix. Notably, SAPS 0.3, PEGL 1.0, and PEGP 1.0 displayed superior results with values of 2.68, 2.68, and 2.70, respectively, indicating enhanced particle packing and reduced void content. The fineness modulus also increased in several modified mixes, suggesting a coarser yet more cohesive particle distribution beneficial for paste stability and flow. While SAPS 0.3 and PEGL 1.0 exhibited moderate fineness (2.68 and 2.64), PEGP 1.0 achieved a slightly higher value (2.93), reflecting improved particle interlock and internal structure formation. Bulk density values remained close to the control (1560 kg/m^3), with PEGL 1.0 and PEGP 1.0 recording 1527 and 1526 kg/m^3, respectively. Although SAPS 0.3 had a marginally lower density (1478 kg/m^3), its balanced fineness and density characteristics make it a stable option for optimized internal curing performance.

The chemical analysis of the Ordinary Portland Cement (OPC) used in this study reveals that calcium oxide (CaO) is the predominant constituent, accounting for approximately 62.32% of the total composition. This high calcium content contributes significantly to the development of strength-bearing compounds such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S) during hydration. The presence of silicon dioxide (SiO_2) at 21.41% plays a crucial role in forming these silicate phases, which are primarily responsible for long-term strength gain. Minor constituents such as aluminum oxide (Al_2O_3) and ferric oxide (Fe_2O_3), present at 5.54% and 4.47%, respectively, enhance the formation of aluminate and ferrite phases, improving early-age reactions and setting characteristics. Magnesium oxide (MgO) is observed at 1.23%, a permissible level that aids in densifying the matrix without causing expansion issues. The measured SO_3 content of 2.83% ensures adequate regulation of setting time, while the loss on ignition (1.05%) indicates minimal unburnt residues and moisture content, confirming the cement's high quality. Alkalis such as K_2O and Na_2O were found negligible, implying reduced risk of alkali–silica reactivity in concrete applications. Overall, the composition demonstrates that the OPC conforms well to the chemical requirements for structural concretes with reliable strength and durability performance.

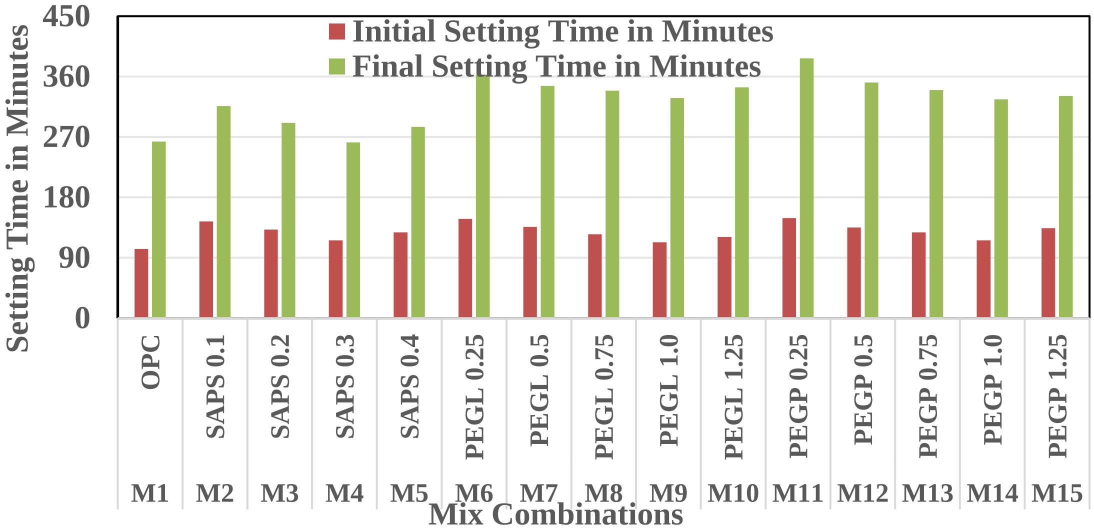
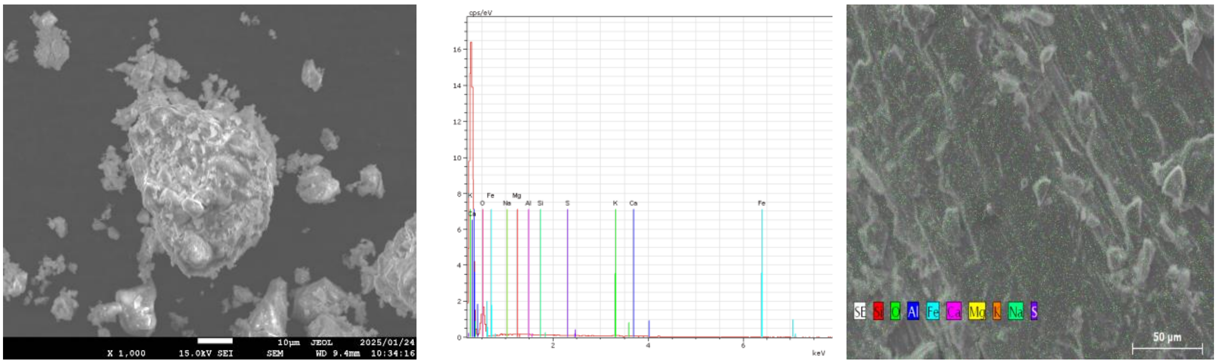


Fig. 1. Initial and final setting times of OPC paste incorporating different self-curing agents (SAPS, PEGL, and PEGP) at the investigated dosages

In the present study, the "plasticizing" role of PEG (PEGL/PEGP) is inferred from the fresh-property response at a constant w/c ratio, where mixes containing PEG maintained/improved workability relative to the control Fig.1 and exhibited a measurable change in setting-time behavior Fig.1. These observations are consistent with PEG's ability to improve particle dispersion and reduce inter-particle friction, which can manifest as improved flowability and/or altered setting kinetics. Regarding the "film-forming" description, this work does not directly measure polymer-film thickness or continuity.

3.2. SEM Analysis of Control Concrete Mix and SCA

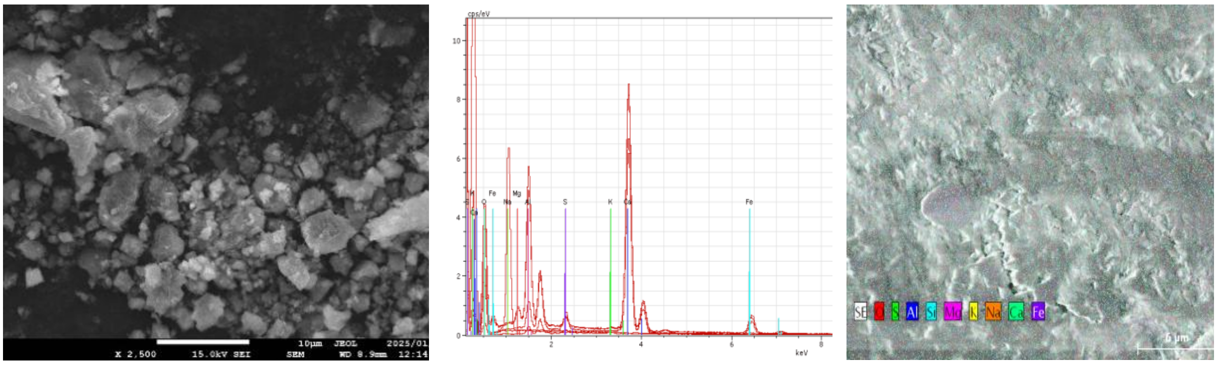
The SEM micrograph of Control mix at 10 μm magnification reveals an irregular morphology characterized by angular, flaky, and fractured particles are shown in Figure 2. The surface texture appears dense and heterogeneous with a combination of fine and coarse grains. These irregularly shaped particles are indicative of clinker-based production, where grinding processes influence the final size and morphology. The relatively rough surfaces and diverse particle sizes enhance the reactivity of cement during hydration by increasing the specific surface area. primarily indicates differences in microstructural compactness and pore features among the mixes rather than providing direct proof of specific hydration phases.



SEM Analysis of Control sample at 10 µ

EDX Analysis of Control sample

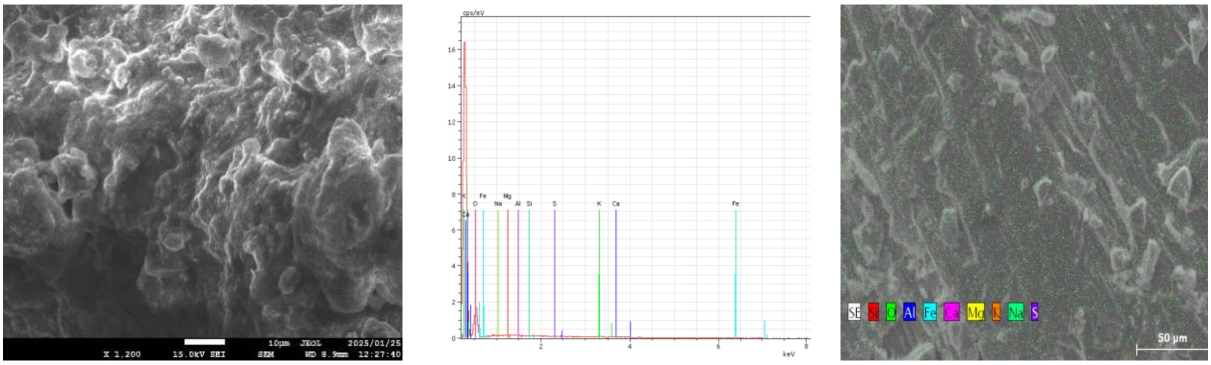
EDS elemental map of Control sample



SEM Analysis of SAPS sample at 10 µ

EDX Analysis of SAPS sample

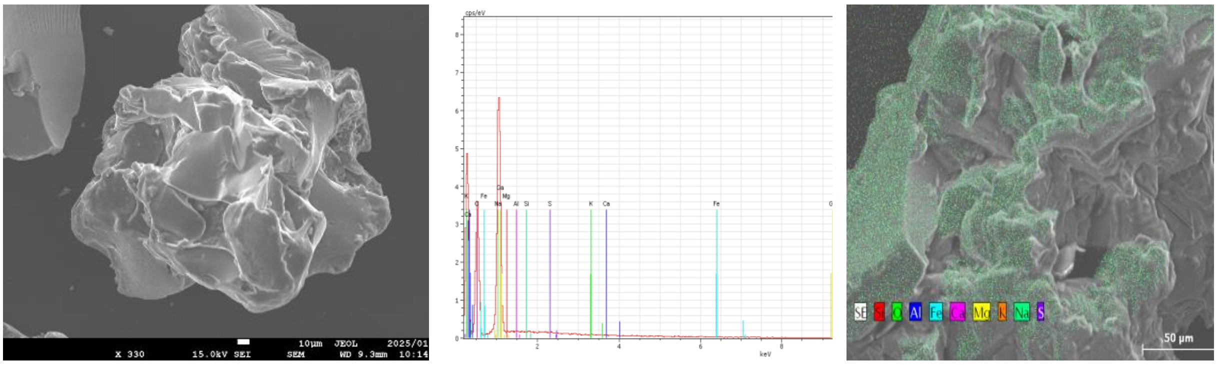
EDS elemental map of SAPS sample



SEM Analysis of PEGL sample at 10 µ

EDX Analysis of PEGL sample

EDS elemental map of PEGL sample



SEM Analysis of PEGP sample at 10 µ

EDX Analysis of PEGP sample

EDS elemental map of PEGP sample

Fig. 2. SEM and EDX analysis of control concrete mix, curing agents

Compared with the control, the optimum self-curing mixes show a denser and more continuous matrix with fewer visible connected pore features, which is consistent with the observed reductions in transport-related durability indices and improved strength retention under limited curing [29]. The SAPS sample exhibits a porous, sponge-like microstructure under SEM at 10 µm resolution. Compared to Control, the SAPS particles are more round and lighter in structure, often forming aggregates with visible interparticle voids. The highly porous morphology suggests its effectiveness in moisture retention, making it suitable for internal curing applications. The presence of microchannels and pores also facilitates slow water release, supporting prolonged hydration in cementitious systems.

PEGL, in its dried or processed form for SEM, displays smooth, globular morphology with relatively low surface roughness. The structure lacks the granularity observed in Control and SAPS. Instead, the micrograph highlights a waxy or film-like coating over a substrate, often interpreted as the residue from a viscous polymer. The compact appearance and absence of distinct crystalline or angular particles imply its polymeric, amorphous nature. Such smooth films suggest the material's ability to coat cement particles, potentially reducing evaporation and improving self-curing effects.

In contrast to its liquid counterpart, PEGP shows a more crystalline and granular structure in the SEM images. The particles are irregularly shaped but more defined compared to PEGL. PEGP appears as compact clusters of fine powder with less porosity than SAPS and more textural contrast than PEGL. The crystalline nature of PEGP may influence its dissolution and water interaction behavior during mixing, thereby contributing differently to internal curing dynamics.

3.3. Workability Characteristics of Concrete mixes with Different Curing Agent

The influence of internal curing agents on the workability of concrete mixes with varying SCA combinations is clear from variations in slump. Figure 3 shows the variation in slump values of various concrete mixes. The Control mix recorded a slump of 116 mm serving as the reference benchmark. Among the modified mixes, PEGL 1.0 (125 mm) and PEGL 0.25 (124 mm) exhibited the highest slump values, reflecting enhanced fluidity and ease of placement due to the liquid form of the polyethylene glycol, which may reduce internal friction and improve flow. SAPS 0.3 (119 mm) and PEGP 1.0 (118 mm) also demonstrated good slump performance, indicating favorable dispersion characteristics. These values suggest improved water retention and particle mobility, which are beneficial for pumpability and finish ability during construction. Drastic drop in slump is observed in the concrete mixes with SCA addition beyond threshold limit. The threshold limit for getting highest slump for the SAPS is 0.3%, and 1% for both the PEG admixture. Overall, SAPS 0.3, PEGL 1.0, and PEGP 1.0 offered the most desirable workability profiles—sufficiently flowable yet cohesive—making them well-suited for practical mixing and placing operations without segregation or excessive bleeding.

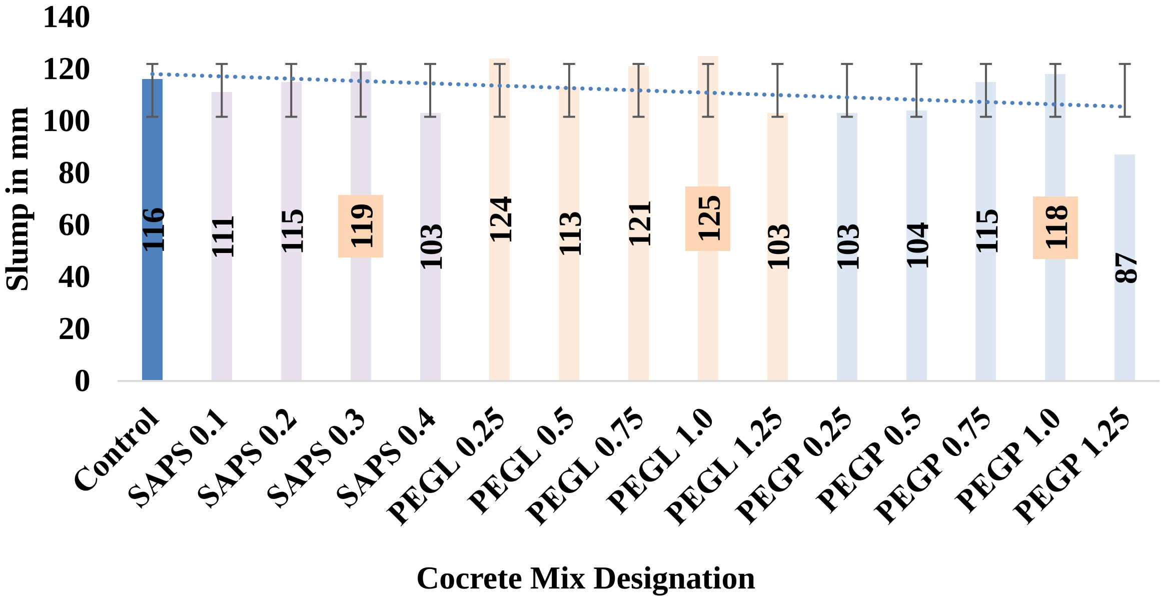


Fig. 3. Workability of fresh concrete mixes with different curing agents

3.4. Compressive Strength of Concrete Mixes with Different Dosages of Curing Agents Under Water Curing Regime

Figure 4 illustrates the compressive-strength development of the concrete mixes under complete water curing. In the revised interpretation, the plotted means and their error bars are considered together; therefore, the optimum mixes (particularly SAPS 0.3%, PEGL 1.0%, and PEGP 1.0%) are described as showing higher mean strength than the control, while claims of clear superiority are limited to trends that remain evident after considering the variability. The control mix achieved 36.7 MPa and 43.8 MPa at 28 and 56 days, respectively, whereas SAPS 0.3% recorded the highest mean value at 28 days (41.2 MPa). PEGL 1.0% and PEGP 1.0% also showed favorable strength development, but where the error-bar ranges are close, the results are interpreted as positive performance trends rather than absolute separation. In a similar context, polyethylene glycol powder (PEGP) at a dosage of 1.0% demonstrated compressive strengths of 39.6 MPa at 28 days and 43.9 MPa at 56 days. In comparison to the Control mix, these numbers represent an 8% rise at 28 days and a slight 0.09% improvement at 56 days. The steady increase in strength suggests that PEGP helps to maintain hydration and improve the concrete's long-term structural performance by encouraging workability and internal curing [30-33].

It is important to recognize the inherent tradeoff associated with SAPS-based internal curing. SAPS particles temporarily absorb part of the mixing water and subsequently release it as internal relative humidity decreases, which promotes continued hydration, refines the pore structure, and can improve later-age performance—particularly under limited external curing. However, once SAPS desorbs, the polymer shrinks and may leave macro voids (SAPS imprints) within the hardened matrix; these voids can act as stress concentrators and may reduce compressive strength when SAPS content is excessive, dispersion is non-uniform, or absorbed water is not properly accounted for during mixture proportioning.

All percentage improvements are now calculated relative to the Control mix under the same curing regime and at the same testing age. Thus, water-cured mixes are compared with the water-cured Control, air-cured mixes with the air-cured Control, and alternate-cured mixes with the corresponding alternate-cured Control. Where comparison is made with the Control mix under complete water curing, the term strength recovery ratio is used instead of percentage improvement. This distinction removes ambiguity and provides a clearer interpretation of the effect of internal curing agents under different curing conditions.

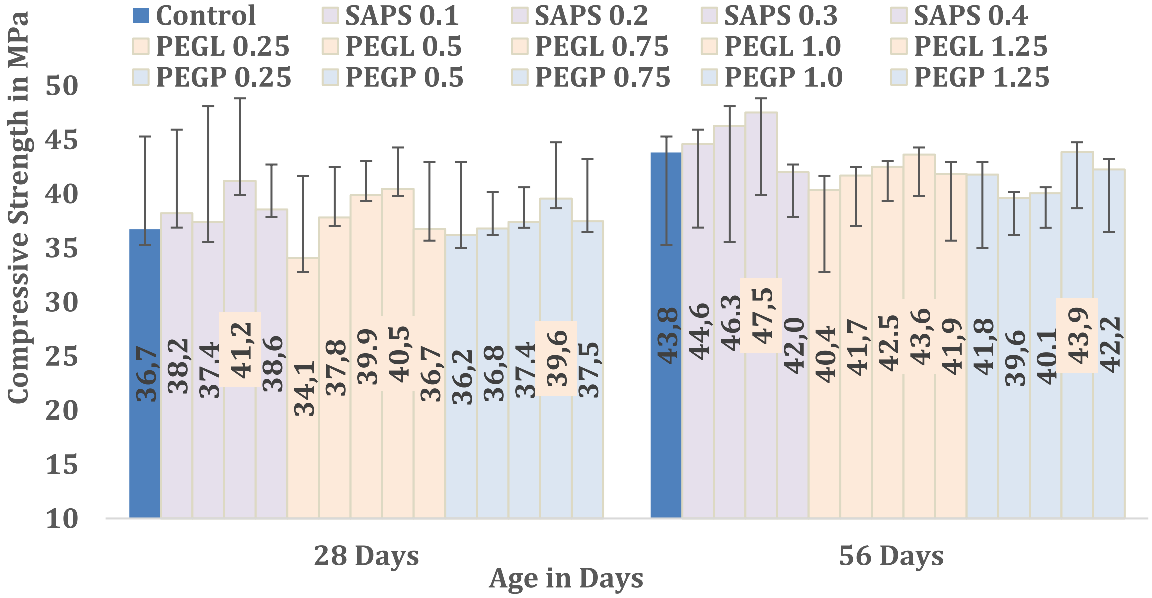


Fig. 4. 28-days and 56-days compressive strength of concrete mixes with different dosages of curing agents under water curing regime

These results demonstrate that SAPS 0.3 outperformed all other mixes, offering the most substantial improvement across all ages. PEGL 1.0 and PEGP 1.0 also showed competitive strength development, particularly at 28 days, supporting their use in enhancing mechanical performance. Therefore, the strategic use of these curing agents can offer a sustainable pathway to improve long-term concrete strength through enhanced internal hydration dynamics.

3.5. Compressive Strength of Concrete Mixes with Different Dosages of Curing Agents Under Air Curing

Air curing typically reduces strength development because of limited moisture availability; however, Figure 5 shows that the internally cured mixes maintained higher mean compressive strength than the corresponding control under air curing. The revised text has been aligned with the plotted error bars, and the interpretation now distinguishes between clear improvement and marginal difference. SAPS 0.3%, PEGL 1.0%, and PEGP 1.0% exhibited the most favorable average response at 28 and 56 days, indicating the beneficial effect of internal curing under moisture-deficient conditions, while smaller differences among some mixes are discussed more cautiously where the variability ranges overlap.

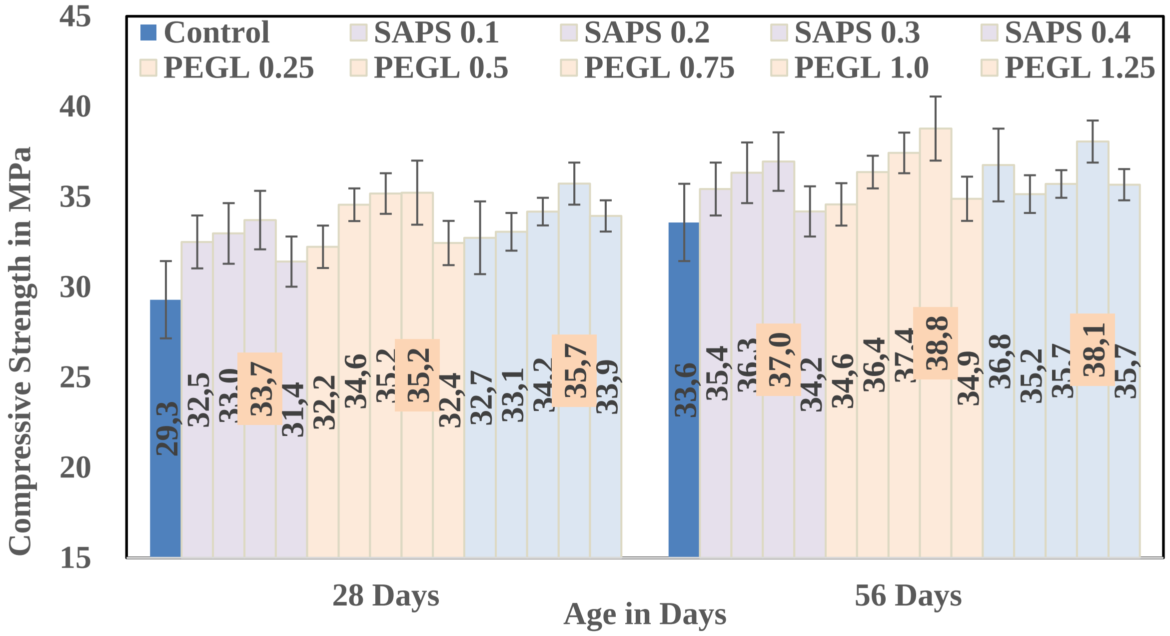


Fig. 5. 28-days and 56-days compressive strength of concrete mixes with different dosages of curing agents under air curing regime

Among the air-cured mixes, PEGP 1.0%, PEGL 1.0%, and SAPS 0.3% showed the highest mean compressive strengths. However, in the revised manuscript these rankings are interpreted together with the error bars rather than on mean values alone. Accordingly, the discussion now states that these mixes demonstrated the most favorable average performance under air curing but avoids overstatement where the variability ranges are comparable. These curing agents significantly reduce strength loss associated with air curing and outperform traditional Control mix, making them excellent candidates for environments with limited water availability or inadequate external curing conditions [36],[37]. The error-bar comparison indicates that the performance enhancement of SAPS 0.3%, PEGL 1.0%, and PEGP 1.0% is not merely numerical, but is supported by consistent replicate behavior. This strengthens the interpretation that internal curing mitigates the adverse influence of insufficient external moisture.

Fig.6 & 7 gives the comparison of compressive strength of concrete at 3, 7, 14, 28 and 56 days under complete water & air curing regime along with strength recovery of complete air cured concrete at various ages over that of Control mix under complete water curing regime at respective age.

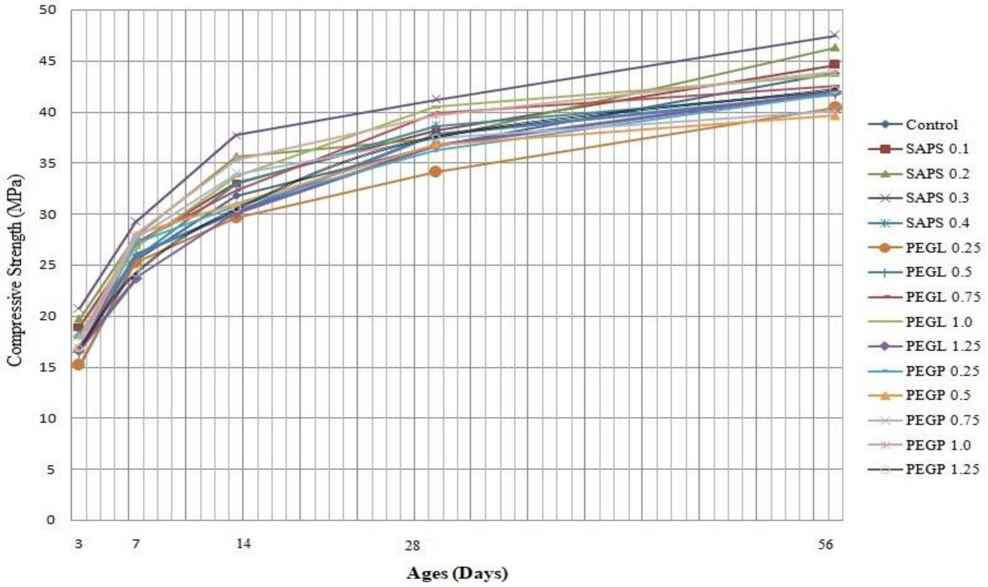


Fig. 6. Comparison of concrete compressive strength at different ages under water curing regimes

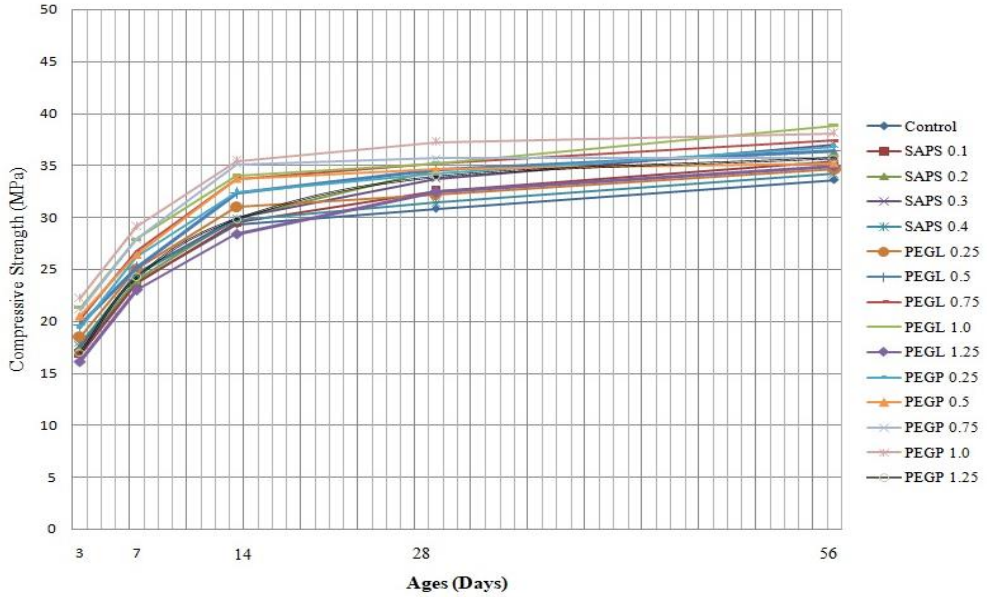
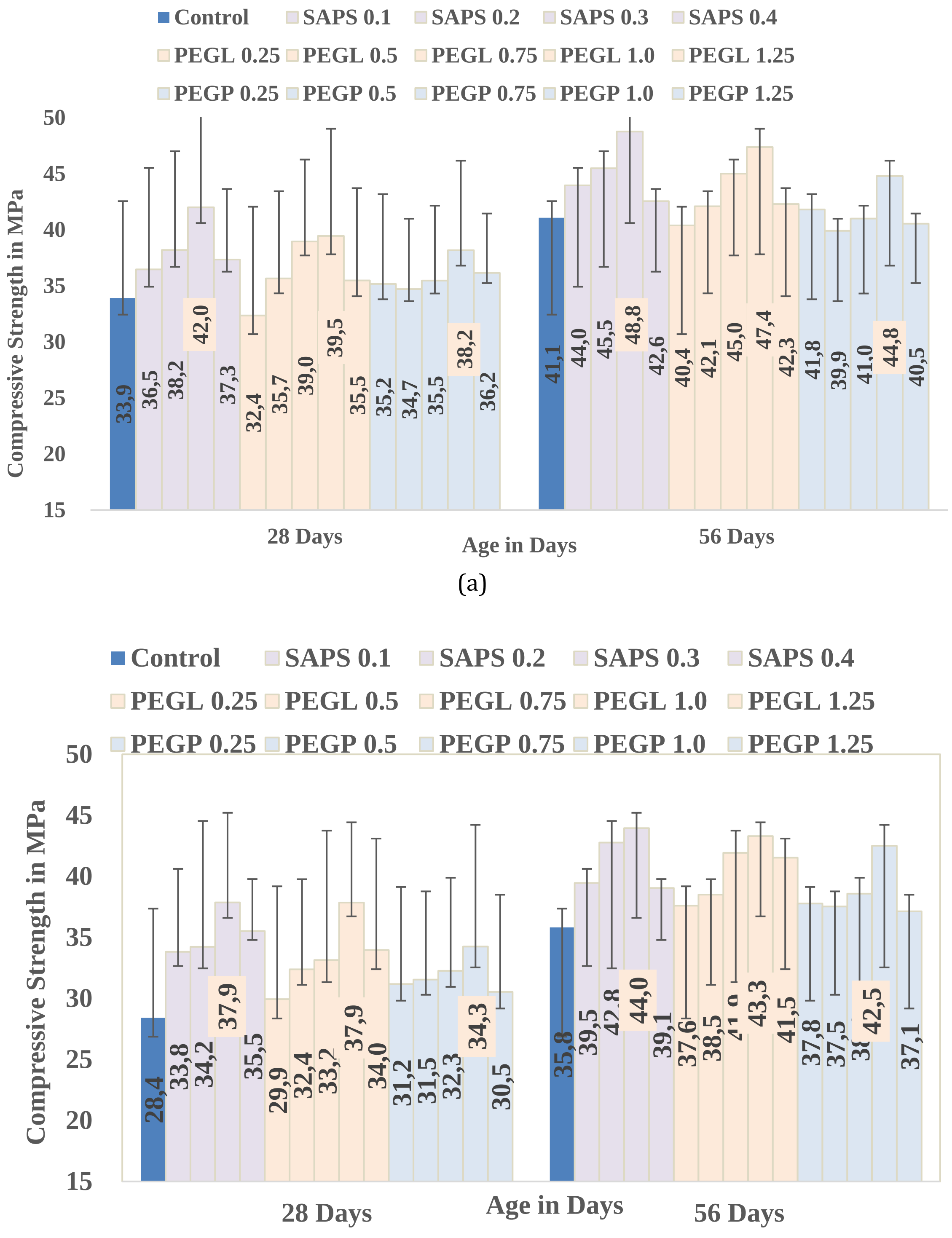


Fig. 7. Comparison of concrete compressive strength at different ages under air curing regimes

The strength improvement is evident with internal curing compounds – at SAPS of 0.3% with 92% recovery at 28 Days and 84% at 56 Days, PEGL 1% with 96% at 28 days and 88% at 56 Days and PEG Powder 1% the recovery is 97% at 28 Days and 87% at 56 Days over corresponding 28-days & 56-days strength of Control mix under complete water curing. These are the optimal dosage and higher recovery of strength for Air curing as compared to that of control mix under complete water curing regime. The corresponding strength recovery of control mix under complete air curing over that of control mix under complete water curing is only 80% at 28 days and 77% at 56 days; clearly indicating the benefits of using SCA when no water curing is done.

3.6. Compressive Strength of Concrete Mixes with Different Dosages of Curing Agents under Varying Air and Water Curing Regimes

The compressive strength performance of M30 grade concrete at 28 and 56 days under varying air & water curing conditions shows that the inclusion of internal curing agents substantially improves strength development compared to Control mix as shown in Figure 8a and 8b. For alternate curing, the 28-day control strengths are 33.9 MPa (7d air + 21d water), 41.1 MPa (7d air + 49d water), 28.4 MPa (7d water + 21d air), and 35.8 MPa (7d water + 49d air). The control mix achieved 28-days compressive strengths of 33.9 MPa, 41.1 MPa, 28.4 MPa, and 35.8 MPa under the following curing regimes: 7-day air + 21-day water, 7-day air + 49-day water, 7-day water + 21-day air, and 7-day water + 49-day air, respectively.



(a)

(b)

Fig. 8. 28-Days and 56-Days compressive strength of concrete mixes with different dosages of curing agents under 7-days air and 21/49-days (a) water curing regime (b) air curing regime

Among all mixes, SAPS 0.3 consistently outperformed Control mix in every condition. It reached 42 MPa in the 7-day air + 21-day water regime, which is about 24% higher than Control mix under same curing regime. Under prolonged water curing (7-day air + 49-day water), it achieved 48.8

MPa, marking a 19% gain over Control mix under same curing regime. Even with reduced curing (7-day water + 21-day air), SAPS 0.3 showed 37.9 MPa, about 33% higher, and under prolonged air curing, it reached 44.0 MPa—an increase of roughly 23% over Control mix under respective curing regimes. This illustrates SAPS 0.3's superior capacity for maintaining internal moisture and promoting extended hydration. In particular, SAPS 0.3% showed a consistently higher mean strength than the control under both early-air/late-water and early-water/late-air conditions. The error bars help demonstrate that these gains are associated with a systematic internal-curing effect rather than random specimen-to-specimen variation.

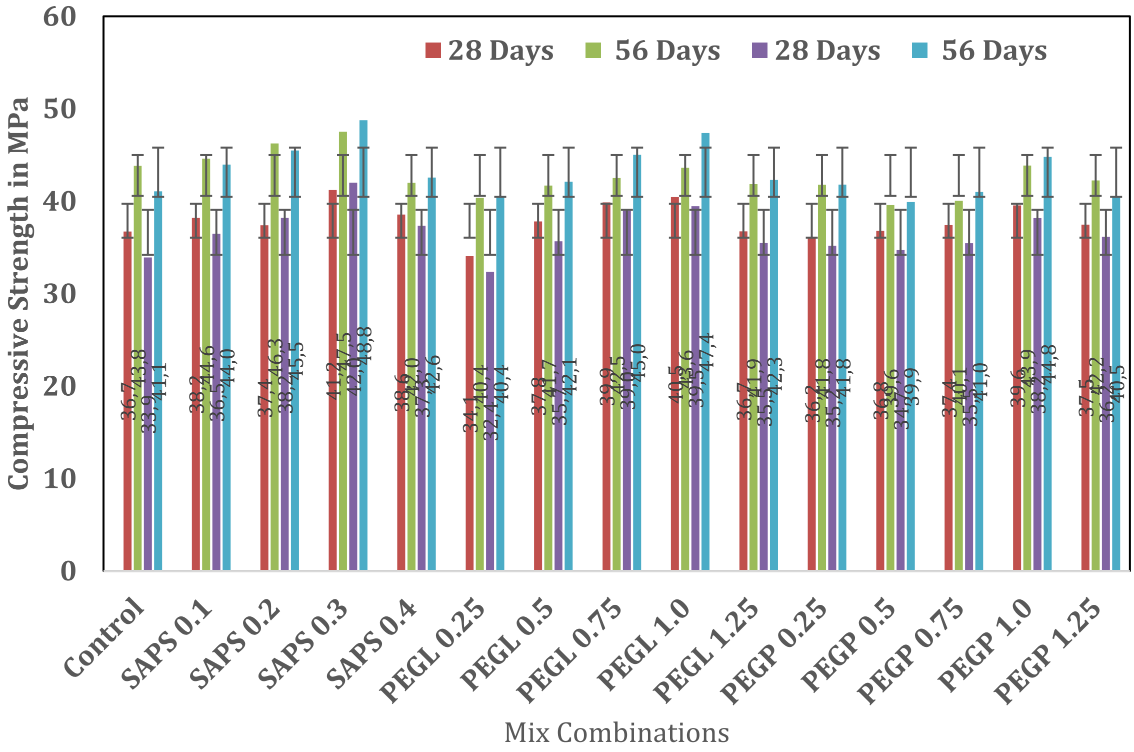


Fig. 9. Comparison of concrete compressive strength at different ages under complete water curing and 7-day air+21/49-day water curing

Figure 9 gives the Compressive strength of concrete at 3, 7, 14, 28 and 56 days under complete water & "7-days air plus 21/49-days water" curing regime along with strength recovery of 7-days air cured concrete at various ages over that of Control mix under complete water curing regime at respective age. Strength improvement is evident with internal curing compounds – at SAPS of 0.3% with 114% recovery at 28 Days and 111% at 56 Days, PEGL 1% with recovery 107% at 28 Days and 108% at 56 Days and PEG Powder 1% with recovery 104% at 28Days and 102% at 56 days are the optimal dosage and recovery of strength is higher at 7-days air curing and later water curing as compared to that of control mix under complete water curing regime. The corresponding strength recovery of control mix under complete air curing over that of control mix under complete water curing is only 92% at 28 days and 94% at 56 days: clearly indicating the benefits of using SCA under inadequate curing regime.

Fig.10 gives the Compressive strength of concrete at 3, 7, 14, 28 and 56 days under complete water & "7-days water plus 21/49-days air" curing regime along with strength recovery of 7-days air cured concrete at various ages over that of Control mix under complete water curing regime at respective age. Strength improvement is evident with internal curing compounds – at SAPS of 0.3% recovery 103% at 28 Days and 100% at 56 Days, PEGL 1% recovery 103% at 28 Days and 99% at 56 Days PEG Powder 1% recovery of 93% at 28 Days and 97% at 56 Days are the optimal dosage and recovery of strength is higher at Air curing as compared to that of control mix under complete water curing regime. The corresponding strength recovery of control mix under complete air curing over that of control mix under complete water curing is only 77% at 28 days and 82% at 56 days; clearly indicating the benefits of using SCA when no water curing is done. Consequently, SAPS dosage must be optimized so that the hydration benefit outweighs the potential void-induced strength penalty: at an optimum SAPS level the enhanced hydration and reduced microcracking can compensate for the presence of SAPS voids, whereas beyond the optimum the increased void volume can dominate and cause strength reduction.

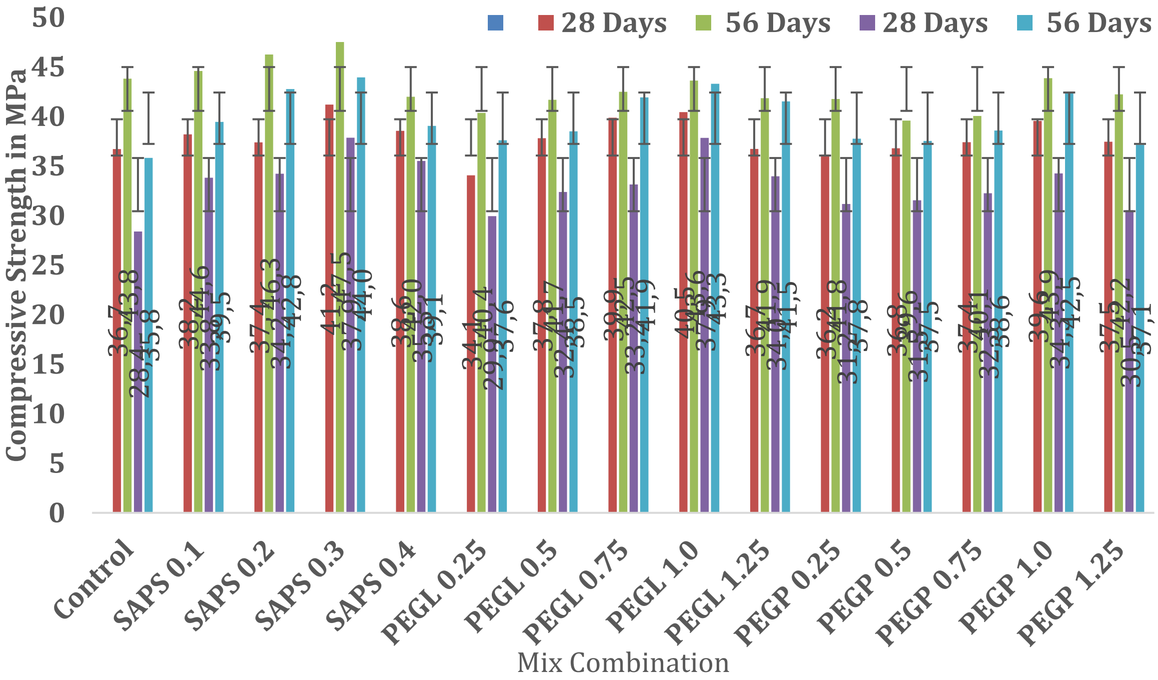


Fig.10. Comparison of concrete compressive strength at different ages under complete water curing and 7-day water+21/49-day air curing

3.7. Flexural and Split Tensile Strength of Concrete Mixes with different dosages of Curing Agents under 28-days of Water Curing Regime.

The flexural and split strength performance of M30 grade concrete at 28 days under complete water curing conditions shows that the inclusion of internal curing agents substantially improves strength development compared to Control mix as shown in Figure 11 and 12. The control mix achieved flexural strengths of 2.9 MPa at 28-days and 3.6 MPa at 56 days and split tensile strengths 2.5 MPa at 28 days and 3.2 MPa at 56 days. Among all mixes, PEGP 1.0 consistently outperformed Control mix in every condition. It reached flexural strength of 4.0 MPa at 28 day and 4.50 MPa at 56 days and a split tensile strength of 3.4 MPa at 28 day and 3.7 MPa at 56 days.

The flexural and split tensile results were also evaluated with variability measures. The optimum internal-curing dosages showed improved mean tensile-related performance compared with the control, while the standard deviations remained within an acceptable range for concrete testing. This suggests that the enhanced tensile response is associated with a more uniform hydration profile and reduced microcrack development, rather than being an artifact of experimental scatter alone.

In particular, the optimum dosages (SAPS 0.3%, PEGL 1.0%, PEGP 1.0%) produced the most consistent improvement, whereas higher dosages did not necessarily translate to proportional gains, indicating that there is an optimum internal curing demand beyond which benefits plateau. The flexural response is discussed relative to the control under each curing regime to isolate the curing effect, and the observed improvements are consistent with the denser microstructure identified in SEM. Split tensile strength is strongly influenced by crack initiation and propagation through the paste and ITZ, making it a useful indicator of curing effectiveness. The internally cured mixes demonstrated improved tensile response compared with the corresponding control because internal curing promotes a more uniform hydration profile and reduces drying gradients, thereby limiting microcrack formation. The improvement was more pronounced under air and alternate curing regimes, where external curing is insufficient and internal water release becomes more influential. The results suggest that internal curing primarily enhances tensile resistance by improving cohesion and reducing connectivity of microcracks, rather than by simply increasing compressive strength alone.

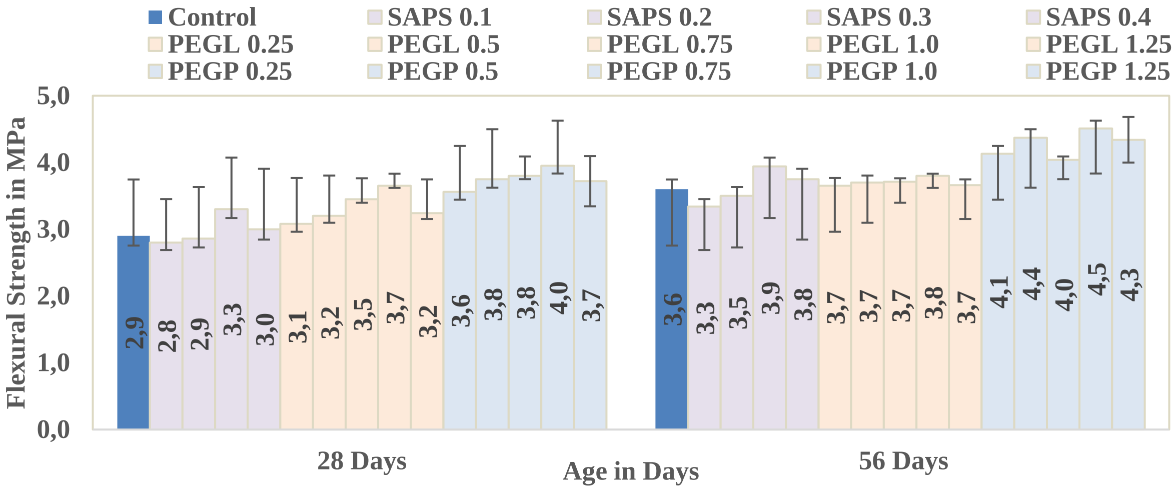


Fig. 11. 28-Days and 56-days flexural strength of concrete mixes with different dosages of curing agents under 28-days water curing regime

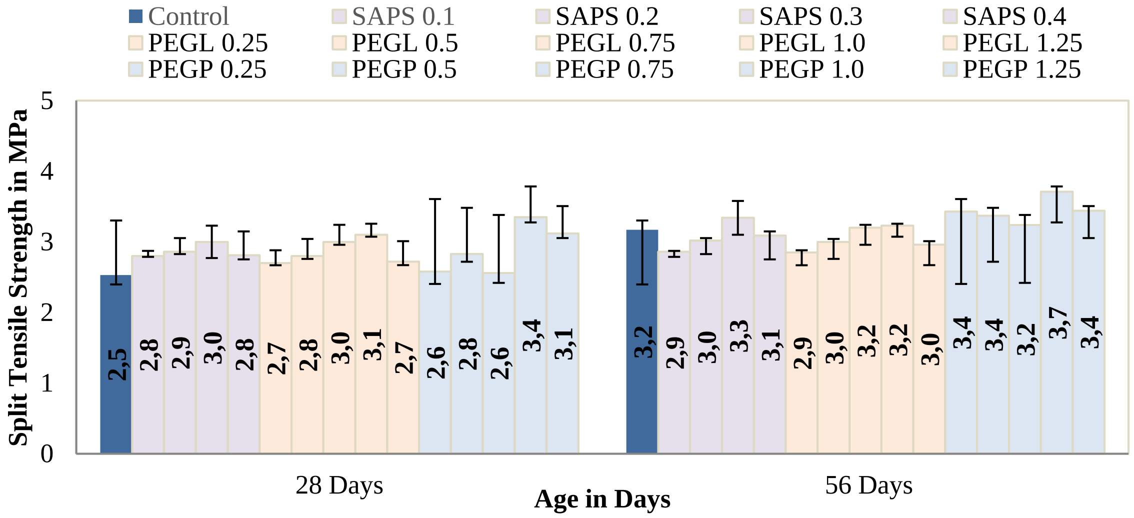


Fig. 12. 28 days and 56 days split tensile strength of concrete mixes with different dosages of curing agents under 28-days water curing regime

3.8. Durability Properties of Concrete Mixes with different dosages of Curing Agents

Rapid Chloride Penetration Test (RCPT) results are reported as the total charge passed (Coulombs) in accordance with ASTM C1202. The control mix showed 2426 C under complete water curing and 2110 C under complete air curing, which falls in the "Moderate" chloride-ion penetrability range (2000–4000 C). Key performance parameters such water absorption, sorptivity, and rapid chloride permeability (RCPT), as listed in Table 6, are crucial for assessing durability of concrete. [38] state that these indications offer a thorough understanding of the concrete's ability to withstand fluid ingress and chloride penetration, both of which have a direct impact on the material's long-term behavior under harsh environmental circumstances. Water absorption shows how susceptible the concrete matrix is to moisture intrusion and is a direct indicator of the interconnected pore network within it. Therefore, the RCPT trend is interpreted alongside transport-related indicators. Consistently, PEGP 1.0 also showed reduced water absorption (2.73%) compared with the control (5.17%) under water curing, supporting a denser pore network.

Table 6. Durability properties of concrete mixes with different dosages of curing agents

Mix Designation	Concrete Durability Properties at 28-days under Water Curing			Concrete Durability properties at 28-days under Air Curing		
	Water Absorption at 28 days (%)	Sorptivity (mm/min^0.5)	RCPT (Coulombs)	Water Absorption at 28 days (%)	Sorptivity (mm/min^0.5)	RCPT (Coulombs)
Control	5.17	0.196	2426	4.92	0.178	2110
SAPS 0.1	4.21	0.168	1776	4.01	0.16	1545
SAPS 0.2	4.57	0.25	1700	4.35	0.155	1400
SAPS 0.3	2.79	0.158	1330	2.66	0.143	1300
SAPS 0.4	3.87	0.319	2671	3.69	0.225	2323
PEGL 0.25	4.28	0.161	2029	4.08	0.146	1765
PEGL 0.5	2.94	0.239	2328	2.8	0.15	2025
PEGL 0.75	4.42	0.306	1649	4.21	0.12	1434
PEGL 1.0	2.58	0.099	1385	2.46	0.089	1205
PEGL 1.25	3.57	0.133	3147	3.4	0.121	2737
PEGP 0.25	4.22	0.32	2147	4.02	0.195	1867
PEGP 0.5	4.37	0.228	2419	4.16	0.15	2104
PEGP 0.75	3.72	0.205	2505	3.54	0.186	2179
PEGP 1.0	2.73	0.19	1578	2.6	0.17	1503
PEGP 1.25	4.69	0.253	1385	4.47	0.225	1205

The reduction in water absorption, sorptivity, and RCPT in the optimum self-curing mixes should be interpreted in terms of transport-path refinement rather than as isolated improvements. Internal curing maintains internal moisture, sustains hydration, reduces self-desiccation and drying-induced microcracking, and improves the ITZ, thereby lowering pore connectivity and increasing tortuosity of fluid-transport pathways. This mechanism explains why the optimum mixes showed simultaneous reductions in all three durability indicators. At the same time, SAPS-based systems require critical interpretation because desorbed SAPS particles may leave localized voids. At suitable dosage, the hydration and crack-control benefits outweigh the adverse effect of these voids; however, at excessive dosage the void effect may offset durability gains. This interpretation is consistent with recent literature reporting that SAPS improves durability through hydration continuity and crack mitigation, while also emphasizing the need to control pore formation associated with SAPS domains.

The durability performance is better with internal curing compounds under air cured regime in comparison to control concrete with SAPS at 0.3% has 46% lower water absorption, 20% lower Sorptivity, 45% lower RCPT, with PEGL at 1% has 50% lower water absorption, 20% lower Sorptivity, 45% lower RCPT, 40% lower sorptivity, 45% lower RCPT, with PEGP at 1 % has 40 % lower water absorption, 10% lower Sorptivity, 65% lower RCPT. The PEGP 1.0 mix recorded 1578 Coulombs under water curing. This value was rechecked and is retained as correct. Since the RCPT was conducted in accordance with ASTM C1202, including the standard vacuum-saturation procedure and 60 V DC for 6 h, the low value is considered to reflect the improved resistance of the optimum mix to ionic transport under the adopted test conditions. In the revised manuscript, this result is discussed together with water absorption, sorptivity, and SEM evidence, and is interpreted cautiously as an indication of very low charge passed, rather than as a stand-alone claim of equivalence to UHPC or silica-fume concrete.

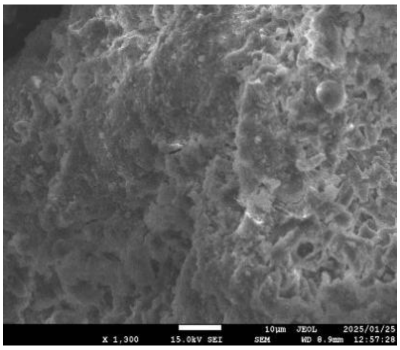
For the durability indices, the addition of error bars and variability measures improves the interpretation of water absorption, sorptivity, and RCPT results. The optimum self-curing mixes consistently yielded lower average transport-related values than the control, and the statistical spread remained sufficiently controlled to support the overall ranking of the mixes. These results indicate that the observed reduction in permeability-related properties is systematic and aligns with the microstructural densification identified in SEM observations.

Sorptivity, which reflects how easily moisture enters surface-connected pore networks, is a crucial indicator of water uptake in unsaturated concrete by capillary action. The results in Table-6 clearly show that addition of these compounds helps in the reduction of the sorptivity of the concrete. The optimal dosage of SAPS is 0.3% and that for PEGL and PEGP are 1%. Among the three types the PEGL at 1% dosage is giving the best sorptivity performance. Sorptivity reflects the rate of capillary water uptake and is sensitive to near-surface pore connectivity. Lower sorptivity values in the optimum self-curing mixes indicate reduced capillary continuity and improved resistance to moisture ingress. This outcome is consistent with improved hydration continuity and fewer connected pores, particularly under limited curing. Sorptivity trends complement water absorption by emphasizing transport kinetics rather than total absorbed water.

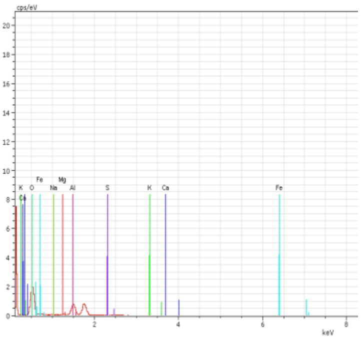
3.9. SEM Analysis of 28-day Aged Concrete Samples

Control mix concrete's SEM micrograph, which shows a heterogeneous microstructure with partial densification, is shown in Figure 13 following 28 days of curing. Unhydrated cement particles, scattered calcium hydroxide (CH) crystals, and calcium silicate hydrate (C–S–H) phases make up the matrix. Isolated voids exhibit needle-shaped ettringite structures, but a porous interfacial transition zone (ITZ) and visible microcracks indicate insufficient microstructural refinement. Conversely, the SEM analysis of concrete that has been treated with superabsorbent polymers (SAPS) reveals a microstructure that is noticeably denser and more uniform. Long-term internal curative activity made possible by SAPS is indicated by the decrease in visible pore gaps and the uniform distribution of hydration products. The matrix is dominated by well-formed C-S-H gel, which minimizes the production of microcracks and encapsulates previously unhydrated zones. Furthermore, it is clear that SAPS seems to encourage secondary hydration.

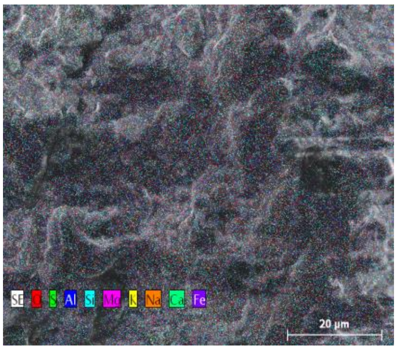
These results demonstrate how well SAPS works to improve matrix densification and reduce autogenous shrinkage, which in turn improves the concrete's overall durability and structural performance [39-41]. At 28 days, the PEGL-modified concrete's SEM microstructure displays a comparatively compact and smooth shape. The matrix has a coated look, most likely because cement particles are encased in polyethylene glycol films, which slow evaporation and encourage hydration. In comparison to the control mix, the fine C-S-H needles are closely packed and have fewer pores. Nevertheless, polymer remnants can still be seen in some areas, indicating that the hydration products are partially encapsulated.



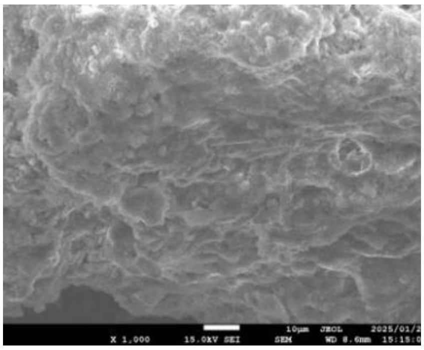
SEM Analysis of Control Concrete at 10 µ



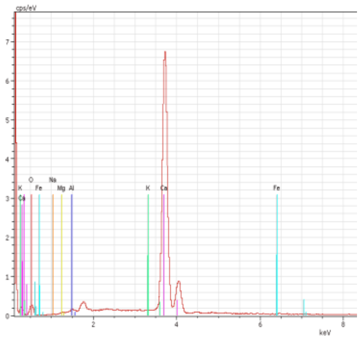
EDX Analysis of Control Concrete



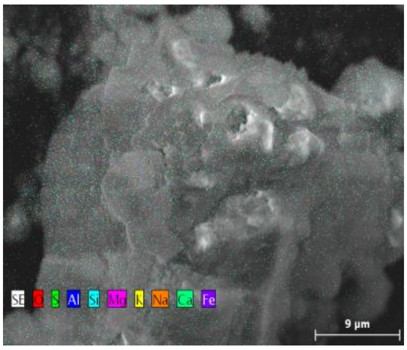
EDS elemental map of Control Concrete



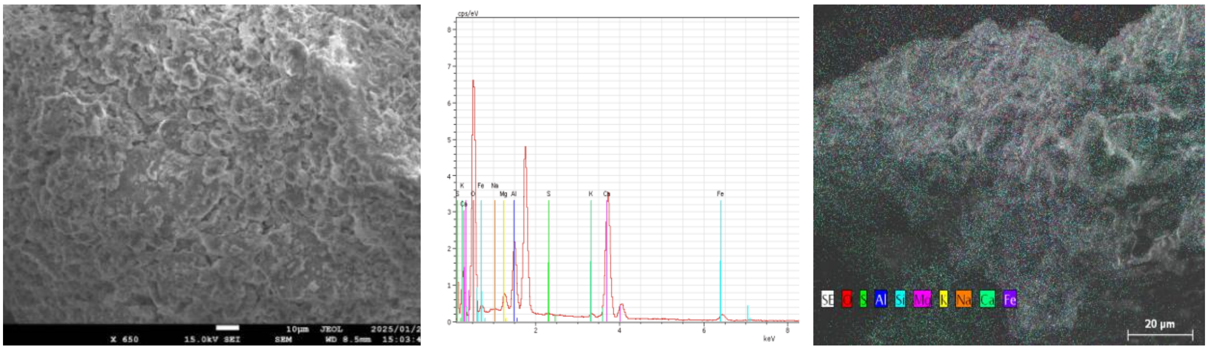
SEM Analysis of SAPS 0.3% Concrete at 10 µ



EDX Analysis of SAPS 0.3% Concrete



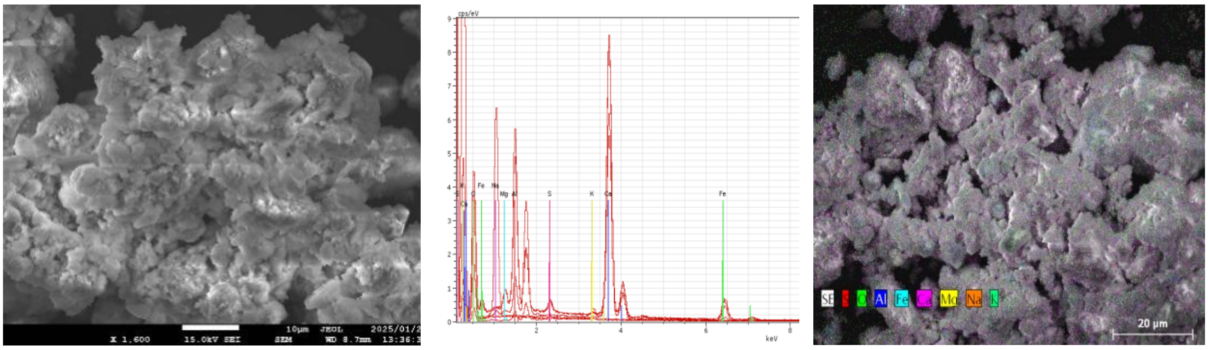
EDS elemental map of SAPS 0.3% Concrete



SEM Analysis of PEGL 1% Concrete at 10 µ

EDX Analysis of PEGL 1% Concrete

EDS elemental map of PEGL 1% Concrete



SEM Analysis of PEGP 1% Concrete at 10 µ

EDX Analysis of PEGP 1% Concrete

EDS elemental map of PEGP 1% Concrete

Fig.13. SEM and EDX analysis of concrete mixes with curing agents at age of 28 days

According to [42], PEGL seems to encourage self-curing through film creation, guaranteeing water retention at an early age and ultimately enhancing the degree of hydration and structural density [43]. Concrete with PEGP (powdered form) at 1% exhibits a more crystalline and interconnected microstructure than PEGL. SEM images show a high concentration of well-formed C–S–H and interlaced fibrous structures. The granular form of PEGP allows for gradual dissolution, sustaining moisture availability during the hydration period. The matrix shows limited unhydrated clinker and a tighter pore network. Compared to PEGL, the structure appears more rigid and mineralized, with better distribution of hydration products and improved bonding in the ITZ zones. This suggests PEGP's efficacy in prolonged internal curing.

The SEM analysis at 28 days clearly shows the beneficial role of self-curing agents in enhancing the concrete microstructure. SAPS improves hydration through its porous structure, while PEGL offers a coating-based mechanism for moisture retention. PEGP, with its crystalline and dissolvable properties, proves to be highly effective in sustaining hydration and improving matrix densification. All modified mixes show superior microstructural characteristics compared to the control mix, indicating the effectiveness of internal curing strategies in improving long-term durability and performance.

4. Conclusions

This study comprehensively evaluated the performance of M30 grade concrete incorporating self-curing agents SAPS, PEGL, and PEGP under various curing regimes. Strength improvement is evident with internal curing compounds as seen from the higher strength recovery of concrete with internal curing compounds under various air curing regimes over that of Control mix under complete water curing regime compared to that of Control mix under air curing vis-à-vis Control mix under complete water curing regime. The optimal dosages giving the highest strength recovery being SAPS at 0.3% PEGL at 1% and PEG Powder with 1%. Under alternate curing (7 d air + 21 d water), SAPS 0.3% delivered a pronounced gain at 28 days (33.9 to 42.0 MPa; +24%), indicating that internal curing is particularly beneficial when early curing is inadequate.

The durability performance has also shown improvement with internal curing compounds in case of air cured regime as comparison to Control concrete. SAPS at 0.3%, PEGL at 1% and PEGP at 1% being the optimal dosage for improved durability performance. Under water curing, water absorption reduced substantially from 5.17% (control) to 2.73% (PEGP 1.0%), demonstrating improved resistance to capillary transport. SEM analysis validated these results by revealing a denser, crack-free matrix with improved C–S–H formation and reduced porosity in self-cured samples. SAPS introduced internal micro-reservoirs aiding prolonged hydration, while PEGL formed hydration-promoting polymer films. PEGP provided sustained moisture release due to its crystalline structure and contributed to a more mineralized matrix. In summary, SAPS at 0.3% and PEGP, PEGL at 1.0% dosage emerged as the most effective self-curing agent, especially under limited external curing scenarios, offering highest strength recovery, substantial reduction in permeability, and a highly refined microstructure compared to control mix under respective curing regimes. These findings advocate for the application of SAPS, PEGP and PEGL in sustainable construction, particularly in arid, or inaccessible environments, where complete water curing is impractical. The addition of these internal curing compounds majorly recovers the loss of strength & durability on account of inadequate curing.

Beyond conventional cast concrete, self-curing materials such as SAPS, PEGL, and PEGP show strong potential for 3D concrete printing, where rapid moisture loss, early-age shrinkage, and weak interlayer bonding are major challenges. Recent studies indicate that PEG-based systems can improve internal curing, mechanical strength, and interlayer performance in printed cementitious materials, while SAPS-based systems can enhance printability and bonding when their absorption and desorption behavior is properly controlled. These materials also offer clear advantages for green construction by reducing external curing water demand, improving durability, and extending service life through lower shrinkage and permeability. Their sustainability potential can be further strengthened by combining them with low-carbon materials such as GGBS and by developing advanced alkali-resistant or bio-based SAPS, making self-curing concrete a promising pathway toward durable, resource-efficient, and low-maintenance infrastructure.

Acknowledgement

The authors acknowledge that this study is supported by Nanotech Research Center, SRM Institute of Science and Technology, Kattankulathur.

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