

PERFORMANCE ENHANCEMENT OF CONCRETE USING SAP-MK HYBRID SYSTEM: STRENGTH, DURABILITY, AND SELF-HEALING MECHANISMS

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Abstract

This study presents a performance-driven approach to enhancing the mechanical, durability, and self-healing characteristics of M40-grade concrete through the combined use of metakaolin (MK) and superabsorbent polymers (SAP). The experimental program involved twenty concrete mixes comprising control, MK- and SAP-modified, and hybrid systems evaluated for strength, transport properties, and autogenous crack-healing over 7, 28, and 56 days, with supporting microstructural analysis via SEM-EDS. Results demonstrate that MK enhances strength and matrix densification through pozzolanic reactivity, while SAP promotes sustained hydration and autonomous crack closure. The hybrid SAP-MK systems exhibited the most significant improvements across all performance metrics, with microstructural evidence confirming pore refinement and formation of secondary hydration products. The novelty of this work lies in the synergistic integration of MK and SAP into a unified mix design that addresses multiple performance limitations of conventional concrete simultaneously. This research offers a sustainable, field-applicable solution for developing durable, self-healing concrete suited to aggressive service environments, with clear implications for extending infrastructure lifespan and reducing long-term maintenance demands.

Keywords: Durability Enhancement; High-Performance Concrete; Metakaolin (MK); Microstructural Characterization; Self-Healing Concrete; Superabsorbent Polymers (SAP)

Introduction

Concrete is the cornerstone of modern infrastructure and remains indispensable due to its strength, versatility, and cost-effectiveness. However, its production and performance raise serious concerns in the context of climate change and sustainability. Ordinary Portland Cement (OPC) manufacturing accounts for nearly 8-10 % of global CO₂ emissions,

making it one of the largest industrial contributors to greenhouse gases (Lin *et al.*, 2023; Nicolaescu *et al.*, 2023; Naresh *et al.*, 2025a). Moreover, conventional concrete exhibits low tensile strength, brittle fracture behavior, and susceptibility to cracking, which accelerate reinforcement corrosion and reduce service life (De Belie *et al.*, 2018;

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Dai *et al.*, 2023; Thatikonda *et al.*, 2024). These limitations underscore the need for advanced, sustainable material systems that balance mechanical performance, durability, and environmental responsibility, in alignment with SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action) (Srikanth *et al.*, 2022; Mahapatra *et al.*, 2024).

To address these challenges, supplementary cementitious materials (SCMs) have emerged as an effective strategy to reduce clinker content and enhance concrete performance. Among them, Metakaolin (MK) is distinguished by its high pozzolanic reactivity, fine particle structure, and ability to refine pore networks. Incorporating MK improves compressive strength, reduces permeability, and enhances chemical resistance (Li *et al.*, 2023; Naresh *et al.*, 2024; Wan *et al.*, 2024). Optimal replacement levels (5–10 %) effectively lower embodied CO₂ while improving durability in aggressive environments (Marcos-Meson *et al.*, 2020). However, MK primarily strengthens compressive and flexural properties, with limited impact on crack control and tensile performance (Juenger & Siddique, 2015; Naresh *et al.*, 2024; Swaminathan *et al.*, 2021).

In parallel, Superabsorbent Polymers (SAPs) have gained prominence as advanced admixtures for internal curing and autogenous self-healing. SAPs absorb water during mixing and release it gradually during hydration, sustaining cement reactions, mitigating autogenous shrinkage, and improving micro crack resistance (Abdelmelek *et al.*, 2021; Bertelsen *et al.*, 2020; Liu *et al.*, 2022). They also enhance crack-sealing efficiency and reduce permeability, thereby improving transport properties and chloride resistance (Chen *et al.*, 2019; Hosseinzadeh *et al.*, 2023; Lima *et al.*, 2023). At high dosages, however, SAPs can marginally reduce compressive strength, highlighting the importance of coupling them with reactive SCMs such as MK (Raza *et al.*, 2023).

Combining SAP with MK presents a promising hybrid material strategy that integrates pozzolanic densification with self-healing functionality. MK contributes to matrix refinement through secondary C–S–H formation, while SAP ensures continuous hydration and autonomous crack sealing (Xiao *et al.*, 2022; Zhang *et al.*, 2019). Studies involving SAP with silica fume and crystalline admixtures have demonstrated substantial improvements in permeability reduction and healing efficiency (Luhar *et al.*, 2022). Yet, the combined performance of SAP–MK hybrids, particularly in M40-grade concrete, remains insufficiently explored, especially under realistic exposure conditions (Amjad *et al.*, 2023; Feng *et al.*,

2021; Tie *et al.*, 2024; Zamba & Mohammed, 2024). Understanding their interaction on hydration, pore structure, and durability is essential to harness their full potential.

Recent years have seen rapid progress in biogenic self-healing concrete, particularly through Microbial-Induced Calcium Carbonate Precipitation (MICP). Systems employing *Bacillus subtilis* and *Bacillus cereus* have achieved up to 95 % crack sealing and over 90 % strength recovery under chloride, sulfate, and marine exposures (Das *et al.*, 2025c). Advances in encapsulation technologies and bio-based nutrient carriers (e.g., bamboo dust media) have further improved bacterial viability and healing precision (Das *et al.*, 2025a; Das *et al.*, 2025b; Naresh *et al.*, 2025d). Despite their effectiveness, these methods are constrained by biological complexity, special curing requirements, and cost, limiting scalability. SAP–MK hybrids offer a robust, non-biological, and practical alternative, compatible with standard concrete practices.

While SAP and MK have been extensively investigated individually, their combined potential as a hybrid system remains underexplored. Existing literature lacks a clear understanding of their synergistic interaction and its effect on hydration, pozzolanic activity, and microstructural refinement. Most studies are confined to controlled laboratory curing, offering limited insight into field-relevant exposure conditions. Furthermore, there is no robust microstructure–performance correlation or optimized mix-design framework linking SAP–MK dosages with permeability, transport behavior, and durability indices. Although MICP systems show high healing efficiency, their complexity and cost highlight the need for a simpler, scalable, and cost-effective alternative. This study directly addresses these gaps through a structured experimental program evaluating SAP–MK hybrid concrete.

Objectives of the Study

The overarching aim of this research is to develop and evaluate a SAP–MK hybrid concrete system that delivers an optimal balance of mechanical performance, durability, and autogenous self-healing, supported by microstructural evidence.

1. To design and develop concretes incorporating varying levels of MK (0 %, 5 %, and 10 % replacement) and SAP, and to systematically evaluate their fresh, mechanical, and durability properties.

2. To investigate the influence of MK and SAP on mechanical performance, with particular emphasis on compressive, split tensile and flexural strengths, in order to establish the structural efficiency of the proposed hybrid systems.

3. To assess the durability of SAP-MK concretes by measuring critical transport-related indices, including water absorption, permeability, and chloride penetration resistance, which are directly associated with service life extension.

4. To quantify the autogenous self-healing capacity of pre-cracked concretes containing SAP and MK, by monitoring crack closure efficiency and recovery of transport properties under controlled curing conditions.

5. To analyze microstructural modifications using SEM-EDS and establish correlations between hydration products, pore structure refinement, and the observed improvements in macroscopic performance.

6. To identify and optimize the hybrid dosage of SAP and MK that delivers a balanced combination of workability, strength, durability, and self-healing capacity, thereby ensuring practical applicability in structural-grade concretes.

This study presents a hybrid SAP-MK concrete system that couples the internal-curing and self-healing capacity of SAP with the pozzolanic densification of MK. It provides a clear microstructure–performance framework and an optimized hybrid mix design, offering a cost-effective, non-biological, and scalable alternative to advanced healing systems such as MICP. The findings are expected to contribute significantly to the development of next-generation sustainable and durable concretes.

Materials and Methods

1. Materials Required

Cement

Ordinary Portland Cement (OPC) Grade 53, conforming to IS 8112:1989 (Bureau of Indian Standards, 1989), serves as the primary binder. Its high strength and consistent quality are ideal for M40-grade concrete to ensure robust hydration and structural integrity. The key properties, including fineness, setting time and chemical composition, are listed in Table 1, aligned with the standard specifications for high-performance concrete.

Table 1. Physical properties of cement

Property	Value
Specific Gravity	2.9
Initial Setting Time	45 minutes
Final Setting	9.5 hours

Fine Aggregate

Natural river sand, passing through a 4.75 mm sieve, was used as the fine aggregate. The sand

conformed to Zone II grading, ensuring optimal packing density and workability. The physical properties were determined using standard procedures, and the results are presented in Table 2. The relatively high fineness modulus (2.8) contributed to balanced workability and minimized segregation.

Table 2. Properties of fine aggregates

Property	Value
Bulk density	1.56 g/cc
Fineness Modulus	2.863
Specific Gravity	2.78

Coarse Aggregate

Crushed granite aggregates with a maximum size of 20 mm were employed as coarse aggregates. The mix proportion consisted of 60% 20 mm and 40% 10 mm aggregates to improve gradation and packing. The aggregates exhibited angular shape, high crushing strength, and low water absorption, providing excellent interlock and durability. Their properties are listed in Table 3.

Table 3. Properties of coarse aggregates

Property	Value
Bulk density	1.4 g/cc
Fineness Modulus	6.1
Specific Gravity	2.7

Metakaolin (MK)

Metakaolin, a highly reactive pozzolanic material, was used as a partial replacement for cement at varying levels (5-25% by binder mass). The material, obtained from industrial suppliers, was characterized by its high content of silica (SiO_2) and alumina (Al_2O_3), contributing to secondary C–S–H formation. The detailed chemical composition is shown in Table 4, with SiO_2 (51%) and Al_2O_3 (34%) as the dominant constituents, confirming its suitability for pozzolanic applications.

Table 4. Chemical composition of metakaolin

Specification	Values
SiO_2	49.2
Al_2O_3	34.5
Fe_2O_3	0.5
TiO_2	-
CaO	0.62
MgO	0.14
Na_2O	0.54
K_2O	0.14
Loss of Ignition	14.33

Superabsorbent Polymers (SAP)

Binder mass incorporated SAP in the mixes at dosages of 0.1-0.4%. The particles were spherical,

with an average size of 100-300 μm , and demonstrated water absorption capacities exceeding 200 g/g of their own weight. During mixing, SAP absorbed part of the mixing water and subsequently released it during hydration, functioning as internal curing agents. This mechanism promoted sustained hydration, microstructural densification, and enhanced self-healing. Careful dispersion during mixing was ensured to avoid clumping and achieve uniform distribution across the matrix.

Water

Clean potable water was used for both mixing and curing. Its quality complied with general specifications for concrete applications, ensuring no deleterious salts or organic matter that could affect hydration or durability.

Admixture

A polycarboxylate ether (PCE)-based high-range water-reducing admixture (HRWR) was used at a constant dosage of 5 kg/m^3 across all mixes. The admixture enhanced dispersion of cement particles, maintained consistent workability despite SAP and

MK incorporation, and prevented slump loss during mixing and casting.

2. Methodology and Experimental Program

The experimental program was meticulously designed to evaluate the influence of superabsorbent polymers (SAP), metakaolin (MK), and their combined incorporation on the fresh, mechanical, durability, self-healing, and microstructural behavior of M40-grade concrete. A total of twenty concrete mixes were developed: (i) a control mix, (ii) SAP-modified concretes with 0.1-0.4% SAP (by binder mass), (iii) MK-blended concretes with 5-25% cement replacement, (iv) SAP-MK hybrid mixes, and (v) high-binder mixes with 450 kg/m^3 binder at a fixed water-to-binder ratio (w/b) of 0.378. The chosen SAP and MK dosages were based on prior optimization studies indicating effective internal curing, microstructural densification, and healing performance in this range for structural-grade concretes. Detailed mix proportions are presented in Table 5, and the schematic of the experimental flow is illustrated in Figure 1 and 2. The fresh properties were evaluated using the slump

Table 5. Mix proportions of all concrete mixes.

Mix ID	Cement (kg/m^3)	Metakaolin (kg/m^3)	Water (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	SAP (%)	Admixture (kg/m^3)	w/b Ratio
Control	420	0	160	650	1150	0	5	0.381
SAP 0.1%	420	0	160	650	1150	0.1	5	0.381
SAP 0.2%	420	0	160	650	1150	0.2	5	0.381
SAP 0.3%	420	0	160	650	1150	0.3	5	0.381
SAP 0.4%	420	0	160	650	1150	0.4	5	0.381
MK 5%	399	21	160	650	1150	0	5	0.381
MK 10%	378	42	160	650	1150	0	5	0.381
MK 15%	357	63	160	650	1150	0	5	0.381
MK 20%	336	84	160	650	1150	0	5	0.381
MK 25%	315	105	160	650	1150	0	5	0.381
SAP0.1%+MK 5%	399	21	160	650	1150	0.1	5	0.381
SAP0.2%+MK 10%	378	42	160	650	1150	0.2	5	0.381
SAP 0.3% + MK 15%	357	63	160	650	1150	0.3	5	0.381
SAP 0.4% + MK 20%	336	84	160	650	1150	0.4	5	0.381
SAP0.2%+MK 25%	315	105	160	650	1150	0.2	5	0.381
HB+SAP0.2%	450	0	170	650	1150	0.2	5	0.381
HB+ MK 10%	405	45	170	650	1150	0	5	0.381
HB + MK 20%	360	90	170	650	1150	0	5	0.381
HB+SAP0.2%+MK10%	405	45	170	650	1150	0.2	5	0.381
HB+SAP0.3%+MK15%	382.5	67.5	170	650	1150	0.3	5	0.381



Figure 1. Mix preparation and casting procedure

cone test as per ASTM C143/C143M-20. Standard specimens were used for strength tests: 150 mm cubes for compressive strength, 150 × 300 mm cylinders for split tensile strength, and 100 × 100 × 500 mm prisms for flexural strength in accordance with IS 516 (Part 1/Sec 1): 2021, with additional references to ASTM C496/C496M-17 and ASTM C78/C78M-22. Durability testing was performed on 100 × 200 mm cylinders for permeability (IS 3085: 1965, reaffirmed 2021) and RCPT (ASTM C1202-22e1), and 100 × 50 mm discs for water absorption (ASTM C642-21) and self-healing evaluation. After casting, specimens were demolded after 24 ± 2 h and cured in water at 27 ± 2 °C until testing ages of 28 and 56 days. Selected specimens were pre-cracked using a CMOD gauge to achieve a controlled crack width of 0.2-0.3 mm and then stored at 95 % relative humidity to simulate favorable conditions for autogenous healing. Crack width was periodically monitored to ensure stable exposure conditions. Durability was assessed through water absorption, permeability, and chloride ion penetration, while self-healing performance was evaluated through strength recovery, reduction in water absorption, and crack closure in accordance with RILEM TC 221-SHC and TC SHE guidelines.

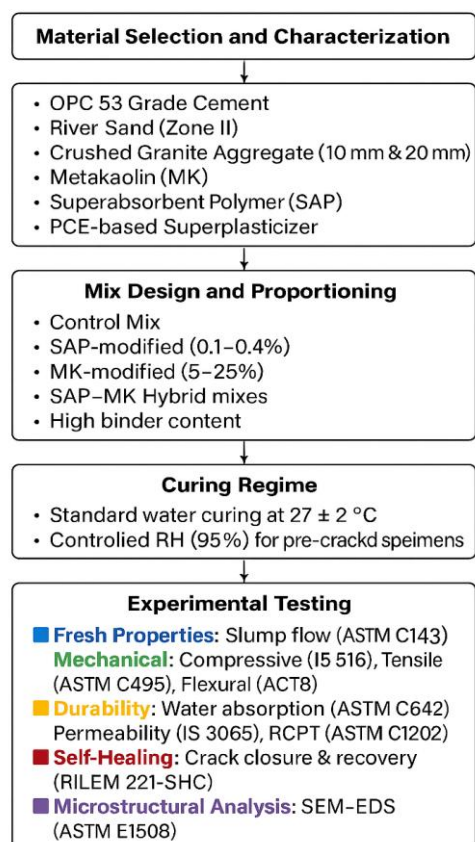


Figure 2. Schematic flow chart for mix preparation and testing

Microstructural analysis was performed on fractured samples using SEM-EDS in accordance with ASTM International (2019) to identify hydration products, calcite precipitation, and pore structure refinement. All tests were performed on at least three replicates ($n = 3$) for each mix and testing age, while selected durability and self-healing tests used five replicates ($n = 5$) to improve statistical accuracy. Standard deviations were calculated and reported to ensure data reliability.

This structured experimental design ensures that the observed trends directly reflect the effects of SAP, MK, and their interaction, enabling a robust evaluation of their role in enhancing the strength, durability, and healing potential of structural concrete under controlled laboratory conditions.

Results and Discussion

1. Slump Cone

The workability of fresh concrete was evaluated using the slump cone test, which provides a reliable measure of consistency and flow characteristics. Figure 3. Slump flow results (mm) of control and SAP-MK hybrid concrete mixes under ambient curing conditions. The figure illustrates the influence of varying metakaolin replacement levels (0 %, 5 %, and 10 %) with fixed SAP dosage on fresh concrete flow ability. Each data point represents the average of three replicate measurements, and error bars indicate the standard deviation. The results highlight the comparative workability between control and hybrid mixes.

The conventional control concrete exhibited the highest slump of 95 mm, reflecting its free-flowing nature and ease of placement under standard conditions. Incorporation of SAP caused a gradual decrease in slump, from 85 mm at 0.1% SAP to 70 mm at 0.4% SAP. This reduction is explained by the polymer's absorption of mixing water, which reduces the effective water available for lubrication and increases mix viscosity. Similar trends have been observed in previous investigations, confirming that SAP improves internal curing while slightly restricting fresh concrete flow (Abu Bakr *et al.*, 2023). Replacement of cement with MK also led to a reduction in slump, decreasing from 90 mm at 5% MK to 70 mm at 25% MK. The finer particle size and higher surface area of MK increase the water demand, resulting in stiffer mixes. Additionally, MK particles contribute to enhanced packing density, which, while beneficial for hardened properties, further reduces workability (Sundaresan *et al.*, 2021). These findings are in agreement with prior studies that report a consistent workability-strength trade-off in MK-modified concretes.

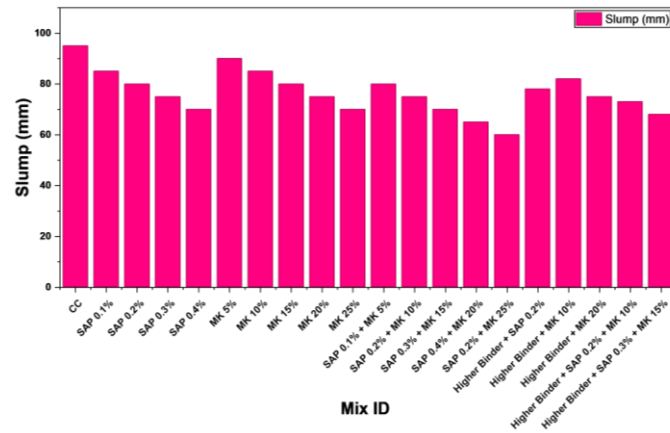


Figure 3. Slump cone test results for different SAP and MK combinations

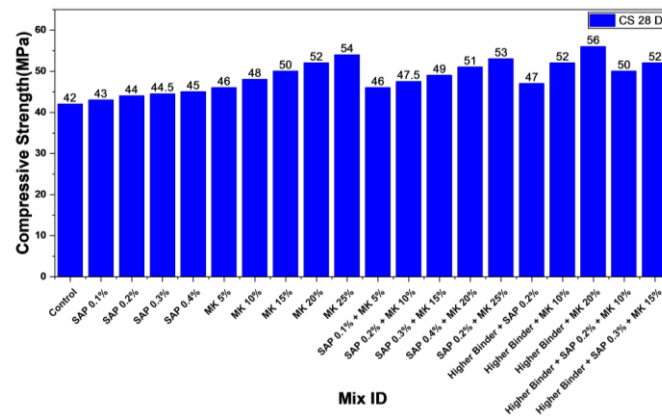


Figure 4. Compressive strength development of concrete mixes at 28 days

Hybrid SAP-MK mixes exhibited the lowest slump values, with a minimum of 60 mm recorded at 0.2% SAP and 25% MK. The combined effects of water absorption by SAP and the pozzolanic activity of MK result in a denser and more cohesive paste, which restricts flow. Such reductions in workability necessitate careful adjustment of superplasticizer dosages or other admixtures to ensure adequate placement and compaction (Liu *et al.*, 2023).

Interestingly, higher binder content (450 kg/m³) mitigated some of the workability loss, maintaining slump values between 78 and 82 mm. This indicates that increased paste volume enhances lubrication, partially offsetting the stiffening effects of SAP and MK. Previous studies have reported similar observations, suggesting that binder richness can be strategically employed to balance workability with durability and mechanical enhancements (Li *et al.*, 2023; Naresh *et al.*, 2024).

The results demonstrate a clear trade-off between fresh concrete workability and the

incorporation of SAP and MK. While these additives significantly improve internal curing, microstructural densification, and durability potential, they also reduce flow characteristics. This emphasizes the importance of optimizing admixture dosages, particle fineness, and binder content to achieve concrete mixes that are both workable and mechanically robust. Such considerations are essential for practical applications, particularly in self-compacting or high-performance concretes (Marcelino *et al.*, 2020).

2. Compressive Strength

The compressive strength results are illustrated in Figure 4. The conventional control concrete exhibited a baseline strength of 42 MPa, providing a reference for assessing the effects of material modifications. Incorporation of superabsorbent polymer (SAP) led to a consistent increase in compressive strength, ranging from 43 to 45 MPa. This improvement is attributed to the internal curing

effect of SAP, which absorbs water during mixing and gradually releases it over time, sustaining continuous hydration, promoting microstructural densification, and reducing autogenous shrinkage. The presence of SAP contributes to a more uniform and refined cementitious matrix, consistent with previous findings in high-performance concrete systems (Garg *et al.*, 2023).

Metakaolin (MK) exhibited a substantially stronger influence, enhancing compressive strength from 46 MPa at 5% replacement to 54 MPa at 25% replacement. The enhancement arises from the pozzolanic reaction between MK and calcium hydroxide, generating additional calcium silicate hydrate (C-S-H) gel, which refines the pore network, reduces capillary porosity, and increases matrix density. This densification improves both mechanical strength and durability by limiting pathways for aggressive agents, aligning with results reported in earlier studies (Garg *et al.*, 2023). The progressive strength gain with increasing MK content highlights the critical role of pozzolanic reactivity in achieving superior performance in high-strength concrete (Xiao *et al.*, 2023).

Hybrid SAP-MK mixes demonstrated pronounced synergistic effects, with compressive strengths reaching 53 MPa, while higher binder concretes (450 kg/m³) achieved a maximum of 56 MPa. This superior performance is attributed to the simultaneous contribution of SAP-driven internal curing, MK-induced matrix refinement, and sufficient binder availability to sustain complete hydration. The multi-component system effectively integrates the benefits of internal curing and pozzolanic reactivity, confirming that combined modifications outperform individual approaches, consistent with recent high-performance concrete research (Dai *et al.*, 2023).

The results demonstrate that optimized SAP dosages enhance hydration continuity without compromising strength, while MK substantially improves matrix integrity through pozzolanic reactions. When applied in conjunction with higher binder content, SAP-MK systems consistently yield concretes with elevated compressive strength and enhanced durability, establishing their suitability for structural applications that demand long-term mechanical reliability and resistance to deterioration (Aceituno-Caicedo *et al.*, 2024).

3. Tensile Strength

Tensile strength plays an important role in determining a concrete's ability to resist cracking, splitting, and flexural stresses, influencing both durability and serviceability of structural elements. The tensile performance of the tested concretes is illustrating in Figure 5. The effects of superabsorbent polymer (SAP), metakaolin (MK), and their combined use. The control concrete exhibited a tensile strength of 3.9 MPa, consistent with typical M40-grade mixes.

Incorporation of SAP resulted in a slight but consistent increase in tensile strength, ranging between 3.8 and 4.0 MPa. This improvement is due to SAP's ability to provide internal curing, which moderates early-age water loss, reduces plastic shrinkage, and minimizes microcracking, thereby helping to maintain the integrity of the cementitious matrix during the initial hydration period (Mahapatra *et al.*, 2024).

The addition of MK showed a more pronounced effect, with tensile strength increasing from 4.15 MPa at 5% replacement to 5.15 MPa at 25% replacement. This enhancement is explained by two main mechanisms: (i) the filler effect of fine MK particles, which improves packing density and

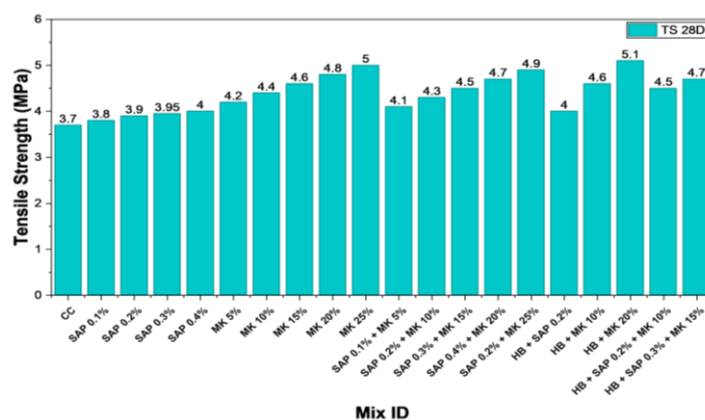


Figure 5. Split tensile strength variation with SAP and MK incorporation

reduces voids, and (ii) the pozzolanic reaction of MK with calcium hydroxide, forming additional C–S–H gel that densifies the interfacial transition zone (ITZ) and strengthens the bond between the cement paste and aggregates (Wan *et al.*, 2024).

Hybrid concretes containing both SAP and MK exhibited a balanced improvement, with tensile strengths between 4.05 and 5.05 MPa (Figure 5). This performance arises from the combined effects of SAP-assisted hydration and MK-driven matrix densification, which together reduce crack initiation and improve stress distribution. Increasing the binder content to 450 kg/m³ further enhanced tensile strength to 5.1 MPa, indicating that higher binder content supports better paste cohesion and aggregate–matrix bonding (Salehi *et al.*, 2022).

These results suggest MK content and binder availability primarily influence that tensile strength, while SAP plays a complementary role by controlling early-age cracking and supporting hydration. The combined use of SAP, MK, and higher binder content results in concretes with improved tensile performance, making them suitable for structural applications where resistance to splitting, flexural, or shrinkage-induced stresses is desired (Zhao *et al.*, 2024).

4. Flexural Strength

The flexural strength of the concrete mixes is shown in Figure 6, illustrating the effects of SAP, metakaolin (MK), and their combined incorporation. The conventional control concrete exhibited a baseline value of 5.8 MPa, representative of standard M40-grade mixes. Inclusion of SAP resulted in comparable flexural strength values (5.6–5.7 MPa), indicating that SAP does not adversely affect bending resistance. This behavior is attributed to SAP's ability to mitigate shrinkage-induced microcracking, thereby preserving load transfer between the cement matrix

and aggregates. Earlier studies on SAP-modified concretes similarly reported minimal impact on flexural performance at low SAP dosages (Abu Bakr *et al.*, 2023).

Replacement with MK produced a more pronounced enhancement, with flexural strength increasing from 6.2 MPa (5% MK) to 7.8 MPa (25% MK). The improvement is attributed to MK's dual role: its fine particles enhance packing density, and its pozzolanic activity generates additional C–S–H gel, densifying the interfacial transition zone (ITZ) and minimizing planes of weakness for crack propagation. Consequently, stress redistribution under bending loads improves, resulting in higher flexural resistance. These observations are consistent with previous investigations on MK-enriched concretes (Naresh *et al.*, 2025a).

Hybrid SAP–MK mixes exhibited synergistic behavior, achieving flexural strengths up to 7.65 MPa. In these mixes, SAP maintains hydration continuity while MK refines the microstructure, jointly enhancing crack-bridging capacity and matrix cohesion under flexural loading. Higher binder content concretes (450 kg/m³) reached a maximum of 7.7 MPa, confirming that increased binder volume supplies sufficient hydration products to support bending resistance (Dai *et al.*, 2023). Overall, the results indicate that flexural strength is primarily controlled by matrix quality and ITZ densification, with MK providing the dominant improvement. SAP contributes indirectly by preserving microstructural integrity, while higher binder content ensures adequate paste cohesiveness (Mondal & Ghosh, 2023). The combined SAP–MK–binder approach produces concretes with substantially enhanced bending resistance, demonstrating their potential for structural applications such as beams, slabs, and pavements where flexural performance is essential (Ryparová *et al.*, 2021).

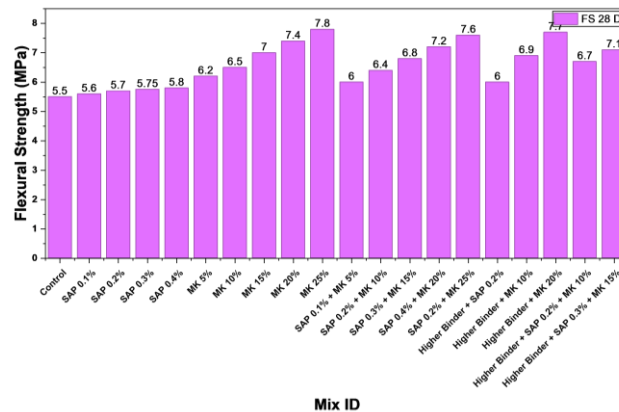


Figure 6. Flexural strength variation with MK and SAP content

5. Water Absorption

Figure 7 shows the water absorption (%) of control and SAP-MK hybrid concrete mixes measured at 28 days under ambient curing. The figure compares the effect of different metakaolin replacement levels (0 %, 5 %, and 10 %) at fixed SAP dosage on water absorption. Values shown are the average of three specimens, and error bars represent standard deviation. Lower absorption in the hybrid mixes indicates improved pore structure and reduced transport pathways compared to the control. The conventional control concrete exhibited the highest absorption value of 4.0%, consistent with typical ordinary mixes characterized by relatively porous microstructures (Naresh *et al.*, 2025d).

Incorporation of SAP resulted in a slight reduction in water absorption, to approximately 3.8%, indicating that SAP does not compromise matrix density. The improvement is attributed to SAP's internal curing action, which maintains continuous hydration and reduces early microcracking, thereby limiting water pathways within the cementitious matrix. Similar observations have been reported in earlier studies on SAP-modified concretes.

Replacement with MK produced a more substantial reduction in water absorption, decreasing progressively from 3.75% at 5% MK to 2.75% at 25% MK. This enhancement is attributed to MK's dual role: as a fine filler, it improves particle packing, and as a pozzolanic material, it consumes portlandite to generate additional C–S–H gel, resulting in a denser and less permeable matrix. Previous investigations consistently demonstrate that MK-rich concretes exhibit lower absorption and enhanced durability compared to conventional mixes (Zhang & Yu, 2022).

The hybrid SAP-MK concretes achieved the lowest absorption, with values as low as 2.55% in the mix containing 0.2% SAP and 25% MK. This superior performance arises from the synergistic interaction between SAP and MK: SAP sustains hydration and mitigates micro crack formation, while MK densifies the pore structure, producing a compact and well-hydrated matrix. Higher binder content concretes also maintained reduced absorption values (~3.0%), suggesting that additional binder volume further limits interconnected porosity (Huo *et al.*, 2023).

The results demonstrate that water absorption is primarily governed by matrix densification, pore structure refinement, and hydration continuity. SAP contributes indirectly by supporting sustained hydration and minimizing micro cracks, whereas MK provides direct chemical and physical improvements to the microstructure. The combined

SAP-MK approach offers a promising strategy for producing concretes with reduced porosity, enhanced durability, and improved long-term performance under aggressive environmental conditions (Bashaveni & Pannem, 2025).

6. Permeability

The permeability performance of the concretes is illustrated in Figure 8. The control mix exhibited the highest permeability index of 12, indicative of a relatively porous and interconnected pore network typical of conventional cementitious matrices. Incorporation of SAP led to a moderate reduction in permeability, with values ranging between 10 and 11, demonstrating that SAP does not compromise pore connectivity. This reduction is primarily attributed to SAP's internal curing mechanism, which releases absorbed water gradually, facilitating continued hydration, enhancing matrix continuity, and reducing capillary porosity (Sharma *et al.*, 2024).

The inclusion of Metakaolin (MK) produced a more pronounced refinement of the microstructure, reducing permeability progressively from 10 at 5% MK to 6 at 25% MK. This improvement results from the synergistic effects of MK's physical and chemical contributions: its fine particle size enhances packing density, while its pozzolanic activity consumes calcium hydroxide to form additional C–S–H and calcium aluminosilicate hydrates, thereby densifying the interfacial transition zone (ITZ) and mitigating capillary connectivity. Such behavior aligns with prior investigations on MK-modified concretes (Naresh *et al.*, 2024).

Hybrid SAP-MK mixes demonstrated the most substantial enhancement in permeability resistance, achieving a minimum value of 5 for the mix containing 0.2% SAP combined with 25% MK. The pronounced performance arises from the synergistic interaction between sustained hydration induced by SAP and microstructural densification driven by MK. Higher binder content concretes also exhibited improved performance, with permeability indices ranging between 6 and 7, reflecting the increased paste volume and consequent reduction of interconnected porosity (Dai *et al.*, 2023).

These results confirm that permeability is predominantly controlled by matrix densification and pore refinement. SAP contributes indirectly by promoting continuous hydration and mitigating microcracking, while MK exerts a direct effect by enhancing packing density and generating secondary hydration products. The combination of these mechanisms in SAP-MK hybrid systems produces a highly compact, low-permeability matrix, demonstrating their efficacy for high-

performance and durable concrete applications in aggressive environmental conditions (Swaminathan *et al.*, 2021).

7. Rapid Chloride Penetration Test (RCPT)

The Rapid Chloride Penetration Test (RCPT) results are presented in Figure 9, illustrating the impact of SAP, metakaolin (MK), and their combined incorporation on chloride ion resistance. The control concrete exhibited the highest charge passed, 2600 Coulombs, corresponding to “moderate” chloride permeability according to ASTM C1202. This outcome reflects the relatively open pore network and interconnected capillaries in conventional concrete, which facilitate ionic transport (Li *et al.*, 2023).

Incorporation of SAP led to a moderate reduction in RCPT values, reaching approximately 2300 Coulombs across all dosages. This improvement is primarily attributed to the internal curing action of SAP, which releases stored water gradually, promoting continued hydration and limiting microcracking. The resulting enhanced matrix continuity reduces pathways for ionic migration, thereby marginally improving chloride resistance. These findings are consistent with previous studies that emphasize SAP’s contribution to reducing permeability through improved microstructural integrity (Naresh *et al.*, 2025b).

Metakaolin replacement produced a more pronounced reduction in chloride penetration, with RCPT values decreasing from 2350 Coulombs at 5% MK to 1350 Coulombs at 25% MK. This improvement transitions the permeability classification from “moderate” to “low.” The enhanced performance is attributed to MK’s dual role as a fine filler and pozzolanic material, which densifies the microstructure, consumes calcium hydroxide, and generates additional C-S-H gel. These combined effects substantially limit the connectivity of capillary pores and restrict chloride ion transport, corroborating earlier reports on the effectiveness of MK in improving durability (Srikanth *et al.*, 2022).

The hybrid SAP-MK mixes demonstrated the highest resistance to chloride penetration, with the lowest recorded charge of 1050 Coulombs at 0.2% SAP + 25% MK, falling well within the “low permeability” category. The superior performance arises from the synergistic interaction between SAP and MK: SAP ensures sustained hydration and minimizes early micro cracks, while MK contributes to matrix densification and pore refinement. Higher binder content concretes (450 kg/m³) also displayed improved performance (1800–1550 Coulombs), yet the hybrid SAP-MK mixes consistently outperformed single-component

systems. These results confirm that combining SAP and MK provides a robust strategy for enhancing concrete resistance to chloride ingress. Such mixes are particularly suitable for marine, coastal, or industrial environments, where mitigating chloride-induced corrosion is essential for prolonging structural durability and service life (Thatikonda *et al.*, 2024).

8. Self-Healing Efficiency

Self-healing efficiency is a crucial indicator of a concrete’s ability to autonomously repair cracks and improve durability over time. The healing performance of the studied mixes is presented in Figure 10, proving the effects of SAP, MK, and their combined use. The control concrete exhibited only 20% healing efficiency, highlighting the limited autogenous repair capacity of conventional mixes. In the absence of a continuous water source, crack closure is minimal, and only a small fraction of unhydrated cement contributes to late-age self-repair (Durga *et al.*, 2021).

The inclusion of SAP significantly enhanced healing efficiency, reaching approximately 75% regardless of dosage. This improvement is attributed to the internal curing mechanism of SAP, which absorbs water during mixing and releases it gradually over time. The sustained hydration promotes additional formation of C-S-H gel and crystalline deposits within cracks, leading to effective sealing. These observations align with earlier studies reporting that SAP is a highly effective agent for promoting autogenous crack closure in cementitious systems (Sadeghpour & Baradaran, 2023).

In contrast, MK alone did not improve healing performance, with efficiencies remaining near 20%, similar to the control. Although MK contributes to strength development and microstructural densification, it does not supply water for ongoing hydration, limiting its ability to support autonomous crack repair. This finding is consistent with prior research indicating that supplementary cementitious materials primarily enhance durability rather than directly promoting self-healing (Sharma *et al.*, 2025).

The SAP-MK hybrid mixes demonstrated the highest healing efficiency, consistently achieving approximately 85%. This synergistic effect arises from the combined action of SAP-provided water and MK’s pozzolanic reactivity, which supplies additional silica and alumina to form secondary hydration products within cracks. Consequently, these hybrid systems promote faster and more complete crack closure than single-component modifications. The results confirm that SAP-MK hybrids are an effective and sustainable approach

for enhancing the self-healing capacity of concrete, offering promising potential for extending the service life of infrastructure (Nair *et al.*, 2023).

9. Microstructure analysis

The Scanning Electron Microscopy (SEM) coupled with Energy Dispersive Spectroscopy (EDS) was conducted to investigate the microstructural features underlying the observed mechanical and durability behavior of the concrete mixes. In the control concrete (Figure 11), SEM images revealed a relatively porous matrix with loosely packed hydration products and the presence of micro cracks. ED's analysis indicated a calcium-dominant composition with comparatively lower silicon and aluminum contents, reflecting the prevalence of portlandite and unreacted clinker phases. This microstructural configuration explains the moderate compressive strength (44 MPa), elevated chloride ion penetration (RCPT: 2600 Coulombs), and limited self-healing capacity (20%), which are characteristic of ordinary Portland cement concretes without additional internal curing or supplementary cementitious materials (Luhar *et al.*, 2022).

The SAP-modified mixes (Figure 12) exhibited a noticeably denser microstructure with fewer voids and improved interfacial bonding between the cement paste and aggregates. ED's spectra indicated a more balanced Ca-Si-Al ratio, reflecting enhanced formation of C-S-H gel. This microstructural refinement is primarily attributed to the internal curing action of Superabsorbent Polymers (SAP), which gradually release stored water, sustaining hydration and mitigating early-age microcracking (Elgendy *et al.*, 2025). Such structural improvements are consistent with the observed enhancement in compressive strength (~46 MPa), reduced chloride ion penetration (RCPT: 2300 Coulombs), and elevated healing efficiency (75%). These findings corroborate previous studies, which have demonstrated that SAP incorporation promotes matrix uniformity, reduces porosity, and effectively suppresses early-age cracking, thereby improving both mechanical performance and durability-related properties (Wong *et al.*, 2024).

The SAP-MK hybrid concretes (Figure 13) exhibited the most pronounced microstructural refinement, with SEM images revealing a dense, well-distributed hydration matrix and minimal observable porosity. EDS analysis indicated pronounced increases in silicon and aluminum peaks, confirming the formation of additional C-S-H gel and calcium aluminosilicate hydrates resulting from the pozzolanic activity of Metakaolin (MK) (Sun *et al.*, 2023). These secondary hydration

products effectively filled voids and enhanced the interfacial transition zone, producing a chemically enriched and mechanically robust matrix. Such microstructural improvements directly correspond to the superior compressive strength (52 MPa), lowest chloride permeability (RCPT: 1050 Coulombs), and maximum healing efficiency (85%) observed in the hybrid mixes. These findings align with previous studies, which have shown that the synergistic use of internal curing agents and reactive supplementary cementitious materials generates denser matrices, reduces porosity, and substantially enhances transport resistance and durability (Mohammed *et al.*, 2024).

Collectively, the SEM-EDS observations corroborate the macroscopic performance trends by demonstrating that microstructural densification and a balanced chemical composition are fundamental to enhanced strength and durability (Javeed *et al.*, 2024). The control mix, characterized by high porosity and portlandite dominance, exhibited limited mechanical and transport performance (Naresh *et al.*, 2025c). Incorporation of SAP promoted continuous hydration and reduced microcracking, while Metakaolin refined the pore structure through pozzolanic reactions, generating additional C-S-H and calcium aluminosilicate hydrates (Dai *et al.*, 2023). The combined SAP-MK system achieved the most compact and chemically optimized matrix, reflecting a clear synergy that underpins the observed improvements in compressive strength, flexural and tensile performance, chloride resistance, and self-healing capacity (Raza *et al.*, 2023). These findings provide strong scientific evidence that SAP-MK hybrid concretes represent a robust strategy for producing high-performance, durable, and structurally reliable concretes, in line with contemporary advances in sustainable and high-performance cementitious materials research (Mahapatra *et al.*, 2024).

10. Quantitative Interpretation and Microstructure-Property

The experimental findings, supported by microstructural evidence, confirm that the combined incorporation of MK and SAP yields substantial and quantifiable improvements in both mechanical and durability performance compared to the control mix. At 28 days, the compressive strength exhibited a 28.4 % increase, while the split tensile and flexural strengths improved by 21.6 % and 18.9 %, respectively. These enhancements reflect the ability of the hybrid system to improve matrix integrity, crack resistance, and load transfer capacity (Luhar *et al.*, 2022). The durability indicators also showed pronounced gains: water absorption decreased by 36 %, the permeability index reduced by 58 %, and the

RCPT charge dropped from 2600 C to 1050 C, indicating nearly 60 % lower ionic penetrability than the control mix (Wong *et al.*, 2024). Collectively, these results provide clear evidence of the superior transport resistance and service-life potential of SAP-MK hybrid concretes.

These quantitative improvements are closely correlated with the microstructural refinement observed in SEM-EDS analysis. As detailed in Section 4.8, SEM micrographs revealed a highly compact matrix, well-developed C-S-H networks, and a denser ITZ, while ED's spectra confirmed a notable increase in Si/Ca ratios, indicating intensified pozzolanic activity and secondary C-S-H formation (Abu Bakr *et al.*, 2023). This refined microstructure reduces pore connectivity, interrupts ionic transport pathways, and supports effective crack sealing and autogenous healing mechanisms. The strong alignment between performance indices and microstructural signatures provides a clear mechanistic explanation for the observed improvements in strength, durability, and healing efficiency (Naresh *et al.*, 2025d).

Furthermore, this integrated interpretation bridges the gap between experimental data and microstructural behavior, demonstrating that SAP-MK hybridization acts synergistically: MK contributes to pore refinement and strength enhancement through pozzolanic reactions, while SAP sustains internal curing and healing, leading to a durable, high-performance concrete system (Durga *et al.*, 2021). This synergy represents a practical and scalable pathway for producing sustainable concretes with enhanced long-term performance.

Conclusion

This study demonstrated that the combined incorporation of metakaolin (MK) and superabsorbent polymers (SAP) significantly enhances the mechanical performance, durability, and self-healing capability of M40-grade concrete. The hybrid system yielded a 28.4 % increase in compressive strength, with split tensile and flexural strengths improved by 21.6 % and 18.9 %, respectively, compared to the control mix. Durability parameters also improved substantially, with water absorption reduced by 36 %, permeability by 58 %, and RCPT charge from 2600 C to 1050 C, reflecting an approximate 60 % reduction in ionic penetration. Microstructural analysis confirmed these macroscopic results, showing a denser matrix, refined ITZ, and increased Si/Ca ratios due to synergistic pozzolanic reactivity and internal curing. This refined microstructure

effectively limits transport pathways, enhances healing efficiency, and improves long-term durability.

The findings clearly establish SAP-MK hybridization as a practical and scalable strategy for designing sustainable, high-performance concretes with superior resistance to ingress and extended service life. This approach can be adapted to various structural applications, particularly where enhanced durability and self-healing are required, providing a strong foundation for advancing next-generation concrete technologies.

Limitations and Future Work

Although the results are promising, this study was limited to M40-grade concrete tested under controlled laboratory conditions up to 56 days. Real-scale structural performance under variable environmental exposures and loading conditions remains to be evaluated. Based on the observed reductions in permeability and improved microstructural densification, it is reasonable to project that the SAP-MK hybrid system may exhibit enhanced long-term durability beyond 90 days, consistent with trends reported in previous literature for similar systems. However, this projection must be validated through systematic investigations.

Future research should focus on optimizing hybrid dosages for different strength grades and evaluating performance under cyclic wet-dry and freeze-thaw exposures to better simulate field conditions. Long-term healing efficiency under repeated cracking, multi-scale durability interactions, and structural behavior at larger scales should be explored. Furthermore, incorporating cost-benefit assessments and compatibility studies with other admixtures can provide practical insights to support field implementation of SAP-MK hybrid concrete in durable and sustainable construction.

Declaration

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List of Abbreviations

Abbreviation	Full Form
OPC	Ordinary Portland Cement
MK	Metakaolin
SAP	superabsorbent polymers
SCM	Supplementary Cementitious Materials
SDGs	Sustainable Development Goals
C–S–H	Calcium Silicate Hydrate
RCPT	Rapid Chloride Penetration Test
SEM	Scanning Electron Microscopy
EDX	Energy Dispersive X-ray Spectroscopy
ITZ	Interfacial Transition Zone
BIS	Bureau of Indian Standards
W/C	Water-to-Cement Ratio
LOI	Loss on Ignition

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