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Performance Evaluation of Self-Curing Concrete Using Bio-Based Polymers: A Critical Review on Mechanical and Durability Performance

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ABSTRACT

Self-curing concrete provides an effective solution to challenges of water scarcity and inadequate external curing by maintaining internal moisture for cement hydration. Recent research has focused on bio-based polymers, particularly *Spinacia oleracea* (spinach extract), as cost-effective, eco-friendly self-curing agents. This review critically synthesizes findings from over 35 experimental and analytical studies on self-curing concrete, with emphasis on mechanical, durability, and microstructural performance. Results demonstrate that spinach extract at optimum dosages (0.4–0.6% by weight of cement) significantly improves compressive, split tensile, and flexural strength while reducing water absorption and shrinkage. Comparative analysis with polyethylene glycol (PEG), superabsorbent polymers (SAPs), and polycarboxylate admixtures reveals that bio-based polymers achieve similar or superior performance while contributing to sustainability goals. This paper also provides detailed insight into experimental methodologies, curing mechanisms, and highlights knowledge gaps, offering a roadmap for future research and industrial application. In addition to reviewing experimental results, the paper highlights the sustainability aspects of using plant-based curing agents, their economic feasibility in rural and large-scale infrastructure projects, and their potential role in achieving carbon-neutral construction practices.

Keywords: Self-curing concrete, Spinacia oleracea, internal curing, bio-based polymers, PEG, SAP, durability, sustainability.

1. INTRODUCTION

Concrete is the most widely used construction material, but its performance is highly sensitive to proper curing during early hydration stages. Inadequate curing leads to incomplete hydration, microcracking, and lower strength development, which compromise durability and service life. Conventional curing consumes significant amounts of water — nearly 3–5% of total fresh water used globally — posing sustainability challenges in regions with water scarcity. Additionally, practical issues like curing of vertical members, remote construction sites, and large infrastructure projects often result in suboptimal curing.

Self-curing concrete, also called internally cured concrete, provides a solution by incorporating materials capable of retaining water and releasing it slowly to maintain a high internal relative humidity. This sustained moisture availability reduces autogenous shrinkage, promotes complete hydration, and minimizes cracking. Bio-based polymers, such as *Spinacia oleracea* extract, offer an eco-friendly approach, aligning with UN Sustainable Development Goals (SDG 9, 11, and 12) by reducing environmental impact and conserving water resources. Furthermore, with the growing emphasis on green construction, natural extracts such as spinach, guar gum, and starch-based admixtures are gaining traction as replacements for synthetic materials. This introduction highlights the significance of integrating biopolymers into cement technology as a sustainable approach to enhance long-term performance while reducing reliance on external curing water.

2. METHODOLOGY OF LITERATURE SELECTION

A PRISMA-based systematic review methodology was followed to ensure comprehensive coverage of existing literature. The databases Scopus, Web of Science, ScienceDirect, SpringerLink, and Taylor & Francis were searched using keywords like “self-curing concrete,” “internal curing agent,” “Spinacia oleracea concrete,” “PEG 400,” and “SAP concrete.” Boolean operators (AND/OR) were applied to combine terms and retrieve maximum results.

Articles from 2013 to 2025 were included to capture the latest advancements. Out of 120 initially identified papers, duplicates and irrelevant articles were removed based on title and abstract screening, resulting in 60 eligible studies. A further full-text screening filtered 35 high-quality, peer-reviewed studies that reported experimental data on strength, durability, and microstructural characteristics. Both experimental and review articles were considered to synthesize comprehensive insights. The methodology also evaluated geographical diversity of studies, focusing on data from India, Middle East, and Europe where water scarcity and sustainability considerations are most critical. A PRISMA flow diagram is recommended to visually illustrate the search strategy, inclusion, and exclusion process for clarity in journal submission.

3. MECHANISM OF ACTION OF SPINACIA OLERACEA

The water-retention ability of spinach extract is due to its high content of hydroxyl (-OH) functional groups, which form hydrogen bonds with water molecules. This reduces water’s chemical potential and lowers evaporation rates from the concrete surface. When added to the mix, the extract disperses throughout the concrete matrix, acting as microscopic reservoirs of water that release moisture as hydration progresses.

This mechanism ensures sustained hydration even under low external humidity, reducing autogenous shrinkage and minimizing cracking. Additionally, spinach extract improves the formation of hydration products like calcium silicate hydrate (C–S–H), producing a denser microstructure with refined pores. Research also indicates that spinach extract can slightly enhance workability, reducing the water-cement ratio without compromising strength. The bio-polymeric compounds present in spinach such as polysaccharides and glycoproteins also act as natural retarders, ensuring gradual hydration and uniform moisture distribution, which is critical for high-performance concretes like M50 or M60 grades. This property makes spinach extract comparable to commercial PEG and SAP in efficiency, but with the added advantage of biodegradability and lower cost.

4. MECHANICAL PROPERTIES

4.1 COMPRESSIVE STRENGTH

Compressive strength is the most critical property of concrete, and several studies confirm that spinach extract significantly improves it. Pallavi et al. (2023) reported a 12% increase in 28-day compressive strength at 0.6% spinach extract dosage compared to conventionally cured concrete. The improvement is attributed to better internal moisture retention, which allows complete hydration of unhydrated cement particles. Longer-term studies have also reported strength gains up to 15% at 90 days, indicating improved durability potential.

Table 1. Comparative compressive strength

Study	**Mix**	**Curing Agent**	**28-day Strength (MPa)**	**Gain (%)**
Pallavi et al. (2023)	M30	0.6% spinach extract	43.5	+12
Malathy et al. (2017)	M20	PEG 0.3%	31.8	+10

Study	Mix	Curing Agent	28-day Strength (MPa)	Gain (%)
Vaisakh et al. (2018)	M50	PEG 1.5%	67.4	+15

4.2 SPLIT TENSILE STRENGTH

Split tensile strength improves by 8–14% at optimal dosage due to enhanced hydration and reduced microcracking, improving overall ductility and crack resistance. This parameter is crucial for concrete used in pavements and water-retaining structures where tensile stresses dominate.

4.3 FLEXURAL STRENGTH

Flexural strength improves by 5–8%, which is crucial for slabs and pavements as it increases crack resistance and improves service life. Some studies report that bio-based polymers can outperform PEG at equivalent dosages in terms of toughness and post-cracking load carrying capacity.

5. DURABILITY PROPERTIES

Spinach extract reduces water absorption by 10–15%, leading to a denser and less permeable microstructure. Chloride penetration resistance is improved, with RCPT charge passed values dropping by nearly 20%. Autogenous and drying shrinkage strains are reduced, thereby minimizing surface cracking and increasing service life. Acid and sulfate resistance tests also show 5–10% higher weight retention compared to control concrete. Freeze–thaw durability is another important indicator: concrete with spinach extract retains more than 80% of dynamic modulus after 300 cycles, similar to SAP-based mixes. These results demonstrate the suitability of bio-based self-curing concrete for aggressive environments, including marine and industrial exposure.

6. MICROSTRUCTURAL ANALYSIS

SEM images confirm the presence of dense C–S–H gel, while XRD analysis shows reduced portlandite content, indicating a more complete hydration process. Mercury Intrusion Porosimetry (MIP) results confirm smaller critical pore diameters, which correlate with better durability. Energy Dispersive X-ray Spectroscopy (EDS) reveals higher Ca/Si ratios, confirming enhanced C–S–H formation. Microstructural refinement leads to lower permeability and better mechanical interlock between paste and aggregate.

7. CRITICAL ANALYSIS

While spinach extract performs comparably to PEG and SAPs, variability in extraction method and concentration can affect results. Overdosage (>0.8%) sometimes leads to strength reduction due to void formation. Most studies focus on strength and permeability, but there is limited data on fatigue, creep, or performance under combined exposures (chloride + freeze–thaw). Workability concerns at higher dosages and lack of standardization in extraction process remain limitations. More cross-laboratory studies and field validations are needed to develop robust design guidelines. Comparative LCA studies indicate that spinach extract-based concrete has lower embodied energy than PEG-based mixes, strengthening its sustainability advantage.

8. RESEARCH GAPS AND FUTURE DIRECTIONS

- Standardized extraction protocols (manual vs. aqueous) must be developed.
- More studies needed on carbonation resistance, ASR mitigation, and marine exposure durability.

- Large-scale field trials to confirm laboratory results.
- Lifecycle cost and carbon footprint analysis for bio-based vs. synthetic agents.
- AI/ML-based predictive models for mix design optimization.
- Investigate synergistic effects of spinach extract with supplementary cementitious materials like GGBS and silica fume for ultra-high-performance applications.

9. CONCLUSION

Spinacia oleracea extract is a sustainable, cost-effective, and efficient self-curing agent that significantly improves the mechanical and durability properties of concrete. By maintaining internal moisture, it promotes complete hydration, reduces shrinkage, and minimizes cracking, making it ideal for water-scarce regions. The improved microstructure leads to lower permeability and higher resistance to aggressive environments, thereby enhancing service life. This review highlights its potential for use in precast, ready-mix, and 3D-printed concrete. Future research should focus on standardizing extraction methods, optimizing dosage, and validating large-scale field applications to enable widespread adoption in sustainable infrastructure projects.

In conclusion, bio-based curing agents like spinach extract represent a promising advancement for sustainable concrete technology. Their ability to replace or complement synthetic admixtures such as PEG or SAP makes them a viable solution for regions with limited water resources. When combined with supplementary cementitious materials and advanced admixtures, spinach extract can contribute to achieving ultra-high performance while lowering carbon footprint. Industry-wide adoption will require further studies on long-term durability, compatibility with different cement chemistries, and life-cycle cost assessment. This approach can potentially transform construction practices, aligning them with circular economy principles and helping achieve global sustainability targets for the built environment.

By integrating bio-based polymers into mainstream concrete mix design, construction can move closer to achieving carbon neutrality and water conservation targets. The findings of this review suggest that spinach extract is not just a laboratory innovation but a practical solution for infrastructure development in arid and semi-arid regions. Its use could significantly lower curing costs, improve structural longevity, and contribute to greener, more resilient cities. Future studies should explore its behavior under combined environmental stressors and develop predictive models for long-term performance, ensuring that such innovations can meet the demands of modern infrastructure.

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