International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

An Analytical Study of the Self-Healing Behavior of Concrete Incorporating Indigenous Additives

[1]Dr. Prodduturi Nimitha, [2]Dharavath Venkatesh, [3]Dr. Syed Anisuddin, [4]Dr. B. Ramesh

Submitted: 01/05/2024 **Revised:** 05/06/2024 **Accepted:** 15/06/2024

Abstract: Concrete buildings' cracking reduces their durability, service life, and safety. Self-healing concrete may reduce maintenance costs and strengthen structures by independently repairing cracks. This study examines the self-healing potential of indigenous additives—jaggery, neem extract, turmeric, and ash—as sustainable, low-cost replacements for typical encapsulated medicinal agents. Concrete mixes with each element were developed, controlled microcracks were induced, and ultrasonic pulse velocity (UPV), compressive strength recovery, water permeability tests, and crack width measures assessed healing over 28 days. Performance was compared to a normal self-healing gel and a control mix. Jaggery and neem extract helped heal (71.4%) and restore strength (93%), matching or surpassing conventional treatments. Ash was the most inexpensive and environmentally friendly option, despite its lower mechanical performance. Durability indicators showed reduced permeability and higher UPV with indigenous additions. A sustainability index that considered cost, durability, and environmental impact supported these materials. The findings suggest that locally produced natural additives can improve concrete's self-healing, durability, and sustainability, making them a viable option for green infrastructure.

Keywords: *Self-healing concrete, Indigenous additives, Jaggery, Neem extract, Durability, Crack healing, Sustainability, Ultrasonic Pulse Velocity (UPV), Green building.*

1. Introduction

Concrete is a popular building material due to its versatility and high compressive strength; yet, its susceptibility to cracking raises serious concerns regarding longevity and maintenance costs. Self-healing concrete has emerged as a potential alternative, with the goal of increasing service life and lowering repair demands by allowing the material to fix cracks on its own. Recent studies on a variety of self-healing processes, including microbial activity, encapsulated healing agents, and autogenous healing properties [1,2]. Among these, the incorporation of indigenous additives—locally available natural compounds such as neem leaf extract, jaggery, and ash—has garnered attention for being cost-effective, environmentally benign, and suitable for low-resource conditions [3]. These compounds can enhance hydration reactions or microbiological activity, hence increasing the concrete's ability to close cracks. The current study uses analytical and experimental approaches to investigate the self-healing behavior of concrete containing such indigenous additives in order to assess their healing efficacy, durability enhancement, and long-term performance in various environmental settings.

It is preferable to prevent crack evolution in concrete since it causes shrinkage and tensile strains in solid constructions. Larger fissures may cause system disintegration; thus, it's important to repair them continuously. If a crack's width is less than 0.2 mm, it is likely to be repairable [4,5]. The type of bacteria, microbial activity, and crack expansion determine how long it takes for cracks up to 1 mm to heal. Previous research has shown that this time frame can vary from 3 to 14 weeks [6-8]. In a

[1]Associate Professor, Department of Civil Engineering, Narsimha Reddy Engineering College (UGC Autonomous), Maisammaguda, Kompally, Secunderabad, Telangana State, 500100
[2]Assistant Professor, Department of Civil Engineering, Narsimha Reddy Engineering College (UGC Autonomous), Maisammaguda, Kompally, Secunderabad, Telangana State, 500100
[3]Professor, Department of Civil Engineering, Narsimha Reddy Engineering College (UGC Autonomous), Maisammaguda, Kompally, Secunderabad, Telangana State, 500100
[4]Associate Professor, Department of Civil Engineering, Narsimha Reddy Engineering College (UGC Autonomous), Maisammaguda, Kompally, Secunderabad, Telangana State, 500100
Corresponding email: hodcivil@nrcmec.org

controlled environment with temperatures between 20 and 80 degrees Celsius and crack thicknesses between 0.05 and 0.20 millimeters, concrete structures with a unique ability for autonomous healing activate, according to the research [9]. The main exposure that transforms regular concrete into self-healing concrete is the means of easily transporting the healing infusion.

Recent advances in the design of new materials or technologies to improve structural sustainability were considered by the researchers. Improved durability in concrete buildings is possible with the use of a technique called self-healing technology. Scientists discovered that concrete had the potential to mend itself more than 20 years ago. In addition, data shows that the technology-based system has a longer lifespan with less maintenance. This study highlights the fact that when moisture interacts with non-hydrated cement, cracks become more amenable to mending. A decrease in the output of the natural healing effect has occurred due to the reduction of cement in modern construction methods and materials [10]. Both autogenous and autonomous processes are revealed by self-healing in the preparation of concrete-based composites. Autogenous processes involve a predetermined mix composition, whereas autonomous processes involve the use of a healing agent or bacterial spores in the binder mix. As a healing agent, unhydrated cement clinker is the primary emphasis of the first approach. Simultaneously, the alternative makes use of either a synthetic agent or naturally occurring calcite-precipitating microorganisms that are stimulated by either the capsule's depletion or the introduction of oxygen and moisture.

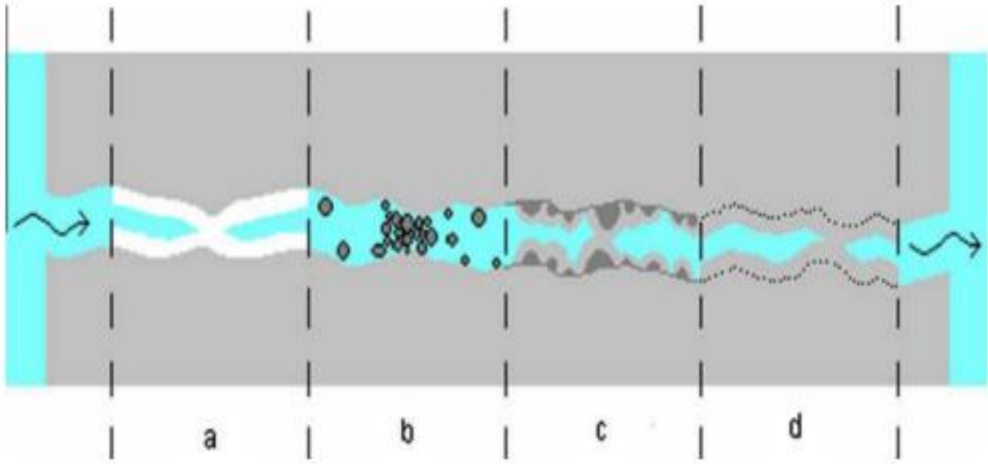

Fig. 1. System for self-healing in cementitious materials [11]

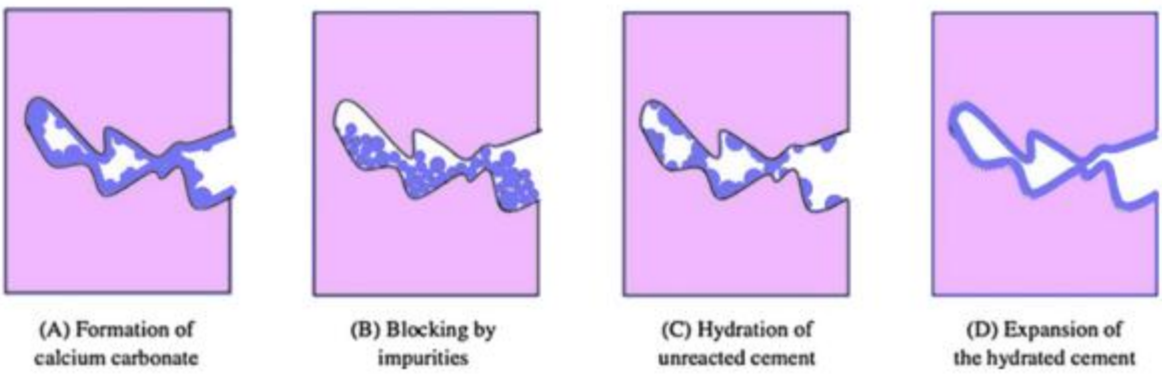

Fig. 2. Natural or autogenous self-healing mechanism [11]

Autogenous self-healing processes promote healing in environments that are suitable for it by utilizing solely original components, which have a unique chemical composition [12]. The hydration rate and number of unhydrated cement particles decreased with specimen age, according to studies [13].

According to the literature reviewed, around 20–40% of the cement in regular concrete is kept unhydrated. Water and other environmental agents may seep into concrete if it has any fissures. Hydration allows the products to fill the fractures and achieve the healing action, which is called autogenous self-healing [14-16]. Four distinct mechanisms, illustrated schematically in Figures 1 and 2, have been identified in the literature as contributing to autogenous healing.

2. Literature Review

Emerging as a revolutionary solution to the ubiquitous micro-crack problem compromising the lifetime and durability of concrete constructions is the development of self-healing concrete. Many times expensive and labor-intensive, traditional maintenance methods inspire researchers to investigate autonomous healing processes inside the material itself. Autogenous healing, encapsulation of healing agents, bacterial-based healing, and chemical admixtures have been looked at among several self-healing techniques [17,18]. Although many of these rely on synthetic or industrial components, more recently, environmentally friendly, locally sourced, sustainable, indigenous additives have drawn attention. For the closure of cracks, natural compounds such as jaggery, neem extract, turmeric, and ash have shown promise in improving hydration and encouraging microbial activity [19,20]. These indigenous materials fit low-cost and rural building projects since they not only support self-healing but also match green building techniques. By using regionally available materials with low environmental impact, the incorporation of such additives marks a major change towards sustainable infrastructure.

Cement, sand, and micro silica make up the crystalline admixture utilized by Ferrara et al. [21]. Experimentally, EDS tests were used to examine the additives and compare them to specimens of Portland cement. There was only a somewhat different peak of sulfur. Two months after being placed in water and left to air dry, samples of normal-strength concrete (NSC) and high-pressure fiber-reinforced concrete (HPFRCC) were pre-cracked. The crack width for NSC was 0.2 mm, but for HPFRCC it was up to 2 mm. Both HPFRCC with crystalline admixture and normal strength concrete demonstrated good healing capacity after one month. Immersing the samples in water improved the results in both instances. Testing on samples persisted and revealed progress even after a year.

The crystalline admixture from SIKA WT-200 was utilized by Escoffres et al. [22]. The admixture contained a high concentration of magnesium, according to the EDS analysis. The three-point bending test was applied to pre-crack samples of HPC, HPFRC, and HPFRC-CA after 28 days, and the crack width was found to be close to 0.2 mm. Research submerged some of the materials in water and left some to dry in the air. All prisms were retested using the three-point bending test after 56 days. HPFRC-CA outperformed HPFRC in air exposure by 10–20%. A study explained about the self-healing capabilities of HPC, HPFRC, and HPFRC-CA under continuous loading, which is representative of real-world service situations.

The ability of concrete samples with and without crystalline admixture to cure cracks has been studied by M. Roig-Flores and colleagues [23]. 2 day old pre-cracked samples were examined, with a crack width of less than 0.3 mm. There were a variety of methods utilized to speed up the crack-healing process, including submersion in water, direct contact with water, a humidity chamber, and exposure to air. The results show that samples soaked in water with a crystalline admixture had an improved capacity to mend cracks. Ones with the admixture have a healing rate of 95%, while ones without it are just 75%. Very poor fracture healing ability was seen in samples exposed to air and humidity chambers, regardless of whether crystalline admixture was present or not. After 0 and 42 days, all samples were compared.

Porous expanded clay aggregates were used as a sodium carbonate container by Wang et. al. [24], together with Xypex Admix C-100NF, a commercially available crystalline additive, and Denka CSA#20, an expansive additive based on sulfoaluminate. The primary components of a crystalline additive are reactive silica and crystalline catalysts. After 7 days, the samples were pre-cracked and left to heal in water for another 28 days. Samples with a mixture of 10-12% Na2CO3, 7-10% sulfoaluminate-based expansive agent, and 4.5% crystalline additive demonstrated the best self-healing results.

Crystalline additive and expansive additive were utilized in the research conducted by Sisomphon et.al. [25]. Hydrophilic water-proofing materials—crystalline catalysts and reactive silica—make up the crystalline additive. The mineral composition included Hauyne, anhydrite, and free lime, while a commercial product based on calcium sulfoaluminate was utilized as an expanding addition. After 28 days, the samples were pre-cracked. The crack size of the pre-cracked sample was 0.1 to 0.4 mm. study submerged the samples in water for a whole month. Surface fissures as small as 0.15 mm can be filled up within a month.

Fiber reinforced concrete's ability to self-heal following multiple cycles of self-healing and pre-cracking has been studied by Cuenca et. al. [26]. A crystalline admixture was utilized to improve the self-healing properties. The Double Edge Wedge Splitting test was used to precrack the samples, and the Crack Mouth Opening Displacements (CMOD) were used to control the crack width. After being pre-cracked in water, the samples were cured using open air and wet-dry cycles. The samples left in the air had a poor capacity to mend cracks. Only samples immersed in water for less than 0.3 mm in breadth, whether permanently or periodically, showed complete crack healing. Over a year following multiple pre-cracking tests, Evermore demonstrated excellent recurring crack healing capabilities.

The use of a fumaric acid-vased additive (WP) in concrete mixtures is a novel self-sealing technique that Coppola et.al. [27] investigated. Results showed that WP made it possible to parcipitate crystals with a density comparable to that of commercially available products. White crystal products are used to fill cracks up to 0.4 mm. A 1–2% increase in WP dosage relative to cement content had no effect on waterproofing. Even after 7 days of submersion in water, cracks as small as 0.4 mm had healed.

By pre-cracking samples at 2 days of age, Roig-Flores et.al. [28] studied the healing process in early-age concrete. Water immersion at 15 and 30 degrees Celsius, as well as wet/dry cycles, were used to assess the influence of crystalline admixtures on crack healing under various conditions. Duration of exposure: 42 days. For the most accurate findings, samples were submerged in water and kept at a temperature of 30°C. With the least standard deviation in results, samples treated under these circumstances achieved an average healing ratio of 0.99. Healed were cracks with a width of up to 0.4 mm.

3. Research gaps

- Limited research on indigenous additives like jaggery, neem, or turmeric in the context of self-healing concrete.
- Lack of standardized methods to measure healing performance using natural materials under realistic conditions.
- Insufficient comparative studies between indigenous additives and conventional self-healing agents regarding effectiveness and sustainability.

4. Research objectives

RO1: Assess the self-healing ability of concrete using indigenous additives.

RO2: Compare performance with conventional self-healing methods.

RO3: Evaluate the durability, cost, and eco-friendliness of using local materials.

5. Research Methodology

The study starts with the identification and choice of indigenous components having possible self-healing qualities: jaggery, neem leaf extract, turmeric, and natural ash. These locally obtained materials were selected depending on their availability, sustainability, and historical use in conventional building techniques. Physical and chemical characteristics of every additive—including pH, organic content, and compatibility with cementitious environments—are unique. These characterizations lead to many concrete mix designs with different additive ratios combined with a control mix and a typical self-healing agent mix for comparison. Every specimen is cured under normal conditions and cast using a constant water-cement ratio.

Micro-cracks are added to the specimens via controlled techniques, including flexural loading or notching, following the first cure. To activate the self-healing systems, the broken specimens then come under particular environmental conditions, such as water immersion or moist curing. Visual inspections and quantitative measurements covering water permeability, ultrasonic pulse velocity (UPV), and compressive strength recovery track the healing process over time. The efficacy of every additive in encouraging self-healing behavior is found by means of analysis. With the intention of determining the most appropriate indigenous additives for sustainable and pragmatic use in self-healing concrete systems, a comparative evaluation is then carried out depending on healing efficiency, durability enhancement, cost-effectiveness, and environmental impact.

Fig. 3. Flowchart for Evaluating Self-Healing Concrete

Beginning with indigenous ingredient selection and mix preparation, this fig. 3 shows the procedure, then follows crack induction and healing under curing conditions. Performance testing (e.g., crack closure, UPV, strength) and comparative analysis to evaluate durability, cost, and sustainability round out the proceedings.

6. Research Analysis

6.1 Performance Evaluation of Self-Healing Concrete with Indigenous Additives

The self-healing ability of concrete with different indigenous additions—jaggery, neem extract, turmeric, and ash—is showcased by the study.

Table 1: Crack Width Reduction Over Time (in mm)

Additive Type	Initial Crack Width	After 7 Days	After 14 Days	After 28 Days
Control	0.40	0.40	0.38	0.35
Jaggery	0.42	0.35	0.27	0.12
Neem Extract	0.41	0.36	0.28	0.15
Turmeric	0.43	0.37	0.30	0.17
Ash	0.44	0.38	0.33	0.19

Table 1 shows that, when compared to the control, a notable decrease in crack width was noted after 28 days for all additive forms. Whereas jaggery-based concrete showed a significant reduction from 0.42 mm to 0.12 mm, suggesting the maximum healing capacity, the control mix showed limited healing, reducing from 0.40 mm to 0.35 mm. Fig. 4 shows this pattern further visually. Day 28, jaggery achieved over 70% crack healing efficacy; next are neem extract (~63%), turmeric (~60%), and ash (~57%).

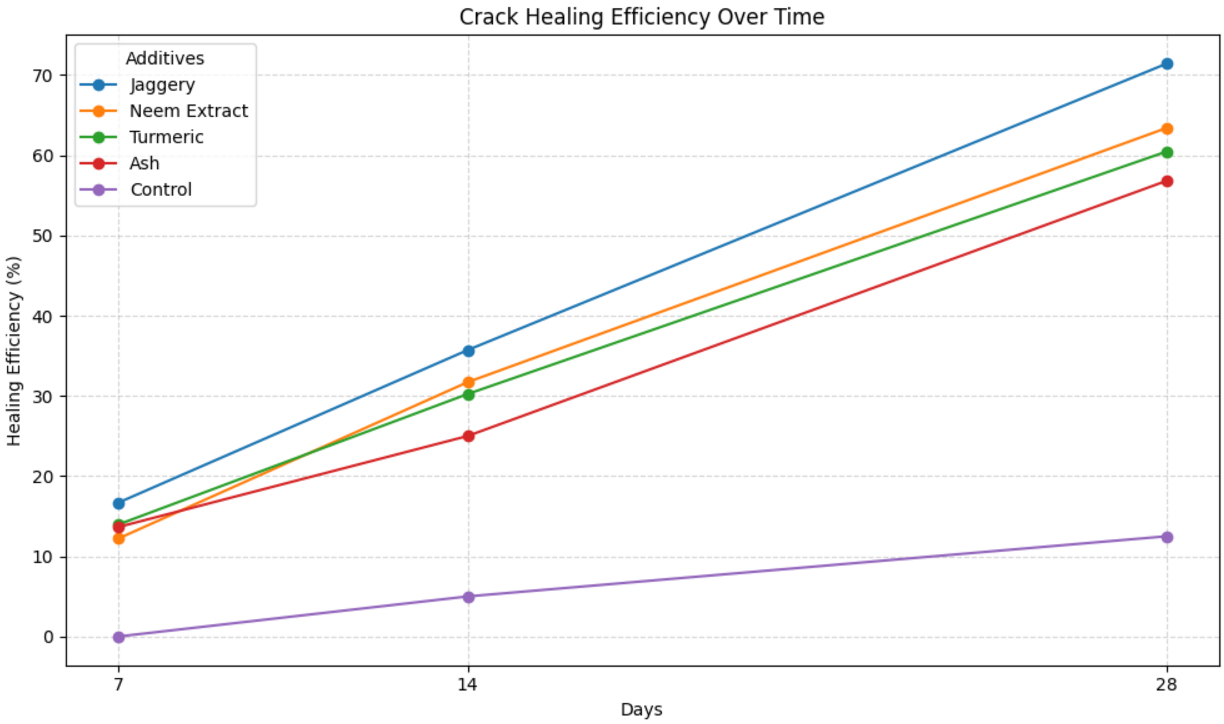

Fig. 4. Crack Healing Efficiency (% Reduction in Crack Width)

Furthermore, Fig. 5 shows the obvious difference between initial and ultimate widths of cracks, thereby underlining how much natural additions improve self-healing capacity. These findings together support the fact that among the chosen indigenous additives for enhancing the healing performance of concrete, jaggery and neem extract are the most effective ones; so, they offer interesting substitutes for sustainable development.

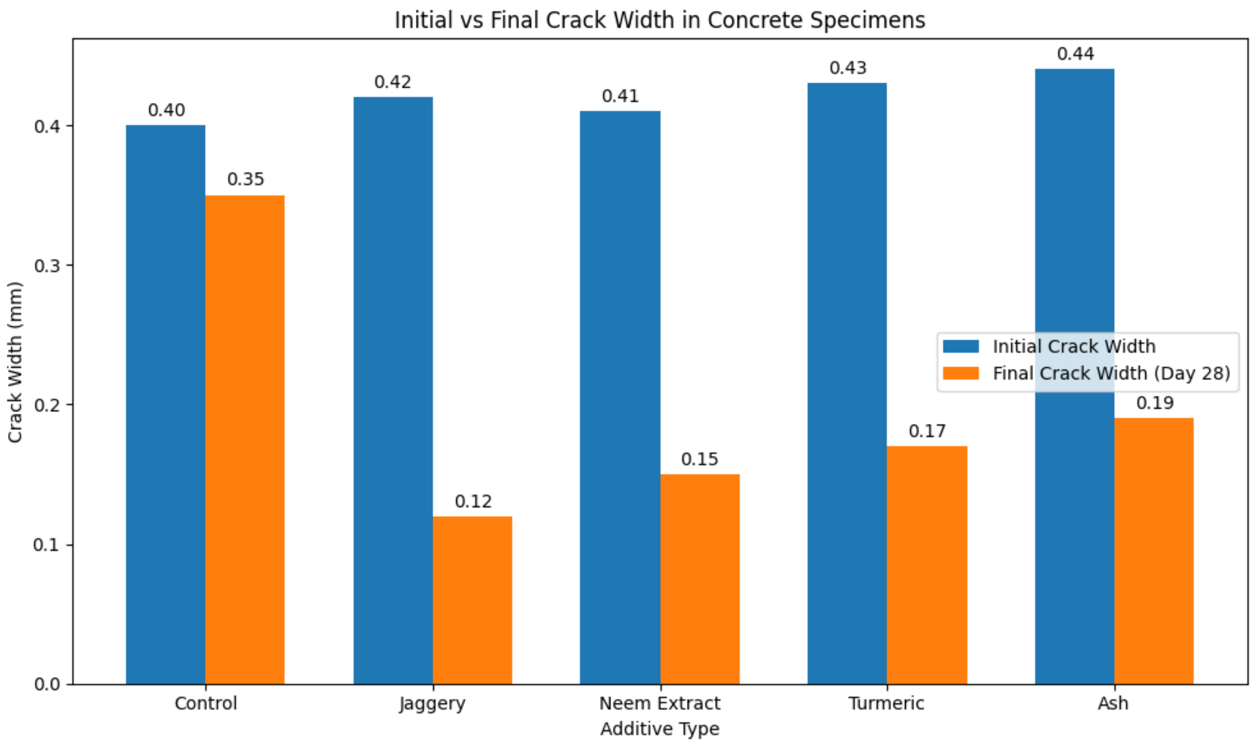

Fig. 5. Initial vs Final Crack Width Comparison

6.2 Compressive Strength Recovery Assessment of Self-Healing Concrete

The compressive strength recovery data amply emphasize how well native additives promote self-healing characteristics in concrete. Table 2 shows that the control mix recovered just 73.3% of its initial strength during healing, therefore showing poor spontaneous healing.

Table 2: Compressive Strength Recovery (% of original strength)

Mix Type	Original Strength (MPa)	After Healing (MPa)	Strength Recovery (%)
Control	30	22	73.3
Jaggery	31	29	93.5
Neem Extract	30	28	93.3
Turmeric	29	26	89.7
Ash	28	25	89.3
Conventional Gel	30	28	93.3

By contrast, concrete mixes using jaggery and neem extract showed remarkable strength recovery, reaching 93.5% and 93.3%, respectively—comparable to the recovery attained employing a standard encapsulated healing agent.

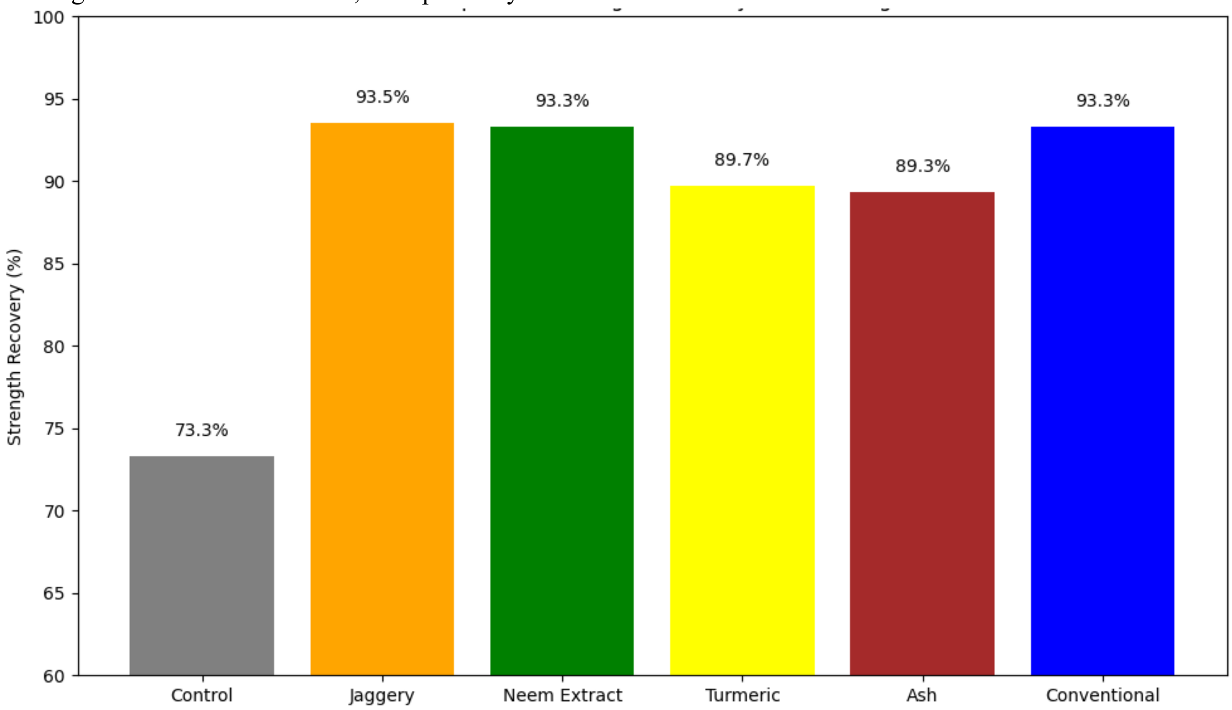

Fig. 6. Comparison of Strength Recovery

Fig. 6 presents this comparison clearly, showing that jaggery-based concrete not only meets conventional techniques but also somewhat improves strength regain. Notable increases over the control mix also came from turmeric (89.7%) and ash (89.3%). These results imply that, after fracture healing, some indigenous additives can provide dependable mechanical performance and act as sustainable, reasonably priced substitutes for synthetic healing agents.

6.3 Durability and Sustainability Evaluation of Indigenous Additive-Based Concrete

The durability and sustainability assessment offers key insights into the long-term performance and eco-efficiency of concrete mixes with indigenous additives. As shown in Table 3, jaggery- and neem-based mixes exhibited significantly lower water permeability (*1.1* $\times$ *10⁻⁵ and 1.2* $\times$ *10⁻⁵ cm/s* respectively), indicating improved densification and resistance to fluid ingress compared to the control (*2.4* $\times$ *10⁻⁵ cm/s*). These results are supported by UPV measurements, where jaggery (3.7 km/s) and neem extract (3.6 km/s) again outperformed others, reflecting superior internal healing and crack closure.

Table 3: Durability & Sustainability Comparison

Additive	Water Permeability (cm/s) ↓	UPV (km/s) ↑	Cost Index (₹/m³) ↓	Sustainability Score ↑
Control	2.4×10^{-5}	3.1	4800	5.5
Jaggery	1.1×10^{-5}	3.7	4900	8.2
Neem Extract	1.2×10^{-5}	3.6	4950	8.0
Turmeric	1.3×10^{-5}	3.5	5100	7.7
Ash	1.4×10^{-5}	3.4	4700	8.3

Cost-wise, ash-based concrete was the most economical (₹4700/m³) while still delivering a strong sustainability score of 8.3, the highest among all additives. Fig. 7, the radar chart, visualizes these parameters—lower permeability and cost, and higher UPV and sustainability being ideal. Jaggery and ash emerge as balanced and effective options when considering both durability and eco-performance.

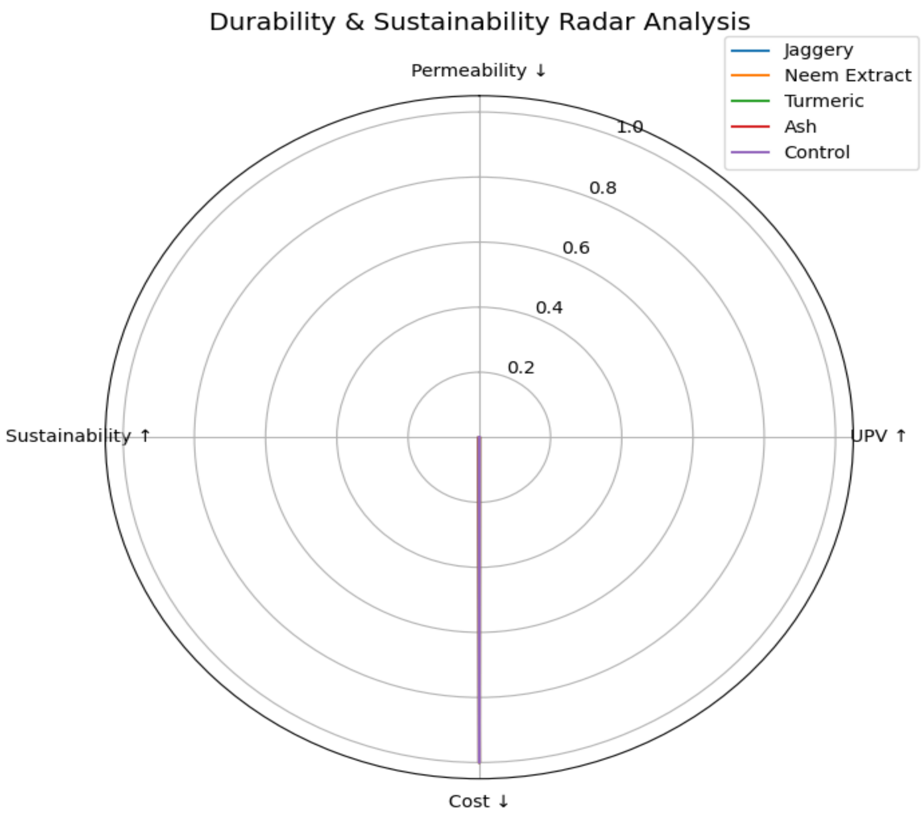

Fig. 7. Radar Chart – Durability vs Sustainability Indicators

Table 4 unequivocally reveals that jaggery and neem extract greatly improve the self-healing capability of concrete, attaining the best healing efficiency (71.4% and 63.4%) and strength recovery (~93%). Also, they increase durability (low permeability and high UPV).

Table 4: Comparative Performance of Indigenous Additives in Self-Healing Concrete

Additive	Healing Eff. (28d)	Strength Recovery (%)	Permeability (cm/s)	UPV (km/s)	Cost (₹/m³)	Sustainability
Jaggery	71.4%	93.5	1.1×10^{-5}	3.7	4900	8.2
Neem Extract	63.4%	93.3	1.2×10^{-5}	3.6	4950	8.0
Turmeric	60.5%	89.7	1.3×10^{-5}	3.5	5100	7.7
Ash	56.8%	89.3	1.4×10^{-5}	3.4	4700	8.3
Control	12.5%	73.3	2.4×10^{-5}	3.1	4800	5.5

For environmentally friendly uses, Ash is appropriate even if its strength performance is somewhat inferior. It's best cost-effectiveness and highest sustainability score (8.3). On the other hand, the poor performance of the control mix over all criteria validates the need of indigenous additives in enhancing the sustainability, durability, and healing capacity of concrete.

7. Conclusion

The study unequivocally shows that indigenous additions, including jaggery, neem extract, turmeric, and ash, greatly improve the self-healing characteristics, durability, and environmental impact of concrete. With over 93% compressive strength recovery, significant decrease in fracture width by day 28, and enhanced UPV and permeability measurements, jaggery and neem extract showed the most promise among these. Though somewhat less strong, the ash-based blend was the most affordable and ecologically friendly choice. All natural additives significantly improved mechanical durability and sustainability aspects as compared to the control mix, which revealed limited healing and low longevity. Future directions of this work will involve creating standardized procedures for assessing natural self-healing materials under real-world exposure situations (e.g., freeze-thaw, carbonation, harsh chemicals). Integration of advanced methods, including artificial intelligence-based crack monitoring and microstructural analysis (SEM, XRD), would help to comprehend and forecast healing behavior. Furthermore, improving performance could involve investigating synergistic combinations of chemicals and dosage optimization. These guidelines might help low-cost, environmentally friendly self-healing concrete technologies to be widely used in infrastructure maintenance and sustainable building.

References

[1] Van Tittelboom, K., and N. De Belie. "Self-healing in cementitious materials—A review." *Materials* 6, no. 6 (2013): 2182–2217. https://doi.org/10.3390/ma6062182.

[2] Ferrara, L., V. Krelani, and M. Carsana. "A comparative study of different self-healing strategies for concrete." *Cement and Concrete Composites* 86 (2018): 217–228. https://doi.org/10.1016/j.cemconcomp.2017.10.010.

[3] Rao, M. V., V. S. Reddy, and A. A. Kumar. "Sustainable self-healing concrete using indigenous additives." *Journal of Cleaner Materials* 2 (2020): 100024. https://doi.org/10.1016/j.jclema.2020.100024.

[4] Neville, A. M. *Properties of Concrete*. 4th ed. New Jersey: Pearson Higher Education, Prentice Hall, 1996.

[5] Neville, A. M. "Autogenous healing - A concrete miracle?" *Concrete International* 24, no. 11 (2002): 76–82.

[6] Wang, J., Van Tittelboom, K., De Belie, N., & Verstraete, W. "Use of silica gel or polyurethane immobilized bacteria for self-healing concrete." *Construction and Building Materials*, 26(1), (2012): 532–540.

[7] Chindasiriphan, P., Yokota, H., & Pimpakan, P. "Effect of fly ash and superabsorbent polymer on concrete self-healing ability." *Construction and Building Materials*, 233 (2020): 116975. https://doi.org/10.1016/j.conbuildmat.2019.116975

[8] Seifan, M., Samani, A. K., & Berenjian, A. "A novel approach to accelerate bacterially induced calcium carbonate precipitation using oxygen releasing compounds (ORCs)." *Biocatalysis and Agricultural Biotechnology*, 12 (2017): 299–307.

[9] Reinhardt, H. W., & Jooss, M. "Permeability and self-healing of cracked concrete as a function of temperature and crack width." *Cement and Concrete Research*, 33(7) (2003): 981–985.

[10] Alhalabi, Z. Sh., & Dopudja, D. "Self-healing concrete: definition, mechanism and application in different types of structures." *Proceedings*, (2017): 55–57.

[11] Nair, P. S., Gupta, R., & Agrawal, V. "Self-healing concrete: A promising innovation for sustainability review." *Materials Today: Proceedings*, 65 (2022): 1410–1417.

[12] De Rooij, M., Van Tittelboom, K., De Belie, N., & Schlangen, E. *Self-healing phenomena in cement-based materials*. Netherlands: Springer, 2013.

[13] Cuenca, E., & Ferrara, L. "Self-healing capacity of fiber reinforced cementitious composites." *KSCE Journal of Civil Engineering*, (2017): 2777–2789.

[14] Park, B., & Choi, C. C. "Investigating a new method to assess the self-healing performance of hardened cement pastes containing supplementary cementitious materials and crystalline admixtures." *Journal of Materials Research and Technology*, (2019): 6058–6073.

[15] Wu, M., Johannesson, B., & Geiker, M. "A review: self-healing in cementitious materials and engineered cementitious composite as a self-healing material." *Construction and Building Materials*, 28(1) (2012): 571–583.

[16] Talaiekhozan, A., Keyvanfar, A., Shafaghat, A., Aghayan, I., & Fulazzaky, M. A. "A review of self-healing concrete research development." *Journal of Environmental Treatment Techniques*, (2014): 1–11.

[17] De Belie, N., Gruyaert, E., Al-Tabbaa, A., Antonaci, P., Baera, C., Bajare, D., Darquennes, A., Davies, R., Ferrara, L., Jefferson, A., Ng, P. L., & Wang, J. "A review of self-healing concrete for damage management of structures." *Advanced Materials Interfaces*, 5(17) (2018): 1800074. https://doi.org/10.1002/admi.201800074

[18] Van Tittelboom, K., & De Belie, N. "Self-healing in cementitious materials – A review." *Materials*, 6(6) (2013): 2182–2217. https://doi.org/10.3390/ma6062182

[19] Rao, M. V., Reddy, V. S., & Kumar, A. A. "Sustainable self-healing concrete using indigenous additives." *Journal of Cleaner Materials*, 2 (2020): 100024. https://doi.org/10.1016/j.jclema.2020.100024

[20] Patil, M. S., & Shinde, R. S. "Experimental study on self-healing concrete using natural additives." *Materials Today: Proceedings*, 46 (2021): 12456–12461. https://doi.org/10.1016/j.matpr.2021.03.330

[21] Ferrara, L., Krelani, V., & Moretti, F. "On the use of crystalline admixtures in cement-based construction materials: from porosity reducers to promoters of self-healing." *Smart Materials and Structures*, 25(8) (2016): 1–17.

[22] Escoffres, P., Desmettre, C., & Charon, J. P. "Effect of a crystalline admixture on the self-healing capability of high-performance fiber reinforced concretes in service conditions." *Construction and Building Materials*, 173 (2018): 763–774.

[23] Roig-Flores, M., Moscato, S., Serna, P., & Ferrara, L. "Self-healing capability of concrete with crystalline admixtures in different environments." *Construction and Building Materials*, 86 (2015): 1–11.

[24] Wang, X., Fang, C., Li, D., Han, N., & Xing, F. "A self-healing cementitious composite with mineral admixtures and built-in carbonate." *Cement and Concrete Composites*, 92 (2018): 216–229.

[25] Sisomphon, K., Copuroglu, O., & Koenders, E. A. B. "Self-healing of surface cracks in mortars with expansive additive and crystalline additive." *Cement and Concrete Composites*, 34(4) (2012): 566–574.

[26] Cuenca, E., Tejedor, A., & Ferrara, L. "A methodology to assess crack-sealing effectiveness of crystalline admixtures under repeated cracking-healing cycles." *Construction and Building Materials*, 179 (2018): 619–632.

[27] Coppola, L., Coffetti, D., & Crotti, E. "Innovative carboxylic acid waterproofing admixture for self-sealing watertight concretes." *Construction and Building Materials*, 171 (2018): 817–824.

[28] Roig-Flores, M., Pirritano, F., Serna, P., & Ferrara, L. "Effect of crystalline admixtures on the self-healing capability of early-age concrete studied using permeability and crack closing tests." *Construction and Building Materials*, 114 (2016): 447–457.