Sustainable Concrete Incorporating Waste Marble, Polypropylene Fibres and Microbial-Induced Calcite Precipitation: A Review of Mechanical Performance, Durability and Machine-Learning-Based Prediction

Arya Katkar[1], Mayura M Yeole[2]

Department of Civil Engineering, Pimpri chinchwad college of Engineering and Research, Ravet, Pune, Maharashtra, India.

DOI: https://doi.org/10.51244/IJRSI.2026.1310000168

Received: 19 October 2026; Accepted: 24 October 2026; Published: 11 November 2026

ABSTRACT

The construction industry is increasingly exploring sustainable concrete technologies to reduce the consumption of natural resources, minimize industrial waste disposal and improve the service life of concrete structures. Waste marble powder and marble fines have attracted considerable attention as potential constituents of concrete, while polypropylene fibres can improve crack resistance and microbial-induced calcite precipitation (MICP) offers a promising approach to biological crack healing. In parallel, machine learning (ML) techniques provide opportunities to predict concrete properties and optimize mixture proportions using experimental and published datasets. This review examines the potential of integrating waste marble, polypropylene fibres and microbial self-healing mechanisms into sustainable concrete. The influence of waste marble on hydration, workability, strength and durability is discussed alongside the crack-control mechanisms of polypropylene fibres and the mineral precipitation processes associated with bacterial self-healing. The applicability of machine-learning methods for predicting mechanical properties, durability indicators and crack-healing performance is also reviewed. Particular attention is given to research gaps concerning material compatibility, optimum replacement levels, bacterial viability, long-term performance, environmental assessment and model generalization. The review identifies the need for systematic experimental investigations supported by explainable and independently validated predictive models. Such an integrated approach could contribute to the development of durable, resource-efficient concrete, provided that the proposed combinations are validated through controlled laboratory testing.

Keywords: Sustainable concrete; waste marble powder; polypropylene fibres; microbial-induced calcite precipitation; self-healing concrete; durability; machine learning.

INTRODUCTION

Concrete is one of the most widely used construction materials because of its availability, versatility and capacity to resist compressive loads. However, conventional concrete production involves substantial consumption of cement, aggregates and water. Cement production also contributes to greenhouse-gas emissions, while the extraction of natural aggregates can cause environmental disturbance. At the same time, marble processing generates considerable quantities of powder and fine waste that require appropriate management. The reuse of such waste in concrete offers an opportunity to reduce the demand for conventional materials and divert industrial residues from disposal [8–15].

The performance of concrete is influenced not only by its initial strength but also by its ability to resist cracking, moisture ingress and environmental deterioration. Polypropylene fibre-reinforced concrete has therefore received attention because fibres can restrict crack development and improve the behaviour of concrete after cracking. Reviews by Liu et al. [17] and Abdulkareem et al. [18] discuss the influence of polypropylene fibres on water absorption, permeability, chloride penetration, carbonation and freeze–thaw resistance.

Another promising development is microbial-induced calcite precipitation (MICP), in which selected microorganisms promote mineral precipitation that can seal cracks in cementitious materials. Bacteria-based self-healing concrete has been investigated as a means of reducing crack-related deterioration and potentially extending the service life of concrete structures [19–25].

Recent advances in artificial intelligence and machine learning have further expanded the possibilities for concrete mixture design and performance prediction. Data-driven methods can establish relationships between mixture constituents, curing conditions and measured material properties [7, 27]. Their application may reduce the number of preliminary trial mixtures, although reliable predictions depend on the quality and representativeness of the training data.

Against this background, the present review examines the individual contributions of waste marble, polypropylene fibres and MICP, together with the potential role of machine learning in predicting concrete performance. It also identifies the limitations that must be addressed before these technologies can be combined into a practically applicable sustainable concrete system.

2. Waste Marble in Sustainable Concrete

2.1 Characteristics and potential applications

Waste marble is generated during quarrying, cutting, polishing and finishing operations. Depending on the processing method, it may be available as powder, slurry, fine aggregate or larger stone fragments. Its suitability for concrete depends on particle-size distribution, mineralogical composition, moisture content and the presence of impurities.

Marble powder has been investigated as a partial replacement for cement because its fine particles can influence particle packing and the microstructure of the cementitious matrix. Its use as a fine aggregate replacement may also help utilize waste that would otherwise require disposal. However, these two applications should be distinguished because the mechanisms governing their performance are different [8–15].

Sathe et al. [3] investigated the effects of waste marble used as a partial replacement for cement and fine aggregate, considering mechanical properties, durability and microscopic characteristics. Their work is directly relevant to assessing the feasibility of incorporating marble waste into concrete. The broader literature also examines the effects of marble powder on strength development, permeability and hardened concrete properties [8–12].

2.2 Influence on fresh and hardened properties

The effect of marble powder on concrete depends on its replacement percentage, fineness, chemical composition and interaction with other mixture constituents. At suitable proportions, fine particles may improve packing by filling spaces between larger particles. This can contribute to a denser matrix when the water content, paste volume and particle grading are appropriately controlled.

However, excessive replacement of cement with a predominantly filler-type material can reduce the quantity of reactive cementitious constituents. Consequently, strength development may be affected, particularly when the replacement level is high or curing conditions are inadequate. Similarly, replacing fine aggregate with marble waste changes the grading and surface characteristics of the aggregate system and may influence workability and water demand.

The influence of marble powder should therefore not be generalized as uniformly beneficial. The optimum replacement level must be established for the specific material source and concrete mixture. Mechanical testing should include compressive strength, splitting tensile strength and flexural strength, while durability assessment should consider water absorption, sorptivity and permeability. Microscopic techniques, including scanning electron microscopy where available, can help explain observed changes in the interfacial transition zone and pore structure [3, 8–15].

2.3 Sustainability considerations

The environmental benefit of using waste marble depends on more than the quantity of waste incorporated into concrete. Collection, drying, grinding, transportation and processing also consume energy and resources. A meaningful sustainability assessment should therefore compare the environmental impacts of the proposed mixture with those of a conventional reference mixture.

In addition, the replacement of cement with marble powder should be evaluated alongside the resulting strength and service-life performance. A mixture that uses more waste but experiences substantial strength loss or reduced durability may not provide the expected environmental advantage. Future studies should combine mechanical performance with life-cycle assessment and cost analysis to determine whether the material substitution provides a net benefit.

3. Polypropylene Fibres and Crack Control

Polypropylene fibres are synthetic fibres commonly used to control plastic shrinkage cracking and improve crack distribution in concrete. Their influence depends on fibre length, diameter, volume fraction, dispersion and bond with the cementitious matrix. Liu et al. [17] reviewed the durability performance of polypropylene fibre-reinforced concrete, including water absorption, permeability, chloride penetration, sulphate resistance, freeze–thaw behaviour, carbonation and fire performance. Abdulkareem et al. [18] similarly examined the influence of polypropylene fibres on concrete durability.

Fibres can bridge developing cracks and distribute tensile deformation across multiple cracks rather than allowing deformation to concentrate entirely at a single location. This mechanism can improve crack control and may reduce the rate at which harmful substances enter the concrete. However, the extent of improvement depends on the crack width, fibre distribution and quality of the surrounding matrix.

Excessive fibre content or poor mixing can lead to fibre balling, reduced workability and non-uniform distribution. Weak fibre–matrix bonding may also limit the effectiveness of the fibres. Accordingly, the optimum fibre content should be selected through trial mixtures rather than assumed to be universally applicable [17, 18].

When waste marble and polypropylene fibres are used together, the performance of the combined mixture may depend on interactions between particle packing, paste volume, workability and fibre dispersion. A denser matrix may support durability, while fibres may help control crack formation. Nevertheless, the combined benefit must be verified experimentally because changes in matrix composition can also influence fibre bonding and cracking behaviour.

A systematic experimental programme should compare conventional concrete, marble-modified concrete, fibre-reinforced concrete and concrete incorporating both waste marble and fibres. This approach would help isolate the contribution of each constituent and determine whether the combined mixture provides a measurable advantage.

4. Microbial-Induced Calcite Precipitation and Self-Healing Concrete

4.1 Mechanism of microbial self-healing

Concrete cracks may develop because of shrinkage, thermal effects, loading and environmental exposure. Once cracks form, water and aggressive substances may penetrate the concrete, potentially accelerating deterioration. Conventional repair methods can restore performance but may require labour, materials and repeated maintenance.

MICP offers an alternative mechanism in which microorganisms promote the precipitation of calcium carbonate within cracks and pores. Under suitable conditions, the precipitated mineral can partially or completely seal cracks, depending on crack geometry, moisture availability, bacterial activity and the availability of calcium and other required nutrients.

Vijay et al. [22] reviewed bacteria-based self-healing concrete and described the role of bacterial calcium carbonate precipitation in crack sealing. Garga et al. [21] examined MICP mechanisms, concrete applications and associated challenges. Nodehi et al. [20] provided a systematic review of the biomineralization mechanisms and mechanical and durability properties of bacteria-based self-healing concrete.

The effectiveness of MICP depends on the bacterial strain, incorporation method, nutrient system, curing environment and survival of microorganisms in the highly alkaline cementitious matrix. Direct bacterial addition may be affected by the harsh internal environment of concrete, whereas encapsulation or other protective delivery systems may improve bacterial survival. These strategies introduce additional considerations, including cost, compatibility with the matrix and the possible influence of capsules on mechanical properties [20–25].

4.2 Mechanical and durability performance

Bacterial mineral precipitation may reduce the connectivity of cracks and pores, potentially improving water resistance and limiting the ingress of aggressive substances. However, crack closure observed visually does not necessarily demonstrate complete recovery of the original mechanical capacity. A rigorous assessment should therefore distinguish crack-width reduction from recovery of strength, stiffness or impermeability.

The review by Nodehi et al. [20] emphasizes the relationship between bacterial biomineralization and concrete performance, while Wong et al. [23] discuss developments, environmental requirements and remaining challenges in microbial self-healing. Bagga et al. [24] further highlight the potential of modelling to complement experiments in bacterial self-healing concrete.

For concrete containing waste marble, the availability of calcium-bearing constituents, pore structure and transport of moisture may influence the local conditions for mineral precipitation. Nevertheless, the effect of marble waste on bacterial activity and healing efficiency should not be assumed without direct evidence. The compatibility of marble powder, bacteria, nutrients and the cementitious matrix remains an important area for systematic investigation.

4.3 Integration with polypropylene fibres

Polypropylene fibres and bacterial self-healing may provide complementary functions. Fibres can limit crack opening or distribute cracking, while bacterial precipitation may subsequently seal some cracks when suitable conditions are available. This combination could potentially improve both crack control and post-cracking durability.

However, the combination introduces several research questions. Fibre-induced changes in crack width and distribution may affect the accessibility of bacteria and nutrients. Meanwhile, the chemical and physical characteristics of the matrix may affect mineral precipitation and the adhesion of deposited calcium carbonate to crack surfaces.

A suitable study should therefore measure initial crack width, crack closure over time, water permeability before and after healing, and the repeatability of healing under controlled curing conditions. Microscopic examination and mineralogical characterization would help determine whether observed crack closure is associated with calcium carbonate deposition or other mechanisms.

5. Machine Learning for Concrete Performance Prediction

5.1 Applications in concrete technology

Machine learning can identify relationships between input variables and measured concrete properties using data from experiments or published studies. Potential input parameters include cement content, marble replacement percentage, fibre dosage, water-to-binder ratio, aggregate proportions, curing age and bacterial dosage. Output variables may include compressive strength, tensile strength, water absorption, permeability indicators and crack-healing efficiency.

Kudoli and Bala [7] reviewed machine-learning and conventional approaches for predicting physical and mechanical properties of cement and cement mortar. Yeh [26] demonstrated the application of artificial neural networks to high-performance concrete strength modelling. Nithurshan and Elakneswaran [27] reviewed concrete strength prediction models and the broader challenges associated with their application.

For sustainable concrete incorporating waste marble, polypropylene fibres and MICP, predictive models could help identify promising mixture proportions and explore interactions among multiple constituents. Candidate algorithms include multiple linear regression, random forest, support vector regression, artificial neural networks and gradient-boosting methods. The selection of a model should depend on dataset size, data quality, interpretability and validation performance rather than on algorithm complexity alone.

5.2 Model development and validation

A reliable machine-learning workflow should begin with a clearly defined prediction objective and a documented dataset. Experimental observations should be checked for missing values, inconsistent units, duplicate entries and differences in testing procedures. Data from different studies should be combined only after considering differences in materials, curing conditions and measurement methods.

The dataset should then be divided into training and testing subsets, with model parameters selected using suitable validation procedures. Where data are drawn from multiple publications, random splitting alone can lead to overly optimistic results because observations from the same experimental programme may appear in both training and testing subsets. Grouped or study-level validation can provide a more meaningful assessment of the model's ability to generalize to new experimental programmes.

Model performance can be evaluated using the coefficient of determination ((R^2)), root mean square error (RMSE) and mean absolute error (MAE). These indicators should be reported together because no single metric fully characterizes predictive performance. An independent dataset is desirable where sufficient data are available.

Explainable machine-learning techniques, such as feature importance analysis and SHAP-based interpretation, can help identify influential variables and reveal potential interactions. However, feature importance indicates predictive association rather than proving a physical or chemical causal mechanism.

5.3 Limitations of predictive models

The principal limitation of machine learning in this area is the likely scarcity of consistent experimental data for mixtures combining all three components: waste marble, polypropylene fibres and bacterial healing systems. A model trained predominantly on conventional concrete may not accurately predict the performance of a novel hybrid mixture.

Furthermore, crack-healing performance depends on factors such as initial crack width, moisture conditions, healing duration and bacterial viability. If these parameters are not measured consistently, the model may fail to capture the relevant mechanisms.

Accordingly, machine learning should complement rather than replace laboratory experimentation. Predictions for new mixtures must be verified using independently prepared specimens and controlled testing. This is particularly important when a model is used to support engineering recommendations or material optimization.

6. Research Gaps and Future Directions

The reviewed literature establishes separate research foundations for marble waste utilization, fibre reinforcement, bacterial self-healing and data-driven prediction. However, several opportunities remain for integrated investigation.

First, the combined influence of waste marble, polypropylene fibres and MICP requires systematic evaluation. Experimental programmes should establish the contribution of each constituent through control mixtures and carefully selected replacement and dosage levels.

Second, mechanical strength and durability should be assessed together. Compressive strength alone cannot establish whether a mixture offers improved resistance to cracking, water penetration or environmental exposure. A broader testing programme should include tensile and flexural properties, water absorption, sorptivity, permeability and suitable exposure tests.

Third, bacterial self-healing should be evaluated using standardized crack preparation and monitoring procedures. Crack-width reduction, water-tightness recovery and strength recovery should be reported as separate outcomes. Microscopic or mineralogical characterization can provide evidence of the mechanisms responsible for healing.

Fourth, machine-learning models should be developed using traceable experimental data with clearly documented material properties and testing procedures. Study-level validation, uncertainty assessment and explainability should be incorporated to reduce the risk of misleading predictions.

Finally, sustainability and practical feasibility require greater attention. Life-cycle assessment and cost analysis should account for waste processing, fibre production, bacterial delivery systems, nutrient requirements, curing conditions and potential maintenance savings. Long-term performance and field-scale validation are also needed before the technology can be recommended for widespread structural applications.

CONCLUSION

Waste marble, polypropylene fibres and microbial-induced calcite precipitation represent three complementary approaches to improving the resource efficiency and performance of concrete. Waste marble can provide an alternative use for industrial residues and may influence particle packing and hardened properties. Polypropylene fibres can assist crack control, while MICP offers a potential mechanism for sealing selected cracks through mineral precipitation. Machine learning can support the prediction and optimization of concrete properties when sufficient high-quality experimental data are available.

Nevertheless, the effectiveness of these approaches depends on material characteristics, mixture proportions, fibre dispersion, bacterial viability, curing conditions and the specific performance requirements of the concrete. Their combined benefits cannot be assumed from studies of individual constituents and must be established through controlled experiments.

Future research should integrate mixture optimization, mechanical testing, durability assessment, crack-healing evaluation, explainable machine learning and environmental analysis. Such a framework can provide a stronger scientific basis for developing sustainable concrete systems that use industrial waste effectively while maintaining the performance required for practical construction.

REFERENCES

1. P. S. Basavaraj, M. Selvakumar, M. M. Yeole, “Explicit-dynamics assessment of reinforced concrete frame response under TNT blast: Stand-off, charge weight and incidence angle effects,” SSRG International Journal of Civil Engineering, 13(3) (2026) 255–273. https://doi.org/10.14445/23488352/IJCE-V13I3P119
2. K. N. Vishwanath et al., “Freeze–Thaw Resistance of Sustainable Concrete: Experimental Investigation, Damage Mechanisms, and AI/ML-Based Performance Prediction,” International Journal of Artificial Intelligence and Machine Learning, 6(13s) (2026) 218–230. https://doi.org/10.51483/IJAIML.6.13s.2026.218-230
3. S. Sathe, M. Sonawane, M. Yeole, S. Shekokar, P. D. Gunaware, “Effects of waste marble as partial replacement of cement and fine aggregate on the mechanical, durability and microscopic properties of

concrete," Magazine of Concrete Research, 78(17–18) (2026) 1064–1088. https://doi.org/10.1680/jmacr.25.00443

4. M. Guddad et al., "Microbially Induced Calcite Precipitation (MICP)-Based Bio-Mediated Self-Repairing Concrete Incorporating Bacillus subtilis: Mechanical Performance and Chemical Durability Enhancement," International Journal of Civil Engineering, 13(8) (2026) 362–374. https://doi.org/10.14445/23488352/IJCE-V13I8P122
5. A. B. Kudoli, R. S. Patil, M. M. Yeole, "Recent advances in polypropylene fibre-reinforced concrete: A systematic review on mechanical characteristics and durability performance," Journal of Mines, Metals & Fuels, 73 (2025) 2887–2896. https://doi.org/10.18311/jmmf/2025/49411
6. A. B. Kudoli, "To study the properties of concrete by adding Fevicol," International Journal for Research in Applied Science & Engineering Technology, 5(11) (2017) 2063–2066. https://doi.org/10.22214/ijraset.2017.11298
7. A. B. Kudoli, A. Bala, "A comprehensive review of machine learning and traditional models for predicting the physical and mechanical properties of cement and cement mortar," Journal of Mines, Metals & Fuels, 73 (2025) 2923–2931. https://doi.org/10.18311/jmmf/2025/49408
8. Y. Wang, J. Xiao, J. Zhang, Z. Duan, "Mechanical behavior of concrete prepared with waste marble powder," Sustainability, 14(7) (2022) 4170. https://doi.org/10.3390/su14074170
9. "Exploring the potential of waste marble powder as a sustainable substitute to cement in cement-based composites: A review," Construction and Building Materials, 401 (2023) 132887. https://doi.org/10.1016/j.conbuildmat.2023.132887
10. A. Ghani et al., "Experimental study on the mechanical behavior of concrete incorporating fly ash and marble powder waste," Scientific Reports, 14 (2024) 19147. https://doi.org/10.1038/s41598-024-70303-Y
11. "Long term strength and durability parameters of hardened concrete on partially replacing cement by dried waste marble powder slurry," Construction and Building Materials, 198 (2019) 553–569. https://doi.org/10.1016/j.conbuildmat.2018.12.005
12. "Strength, permeation and micro-structural characteristics of concrete incorporating waste marble," Construction and Building Materials, 203 (2019) 45–55. https://doi.org/10.1016/j.conbuildmat.2019.01.079
13. S. Sathe, S. Patil, Y. N. Bhosale, "Investigation of strength, durability, and microstructure properties of concrete with waste marble powder as a partial replacement of cement," World Journal of Engineering, 23(1) (2026) 71–81. https://doi.org/10.1108/WJE-06-2024-0372
14. "Performance evaluation of marble powder and fly ash concrete for non-structural applications," Journal of Building Engineering (2024). https://doi.org/10.1016/j.jobe.2024.108499
15. "Marble Powder as a Sustainable Cement Replacement: A Review of Mechanical Properties," Sustainability, 17(2) (2025) 736. https://doi.org/10.3390/su17020736
16. "Influence of Marble Powder and Polypropylene Fibers on the Strength and Durability Properties of Self-Compacting Concrete (SCC)," Advances in Materials Science and Engineering (2022). https://doi.org/10.1155/2022/9553382
17. Y. Liu, L. Wang, K. Cao, L. Sun, "Review on the Durability of Polypropylene Fibre-Reinforced Concrete," Advances in Civil Engineering (2021), Article 6652077. https://doi.org/10.1155/2021/6652077
18. O. M. Abdulkareem, R. B. Alshahwany, A. A. Mousa, "Durability of polypropylene fiber reinforced concrete: Literatures review," Electronic Journal of Structural Engineering, 22(1) (2022) 14–28. https://doi.org/10.56748/ejse.2225701
19. Y. Tang, J. Xu, "Application of microbial precipitation in self-healing concrete: A review on the protection strategies for bacteria," Construction and Building Materials, 306 (2021) 124950. https://doi.org/10.1016/j.conbuildmat.2021.124950
20. M. Nodehi, T. Ozbakkaloglu, A. Gholampour, "A systematic review of bacteria-based self-healing concrete: Biomineralization, mechanical, and durability properties," Journal of Building Engineering, 49 (2022) 104038. https://doi.org/10.1016/j.jobe.2022.104038

21. R. Garg, R. Garg, N. O. Eddy, "Microbial induced calcite precipitation for self-healing of concrete: A review," Journal of Sustainable Cement-Based Materials, 12(3) (2023) 317–330. https://doi.org/10.1080/21650373.2022.2054477
22. K. Vijay, M. Murmu, S. V. Deo, "Bacteria based self healing concrete – A review," Construction and Building Materials, 152 (2017) 1008–1014. https://doi.org/10.1016/j.conbuildmat.2017.07.040
23. P. Y. Wong et al., "Advances in microbial self-healing concrete: A critical review of mechanisms, developments, and future directions," Science of the Total Environment, 947 (2024) 174553. https://doi.org/10.1016/j.scitotenv.2024.174553
24. M. Bagga et al., "Advancements in bacteria based self-healing concrete and the promise of modelling," Construction and Building Materials, 358 (2022) 129412. https://doi.org/10.1016/j.conbuildmat.2022.129412
25. D. O. Owolabi et al., "Comparative Analysis of Autogenous and Microbial-Based Calcite Precipitation in Concrete: State-of-the-Art Review," Buildings, 15(18) (2025) 3289. https://doi.org/10.3390/buildings15183289
26. I.-C. Yeh, "Modeling of strength of high-performance concrete using artificial neural networks," Cement and Concrete Research, 28(12) (1998) 1797–1808. https://doi.org/10.1016/S0008-8846(98)00165-3
27. M. Nithurshan, Y. Elakneswaran, "A systematic review and assessment of concrete strength prediction models," Case Studies in Construction Materials, 18 (2023) e01830. https://doi.org/10.1016/j.cscm.2023.e01830