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Durability Enhancement in Sustainable Concrete: A Critical Review of Fibre and Polymer Modification, Waste-Based Materials, Freeze– Thaw Resistance, Bio-Mediated Self-Healing and Predictive Modelling

Omkar Dagadu Kangune¹, Anand B. Kudoli^{1*}

Department of Civil Engineering, Pimpri Chinchwad College of Engineering and Research (affiliated to Savitribai
Phule Pune University), Ravet, Pune, Maharashtra, India^{1*}

ABSTRACT: Sustainable concrete is only sustainable if it lasts. A mixture that saves cement or reuses waste but deteriorates early simply moves the environmental burden to future repair. This review examines how four groups of modification—fibres, polymers, waste-based materials and bacterial self-healing agents—affect the durability of concrete, and how data-driven models can support service-life assessment. The discussion is organised around deterioration mechanisms rather than additives: transport of water and ions, cracking, freeze–thaw damage and chemical attack. Fibres reduce crack width and can lower permeability of cracked concrete, but they do not replace air entrainment for frost resistance. Polymer films reduce capillary porosity and improve resistance to ingress when formulation and curing are suitable. Waste marble and recycled aggregates can perform adequately at moderate replacement levels, provided that their effect on pore structure and absorption is controlled. Bacterial calcite precipitation can seal fine cracks and recover water-tightness, although recovery of mechanical capacity is limited. Freeze–thaw resistance depends mainly on the degree of saturation and the air-void system, so dense matrices are not automatically frost-resistant. A matrix linking modifications to durability indicators and a staged durability-assessment framework are proposed. The review recommends that durability claims be based on exposure-specific tests, multiple indicators and independently validated predictive models.

KEYWORDS: Concrete durability; Sustainable concrete; Freeze–thaw resistance; Transport properties; Self-healing concrete; Waste marble; Service-life prediction

I. INTRODUCTION

Most concrete structures are designed for a service life of 50 to 100 years, yet many require major repair long before that because of reinforcement corrosion, freeze–thaw damage, sulphate attack or alkali–silica reaction. Durability problems rarely arise from inadequate compressive strength. They arise from the ease with which water, chlorides, carbon dioxide and sulphates move through pores and cracks, and from the damage that cyclic environmental loading causes over time [1].

At the same time, the cement industry is under pressure to reduce its carbon emissions, and the use of supplementary and waste-derived materials is expanding rapidly [2]. These two agendas meet in the concept of sustainable concrete: a material that uses fewer virgin resources and less clinker while maintaining or extending service life. Modification strategies such as fibres, polymers, waste powders and bacterial agents are frequently proposed for this purpose, but their durability benefits are often inferred from strength results rather than demonstrated directly.

This review addresses that gap. Section 2 describes the review approach. Section 3 outlines the main deterioration mechanisms and the tests used to measure them. Sections 4–7 examine how fibre and polymer modification, waste-based materials, freeze–thaw exposure and bacterial self-healing interact with those mechanisms. Section 8 considers predictive modelling for durability and service life, Section 9 proposes an integrated durability-assessment framework, and Section 10 sets out research priorities.

II. REVIEW APPROACH

This is a critical narrative review. Relevant journal articles and reviews were identified through Google Scholar and Scopus-indexed journals using combinations of concrete durability, permeability, chloride, freeze–thaw, critical degree of saturation, polymer-modified, polypropylene fibre, waste marble, recycled aggregate, bacterial self-healing and service-life prediction. Studies were selected if they reported durability indicators directly, explained the controlling mechanism or reviewed a defined part of the field. Only sources with verifiable bibliographic details and digital object identifiers were retained. Because exposure regimes and test standards vary, results are compared qualitatively.

III. DETERIORATION MECHANISMS AND DURABILITY INDICATORS

Concrete deterioration can be grouped into four interacting processes: (i) transport of water and dissolved ions through the pore system; (ii) cracking from shrinkage, thermal gradients or loading, which creates fast transport paths; (iii) physical damage from freezing of pore water; and (iv) chemical reactions such as carbonation, chloride-induced corrosion and sulphate attack. Because these processes interact—cracks accelerate transport, and transport supplies the water and ions for frost and chemical damage—no single test captures durability. Basheer et al. argued that permeation properties (absorption, permeability and diffusion) are the most useful general indicators of durability, provided the test is matched to the transport mechanism of the exposure [3]. Table 1 lists the main indicators and what each measures.

Table.1. Common durability indicators and the mechanisms they represent.

Indicator	Typical test	Mechanism represented	Key limitation
Water absorption	Immersion absorption	Total accessible porosity	Insensitive to pore connectivity
Sorptivity	Capillary rise	Near-surface capillary transport	Strongly affected by curing and moisture state
Chloride penetration	Rapid chloride permeability or migration tests	Ionic transport	Conductive fillers or fibres can bias results
Carbonation depth	Accelerated carbonation, phenolphthalein	CO ₂ ingress, loss of alkalinity	Accelerated tests may not reflect field rates
Sulphate resistance	Length and mass change in sulphate solution	Expansive reaction products	Long duration
Freeze–thaw resistance	Rapid cycling with mass loss and dynamic modulus	Frost damage, scaling	Saturation and cycle definitions differ between standards
Crack healing	Crack width, water permeability recovery	Self-sealing, autogenous or bacterial	Surface closure may not reflect internal healing

IV. FIBRE AND POLYMER MODIFICATION

4.1 Fibres

Fibres influence durability mainly through cracking. By restraining plastic and drying shrinkage and by limiting the opening of load-induced cracks, fibres reduce the size of the fast transport paths that cracks provide. A review of polypropylene fibre-reinforced concrete reported improvements in resistance to shrinkage cracking, water penetration, chloride ingress and freeze–thaw damage at suitable dosages, while noting that poor dispersion can create voids that offset these benefits [4]. A systematic review of PP fibre concrete reached similar conclusions and stressed that dosage must be balanced against workability [5].

Two qualifications apply. First, fibres improve the durability of cracked concrete; in uncracked concrete their effect on permeability is small and can be negative if fibres entrap air or disturb compaction. Second, fibres do not substitute for an adequate air-void system in frost-exposed concrete. They may restrain internal crack growth during freezing, but the primary protection against frost remains entrained air and a low degree of saturation [6].

4.2 Polymers

Polymer admixtures form films within the cement paste that partially seal capillary pores and bridge microcracks. Ohama described the resulting co-matrix and its lower water absorption and chloride penetration compared with unmodified mortar [7]. Aggarwal et al. found that epoxy and acrylic emulsions reduced water absorption and improved the resistance of mortars to the ingress of aggressive agents [8]. The benefit depends on the polymer–cement ratio and on a curing regime that allows both cement hydration and film formation.

Adhesive-type products used informally on site, such as PVAc-based Fevicol, have been tested as concrete additives [9]. PVAc is, however, susceptible to hydrolysis in wet alkaline conditions, so its long-term durability benefit in continuously wet exposure is uncertain. Formulated latexes such as SBR and acrylics are more appropriate where water resistance is essential.

V. WASTE-BASED MATERIALS AND DURABILITY

5.1 Waste marble

Fine marble powder can refine pore structure by filling voids and providing nucleation sites, which may reduce water absorption at low replacement levels. At higher cement replacement, however, dilution of the reactive binder increases porosity and reduces resistance to ingress. A review of waste marble powder in cement-based composites identified replacement level, fineness and chemical composition as the main controls on durability [10]. Sathe et al. tested waste marble both as partial cement replacement and as partial fine-aggregate replacement and examined durability and microstructure alongside strength [11]. Their approach illustrates a useful practice: separating the binder and aggregate roles so that pore-refinement and dilution effects can be distinguished.

Marble is predominantly calcium carbonate. In sulphate environments at low temperature, carbonate-rich binders may be vulnerable to thaumasite formation, and marble-containing mixtures intended for such exposure should be tested accordingly. This risk is rarely addressed in current studies.

5.2 Recycled aggregates and supplementary materials

Recycled concrete aggregates usually increase water absorption and chloride penetration because of the porous adhered mortar. These effects can be reduced by limiting the replacement level, pre-saturating aggregates or adding pozzolanic materials. High-volume fly ash concrete shows how supplementary materials change performance over time: early-age strength is lower, but continued pozzolanic reaction produces substantial later-age gains [12]. The same reaction refines the pore structure, which is why long curing and testing at later ages are essential when durability of such mixtures is assessed. Sustainability assessment of recycled aggregate concrete should consider service life and structural performance as well as resource savings, because a shorter life can cancel the environmental benefit [13].

VI. FREEZE–THAW RESISTANCE

6.1 Damage mechanisms

Freeze–thaw damage results from the expansion of freezing pore water, hydraulic pressure as unfrozen water is forced through the pore system, and osmotic and crystallisation effects in the presence of de-icing salts. Guo et al. reviewed these mechanisms and the models used to describe them, emphasising that damage accumulates as internal microcracking and surface scaling [1]. The two forms of damage are measured differently: internal damage through loss of relative dynamic modulus, and surface damage through scaled mass.

6.2 Critical degree of saturation and air voids

The single most important variable is the degree of saturation. Li et al. showed that concrete suffers little frost damage until its degree of saturation exceeds a critical value, after which damage develops rapidly within a few cycles [14]. Entrained air protects concrete by keeping the degree of saturation below this critical value and by providing space into which water can be expelled during freezing. A review of additives for frost resistance confirmed that air entrainment, a low water–cement ratio and appropriate supplementary materials are the main design levers, and that dense matrices achieved with silica fume or nano-additives are not frost-resistant without an adequate air-void system [6].

6.3 Sustainable concrete under freeze–thaw

Waste and supplementary materials change pore size distribution and water uptake, so their effect on frost resistance is not predictable from strength alone. Vishwanath et al. investigated the freeze–thaw resistance of sustainable concrete, linked the observed damage to its mechanisms and used AI/ML models to predict performance [15]. Such work is valuable because freeze–thaw tests take weeks to months. It also highlights the need to report saturation procedure, cycle temperature, number of cycles, relative dynamic modulus and mass loss so that datasets from different studies can be combined.

VII. BIO-MEDIATED SELF-HEALING

7.1 Mechanism and evidence

Bacterial self-healing concrete contains dormant spores and nutrients that become active when water enters a crack, precipitating calcium carbonate that seals the crack mouth and part of its depth [16]. Wiktor and Jonkers quantified healing in bacteria-based concrete and showed that cracks up to about 0.46 mm wide could be sealed and made watertight, compared with much narrower cracks in control specimens [17]. Guddad et al. reported improved mechanical performance and chemical durability for concrete containing *Bacillus subtilis* [18]. Recent reviews describe MICP as a promising route to longer service life and lower repair demand, with additional potential in environmental restoration [19]. Wider reviews of self-healing concrete compare bacterial agents with autogenous healing and encapsulated polymers, and conclude that the most suitable mechanism depends on crack width, moisture availability and the required speed of healing [20, 21].

7.2 Measuring healing efficiency

Healing should be measured with several indicators, because surface closure alone can be misleading. Table 2 compares the main measures.

Table.2. Indicators of self-healing efficiency

Indicator	What it shows	Limitation
Surface crack closure (microscopy)	Visible sealing of the crack mouth	May hide unhealed crack depth
Water permeability recovery	Restoration of water-tightness	Depends on crack geometry and test pressure
Chloride or capillary uptake in cracked zone	Resistance to ingress after healing	Fewer standard procedures
Strength or stiffness recovery	Mechanical restoration	Usually small; requires reloading tests
Repeated cracking–healing cycles	Persistence of healing ability	Rarely tested

The main constraints are bacterial survival in the alkaline matrix, availability of moisture and calcium, crack width and the time required for healing. Carriers such as silica gel or polyurethane can protect bacteria but add cost [22]. For durability, the relevant question is whether healing restores resistance to ingress in the actual exposure, not merely whether cracks appear closed.

VIII. PREDICTIVE MODELLING FOR DURABILITY AND SERVICE LIFE

Durability tests are slow, and service-life decisions must be made long before long-term field data are available. Machine-learning methods are therefore increasingly used to predict durability indicators and service life from mixture composition, curing and exposure data. Taffese and Sistonen reviewed machine-learning approaches to durability and service-life assessment of reinforced concrete and identified carbonation, chloride ingress and corrosion as the most studied targets, with data scarcity as the main barrier [23]. A review of traditional and machine-learning models for cement and mortar properties similarly concluded that data-driven models can outperform empirical equations within their training domain but must be validated on independent data [24].

For durability, three practices are especially important: (i) the target must be defined consistently, since mass loss, dynamic modulus and chloride diffusion coefficients are not interchangeable; (ii) exposure variables such as saturation, temperature cycle and duration must be included as inputs; and (iii) validation should hold out whole mixtures or studies rather than individual specimens, to avoid optimistic accuracy from repeated measurements of the same mixture.

IX. AN INTEGRATED DURABILITY-ASSESSMENT FRAMEWORK

Figure 1 proposes a staged framework that moves from exposure classification to verified service-life estimate. The modification is selected only after the dominant deterioration mechanism has been identified; tests are chosen to measure that mechanism; and predictive models are used to extend short-term results, with independent experimental checks.

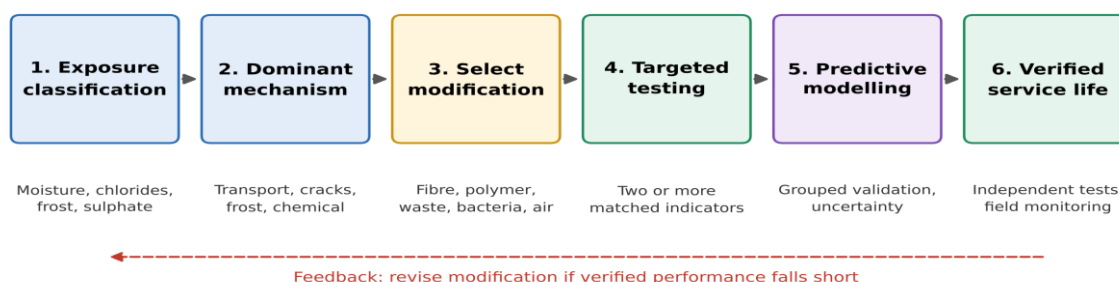


Figure.1. Staged framework for assessing the durability of modified sustainable concrete, from exposure classification to verified service-life estimate.

Table 3 links each modification to the mechanisms it can address and the evidence required.

Table.3.Modification–mechanism matrix for durability design

Modification	Mechanism addressed	Key evidence required	Main caution
Fibres	Crack width, shrinkage cracking	Permeability of cracked specimens, crack-width measurement	No substitute for air entrainment
Polymers	Capillary porosity, microcracking	Sorptivity, chloride penetration, wet–dry exposure	Hydrolysis of some polymers; curing sensitivity
Waste marble	Pore filling (low dose)	Absorption, chloride and sulphate tests at each dose	Dilution at high dose; carbonate-related sulphate risk
Recycled aggregate	— (usually adverse)	Absorption, chloride penetration, carbonation	Requires mix compensation
Bacterial healing	Crack sealing	Permeability recovery, repeated healing	Crack-width and moisture limits
Air entrainment (reference)	Frost damage	Air-void parameters, freeze–thaw cycling	Strength reduction

X. RESEARCH PRIORITIES AND CONCLUSION

Four research priorities emerge. First, durability claims should be tested directly, with at least two indicators matched to the expected exposure. Second, freeze–thaw studies should report degree of saturation and air-void parameters so that results can be compared and pooled. Third, bacterial self-healing should be evaluated through permeability recovery and repeated healing, not surface closure alone. Fourth, predictive models should be trained on consistently defined targets and validated on independent mixtures.

The main conclusions are as follows.

1. Durability is governed by transport, cracking, frost and chemical processes, not by compressive strength. Each claim should be supported by tests that measure the relevant mechanism.
2. Fibres improve the durability of cracked concrete by limiting crack width; polymers reduce capillary transport when formulation and curing are suitable. Neither replaces air entrainment for frost resistance.
3. Waste marble and recycled aggregates can perform adequately at moderate replacement levels, but dilution, absorption and source variability must be controlled, and binder and aggregate roles should be distinguished.
4. Freeze–thaw resistance depends mainly on the degree of saturation and the air-void system; dense matrices are not automatically frost-resistant.
5. Bacterial self-healing can restore water-tightness of fine cracks, but recovery of mechanical capacity is limited and depends on moisture and crack width.
6. Machine-learning models can shorten durability assessment, provided targets are consistent, exposure variables are included and validation is independent.

CRediT authorship contribution statement

Omkar Dagadu Kangune: Investigation, Data curation, Visualization, Writing – original draft. **Anand B. Kudoli:** Conceptualization, Methodology, Supervision, Validation, Writing – review and editing.

Declaration of competing interest

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Data availability

No new data were generated in this review. All information discussed is available in the cited literature.

Declaration of generative AI use

During the preparation of this work, the authors used ChatGPT solely for language editing and grammar checking. After using this tool, the authors reviewed and revised the content as necessary and take full responsibility for the content of the publication.

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