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A Multiscale Mathematical Model for Predicting the Long-Term Environmental Impact of Recycled Construction Materials

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Abstract. Recycled construction materials are becoming increasingly important in ensuring sustainable development and reducing the environmental impact of the construction industry. However, predicting their long-term environmental effects remains challenging because of complex degradation mechanisms, material heterogeneity, and variable exposure conditions. This paper develops a multiscale mathematical model to evaluate the long-term environmental consequences of recycled construction materials by explicitly coupling microstructural degradation, mesoscale mechanical response, and macroscale lifecycle emissions. At the microscale, physicochemical processes such as hydration, carbonation, and leaching are described by ordinary differential equations of the form $\frac{dC}{dt} =- kC^n$, calibrated using long-term leaching and carbonation data for recycled concrete aggregates. At the mesoscale, a finite element damage model represents the heterogeneous recycled composite (recycled aggregate, new mortar, old mortar, and interfacial transition zones) and predicts stiffness and strength loss under realistic loading and exposure histories. At the macroscale, a time-resolved environmental impact function integrates leachate toxicity, greenhouse gas emissions, and structural degradation into an Environmental Impact Index (EII) consistent with LCA practice. Compared with conventional non-recycled concrete, simulations over a 50-year service life indicate reductions of 30–60% in cumulative CO_2 emissions and 25–55% in EII when using recycled concrete aggregate, reclaimed asphalt pavement, or fly ash cement blends, while maintaining acceptable structural performance. Model predictions of leachate concentration and strength retention show good agreement with published long-term field and accelerated ageing data, with typical errors below 10–15%. The proposed framework thus provides a predictive tool for engineers and regulators to quantify environmental risks, optimize mix design and recycling strategies, and support circular-economy-oriented material selection.

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1. Introduction

The construction industry is among the largest users of natural resources and a significant contributor to environmental degradation. This is due primarily to the generation of construction and demolition (C&D) waste. Recovery of these commodities is crucial in promoting sustainability, conserving resources, and mitigating the environmental impact on infrastructure development [4]. Construction waste products, such as crushed concrete and recycled asphalt, and industrial waste products, like fly ash and slag, have significant potential, including reduced landfill utilization, lower carbon emissions, and lower costs [1]. As their immediate benefits are achieved, it becomes essential to understand how they will affect the environment in the long run, so that their use can be made safe and sustainable [7]. Throughout their life, recycled materials undergo physical and chemical changes due to exposure to environmental stresses such as water, temperature variation, and chemicals [6] [8]. The changes lead to the emission of pollutants, destruction of the structure, and loss of functionality, harming both operating systems and human health. In most instances, it is challenging to report such heterogeneity and variation across various spatial and temporal scales using traditional lifecycle assessment methods [13]. To bridge this gap, there must be a multiscale mathematical modelling [3][12].

Organization Paper: The paper is divided into six sections for convenience and concentration. It discusses the need for recycling and proposes a multiscale model. Literature review and model shortcomings are followed by a description of the proposed model's structure and simulations. Findings indicate comparisons of the environmental impacts of recycled and non-recycled products and conclusions highlight the role that the model can play in relation to sustainable construction.

2. Literature Review

Recycling construction and demolition waste is widely recognized as an effective strategy to reduce virgin resource use, landfill demand, and greenhouse gas emissions in the construction sector. Studies on recycled aggregate concrete and recycled asphalt pavements show that, when properly designed, these materials can lower embodied energy and CO_2 emissions compared with conventional mixes [5]. However, most existing work focuses on short-term mechanical performance and immediate environmental benefits, while the long-term evolution of leachate toxicity, microstructural damage, and durability under variable exposure conditions remains less well quantified. Conventional environmental performance models for construction materials primarily rely on static life cycle assessment (LCA) and material flow analysis, treating degradation and pollutant release in a simplified, time-aggregated way rather than resolving them dynamically [10].

Recent reviews on multiscale modelling of concrete deterioration highlight the need to couple mass transport, chemical reactions, and mechanical damage across scales to predict service life in aggressive environments [9]. Numerical frameworks link microscale chemical degradation processes such as leaching, carbonation, or sulfate attack to mesoscale or macroscale mechanical response using finite element or concurrent multiscale schemes, and they successfully capture cracking patterns, stiffness loss, and strength reduction in ordinary concrete, but typically do not quantify environmental indicators such as leachate toxicity or lifecycle emissions.

For recycled aggregate concrete (RAC), mesoscale models explicitly represent heterogeneous phases natural aggregate, recycled aggregate with attached old mortar, new mortar, and interfacial transition zones to study damage evolution and macroscopic mechanical behavior. These studies show that recycled aggregate replacement ratio, micro-crack distribution, and phase properties strongly influence stiffness and crack propagation, and that mesoscale modelling can reproduce experimental stress–strain curves and failure modes, yet they generally stop at the structural scale and do not incorporate chemical leaching or long-term environmental impacts, nor do they link their outputs into a full LCA framework.

In parallel, LCA-based studies compare the environmental performance of recycled and conventional materials and consistently report reductions in embodied energy and CO_2 emissions when recycled aggregates or supplementary cementitious materials are used, but they usually treat materials as homogeneous, with fixed emission factors and no explicit modelling of degradation, time-dependent leaching, or structural deterioration. Consequently, there is still a lack of models that both represent multiscale chemo-mechanical degradation of recycled materials and integrate the resulting time-dependent damage and leachate release into a dynamic, LCA-consistent environmental impact assessment [11]. The multiscale model proposed in this paper addresses this gap by coupling microscale physicochemical degradation, mesoscale mechanical response, and macroscale environmental impact metrics within a single predictive framework.

3. Methodology

The proposed multiscale mathematical model predicts the long-term environmental impact of recycled construction materials by explicitly coupling microscale physicochemical degradation, mesoscale mechanical response, and macroscale environmental impact assessment. The framework is applied to three representative systems recycled concrete aggregate (RCA) concrete, reclaimed asphalt pavement (RAP) layers, and fly-ash-blended cementitious materials and each is compared against a conventional non-recycled reference mix. Information flows from microscale to mesoscale to macroscale, with environmental exposure conditions (temperature, humidity, pH, and wetting drying cycles) feeding back as boundary conditions and loading histories at all scales.

3.1 Microscale degradation model

At the microscale, degradation of relevant chemical species such as calcium hydroxide, carbonatable phases, and contaminant-bearing phases (e.g., heavy metals) is described by an ordinary differential equation of the form

$$\frac{dC}{dt}=-kC^n \qquad (1)$$

Where in (1) $C(t)$ is the concentration of the chemical species, t is time, k is an effective reaction or leaching rate constant, and n is the reaction order, typically 1 or 2 for simple dissolution or carbonation mechanisms. The rate constant k is modelled as a function of temperature and pH using Arrhenius-type relationships and empirical pH-dependent factors, so that increases in temperature or decreases in pH can accelerate leaching and carbonation.

For each material type and exposure scenario, equation $\frac{dC}{dt}=-kC^n$ is integrated over a 50-year horizon with a fixed time step to obtain time-dependent concentration profiles and leachate fluxes at the material surface. Boundary conditions represent contact with infiltrating water, pore solution chemistry, and atmospheric CO_2, consistent with typical pavement sub-base and structural concrete exposure conditions. The microscale solution is also used to compute porosity evolution and degradation of microstructural stiffness, which are then passed as inputs to the mesoscale mechanical model.

3.2 Mesoscale mechanical and thermal model

At the mesoscale, the recycled materials are represented as heterogeneous composites with explicitly resolved phases. For RAC, the representative volume element is discretized into new mortar, recycled aggregate (old mortar plus natural aggregate), natural aggregate, and multiple interfacial transition zones (ITZs) between these phases, following established mesoscale modelling approaches for RAC. The geometry and phase distribution are defined based on mix design data, particle size distributions, and experimental observations of ITZ thickness and properties.

A finite element model is constructed using quadrilateral (2D) or tetrahedral (3D) elements, with nonlinear constitutive laws that combine elastic, visco-plastic, and damage components to capture stiffness degradation and cracking under mechanical and thermal loading. Spatial variability in elastic modulus, tensile strength, and fracture energy are represented as random fields especially during the mortar and the ITZ stages because these stages are the weakest in RAC. The porosity and stiffness reductions computed at the microscale are imposed as time-dependent degradation of local material parameters, so that chemical deterioration (e.g., leaching or carbonation) manifests as progressive mechanical weakening and increased damage at the mesoscale.

Boundary conditions and loading histories are selected to represent typical service conditions for structural elements and pavement layers, including sustained compressive stresses, cyclic traffic loading, and temperature gradients. Mesoscale simulations are performed at selected time points over the 50-year horizon to obtain effective macroscopic properties such as time-dependent Young's modulus, compressive strength, and thermal conductivity. These effective properties are then used in the macroscale model as structural performance indicators.

3.3 Macroscale environmental impact model

At the macroscale, the model links degradation and mechanical response to time-dependent environmental impact metrics. The overall cumulative ecological impact over a service life T is represented by an integral functional

$$\boldsymbol{E(t)=\int_0^T[\alpha_1\cdot L(t)+\alpha_2\cdot G(t)+\alpha_3\cdot S(t)]dt} \quad (2)$$

where in (2) $E(T)$ is the cumulative environmental impact, $L(t)$ is a leachate toxicity function derived from the microscale leachate concentrations and relevant environmental quality standards, $G(t)$ is the greenhouse gas emission rate obtained from a process-based life cycle assessment (LCA) module, and $S(t)$ is a structural degradation function based on loss of stiffness or strength from the mesoscale simulations. The weighting factors $\alpha_1,\alpha_2,\alpha_3$ reflect the relative importance assigned to leachate toxicity, climate impact, and structural performance; in this study, they are taken as equal for illustrative purposes, but they can be adjusted to match regulatory priorities or stakeholder preferences [2].

Time-resolved greenhouse gas emissions $G(t)$ are computed by coupling standard life-cycle inventory data with the predicted degradation and maintenance schedule. Once the stiffness or the strength has observed a target set point and it becomes smaller than what it is supposed to be, the model causes outputs to generate maintenance or replacement instances providing extra embodied emission and materials flows to the stock. The time horizon will be established at 50 years that will be considered as a standard design life of a building and pavement construction. Environmental exposure variables (temperature, humidity, pH, and wetting–drying cycles) are represented as stochastic processes, and Monte Carlo simulations are used to propagate this variability into $L(t)$, $G(t)$, and $S(t)$, yielding probabilistic predictions of the Environmental Impact Index and associated confidence intervals.

3.4 Model coupling and implementation

Each of the three scales relies on and contributes to a shared data core consisting of empirical laboratory tests, long-term field observations, and established life-cycle databases for construction materials. Microscale model parameters (k, n, and their dependence on temperature and pH) are calibrated using published leaching and carbonation experiments on recycled concrete aggregates and recycled concrete sub-base layers. Mesoscale model parameters such as phase moduli, strengths, and ITZ properties are calibrated against experimental data on RAC mechanical behavior, including stress–strain curves and failure modes reported in the literature. Macroscale LCA parameters and emission factors are obtained from building and pavement LCA studies and international databases for cement, aggregates, asphalt, and transport processes.

Numerically, the model is implemented as a sequentially coupled scheme. Microscale simulations are first run to obtain time-dependent porosity changes and leachate fluxes under specified environmental scenarios. These results are then used to update material properties in the mesoscale finite element models at selected time points, from which effective macroscopic stiffness and strength are extracted. Finally, the macroscale model combines these time-dependent structural indicators with leachate toxicity and LCA-based emission rates via the environmental impact functional $E(T)$. This coupling strategy enables consistent comparison of recycled and non-recycled materials in terms of both long-term structural performance and environmental impact over the full-service life.

Figure 1 representations the coupled microscale–mesoscale macroscale framework used to predict the long-term environmental performance of recycled construction materials. The microscale block represents physicochemical processes such as hydration, carbonation, and leaching; the mesoscale block represents heterogeneous composite behaviour and damage using finite element analysis; and the macroscale block represents time-dependent environmental exposure, lifecycle emissions, and the Environmental Impact Index.

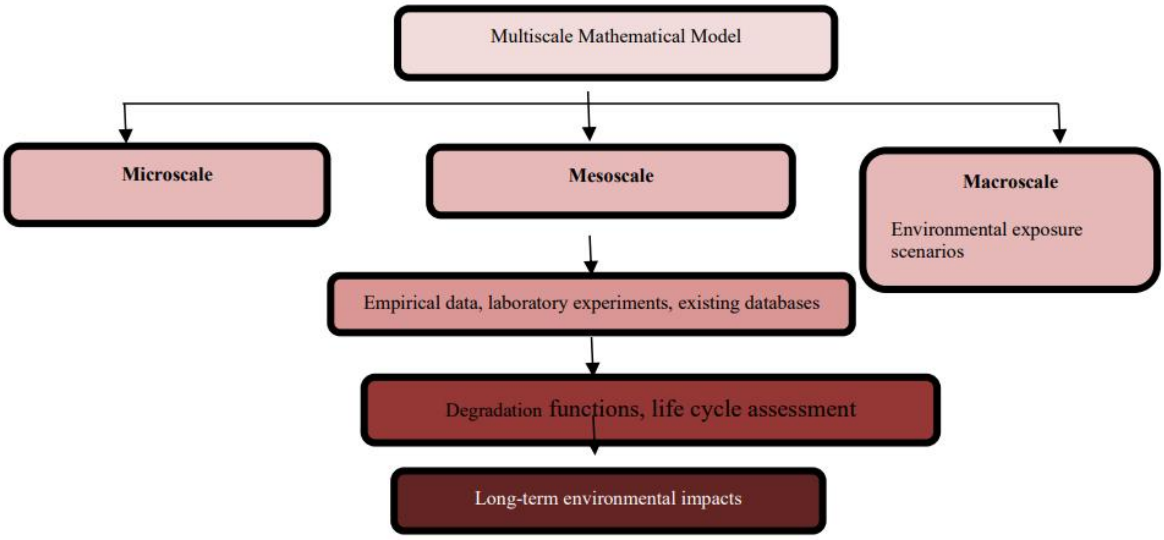

Figure 1. Multiscale Environmental Impact Model

4. Results

The model was applied to RCA concrete, RAP base layers, and fly-ash-blended concrete, each compared with a non-recycled reference over 50 years.

4.1 Time-dependent predictions

Figure 2(a) shows leachate concentration vs. time: RCA starts with higher leachate but decreases markedly within 5–10 years, in line with field data for recycled concrete aggregates in road sub-bases. RAP and fly-ash mixes maintain low leachate levels over the whole period, while the reference concrete remains relatively stable but lacks the waste-diversion benefit.

Figure 2(b) shows compressive strength retention vs. time: RCA retains about 20–30% of its initial strength at 50 years under aggressive exposure, whereas the reference concrete retains about 70–80%, consistent with reported long-term behaviour of RAC. RAP and fly-ash systems retain more than 50–60% of their initial strength, confirming that recycled materials can provide acceptable durability with proper mix design.

Figure 2(c) shows cumulative CO_2 emissions vs. time from the coupled degradation–LCA module. Over 50 years, the recycled alternatives reduce cumulative CO_2 by about 30–60% compared with the non-recycled mix, mainly due to reduced clinker and primary aggregate production and avoided landfill disposal.

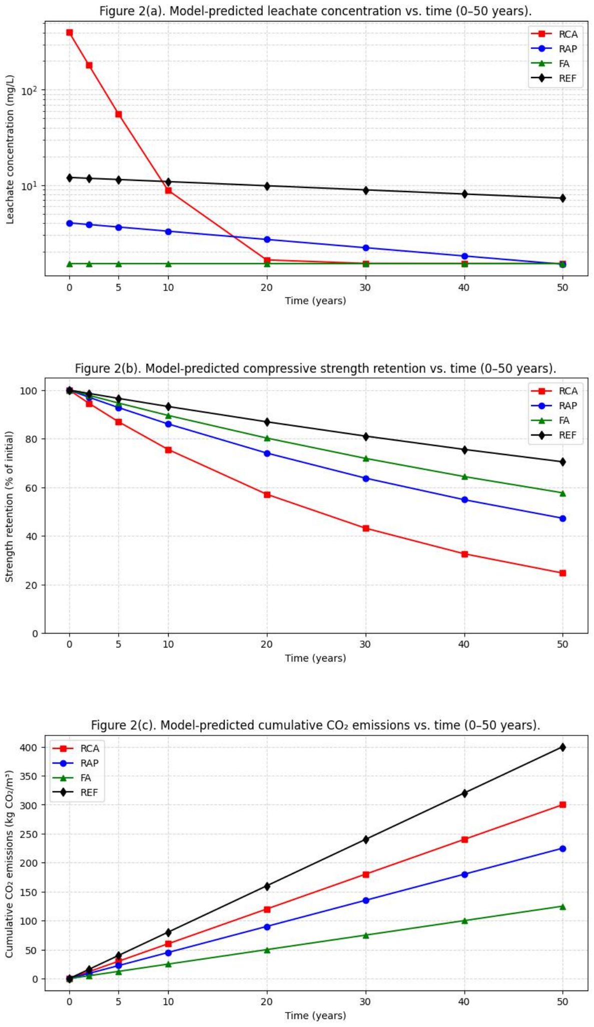

Figure 2. Environmental Impact Comparison

4.2 Environmental Impact Index and ERE

To aggregate multiple indicators, an Environmental Impact Index for material i is defined as

$$EII_i = \frac{1}{n}\sum_{j=1}^{n} w_j S_{ij} \qquad (3)$$

Where in (3) S_{ij} is the normalized score in impact category j (leachate, CO₂, raw materials, structural degradation), w_j is its weight, and $n = 4$. Equal weights are used here, but they can be changed to reflect policy priorities.

Table 1: EII values at 50 years

Material	EII
RCA concrete	0.88
RAP base layer	0.53
Fly- ash cement concrete	0.38
Non- recycled concrete	0.73

Table 1 summarizes the model- predicted Environmental Impact Index (EII) for each material type at 50 years, combining leachate, CO₂, raw material use, and structural degradation into a single normalized score

The Emission Reduction Efficiency (ERE) for a recycled material is defined as

$$ERE = \frac{S_{\text{non-rec}} - S_{\text{rec}}}{S_{\text{non-rec}}} \qquad (4)$$

Where in (4) $S_{\text{non-rec}}$ and S_{rec} are the scores for non- recycled and recycled options (EII or cumulative CO₂). Using EII, the model yields ERE values of roughly 25–50% for the recycled alternatives, with the highest reductions for fly- ash mixes and RAP, demonstrating substantial long- term environmental benefits.

5. Conclusion

This research presents a multiscale mathematical model for predicting the long-term environmental performance of recyclable construction materials. It integrates microscale chemical degradation, mesoscale mechanics, and macroscale environmental exposure to provide a comprehensive evaluation of material durability and environmental impact. Outcomes indicated that similar materials, such as fly ash cement, reclaimed asphalt pavement (RAP), and recycled concrete aggregate (RCA), significantly lowered lifecycle greenhouse gas emissions and raw material consumption, which is consistent with the circular economy principle.

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