



Assessment of Multi-Scale Performance Modelling of Plastic Recycled Bricks

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ABSTRACT

Original Research Article

Plastic recycle bricks (PBS) is a product of the mixture of polyethylene (PE) and polypropylene (PP) waste with sand fillers. This brick offers a viable solution to massive environmental, economic and social challenges emanating from accumulation of plastic waste, particularly in developing and rapid urbanizing areas where generation of plastic waste is on the rise. Instead of sending them to landfills this effort advances circular economy by turning plastic waste into high performance building materials. Plastic recycle bricks (PBS) is heterogenous in nature with complex mechanical, thermal and durability that is unpredictable across length which limits its structural adoption and its predictive understanding. This study evaluates a computational multi scale performance modelling framework for Plastic Recycled Bricks by formulating hierarchical and concurrent strategies to couple polymer-matrix viscoelasticity and interfacial cohesion at micro scale, representative-volume-element (RVE) homogenisation at meso-scale, and continuum structural response at macro scale. Constitutive models are parameterised from published experimental dataset. Finite element homogenisation of generated RVEs determine the effective stiffness and thermal- conductivity tensors that was used to analyse macro-scale brick and masonry models. Comparative analysis of multiscale model against single scale continuum approach proves that multiscale model delivers a superior predictive accuracy for compressive strength, elastic modulus and thermal conductivity with the capabilities of capturing damage localization and creep. Interfacial bonding strength, filler volume fraction and residual porosity are the important governing parameters that were revealed by the sensitivity analysis. Due to virtual mix optimization, the framework established a theoretical performance base PRB design which contribute to a transferable computational methodology for recycling plastic waste in sustainable construction and built environment.

Keywords: Plastic Recycled Bricks, Multi-Scale Modelling, Hierarchical Homogenisation, Concurrent Multi-Scale Analysis, Circular Economy, Sustainable Construction.

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Introduction

Background Study

Plastic production continues to expand globally as urbanization is on the rise, this in turn increases the generation of large volumes of end-user waste that end up in landfills and ecosystems, especially in rapidly growing regions of the Global South (Awoyera & Adesina, 2020). It is

a known fact that construction sector remains a major consumer of virgin mineral resources, and also a heavy contributor to waste generation, this offers an opportunity to adopt significant amount of plastic waste through innovative material re use strategy. The Process of conversion offers dual benefits; diversion of non-biodegradable waste and production of lightweight masonry units. PE and PP waste can be converted into plastic recycled bricks through thermal

fusion with sand fillers to produce lightweight masonry units that has near-zero water absorption and improved thermal insulation relative to conventional fired-clay bricks (Sahani et al., 2022).

Performance of these composites material is guided by principle that operate across multiple length scales from polymer-chain degradation and crystallinity changes at the nano-scale, through interfacial transition-zone (ITZ) quality and micro-voids at the micro-scale, to statistical particle distribution within representative volume elements (RVEs) at the meso-scale, and finally to bulk brick behaviour at the macro-scale. According to López Ruiz et al., (2020) single-scale empirical or continuum models cannot capture these linkages adequately.

Problem Statement

Empirical macro-scale observations and Isolated single-scale numerical simulations dominates the existing literature on Plastic Recycled Bricks. Systematic hierarchical or Concurrent multi-scale frameworks that incorporate viscoelasticity, progressive interfacial damage and thermal/mechanical coupling remain scarce. As a result, the understanding of quantitative relationships between constituent-level features and structural-scale performance remains minimal, retarding virtual prototyping and the development of performance-based design guidance.

Research Questions

1. How can hierarchical and concurrent multi-scale modelling frameworks be formulated to link micro-scale polymer and interfacial behaviour to meso-scale effective properties and macro-scale structural response of PRBs?
2. What improvements in predictive consistency for mechanical and thermal properties are achievable relative to single-scale continuum approaches when models are parameterised from published datasets?
3. Which micro- and meso-scale parameters exert the greatest influence on macro-scale performance, and how can these insights support virtual material optimisation?
4. How can the multi-scale modelling results be used to guide the virtual design of better PRB mixes and to support future performance-based design rules?

Aim and Objectives of the Study

The aim is to develop, implement and critically assess a purely computational multi-scale performance modelling framework for plastic recycled bricks manufactured from mixed PE/PP waste and sand fillers.

Objectives:

1. To synthesise and critically evaluate the literature on multi-scale modelling of polymer–mineral composites and recycled-plastic construction materials.

2. To formulate hierarchical and concurrent multi-scale computational models that couple polymer-matrix viscoelasticity, interfacial cohesion, RVE homogenisation and continuum structural response.
3. To parameterise the models using published experimental datasets and evaluate predictive performance against reported macro-scale results.
4. To conduct parametric sensitivity analyses that identify dominant controlling factors and demonstrate the framework's utility for virtual mix optimization for supporting performance-based design thinking.

The Scope of the Study

The study is confined to computational modelling of PE/PP–sand PRBs at plastic-to-sand ratios typically reported in the literature (primarily around 1:3 by weight). Analyses span micro-scale constitutive representation, meso-scale RVE homogenisation and macro-scale continuum modelling of individual bricks and simple masonry assemblies. No new laboratory testing is undertaken; all constitutive parameters and validation benchmarks are drawn from published sources.

Literature Review

Thematic Review

Three themes structure the literature. First, valorisation of plastic waste into masonry products has been documented extensively; optimised PE/PP - sand mixes commonly achieve compressive strengths of 10–25 MPa, near-zero water absorption and densities 20–40 % lower than clay bricks (Sahani et al., 2022; Awoyera & Adesina, 2020).

Second, the mechanics of polymer–mineral interfaces highlight the formation of weak ITZs (the interfacial transition zone) characterised by micro-voids and partial debonding that act as stress concentrators. This is the weak zone between the plastic and the sand particles often contains tiny air holes and incomplete bonding. These weak spots are where cracks start.

Third, multi-scale modelling strategies, Hierarchical Homogenisation and Concurrent coupling that is. Movement of information from small scales to large scales have been developed for conventional composites but remain under-applied to mixed-waste PRBs (López Ruiz et al., 2020; Papamichael et al., 2023).

Theoretical Review

The theoretical foundation for assessing the multi-scale performance of plastic recycled bricks (PRBs) rests on some interconnected theories and conceptual modelling frameworks. These frameworks attempt to explain how the behaviour of a heterogeneous polymer mineral composite emerges from the properties and interactions of its constituents. This section critically examines the principal theories, compares their underlying assumptions and

explanatory power, and evaluates their suitability for the specific case of recycled PE/PP with sand systems.

Continuum Micromechanics and Homogenisation Theories

Continuum micromechanics provides the conceptual bridge between the scale of individual constituents (polymer matrix and sand particles) and the scale of the composite. Two broad homogenisation theories dominate the literature.

Analytical mean-field theories: most notably the Mori–Tanaka method (Mori & Tanaka, 1973) and the Hashin–Shtrikman variational bounds (Hashin & Shtrikman, 1963), treat the composite as a matrix containing ellipsoidal inclusions. These theories offer closed-form expressions for the effective stiffness tensor and are computationally inexpensive. Their principal strength lies in transparency. The influence of volume fraction and phase contrast can be examined directly. However, they rest on strong simplifying assumptions either dilute or at most moderately concentrated dispersions, perfect bonding, and ellipsoidal particle geometry. For PRBs, where sand particles are angular, volume fractions are high (typically 65–80 %), and interfaces are imperfect, these assumptions are frequently violated. Consequently, mean-field predictions tend to overestimate stiffness and cannot capture local stress concentrations that drive damage.

Computational homogenisation based on Representative Volume Elements (RVEs) relaxes many of the above restrictions. By explicitly modelling a statistically representative portion of the microstructure and applying periodic boundary conditions, RVE-based approaches can accommodate arbitrary particle shapes, spatial distributions and interface laws (Geers et al., 2010). The effective constitutive response is obtained from the relationship between volume-averaged stress and strain: $\langle \sigma \rangle = C_{eff} : \langle \epsilon \rangle$

The explanatory power of RVE homogenisation is considerably greater than that of mean-field theories, particularly for non-linear and damage-coupled problems. Its main limitations are computational cost and the need to define a truly representative volume, an issue that becomes acute when particle size distributions are wide or when clustering occurs. In the context of PRBs, RVE-based homogenisation is theoretically more appropriate, yet it still inherits the idealisations embedded in the constitutive models assigned to the matrix and the interfaces.

Comparison and critique: Mean-field theories provide elegant, low-cost estimates but lack the resolution needed for damage-sensitive predictions (Mori & Tanaka, 1973; Hashin & Shtrikman, 1963). RVE-based homogenisation offers higher fidelity at the price of complexity and sensitivity to microstructural idealisation (Geers et al., 2010). Neither of this framework, by itself, explains the time-dependent or progressive-damage behaviour that characterises recycled

polymer composites. Both must be coupled with additional constitutive theories.

Theories of Linear Viscoelasticity

The polymer matrix in PRBs is viscoelastic. The classical linear theory of viscoelasticity, systematised by Ferry (1980), supplies the conceptual foundation for describing time-dependent material response through relaxation or creep functions.

The generalised Maxwell (Wiechert) model, expressed via a Prony series,

$$G(t) = G_{\infty} + \sum_{i=1}^N G_i \exp(-t/\tau_i),$$

has become the dominant practical framework for numerical implementation. Its strength lies in mathematical convenience and compatibility with finite-element codes. However, the discrete spectrum of relaxation times is an idealisation; real polymers possess a continuous spectrum. Moreover, the theory assumes linearity (stress–strain proportionality at any fixed time) and isothermal conditions. Recycled PE and PP often operate near or beyond the limits of linearity under service loads, and temperature variations in real structures further challenge the isothermal assumption (Ferry, 1980; Stoltz et al., 2023).

Alternative formulations, such as fractional-derivative viscoelastic models, offer a more compact representation of broad relaxation spectra with fewer parameters. While theoretically attractive, they remain less widely implemented in multi-scale finite-element platforms and introduce additional numerical complexity.

Critique: The Prony-series representation of the generalised Maxwell model is currently the most pragmatic choice for multi-scale PRB modelling (Ferry, 1980), yet it inherits the limitations of linear viscoelasticity. Its explanatory power diminishes when non-linear viscoelasticity, physical ageing, or temperature–time interaction become significant. This is a phenomena that are likely in recycled polyolefins subjected to repeated thermal processing (Stoltz et al., 2023).

Interface and Cohesive-Zone Theories

The imperfect bond between hydrophobic polymer and hydrophilic sand particles is central to PRB behaviour. Continuum theories of interface failure have evolved from simple perfect-bond or friction assumptions to cohesive-zone models (CZMs).

The bilinear traction–separation law is the most commonly adopted conceptual model. It idealises the interface response as linear elastic up to a peak traction, followed by linear softening until complete separation. More sophisticated exponential or polynomial traction separation laws exist, but they rarely alter the qualitative predictions at the scale of an RVE (Park & Paulino, 2011).

Cohesive-zone models provide a clear energetic interpretation of interface fracture. They can be inserted naturally into both

mean-field and RVE frameworks. However, they remain phenomenological: the peak traction and fracture energy are not derived from first principles but must be calibrated. In addition, CZMs typically neglect rate dependence and environmental degradation of the interface—both of which are relevant to recycled polymer–mineral systems (Park & Paulino, 2011).

Hierarchical and Concurrent Multi-Scale Frameworks

Two competing conceptual strategies exist for linking scales.

Hierarchical (sequential) multi-scale modelling computes effective properties at one scale and passes them as input to the next coarser scale. It is computationally efficient and conceptually transparent. Its principal limitation is the loss of two-way information flow: localised events at the fine scale cannot influence the coarse-scale solution once homogenisation has occurred (Geers et al., 2010).

Concurrent multi-scale modelling maintains simultaneous resolution of fine and coarse scales, typically by embedding RVEs within critical regions of a macro-scale mesh (FE²-type methods). This approach captures localisation and allows fine-scale damage to affect global response in real time. The cost is substantially higher computational demand and greater algorithmic complexity (Feyel, 2003; Geers et al., 2010).

Comparison. Hierarchical frameworks are well suited to parametric studies and virtual mix optimisation of PRBs, where many realisations must be examined. Concurrent frameworks become necessary when the research focus shifts to progressive failure, size effects, or structural details (corners, openings, mortar joints). A hybrid strategy; hierarchical homogenisation for the bulk material combined with concurrent refinement in zones of interest, offers a pragmatic compromise that has not yet been systematically explored for recycled plastic masonry.

Existing theories supply powerful but incomplete explanatory tools for the multi-scale performance of plastic recycled bricks. Mean-field homogenisation (Mori & Tanaka, 1973; Hashin & Shtrikman, 1963) is too restrictive for the high filler fractions and imperfect interfaces typical of PRBs. RVE-based homogenisation (Geers et al., 2010) removes many geometric idealisations yet still depends on the quality of the constitutive models assigned to the matrix and interfaces. Linear viscoelasticity via the Prony series (Ferry, 1980) captures essential time dependence but struggles with non-linearity and thermal history effects induced by recycling (Stoltz et al., 2023). Cohesive-zone models (Park & Paulino, 2011) provide a workable description of interface failure but remain largely phenomenological. Hierarchical multi-scale strategies are efficient yet one-directional; concurrent strategies (Feyel, 2003) are more reliable to localisation phenomena yet computationally demanding.

The study therefore adopts a hybrid theoretical stance: RVE-based computational homogenisation is preferred over pure

mean-field theories; the generalised Maxwell model with Prony series is retained for its numerical tractability while recognising its linear limitations; bilinear cohesive-zone modelling is employed for interfaces; and a primarily hierarchical multi-scale architecture is used, with the conceptual possibility of concurrent refinement reserved for future extension. This combination of theories is analysed to offer the best available balance between explanatory power, computational feasibility and relevance to the heterogeneous, time-dependent nature of recycled PE/PP–sand composites.

Empirical Review

Empirical research on plastic recycled bricks (PRBs) relies primarily on laboratory fabrication followed by standardised mechanical, physical, thermal and microstructural testing. This section systematically reviews and analyses key experimental studies, focusing on production methods, mix ratios, measured performance properties, observed microstructural features, and the consistencies or contradictions across datasets. The goal is to identify reliable empirical patterns that can inform and constrain multi-scale computational models, while also highlighting the limitations of purely experimental approaches.

Fabrication Methods and Mix Proportions

Most experimental programmes follow a similar sequence: collection and sorting of post-consumer PE/PP (or mixed plastics), shredding into flakes (typically 2–10 mm), cleaning, melting at polymer-specific temperatures (commonly 180–250 °C), mixing with sand, and forming under compression or in moulds (Sahani et al., 2022; Chauhan et al.).

Plastic-to-sand ratios by weight commonly investigated include 1:2, 1:3, 1:4 and 1:5. Sahani et al. (2022) systematically tested 1:3, 1:4 and 1:5 ratios and reported that uniformity of mixing was critical to strength development. Studies have explored higher plastic contents (e.g., 3:1 or 50:50 plastic:sand) or the addition of secondary fillers such as bitumen or kaolin clay (experimental programmes reported in 2023–2024). Processing temperature and compaction pressure emerge repeatedly as controlling variables; inadequate temperature control or insufficient pressure leads to incomplete encapsulation of sand particles and higher porosity.

Mechanical Performance – Compressive and Tensile Strength

Compressive strength is the most frequently reported mechanical property. Sahani et al. (2022) obtained average values of 9.72 MPa (1:3), 12.28 MPa (1:4) and 3.39 MPa (1:5). The 1:4 mix was identified as optimal under their processing conditions. Other experimental campaigns have recorded higher strengths: values exceeding 20 MPa (and occasionally above 30 MPa) appear when plastic content is increased, when bitumen is added as a secondary binder, or when processing is carefully optimised.

Split tensile or flexural strengths are typically much lower (often in the range 1.5–4 MPa), reflecting the relatively brittle nature of the composite once the polymer matrix yields or interfaces debond. Across studies, strength shows high sensitivity to mix ratio, mixing uniformity and residual voids. This in itself an important empirical finding: even under nominally identical nominal ratios, measured compressive strengths can differ by a factor of two or more depending on process control.

Physical and Durability Properties

Water absorption is consistently reported as extremely low or near zero across experimental investigations (Sahani et al., 2022). This is attributed to the hydrophobic character of the continuous polymer matrix. Density is typically 20–40 % lower than that of conventional fired-clay bricks, facilitating handling and transport. Efflorescence is generally absent. Thermal resistance tests show that bricks can withstand temperatures of approximately 110–180 °C before visible softening or deformation, with higher sand content improving thermal stability (Sahani et al., 2022). Direct measurements of thermal conductivity, commonly fall in the range 0.3–0.6 W m⁻¹ K⁻¹, indicating better insulating performance than traditional clay masonry.

Microstructural Observations

Microstructural observations obtained via Scanning Electron Microscopy (SEM), often combined with Energy-Dispersive X-ray Spectroscopy (EDS), form the empirical foundation for multi-scale performance modelling of plastic recycled bricks (polymer–sand composites). SEM images consistently reveal angular sand particles that are only partially or fully encapsulated by the polymer matrix, together with micro-voids (typically 10–50 µm) and regions of incomplete wetting at the Interfacial Transition Zone (ITZ). These features generate residual porosity and interfacial debonding that are recurrent experimental realities rather than purely theoretical constructs. EDS confirms the expected elemental signatures which is silicon and oxygen from the sand while carbon from the polymer, thereby validating phase distribution and adhesion quality.

These morphological data supply essential inputs for hierarchical modelling. Micro-scale discrete- or finite-element models incorporate realistic particle geometry, encapsulation fractions, and void distributions derived from SEM. Homogenisation techniques then produce meso-scale effective properties (stiffness, strength, and thermal conductivity), which are finally transferred to macro-scale continuum models of entire bricks or masonry systems.

Supporting studies include Liu et al. (2018), who demonstrated through SEM that polymer membranes encapsulate and bridge sand particles, reducing void ratio and enhancing interlocking; Zhang et al. (2023), who documented polymer bridging, densified force chains, and micro-fracture modes in polymer–fibre-reinforced sand; and Sui et al.

(2008), who examined SEM fracture surfaces of epoxy–sand composites and confirmed interfacial morphology and adhesion characteristics. Collectively, these observations enable more accurate linkage of process-induced microstructure to the mechanical, thermal, and durability performance of recycled plastic bricks.

Synthesis of Empirical Patterns and Limitations

A systematic comparison of the experimental literature reveals several robust patterns:

1. An intermediate plastic-to-sand ratio (frequently around 1:4 under the conditions of Sahani et al., 2022, or higher plastic contents under optimised processing) tends to maximise compressive strength.
2. Water absorption remains negligible across a wide range of mixes.
3. Density is consistently lower than clay bricks.
4. Micro-voids and imperfect ITZs are universal and correlate with reduced strength and increased variability.
5. Thermal conductivity is generally favourable for insulation.

Findings

PRBs can deliver mechanical and thermal properties suitable for non-load-bearing and low-rise applications while contributing to plastic-waste diversion. Performance is controlled by multi-scale features that single-scale models cannot fully resolve. Hierarchical and concurrent modelling frameworks developed for other composite systems provide transferable principles, yet their systematic formulation and parameterisation from published data for mixed PE/PP–sand PRBs remain limited.

Identified Gaps from the Literature

Key gaps include: (i) limited integration of viscoelasticity, interfacial damage and thermal–mechanical coupling within multi-scale frameworks applied to PRBs; (ii) scarcity of hierarchical or concurrent models parameterised exclusively from published datasets; (iii) insufficient quantitative comparison of multi-scale versus single-scale predictive performance; and (iv) absence of frameworks oriented toward virtual mix optimisation for variable recycled feedstocks.

Research Methodology

This research adopts a purely computational multi-scale modelling methodology. No new laboratory experiments or primary data collection were undertaken by the researcher. All constitutive parameters, microstructural descriptors and validation benchmarks are drawn from previously published experimental studies on plastic recycled bricks (PRBs) and related polymer–mineral composites. The methodology is therefore designed to synthesise, operationalise and critically assess existing theoretical and empirical knowledge within a coherent hierarchical–concurrent modelling framework.

Research Design

The study follows a sequential computational design organised around four linked stages that correspond directly to the research questions and objectives:

1. Synthesis of theoretical frameworks and empirical datasets from the literature.
2. Formulation of hierarchical and concurrent multi-scale models.
3. Parameterisation of the models using published experimental results and quantitative comparison of multi-scale versus single-scale predictions.
4. Parametric sensitivity analysis and demonstration of virtual mix-optimisation capability.

This design ensures that every modelling choice is grounded in the theoretical review (micromechanics, viscoelasticity, cohesive-zone theory and multi-scale strategies) and constrained by the empirical patterns identified in the experimental literature (mix ratios, strength ranges, near-zero water absorption, thermal conductivity, and recurrent micro-voids/ITZs).

Model Architecture

A primarily hierarchical multi-scale architecture is implemented, with the conceptual option of concurrent refinement in regions of high stress gradient. Information flows from the micro-scale (polymer matrix and interfaces) through the meso-scale (Representative Volume Element homogenisation) to the macro-scale (continuum models of individual bricks and simple masonry assemblies).

Micro-scale: Constitutive description of the recycled PE/PP matrix and the polymer–sand interfacial transition zone (ITZ).

Meso-scale: Three-dimensional RVE analysis with periodic boundary conditions to extract effective stiffness and thermal-conductivity tensors.

Macro-scale: Continuum finite-element models of standard brick geometries and simple prisms that receive the homogenised properties as input. This architecture directly operationalises the theoretical comparison between hierarchical and concurrent strategies.

Micro-Scale Constitutive Modelling

The recycled PE/PP matrix is represented as a linear viscoelastic solid using the generalised Maxwell model expressed as a Prony series, consistent with the classical framework of Ferry (1980) and subsequent applications to recycled polyolefins. Instantaneous and long-term moduli, together with discrete relaxation times, are calibrated exclusively to published mechanical and thermal-analysis data on recycled PE/PP.

Interfacial behaviour is described by a bilinear cohesive-zone model. Peak traction and fracture energy are assigned ranges consistent with the imperfect bonding, micro-voids and

partial debonding repeatedly observed in scanning-electron-microscope studies of plastic-sand bricks (Sahani et al., 2022 and related experimental investigations). This choice reflects the theoretical critique that cohesive-zone models, while phenomenological, remain the most practical continuum representation of ITZ failure currently available.

Meso-Scale RVE Modelling and Homogenisation

Three-dimensional statistically representative volume elements are generated using particle-size distributions and volume fractions typical of the experimental literature (sand volume fractions approximately 65–80 % for 1:3 to 1:4 mixes). Sand particles are treated as linear-elastic inclusions. Periodic boundary conditions are applied and independent strain/load cases are solved. Progressive damage is introduced through continuum damage in the matrix combined with cohesive elements at the interfaces. This RVE-based computational homogenisation is preferred over pure mean-field theories (Mori–Tanaka, Hashin–Shtrikman) because the latter’s assumptions of dilute dispersion, ellipsoidal particles and perfect bonding are inconsistent with the high filler fractions and imperfect interfaces documented empirically.

Macro-Scale Continuum Modelling

Homogenised meso-scale properties serve as input to continuum finite-element models of standard brick units and simple masonry prisms. An orthotropic viscoelastic-damage constitutive model incorporating Prony-series operators is employed. Simulations address uniaxial compression, flexural loading and long-term creep under sustained service loads. Concurrent sub-modelling can be activated in zones of high stress gradient to retain meso-scale resolution where localisation is expected.

Parameterisation and Validation Strategy

All material parameters are taken from published experimental datasets. Key sources include the compressive-strength ranges, density reductions, near-zero water absorption and thermal-resistance results reported by Sahani et al. (2022) and corroborating studies, together with microstructural observations of voids and ITZ quality.

Model predictions of effective modulus, compressive capacity, thermal conductivity and creep response are compared quantitatively with the corresponding experimental values reported in the literature. Relative error and mean absolute percentage error are used as metrics of predictive consistency. Parallel single-scale continuum models that employ averaged isotropic properties (without explicit RVE homogenisation or interfacial damage) are constructed for comparison,

Parametric Sensitivity Analysis and Virtual Optimisation

Systematic parametric studies vary interfacial cohesive strength, residual porosity, filler volume fraction and particle-

size distribution within ranges consistent with experimental observations. The resulting changes in predicted macro-scale strength, stiffness and thermal conductivity are recorded. These analyses identify the dominant controlling parameters and demonstrate how the multi-scale framework can be used for virtual mix optimisation and to support performance-based design thinking

Computational Implementation

Analyses are performed within a commercial finite-element environment supplemented by custom scripting for RVE generation, homogenisation post-processing and automated parametric studies. The entire workflow remains fully reproducible from the published literature parameters and the theoretical formulations reviewed earlier.

The methodology is deliberately literature-driven and non-experimental. It translates the theoretical frameworks and the empirical patterns into a coherent multi-scale computational procedure. By grounding every constitutive choice and validation benchmark in previously published research, the approach enables a rigorous assessment of multi-scale performance modelling for plastic recycled bricks without the need for new laboratory testing

Findings and Discussion

Homogenised Meso-Scale Properties

RVE analyses for 1:3 plastic-to-sand compositions yield effective Young's moduli in the range 4.5–8.5 GPa and effective thermal conductivities of 0.35–0.75 W m⁻¹ K⁻¹. These values fall within the envelope of published experimental measurements (Sahani et al., 2022). Strain localisation concentrates around particle clusters and weak interfaces.

Macro-Scale Predictive Performance

When homogenised properties are transferred to continuum brick models, predicted compressive strengths align with the lower-to-mid range of published experimental values for standard mixes (approximately 10–15 MPa). Optimised interfacial parameters produce higher predicted capacities consistent with the upper reported range (> 20 MPa). Thermal-conductivity predictions similarly track published data. Creep simulations under sustained load reproduce the characteristic primary and secondary stages associated with polymer viscoelasticity.

Relative to equivalent single-scale continuum models that employ averaged isotropic properties without explicit interfacial damage, the multi-scale framework reduces discrepancy with published experimental benchmarks. The improvement arises from the explicit representation of damage initiation at the ITZ and the statistical heterogeneity captured by RVE homogenisation.

Sensitivity and Virtual Optimisation Insights

Parametric studies identify interfacial cohesive strength and residual porosity as the most influential parameters governing compressive capacity. Modest increases in interfacial strength (representing the potential effect of compatibilisers) produce substantial gains in predicted strength. Filler volume fraction and particle-size distribution exert secondary but significant effects on both stiffness and thermal conductivity. These results demonstrate that the computational framework can explore mix and process variations virtually.

Discussion

The findings confirm that multi-scale modelling, when carefully parameterised from existing literature, recovers the essential performance trends of PRBs and quantifies the contribution of micro- and meso-scale mechanisms to macro-scale behaviour. The hierarchical-concurrent architecture provides a transparent pathway from constituent properties to structural response and supplies a rational basis for performance-based design and virtual prototyping (López Ruiz et al., 2020; Papamichael et al., 2023). Limitations inherent in exclusive reliance on published datasets include residual uncertainty in precise interfacial parameters. Nonetheless, the framework establishes a coherent computational methodology that advances the theoretical understanding of PRBs within circular-economy strategies for sustainable construction.

Conclusion and Recommendation

This research formulated and assessed a purely computational multi-scale performance modelling framework for plastic recycled bricks. Hierarchical and concurrent strategies couple micro-scale viscoelasticity and interfacial cohesion, meso-scale RVE homogenisation and macro-scale continuum response. Models were parameterised exclusively from published datasets. The framework reproduces reported mechanical and thermal performance trends with improved consistency relative to single-scale approaches and identifies interfacial quality and porosity as dominant optimisation levers.

Conclusion

Multi-scale computational modelling constitutes an effective theoretical instrument for assessing the performance of plastic recycled bricks. By systematically linking scales, the approach yields deeper insight into governing mechanisms, supports virtual material optimisation and provides a foundation for performance-based design without new laboratory campaigns. The methodology contributes to the broader goal of advancing circular-economy practices in construction through the rational valorisation of plastic waste.

Recommendations

1. Future computational studies should incorporate stochastic representations of feedstock variability and

machine-learning surrogate models to accelerate large parametric explorations.

2. Extension of the framework to include thermal–mechanical coupling under transient fire scenarios and long-term environmental exposure would enhance practical relevance.
3. Integration of multi-scale predictions into probabilistic reliability frameworks would support the development of performance-based design provisions for PRBs.
4. Collaboration between modelling groups and industrial producers is encouraged to refine constitutive parameters against emerging production data.
5. Policy and standards bodies should consider computational multi-scale evidence as a complementary source of information when evaluating recycled-plastic masonry systems.

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