Comparative Assessment of Recycled Concrete and Brick-Based Composites for Thermal, Mechanical, and Environmental Performance in Sustainable Construction

DANIAL RANJBARIAN, SEYEDEHZAHRA MIRRAHIMI
Department of Architecture and Energy Faculty of Fine Arts, University of Tehran Tehran, IRAN

Abstract: — This research examines composite materials made from recycled concrete and recycled bricks, comparing their thermal, mechanical, and environmental performance for use in sustainable buildings. The construction industry is currently under pressure due to high embodied carbon, intensive resource consumption, and increasing energy use. Recycling-based materials are a promising response to these issues, but their behavior under simultaneous thermal and mechanical loads is still not fully clarified. To tackle this gap, the study synthesizes results from recent experimental work and numerical simulations. It evaluates how factors such as mix design, use of supplementary materials, and surface treatments affect overall performance. Additives like Phase Change Materials, fly ash, and geopolymer binders are examined as strategies to improve durability and efficiency. The results show that recycled concrete can cut thermal conductivity by up to 76%, stabilize compressive strength by around 20–25%, and reduce Carbon dioxide emissions by about 30–60%. Recycled brick-based composites demonstrate 22–38% lower thermal conductivity, 15–28% higher strength, and 25–40% reductions in embodied carbon. Overall, the findings indicate that carefully optimized combinations of recycled concrete and brick materials can substantially enhance energy efficiency and environmental sustainability in contemporary building design.

Keywords: — Recycled concrete, Recycled brick, Thermal conductivity, PCM, Sustainability.

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1. Introduction

The construction sector is one of the largest contributors to global resource depletion and carbon emissions. To mitigate these impacts, sustainable construction promotes circular strategies, where recycling construction and demolition waste helps reduce embodied carbon and minimize landfill accumulation. Within this context, recycled concrete and recycled brick are particularly important because they represent a large portion of demolition debris and are widely available for reuse in urban construction [1, 2]. Recycled concrete generally exhibits reliable strength and durability, especially when enhanced with fly ash, geopolymer binders, or phase change materials. For example, the incorporation of PCM can lower thermal conductivity by nearly 40% without compromising compressive strength, and supplementary cementitious materials or CO_2-related treatments can reduce CO_2(Carbon dioxide) emissions while slightly improving strength [3,4,5]. Recycled brick, in contrast, provides lower density and superior thermal insulation. Its composites show 33–38% reductions in thermal conductivity, while LC3-based binders enhance compressive performance and reduce embodied emissions [6,7]. Collectively, these studies reveal complementary advantages—mechanical robustness in recycled concrete and insulation efficiency in recycled brick—yet they do not establish how these materials compare under similar design and environmental conditions [8,9]. Most previous investigations have evaluated each material independently, applying different experimental procedures, binder formulations, and climatic conditions. These variations limit the ability to compare results directly and make it uncertain under which circumstances each material performs more

TABLE I. NOMENCLATURE

Symbol / Abbreviation	Description
SCMs	Supplementary Cementitious Materials
RCP	Recycled Concrete Powder
RCA	Recycled Concrete Aggregate
RAC	Recycled Aggregate Concrete
CDW	Construction and Demolition Waste
PCM	Phase Change Material
ITZ	Interfacial Transition Zone
GHG	Greenhouse Gas
FA–SF	Blend of Fly Ash (FA) and Silica Fume (SF)
LCA	Life Cycle Assessment
WCBP	Waste Clay Brick Powder
RBC–EP	Recycled Brick Concrete with Expanded Polystyrene
LC3	Limestone Calcined Clay Cement
RBA	recycled brick aggregate
RFs	Recycled fines
EU	European Union
LECA	Lightweight Expanded Clay Aggregate
OPC–AAC	Ordinary Portland Cement
C&D	Construction and Demolition
ASHP	Air-Source Heat Pump
HRV	Heat Recovery Ventilation
PV	Photovoltaic
EC	Embodied Carbon
GGBS	Ground Granulated Blast Furnace Slag
LDPE	Low-Density Polyethylene
RBMA	Recycled Brick Masonry Aggregate
EPS	Expanded Polystyrene
3DPC	Three-Dimensional Printed Concrete

effectively in sustainable construction. This study addresses that gap by offering a comparative assessment of recycled concrete and recycled brick. It clarifies how each material contributes to environmental efficiency and structural adequacy and highlights their respective potential for advancing low-carbon, energy-efficient building design.

2. Recycled Concrete-based Materials

2.1 Mix Design and Composition

J. Li et al. (2024) (RFs) as (SCMs) and found that fine RFs (<45 µm) improved hydration and compressive strength by refining the pore structure [2]. X. Chen, Y. Li, H. Bai, and L. Ma (2021) Chen et al. (2021) examined Recycled Concrete Powder (RCP) in cement composites and found that incorporating 15% RCP with a (FA–SF) blend (3:2) improved hydration, reduced porosity, and increased compressive strength to 50.6 MPa [4]. J. Dgheim, K. Rizk, Y. Cherif, E. Antczak, E. Farah, and N. El Hajj (2024) investigated M60 concrete with varying (RCA) ratios. Strength decreased beyond 50% RCA, emphasizing optimal replacement for sustainability and performance balance[5]. S. Zhou et al. (2025) evaluated activation methods for residual slag micro powder from recycled concrete. Calcination at 750 °C for 10 min achieved 95.85% activity, improving strength and hydration reactivity[10]. A. M. Joseph, S. Matthys, and N. De Belie (2022) studied (RAC) incorporating (MSWI) bottom ash. A 23% replacement improved compressive strength by 16%, reduced carbonation by 45%, and maintained safe leaching levels within EU limits [11]. Y. Li, J. Long, and X. Chen (2024) studied CO_2 accelerated curing on recycled coarse aggregates, enhancing density by 3.9%, reducing water absorption by 22%, and improving concrete strength and durability [12]. M. Maroszek, M. Rudziewicz, K. Rusin-Zurek, I. Hager, and M. Hebda (2025) investigated 3D-printed concrete incorporating recycled and lightweight additives. (LECA) improved the balance between insulation and strength, while (EPS) provided the lowest thermal conductivity ($\lambda = 0.27$ W/m·K) but significantly reduced compressive strength [13]. I. Wichmann, R. Firdous, and D. Stephan (2023) produced alkali-activated lightweight aggregates from recycled concrete and brick powder. Concrete powder increased density and strength by forming dense geopolymeric bonds during curing [14]. R. Cruz, J. A. Bogas, A. Balboa, and P. Faria (2024) studied compressed earth blocks stabilized with recycled brick powder and cement. Results showed improved water resistance and 35% reduction in thermal conductivity [9].

2.2 Thermal and Mechanical Performance

T. Haller, S. Scherb, N. Beuntner, and K.-C. Thienel (2025) investigated (RAC) incorporating (PCM) and supplementary cementitious materials such as fly ash and silica fume. The results indicated up to a 43% reduction in thermal conductivity and enhanced thermal storage capacity, while maintaining compressive strength stability [15]. C. Mankel, A. Caggiano, A. Koenig, M. Nazari Sam, G. van Zijl, and E. Koenders (2019) simulated and experimentally validated PCM-filled recycled brick mortars, showing improved latent heat storage and stable thermal conductivity, enhancing energy efficiency in cementitious composites [3]. J. X. Deng, X. Li, X. J. Li, and T. B. Wei (2023) evaluated PCM-enhanced recycled insulation panels, showing a 42% reduction in thermal conductivity and stable heat capacity, improving energy efficiency and indoor thermal comfort [16]. .Zhou et al. (2025) investigated recycled concrete with PCM microcapsules, showing 41% thermal conductivity reduction and enhanced phase stability without significant strength loss, improving indoor thermal comfort [10]. C. Xu et al. (2024) investigated lightweight thermal insulation recycled concrete using waste wood and expanded perlite, achieving 76.5% reduction in thermal conductivity with acceptable strength and frost resistance [17]. D. Peiris, C. Gunasekara, D. W. Law, Y. Patrisia, V. W. Y. Tam, and S. Setunge (2025) investigated recycled concrete waste as cement replacement in mortars with microencapsulated PCM and expanded perlite, improving thermal performance ($\lambda \downarrow$ by 35%) while maintaining adequate strength for plaster use [18] . Z. Jia, J. Aguiar, S. Cunha, and C. de Jesus (2023) developed alkali-activated mortars using (CDW) glass and ceramics, achieving a thermal conductivity of $\lambda = 0.43$ W/m·K, a compressive strength of 31 MPa, and improved acoustic insulation [19]. D. Gonzalez-Betancur, A. A. Hoyos-Montilla, and J. I. Tobon (2024) produced hybrid lightweight concrete using recycled (EPS) and a hybrid Ordinary Portland Cement–Autoclaved Aerated Concrete (OPC–AAC) binder, achieving a compressive strength of 32.6 MPa, 21.5% lower density, and improved thermal insulation performance [20]. Zhong et al. (2025) analyzed SSF-reinforced recycled concrete under Na_2SO_4 dry–wet cycles; 1.5% stainless steel fibers improved compressive strength by 25% and enhanced sulfate resistance[1]. I. Khongová, I. Chromkova, and V. Prachar (2022) investigated mortars with recycled concrete and mineral fibers; 25% fiber mix achieved best frost resistance and 26% lower λ (1.225 W/m·K) than reference[21].

2.3 Thermal Improvement Mechanism

B. Zuhair and M. Z. Abdul Ameer (2025) analyzed the mechanical and thermal performance of recycled concrete aggregates treated by carbonation and nano-silica coating, which enhanced the Interfacial Transition Zone (ITZ) strength and reduced thermal conductivity by 18% [22]. S. Zhou et al. (2025) evaluated activation methods for residual slag micro powder from recycled concrete. Calcination at 750 °C for 10 min achieved 95.85% activity, improving strength and hydration reactivity[10]. Y. Li, J. Long, and X. Chen (2024) studied CO_2 accelerated curing on recycled coarse aggregates, enhancing density by 3.9%, reducing water absorption by 22%, and improving concrete strength and durability [12].

2.4 Climate Adaptation and Regional Performance

H. Mahmoud, E. Kuoribo, and N. M. Waly (2025) experimentally evaluated cement blocks with 85% construction waste, achieving 20% lower heat flux and improved thermal stability under hot climate conditions [23] . C. Porras-Amores, P. Martin Garcia, P. Villoria Sáez, M. del Rio Merino, and V. Vitielo (2021) evaluated recycled construction materials from CDW in Spain, showing 8–13% building energy savings and 7% roof insulation improvement, especially in colder climates [24] . Zhang et al. (2025) examined recycled aggregate concrete incorporating PCM and fly ash, achieving 38% lower thermal conductivity and 20% higher thermal energy storage efficiency under hot–humid conditions [1].

2.5 Carbon Reduction and Sustainability Impact

P. Sharma and S. Ghosh (2025) examined thermally treated (RCP) at 650–700 °C as a Supplementary Cementitious Material (SCM) in mortar, achieving a 20% increase in compressive strength and 10–15% lower thermal conductivity, contributing to reduced CO_2 emissions and improved sustainability in (C&D) waste reuse [25]. H. Zhang (2023) analyzed 11 retrofit measures for a mid-rise building in Canada. the results showed a 44% reduction in energy use and an 86% decrease in (GHG) emissions through the application of Air-Source Heat Pump (ASHP), (HRV), and solar (PV) systems [26]. B. Fraga-De Cal et al. (2021) developed geopolymer-based façade panels using CDW, tested in Greece, Italy, and Romania, achieving up to 25% energy savings and reduced GHG emissions[27]. L. S. Silva, M. K. Najjar, C. M. Stolz, A. N. Haddad, M. Amario, and D. T. Boer (2024) evaluated RAC with PCM and fly ash; λ reduced to 0.92 W/m·K, CO_2 emissions decreased 38%, and compressive strength increased 18% [28]. K. Y. Bhavana, S. Usha, T. V. Mallesh, and G. D. Shiva Raju (2024) analyzed (CDW)-based geopolymer blocks. A 50% recycled aggregate replacement achieved a compressive strength of 4.05 MPa and reduced CO_2 emissions through the use of fly ash, validated by ANSYS simulation [29]. O. Douidi, A. Tafraoui, A. Makani, and P. Serna (2024) investigated recycled concrete powder as supplementary cementitious material, finding optimal 20% replacement improves sustainability and maintains compressive strength while reducing cement-related emissions [30]. M. Keyhani, A. Bahadori - Jahromi, C. Fu, P. Godfrey, and H. Zhang (2024) analyzed Embodied Carbon (EC) reduction in UK buildings using Life Cycle Assessment (LCA). Replacing cement with Ground Granulated Blast Furnace Slag (GGBS) achieved a 60–70% reduction in EC and significantly improved overall sustainability [31].

3. Recycled Brick-based Materials

3.1 Mix Design and Composition

O. Salli Bideci, A. Bideci, and A. Ashour (2024) reviewed the use of waste clay brick powder as a supplementary cementitious material, reporting enhanced strength, reduced permeability, and 40% CO_2 reduction potential [32]. oC. Oze, N. Badacsonyi, and E. Mak (2024) investigated mechanochemical activation of waste clay brick powder mixed with glass powder, achieving 7–37% higher active silica and ~8% higher compressive strength [33]. X. F. Chen, X. C. Zhang, and Y. Peng (2025) found that 25% recycled clay brick powder optimally mitigates alkali–silica reaction (95% reduction) and achieves 96.95% pozzolanic activity index, enhancing mortar durability [34].

3.2 Thermal and Mechanical Performance

Z. Zhang, Y. Ji, and D. Wang (2025) demonstrated that fiber-reinforced recycled brick concrete improves compressive and flexural strength by 15–25% and reduces brittleness and crack propagation by 30% [8]. R. E. A. Elhady, D. Tarek, M. M. Ahmed, A. Yousef, and A. Ragab (2024)found that basalt and polypropylene fibers in recycled brick composites enhanced compressive strength by 28% and reduced water absorption by 14%, improving durability [35]. C. Ru, G. Li, F. Guo, X. Sun, D. Yu, and Z. Chen (2022) found that using recycled crushed brick aggregate reduced thermal conductivity by 38% and improved porosity-driven insulation without compromising compressive strength [36].

3.3 Thermal Improvement Mechanism

H. Christen, S. Cho, G. van Zijl, and W. de Villiers (2022) investigated 3D-printed concrete made with (RBA) that was vacuum-impregnated with a paraffin phase change material (PCM) to form PCM-RBA and a PCM-3D printed concrete mix. They concluded that PCM-3DPC achieved the highest predicted and realized number of printable layers, had higher strength than RBA-3DPC but lower than the reference 3DPC, showed no PCM leakage when heated up to 50 °C, and showed no negative effect on long-term (90-day) compressive strength [37]. L. Zhu, S. Lei, and T. Li (2024) examined recycled brick aggregate concrete and structural walls via an orthogonal test (w/c ratio, sand ratio, water per unit volume, RBA replacement) and hot-box/FE analyses, concluding RBA replacement significantly affects thermal conductivity and dry density, RBC walls show heat-transfer coefficients of 2.667–2.792 W/(m^2·K), and using RBC reduces wall heat-transfer by about 38% versus ordinary concrete, with reinforcement having negligible effect[38].

3.4 Climate Adaptation and Regional Performance

R. Briones-Llorente, E. Montero, V. Calderon, S. Gutiérrez-González, and Á. Rodríguez (2018) developed façade panels using recycled slag and polyurethane foam. Thermal conductivity decreased to 0.98 W/m·K. Energy simulations showed improved efficiency across Spanish climates [39]. W. N. Mohamed Abohelal*, Ingy Eldarwish, Hosny Dewer (2023) investigated the effect of using recycled bricks made from red brick waste and Low-Density Polyethylene (LDPE) on the energy efficiency of building exteriors. The results indicated that the recycled bricks achieved a 60% reduction in manufacturing cost and 33.5% lower cooling energy consumption compared with conventional red bricks, due to their lower thermal conductivity (0.71 W/m·K vs. 1.31 W/m·K) and higher compressive strength (15.58 MPa vs. 2.8 MPa) under hot–arid climatic conditions [6]. H. Krstić, I. Miličević, D. Markulak, and M. Domazetović (2021) examined the thermal performance of lightweight concrete walls made with recycled crushed brick and (EPS), referred to as RBC–EP, under moderate continental climatic conditions in Belgrade, Serbia. Laboratory and in-situ tests showed an average thermal conductivity of 0.3789 W/m·K, with U-values ranging from 1.36–1.78 W/m^2·K (uninsulated) and approximately 0.46 W/m^2·K after applying 10 cm of mineral wool insulation, achieving a 70% reduction in heat transmittance while maintaining sufficient mechanical strength [40]. T. Nicholas, T. Cavalline, D. Johnson, and M. Laney (2017) evaluated the thermal performance of mortars containing (RBMA) using the EnergyPlus simulation program under hot–humid (Miami, FL) and hot–dry (Phoenix, AZ) climatic conditions. The results showed that RBMA mortars exhibited comparable or slightly better energy efficiency than conventional C144 mortars, achieving a 2–3% reduction in heat transfer and lower cooling loads in lightweight masonry systems, confirming RBMA as a sustainable and energy-efficient material for warm regions of the United States [41].

3.5 Carbon Reduction and Sustainability Impact

F. Li, S. Jin, P. Cheng, Z. Wang, and Z. Yang (2024) investigated recycled brick aggregate concrete reinforced with polypropylene fibers, showing that replacing part of natural aggregate with recycled brick effectively reduced embodied carbon emissions while improving compressive strength and durability[42]. H. Alghamdi et al. (2024) developed Limestone Calcined Clay Cement (LC3) -based lightweight bricks incorporating waste rockwool. The results showed a thermal conductivity (λ) reduced to 0.36 W/m·K, a 13% reduction in CO_2 emissions, a 42% increase in compressive strength, and high fire resistance [7]. J. Pan, L. Cui, X. Zhang, and J. Zuo (2024) examined using waste brick powder (BP) by replacing 15% of cement with BP and bio-modifying BP with plant-based tannic acid (TA) to enhance its activity, concluding this supports low-carbon construction because cement is described as a "high-carbon" building material and their TA route avoids high-temperature activation with "high carbon emission [43]. M. Małek, P. Smarzewski, M. Kunikowski, and J. Kluczyński (2025) investigated concrete where ground brick powder from construction-and-demolition waste replaced 5–15% of natural fine aggregate, concluding this supports low-carbon circular construction by valorizing brick waste and reducing use of virgin aggregates, while 10% optimized strength and 15% optimized thermal insulation.[44]. Sallı Bideci et al. (2024) reviewed the use of waste clay brick powder as a supplementary cementitious material, reporting enhanced strength, reduced permeability, and 40% CO_2 reduction potential [32].

4. Methodology

This study employs a comparative analytical methodology that integrates data from peer-reviewed publications on recycled concrete and brick-based composites. The workflow, illustrated in Figure 1, outlines the systematic process of data collection, normalization, and category-based comparison to evaluate thermal, mechanical, and environmental performance.

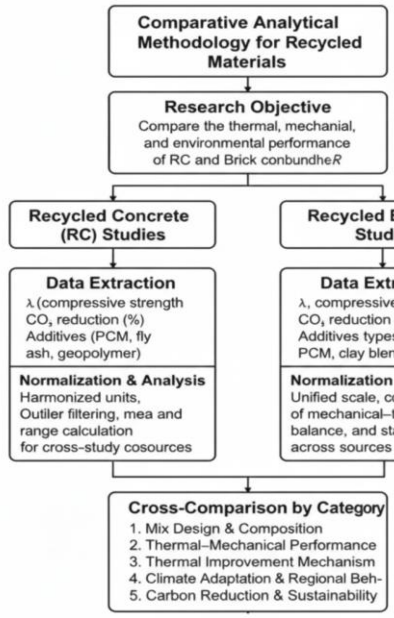

Fig. 1. Comparative analytical methodology for recycled concrete and brick materials.

5. Discussion

The comparative findings from the reviewed studies are summarized in Table 2, presenting normalized data that highlight the key differences in thermal, mechanical, and environmental performance between recycled concrete (RC) and recycled brick (RB) materials across five analytical categories.

TABLE II. COMPARATIVE PERFORMANCE OF RECYCLED CONCRETE AND RECYCLED BRICK MATERIALS

Category	Recycled Concrete	Recycled Brick	Key Findings
1. Mix & Composition	Fine recycled fines (<45 μm) improve hydration and compressive strength; optimal RCA replacement is about 50% [2,5].	Waste clay brick powder used as SCM improves strength/durability; mechanochemical activation enhances reactivity; ~25% brick powder can be optimal for durability/ASR control; recycled brick + LDPE mixes reduce impacts [31,6].	Both reuse C&D waste; brick mixes often rely on powder/activation or polymer additions for performance and impact reduction.
2. Thermal & Mechanical	PCM-based RAC reduces thermal conductivity up to ~43% while keeping strength stable; lightweight recycled concrete can achieve up to ~76.5% λ reduction with acceptable strength [15,44].	Recycled brick mixtures show lower λ (e.g., 0.71 vs 1.31 W/m·K) and reduce cooling energy (~33.5%); recycled brick + EPS walls can cut heat transmittance substantially [6,39].	Brick offers stronger insulation; recycled concrete generally retains higher structural strength.
3. Thermal Improvement Mechanism	Thermal improvement mainly comes from densification/ITZ enhancement through treatments such as carbonation/coatings that reduce λ (~18%), plus binder activation and CO_2 curing improving microstructure [21,10,12].	Thermal improvement is driven by increased porosity or lightweight additives (e.g., LDPE, EPS) lowering density and λ [6,39].	Concrete improves thermally via microstructural densification; brick improves via porosity/lightweight effects.
4. Climate Adaptation	Recycled-concrete systems show reduced heat flux (~20%) and energy savings across climates; PCM/SCM mixes improve thermal response in warm/humid conditions [22,23,1].	Recycled-brick systems perform well in hot-arid, continental, and hot-humid regions, improving envelope energy efficiency [6,40].	Both suit warm climates; brick tends to excel for hot-arid envelopes.
5. Carbon & Sustainability	Recycled-concrete approaches reduce CO_2/EC substantially (e.g., CO_2 ↓ ~38% with strength ↑; EC reduction up to ~60–70% via SCM replacement) [27,30].	Recycled-brick concretes/bricks reduce embodied carbon and improve eco-efficiency; recycled-brick mixes can cut cost and operational energy [41,6] .	Concrete often yields larger absolute CO_2 savings; brick materials offer lower embodied carbon/cost with strong insulation benefits.

6. Conclusion

The comparative analysis of previous studies demonstrated clear differences between recycled concrete and recycled brick composites. Recycled concrete generally provides higher mechanical strength and durability, mainly because of a denser microstructure and stronger binder–aggregate interaction, particularly when combined with supplementary cementitious materials or phase change materials. From an environmental perspective, recycled concrete systems also show meaningful potential for carbon reduction through partial cement replacement and CO_2-related treatments, while still maintaining adequate structural performance; however, their thermal improvement is typically less pronounced than brick-based solutions. In contrast, recycled brick composites exhibit noticeably better thermal behaviour. Their porous texture and lower density lead to substantially lower thermal conductivity (commonly reduced by about 22–38% compared with ordinary concrete), which makes them effective for insulation and energy-efficient envelopes. The main limitation remains mechanical performance, which is generally lower than recycled concrete mixes, restricting their use in primary load-bearing applications. Overall, these complementary properties suggest that recycled concrete is more suitable for structural and load-bearing elements, whereas recycled brick is better suited for non-structural or thermal-insulation components. Combining both materials in hybrid wall or building-envelope systems can balance strength and thermal efficiency, supporting low-carbon and energy-efficient construction. Future research should prioritize long-term durability, coupled moisture–thermal performance, and full-scale validation under different climatic conditions to facilitate broader practical adoption.

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