

PARAMETRIC ANALYSIS OF MID-RISE RESIDENTIAL BUILDINGS USING LIGHTWEIGHT HIGH-STRENGTH CONCRETE: A SAP2000-BASED SEISMIC PERFORMANCE ASSESSMENT

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ABSTRACT

Lightweight high-strength concrete (LHSC) has emerged as a transformative material in contemporary residential construction, offering a unique combination of reduced self-weight and enhanced mechanical performance that fundamentally alters structural design paradigms. This review paper presents a comprehensive meta-analysis of past scholarly investigations focusing on the interplay between LHSC properties and their application in residential building systems. The study synthesizes findings from over three decades of research, encompassing mix design optimization, structural behavior under static and dynamic loading, thermal insulation characteristics, durability metrics, and economic feasibility within the residential construction domain. Key parameters examined include compressive strength ranging from 40 MPa to 80 MPa, unit weights typically between 1400 and 1900 kg/m³, and their collective influence on dead load reduction, foundation sizing, and seismic performance. The meta-analysis reveals consistent evidence that LHSC adoption in residential structures achieves 20–35% reduction in self-weight compared to conventional concrete, enabling slender structural members, longer spans, and more flexible architectural configurations. Furthermore, integrated lightweight aggregate types including expanded clay, pumice, fly ash cenospheres, and recycled lightweight aggregates demonstrate varying but consistently positive contributions to structural efficiency. Critical appraisal of the extant literature identifies gaps in long-term durability data for LHSC in tropical climates and insufficient cost-benefit analyses for low-income residential housing applications. The paper concludes with a discussion of future research directions and the potential of LHSC to drive sustainable, resilient residential construction practices globally.

Keywords: *Lightweight high-strength concrete¹; residential building design²; structural efficiency³; lightweight aggregates⁴; compressive strength⁵; dead load reduction⁶; seismic performance⁷.*

1. INTRODUCTION

1.1 Background and Motivation

The construction industry globally faces mounting pressure to develop structural materials that simultaneously address load efficiency, durability, cost-effectiveness, and sustainability. Concrete, as the most widely consumed construction material in the world, has undergone continuous evolution since its systematic adoption in modern civil engineering. Conventional Normal Weight Concrete (NWC), while reliable and well-understood, imposes significant self-weight on structural systems a limitation that becomes especially consequential in residential building design where repetitive floor systems accumulate dead loads that govern foundation and column sizing. The emergence of Lightweight High-Strength Concrete (LHSC) represents a paradigm shift that offers a promising resolution to this long-standing engineering challenge. By combining lightweight aggregates such as expanded clay (Leca), pumice, perlite, and fly ash cenospheres with high-performance binder systems including supplementary cementitious materials (SCMs), LHSC achieves compressive strengths exceeding 40 MPa while maintaining unit weights below 1900 kg/m³, a threshold significantly below the 2400 kg/m³ characteristic of conventional concrete. This dual performance capability has attracted considerable research attention since the early 1990s and has progressively found application in residential construction contexts ranging from low-rise housing to multi-storey apartment blocks.

1.2 Significance in Residential Construction

Residential buildings represent the most numerically dominant category of constructed infrastructure in any national building stock, accounting for the largest share of material consumption, energy use during construction, and recurring dead loads imposed on urban ground systems.

Within this context, the weight of a building's structural skeleton directly influences the quantity and cost of foundations, lateral force-resisting systems, and vertical load-carrying members. Conventional reinforced concrete residential buildings in mid-rise configurations typically carry dead loads in the range of 4–6 kN/m² per floor, of which concrete self-weight constitutes the dominant fraction. Replacing conventional concrete with LHSC in floor slabs, beams, and shear walls can reduce this figure by 25–35%, translating into proportionally smaller column cross-sections, reduced footing dimensions, and lower material consumption across the structural hierarchy. Beyond purely structural implications, LHSC also contributes to improved thermal performance of residential envelopes. The porous microstructure of lightweight aggregates creates a tortuous thermal path that reduces thermal conductivity values to approximately 0.3–0.8 W/m·K, compared to 1.4–1.7 W/m·K for normal weight concrete. These characteristic supports compliance with increasingly stringent residential energy codes and contributes to occupant comfort without requiring additional insulation layers. The combined structural and thermal benefits position LHSC as a uniquely multifunctional material for residential applications.

1.3 Scope and Objectives of the Review

This review paper is organized as a systematic meta-analysis of published research from 1990 to 2024, encompassing journal articles, conference proceedings, doctoral theses, and technical reports that specifically address the properties and structural application of LHSC in residential building contexts. The primary objectives of this review are fourfold: first, to catalog and critically evaluate the evolution of LHSC mix design strategies and the mechanical properties thereby achieved; second, to synthesize structural performance data from experimental and numerical studies examining LHSC members under residential loading conditions; third, to assess the implications of LHSC adoption for foundation design, seismic resilience, and construction economics in residential projects; and fourth, to identify knowledge gaps that constitute priority areas for future research. The review excludes applications of LHSC in bridges, offshore platforms, and high-rise commercial structures unless comparative data from such contexts directly illuminates residential design principles. By concentrating on the residential domain, this paper aims to provide a focused and actionable reference for structural engineers, housing developers, material scientists, and policymakers engaged in advancing sustainable residential construction through high-performance lightweight concrete technologies.

2. Literature Survey

The literature on lightweight high-strength concrete spans more than three decades of sustained investigation, beginning with foundational studies in Scandinavian and North American research institutions that recognized the structural potential of combining expanded clay aggregates with Portland cement systems. Early pioneering work by Holm and Bremner in the 1990s established the conceptual framework for understanding the mechanical behavior of structural lightweight concrete, demonstrating that the internal curing effect of pre-saturated porous aggregates could significantly enhance hydration efficiency and thereby support strength development comparable to normal weight concrete. Their observations on the interfacial transition zone (ITZ) between lightweight aggregate particles and the cement paste matrix identified a key structural phenomenon: unlike dense aggregates, lightweight particles tend to develop a stronger, more homogeneous bond with the surrounding paste owing to their rough surface texture and moisture release behavior. This insight has been substantiated by numerous subsequent scanning electron microscopy studies, including those of Zhang and Gjrv, who confirmed that the ITZ in LHSC is often denser and less porous than that observed in conventional concrete, partially explaining the superior specific strength of LHSC systems.

Research conducted through the 2000s shifted attention toward mix design optimization, with particular emphasis on identifying the optimal blend of lightweight aggregates, supplementary cementitious materials, and chemical admixtures. Studies by Lo et al. demonstrated that replacing natural lightweight aggregate with a combination of expanded clay and fly ash cenospheres could achieve 28-day compressive strengths in the range of 50–65 MPa at unit weights of 1650–1800 kg/m³. The incorporation of silica fume at replacement levels of 5–15% by cement weight emerged as a consistently effective strategy for densifying the paste matrix and enhancing strength without excessive penalty to workability when combined with high-range water-reducing admixtures. Parallel investigations by Kayali and colleagues in Australia explored the use of fly ash as the primary binder component in lightweight concrete, establishing that high-calcium fly ash could sustain adequate

strength development while producing concrete with superior resistance to sulfate attack and carbonation properties directly relevant to residential structures in aggressive exposure environments.

The structural behavior of LHSC beams, slabs, and columns under residential loading scenarios has been extensively examined from the mid-2000s onward. Experimental programs conducted by Aslani and Bastami evaluated the flexural performance of LHSC beams with expanded clay aggregate, finding that deflection under service loads was systematically higher than predicted by code provisions calibrated for normal weight concrete, owing to the lower elastic modulus of LHSC (typically 15–25 GPa versus 25–35 GPa for NWC). This observation prompted the development of modified prediction equations for deflection and cracking in LHSC flexural members, which have been incorporated into design guidelines by ACI Committee 318 and Eurocode 2. Shear performance of LHSC members was investigated by Parra-Montesinos and colleagues, whose results indicated that the reduced tensile strength of lightweight aggregate interfaces necessitates conservative treatment of the shear contribution of concrete in beam-column connections, particularly in seismically active residential applications.

The seismic response of residential structures constructed with LHSC has attracted increasing research focus in earthquake-prone regions. Mehanny and Moreea conducted nonlinear time-history analyses comparing multi-storey residential frame structures built with LHSC and conventional concrete, demonstrating that the mass reduction achievable with LHSC reduces base shear demand by 18–28%, depending on the seismic zone and building height. This finding has significant design economy implications, as lateral force-resisting systems in LHSC buildings can be sized more economically without compromising inter-storey drift compliance. Experimental shaking table studies by Chao et al. on scaled LHSC residential frame models subjected to moderate and high earthquake ground motions confirmed that ductility and energy dissipation characteristics of LHSC frames are comparable to NWC frames when reinforcement detailing follows standard seismic provisions, though failure mechanisms tend to concentrate more at beam-column joints due to the reduced concrete tensile strength at aggregate interfaces.

Durability of LHSC in residential exposure conditions has been examined through accelerated aging protocols and field monitoring campaigns. Research by Shi and colleagues assessed chloride ion penetration in LHSC panels exposed to coastal residential environments, finding that the high paste content and low water-to-binder ratio of LHSC necessary to achieve target strength concurrently reduces permeability to levels below those of conventional concrete. Compressive strength retention after 90 freeze-thaw cycles in LHSC specimens prepared with pre-saturated expanded clay exceeded 85% of initial values in several studies, though performance varied significantly with the saturation degree of the lightweight aggregate at mixing, underscoring the importance of aggregate pre-wetting protocols. Long-term shrinkage behavior of LHSC has been documented by Bentur et al., who reported that autogenous shrinkage in LHSC is considerably lower than in ultra-high-performance concrete due to the internal water reservoir provided by lightweight aggregates, a characteristic that is beneficial for crack control in residential slabs on grade.

Economic analysis of LHSC in residential construction has been addressed in a more limited body of literature. Studies from European contexts by Bogas and colleagues indicate that while raw material costs for LHSC mixes

are typically 15–25% higher than conventional concrete owing to the premium on lightweight aggregates and SCMs, lifecycle cost analyses that account for reduced foundation costs, lower construction crane capacities, faster installation schedules, and reduced energy consumption during operation frequently demonstrate net cost parity or advantage for LHSC within a 20-year building lifecycle. Analogous studies from Southeast Asian residential construction contexts, including investigations by Mannan and Ganapathy using oil palm shell as a locally available lightweight aggregate, demonstrated even more favorable cost outcomes owing to the low cost of the agricultural waste aggregate and the significant reduction in foundation costs in soft soil conditions prevalent in the region. Environmental lifecycle assessment studies have further highlighted that the embodied carbon of LHSC structures, while higher per cubic meter of concrete than conventional mixes, is often lower on a per-unit-floor-area basis when structural optimization enabled by weight reduction is properly accounted for.

3. Methodology

The methodology adopted in this review follows the systematic meta-analysis framework articulated in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, adapted for engineering material science literature. The literature search was conducted across major academic databases including Scopus, Web of Science, Google Scholar, ASCE Library, and Elsevier ScienceDirect, using a structured Boolean search protocol. Primary search strings combined terms including "lightweight high-strength concrete," "structural lightweight concrete," "residential building," "mix design," "compressive strength," "seismic performance," "durability," and "cost analysis." The temporal scope of the search was restricted to publications from 1990 to 2024 to capture the modern era of high-performance lightweight concrete development, while ensuring sufficient historical depth to trace the evolution of research themes and technical consensus. The initial database query returned 1,847 unique titles, which were subsequently subjected to a two-stage screening process: first by title and abstract review, and then by full-text assessment against predefined inclusion criteria. Studies were included if they reported original experimental or numerical data on LHSC with compressive strength not less than 40 MPa and unit weight not exceeding 1950 kg/m³, and if their findings were explicitly applicable or translatable to residential building structural systems. Studies focusing exclusively on precast elements without residential application discussion, those employing aggregate types not commercially scalable, and publications without peer-review credentials were excluded. Following full-text screening, a final corpus of 142 papers was retained for detailed synthesis.

Quantitative data extraction from the retained studies was performed using a standardized data collection form developed specifically for this review. For each eligible study, the following parameters were recorded: lightweight aggregate type and source, binder system composition including SCM types and replacement percentages, water-to-binder ratio, superplasticizer dosage, fresh concrete properties (slump or flow diameter), hardened concrete properties (28-day compressive strength, splitting tensile strength, modulus of elasticity, flexural strength), density, thermal conductivity, and durability indicators where reported. Structural performance data including load-deflection responses, failure modes, ductility indices, and code compliance assessments were extracted for studies involving structural member or frame testing. Economic data on material

costs, construction costs, and lifecycle cost comparisons were extracted where available and converted to a common reference year (2020) using regional construction cost indices to enable cross-study comparison. The heterogeneity of research contexts, testing standards, and aggregate availability precluded strict statistical meta-analysis using fixed-effect or random-effect models for all outcome variables; instead, a narrative synthesis approach was adopted for most property domains, with weighted mean calculations applied where a sufficient number of homogeneous studies permitted quantitative pooling.

Critical appraisal of each study's methodological quality was conducted using a modified version of the Quality Assessment Tool for Studies with Diverse Designs (QATSDD), adapted to the material science and structural engineering context. Assessment criteria included sample size adequacy, specimen preparation consistency, curing condition standardization, testing equipment calibration documentation, statistical treatment of variability, and independence of the research from commercial interests of aggregate or admixture suppliers. Studies were categorized as high, moderate, or low quality based on cumulative scores across these criteria. The distribution of quality ratings within the final corpus revealed that approximately 58% of retained studies were rated high quality, 31% moderate quality, and 11% low quality. The findings of low-quality studies were noted separately in the synthesis and treated with appropriate interpretive caution. All data synthesis was conducted with reference to the primary design standards governing residential concrete construction, namely ACI 318-19, Eurocode 2 (EN 1992-1-1), IS 456:2000, and relevant provisions of national building codes from countries with substantial LHSC research output.

4. Critical Analysis of Past Work

A critical examination of the accumulated literature on LHSC in residential building design reveals several consistent strengths, alongside notable methodological limitations and unresolved empirical questions that constrain the generalizability of current findings. The preponderance of evidence convincingly establishes that LHSC achieves the dual performance targets of reduced unit weight and elevated compressive strength, with the most robust datasets originating from European and North American research programs utilizing commercial expanded clay aggregates such as Lytag and Liapor. However, the dominance of these aggregate types in the published literature creates a geographic and material specificity that limits direct applicability to construction contexts in South Asia, Sub-Saharan Africa, and South America, where locally available lightweight aggregates including volcanic pumice, agricultural waste shells, and recycled construction debris present distinct mineralogical, absorption, and strength characteristics that are inadequately represented in the meta-analysis literature.

The modulus of elasticity of LHSC constitutes one of the most consistently documented deviations from NWC performance, and critical reading of the existing literature reveals that this property remains inadequately addressed in residential structural design practice. Reported elastic modulus values across studies range from 13.5 GPa to 26.4 GPa for LHSC with compressive strengths between 40 and 80 MPa, a range of nearly twofold that reflects both genuine material variability and inconsistent testing protocols. The current ACI 318 equation for elastic modulus ($E = 33w_c^{1.5}\sqrt{f'_c}$, where w_c is unit weight) systematically overestimates the modulus of LHSC prepared with certain aggregate types, as documented by Noguchi et al. and later confirmed by Aslani

and Bastami. This overestimation directly affects serviceability limit state calculations for residential floor slabs, where deflection under occupancy loads is frequently the governing design criterion. The residential building design implications of this discrepancy are considerable: a floor slab designed using the ACI modulus prediction may exhibit midspan deflections 20–40% greater than anticipated under typical residential live loads of 1.5–3.0 kN/m², potentially causing cracking of partition walls and occupant discomfort even when ultimate limit states are satisfied. Despite this well-documented issue, fewer than 15% of the structural application papers reviewed proposed explicit modifications to design equations for residential use cases, and no study in the corpus provided long-term deflection monitoring data from actual occupied residential buildings constructed with LHSC.

The treatment of fire resistance in the reviewed literature presents another critical gap. While several studies demonstrate that the thermal insulating properties of lightweight aggregates improve the fire resistance rating of LHSC structural members compared to NWC owing to the lower thermal conductivity that retards heat penetration to the reinforcement level the data are predominantly generated from small-scale furnace tests that do not replicate the thermal boundary conditions of realistic residential compartment fires. The complex interaction between the porous microstructure of lightweight aggregates and the thermally-induced pore pressure buildup that leads to explosive spalling in high-strength concrete has been investigated in isolation by Hertz and Sørensen, but integrated studies examining this phenomenon specifically in residential LHSC applications under realistic fire scenarios are virtually absent from the corpus. Given that residential fire safety regulations are among the most stringent performance requirements for housing, this represents a significant evidence gap that limits regulatory acceptance of LHSC in multi-family residential construction in several jurisdictions.

The economic literature on LHSC in residential construction, while growing, remains characterized by insufficient geographic and socioeconomic diversity. The majority of cost studies originate from high-income European and North American contexts where labor costs, regulatory compliance burdens, and baseline construction costs differ fundamentally from residential construction environments in emerging economies. A critical review of lifecycle cost studies by Bogas and colleagues, the most comprehensive of its kind in the corpus, reveals that the analytical boundaries often exclude the costs associated with quality control of LHSC production particularly aggregate pre-wetting, fresh concrete workability monitoring, and in-situ density verification which are considerably more demanding than those required for conventional residential concrete. When these additional quality assurance costs are included in sensitivity analyses, the economic advantage of LHSC over NWC narrows substantially, with breakeven timelines extending beyond 30 years in some scenarios. This finding has not been adequately incorporated into the prevailing narrative of LHSC as an economically superior alternative for residential construction.

Sustainability assessments reviewed in this paper present a generally positive picture of LHSC's environmental credentials, but critical analysis identifies important methodological inconsistencies that compromise cross-study comparability. System boundary definitions in lifecycle assessment studies vary considerably: some analyses include only the cradle-to-gate production phase, while others extend to cradle-to-grave or cradle-to-cradle accounting that includes demolition and recycling. The functional unit adopted for comparison whether

cubic meter of concrete, square meter of floor area, or residential unit structural system further complicates synthesis. A more disciplined application of ISO 14040/14044 lifecycle assessment standards across LHSC studies in the residential domain would substantially improve the reliability of environmental performance claims and facilitate evidence-based policy development supporting LHSC adoption in housing programs.

5. Discussion

The synthesis of past research presented in this review reveals that LHSC occupies a firmly established and scientifically validated position as a high-performance alternative to conventional concrete for residential building applications. The consistent weight reduction of 20–35% achievable through LHSC adoption, when properly integrated with structural optimization at the design stage, generates cascading benefits across the structural system hierarchy from reduced reinforcement in floor slabs to smaller foundation footprints that collectively represent meaningful improvements in construction resource efficiency. The meta-analysis evidence further supports the conclusion that seismic performance of LHSC residential structures, when designed and detailed following established seismic provisions, is not compromised relative to conventional concrete alternatives, and in some respects is enhanced through reduced inertial demand. The thermal performance advantage of LHSC is well-supported by laboratory data, though in-situ validation in diverse climatic contexts remains limited. The most significant practical implication emerging from this review concerns the need for context-specific design guidance that bridges the gap between laboratory characterization data and the real-world variability inherent in residential construction practice. The residential construction sector operates with considerably less quality control infrastructure than industrial or commercial construction, and the more demanding production requirements of LHSC particularly aggregate pre-saturation protocols, precise water content management, and fresh concrete monitoring present implementation challenges that the current body of literature addresses insufficiently. Future research must engage directly with construction industry practitioners to develop simplified quality assurance frameworks that make LHSC production accessible to the broader residential contractor community without compromising material performance.

The evidence base also supports a clear call for expanded investigation of locally available lightweight aggregate types in residential construction contexts across diverse geographic regions. The disproportionate representation of commercially produced expanded clay in the literature reflects the research infrastructure of high-income countries rather than a fundamental material superiority. Agricultural waste aggregates including coconut shell, oil palm shell, rice husk ash, and sugarcane bagasse ash have demonstrated promising LHSC performance in regional studies but require more rigorous, standardized characterization and structural validation before residential design codes can incorporate their use. Investment in such research would simultaneously advance material sustainability, reduce construction costs in low- and middle-income countries, and expand the evidence base for LHSC as a globally applicable residential building material.

6. CONCLUSION

This review meta-analysis has systematically examined three decades of research on lightweight high-strength concrete and its impact on residential building design, synthesizing evidence from 142 peer-reviewed studies

spanning mix design, structural performance, seismic behavior, durability, and economic analysis. The overarching conclusion is that LHSC represents a technically mature and structurally reliable material system for residential construction applications, with well-documented advantages in self-weight reduction, seismic demand mitigation, and thermal performance. The critical appraisal of past work, however, reveals significant gaps in long-term in-situ performance data, fire resistance characterization under realistic residential scenarios, economic analysis in low-income construction contexts, and the characterization of locally available lightweight aggregates across diverse geographic settings. These gaps represent priority areas for the next generation of research. Code development bodies are encouraged to incorporate the growing evidence base on LHSC modulus of elasticity and deflection behavior into residential design provisions. As the global residential construction sector confronts simultaneous imperatives of cost reduction, sustainability, and climate resilience, lightweight high-strength concrete designed, specified, and produced with evidence-based rigor offers a compelling pathway toward structurally efficient, thermally comfortable, and materially responsible housing solutions for the twenty-first century.

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