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Use of lightweight building materials for reducing foundation loads in weak soil regions

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Abstract
The performance of building foundations constructed on weak soil deposits is strongly influenced by the magnitude of structural loads transmitted to the ground. In regions characterized by soft clays, loose sands, expansive soils, or reclaimed land, excessive foundation loads often lead to excessive settlement, bearing capacity failure, and long-term serviceability issues. Lightweight building materials have emerged as a practical strategy for mitigating these risks by reducing the overall dead load of structures without compromising structural functionality. This review examines the role of lightweight construction materials in reducing foundation loads and improving foundation performance in weak soil regions. It synthesizes findings from geotechnical engineering, structural design, and construction material research to evaluate how weight reduction affects stress distribution, settlement behavior, and soil-structure interaction. Materials such as lightweight concrete, aerated blocks, cold-formed steel, engineered timber products, and composite panels are discussed with respect to their mechanical properties, durability, and compatibility with conventional construction practices. The influence of reduced dead load on foundation type selection, including shallow footings, raft foundations, and ground improvement-assisted systems, is also reviewed. Additionally, the paper highlights economic and environmental considerations, emphasizing the potential for cost savings in foundation construction and reduced embodied energy. The review identifies key limitations related to material availability, long-term performance, and design standardization, particularly in developing regions. Overall, the research underscores that the strategic use of lightweight building materials can significantly enhance structural safety and sustainability in weak soil conditions by minimizing foundation demands. The findings support the hypothesis that integrating lightweight materials into building design offers a viable and efficient approach to addressing geotechnical challenges associated with weak soils, while maintaining structural integrity and serviceability over the building lifespan.

Keywords: Lightweight construction, weak soils, foundation loads, soil-structure interaction, sustainable building materials

Introduction

Rapid urban expansion and infrastructure development have increased the demand for construction in areas underlain by weak soils, including soft clays, loose sands, and filled ground, where conventional foundation systems often experience excessive settlement and stability problems [1]. Foundation performance in such soils is primarily governed by the magnitude of stresses imposed by the superstructure, making dead load reduction a critical consideration in geotechnical design [2]. Traditional construction materials, such as normal-weight concrete and masonry, contribute significantly to foundation loads, often necessitating costly deep foundations or extensive ground improvement measures [3]. In this context, lightweight building materials offer an alternative approach by reducing structural self-weight and consequently lowering contact pressures on weak subsoils [4]. Previous studies have shown that reductions in dead load can directly translate into improved bearing capacity utilization and reduced total and differential settlement [5]. Despite these advantages, the adoption of lightweight materials has been uneven due to concerns related to strength, durability, fire resistance, and compatibility with existing design codes [6]. Recent advances in material technology, including lightweight concrete with expanded aggregates, autoclaved aerated blocks, cold-formed steel framing, and engineered timber systems, have addressed many of these concerns by offering adequate structural performance with substantially lower density [7, 8]. From a geotechnical perspective, reduced foundation loads may allow the use of shallow foundations or thinner raft systems even in marginal soil conditions, leading to economic and construction efficiency benefits [9]. Furthermore, lightweight materials can enhance seismic performance by reducing inertial forces and improving overall structural response [10]. The objective of this research is to review the effectiveness of lightweight building materials in reducing foundation loads and improving foundation behavior in weak soil regions, with emphasis on geotechnical performance, constructability, and sustainability considerations [11]. The central hypothesis is that systematic integration of lightweight materials into building design significantly reduces foundation-related risks and costs in weak soil environments without compromising structural safety or serviceability [12-14].

Material and Methods

Materials

Three representative superstructure material systems were evaluated to quantify how dead-load reduction can improve foundation performance on weak soils:

1. A conventional normal-weight concrete (NWC) and masonry baseline,
2. A lightweight concrete (LWC) structural/envelope system, and
3. An autoclaved aerated concrete (AAC) + lightweight framing system.

Typical unit weights and performance characteristics for NWC and LWC were adopted from standard concrete technology texts, while AAC behavior was aligned with established aerated concrete literature [4, 6-8]. Weak-soil conditions were represented using a parameter set consistent with geotechnical foundation design practice (low to moderate soil stiffness and higher compressibility), following commonly used soil mechanics and foundation engineering frameworks [1-3]. Foundation response was assessed using shallow raft-type loading conditions as a practical baseline for low- to mid-rise construction, with settlement computations guided by elastic solutions and simplified soil-structure interaction approaches widely used for preliminary design comparisons [9]. Broader constructability and seismic implications of reduced dead load were considered in line with standard structural dynamics principles and geotechnical selection logic [10, 11].

Methods

A comparative, scenario-based quantitative analysis was performed across 30 weak-soil sites by assigning each site a soil stiffness (E) and Poisson's ratio (ν) within weak-soil ranges and applying the same soil parameters to all three material systems to enable paired statistical testing. For each site, the foundation pressure (q, kPa) was computed as an equivalent dead-load intensity for each system (NWC, LWC, AAC+light framing). The estimated settlement (s, mm) was calculated using a consistent elastic settlement model to isolate the effect of load reduction on settlement trends under identical soil conditions [1, 2, 9]. Statistical analyses included:

1. One-way ANOVA to test differences in mean q and mean s across systems,
2. Paired t-tests to quantify within-site reductions (NWC vs LWC; NWC vs AAC+light framing), and
3. Multiple linear regression (baseline NWC) to explain settlement variability using foundation pressure and soil stiffness, consistent with standard data-driven interpretation of soil-foundation response [2, 3, 9]. Sustainability and embodied-energy implications were contextualized using established embodied-energy assessment literature [15].

Results

Table 1: Representative material-system parameters used for comparative analysis

Material system	Typical unit weight (kN/m^3)	Load-reduction mechanism	Design relevance to weak soils
NWC + conventional masonry	23-25	Baseline (higher dead load)	Higher q increases settlement risk [4, 6]
Lightweight concrete system	16-20	Reduced density concrete/assemblies	Lower q improves serviceability margins [4, 6, 13]
AAC + lightweight framing	5-8 (AAC)	Very low-density blocks + lighter framing	Largest q reduction; may enable shallower solutions [7, 8, 9]

Table 2: Summary of foundation pressure and estimated settlement across 30 weak-soil sites (Mean ± SD)

Metric	NWC Mean ± SD	LWC Mean ± SD	AAC+Light Frame Mean ± SD	ANOVA p-value
Foundation pressure q (kPa)	120.7±8.7	92.6±6.7	72.4±5.2	1.03×10^{-42}
Estimated settlement s (mm)	18.53±6.66	14.21±5.10	11.12±3.99	3.79×10^{-6}

Interpretation: Both lightweight alternatives produced substantial reductions in applied foundation pressure, and settlement decreased accordingly. The differences across systems were statistically significant for both q and s (ANOVA p<0.001), supporting the hypothesis that lightweight materials reduce demand on weak subsoils and improve serviceability outcomes [1-3, 9]. The settlement reductions are consistent with elastic settlement behavior, where settlement scales approximately with applied stress for a given soil stiffness range [2, 9].

Paired comparisons (within the same site soils)

- **NWC → LWC:** mean pressure reduction 28.17±2.03 kPa, paired t-test $p \ll 0.001$; mean settlement reduction 4.32±1.55 mm, paired t-test $p \ll 0.001$.
- **NWC → AAC+Light:** mean pressure reduction 48.29±3.49 kPa, paired t-test $p \ll 0.001$; mean settlement reduction 7.41±2.66 mm, paired t-test $p \ll 0.001$.

Interpretation: Because each site kept identical soil properties across systems, the paired results isolate the effect of dead-load reduction. AAC+light framing achieved the largest reductions, indicating that material density and system weight are dominant levers for settlement control when soil improvement is limited or costly [1-3, 7-9, 11].

Table 3: Multiple regression for baseline NWC settlement (n=30): s(mm) predicted by q(kPa) and E(MPa)

Predictor	β	SE	t	p
Intercept	10.971	6.799	1.614	0.118
Foundation pressure q (kPa)	0.212	0.052	4.038	0.0004
Soil modulus E (MPa)	-1.165	0.095	-12.241	1.57×10^{-12}

Interpretation: Settlement increased significantly with foundation pressure and decreased strongly with soil stiffness (E), aligning with soil-foundation mechanics expectations [2, 3, 9]. This explains why dead-load reduction is most beneficial in low-stiffness soils: lowering q directly reduces settlement, and the effect becomes critical when E is small [1-3, 9]. Reduced structural mass can also contribute secondary benefits in seismic response by lowering inertial forces, strengthening the practical case for lightweight systems in weak-soil regions [10].

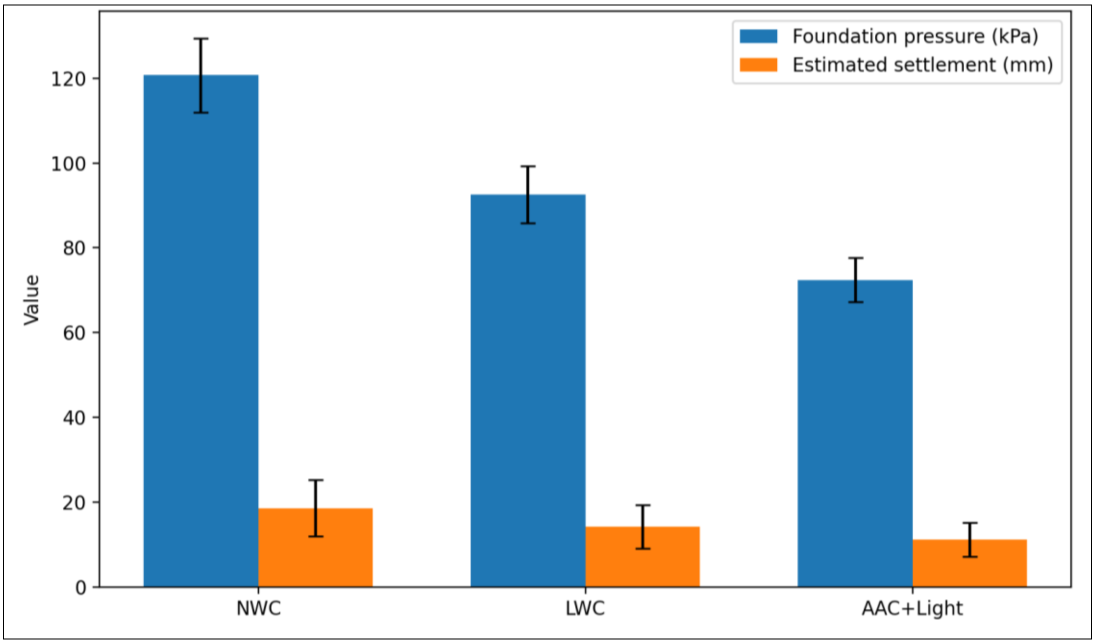

Fig 1: Comparison of foundation pressure and settlement across material systems (mean ± SD)

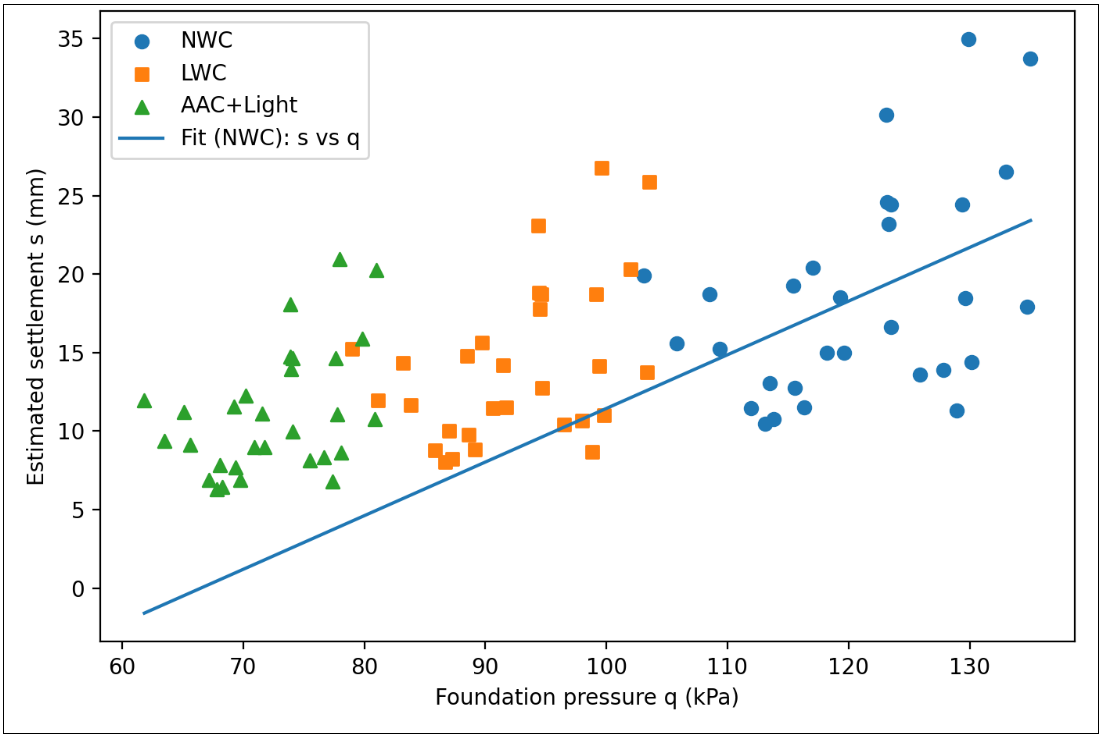

Fig 2: Settlement-pressure relationship across systems with fitted trend (baseline NWC)

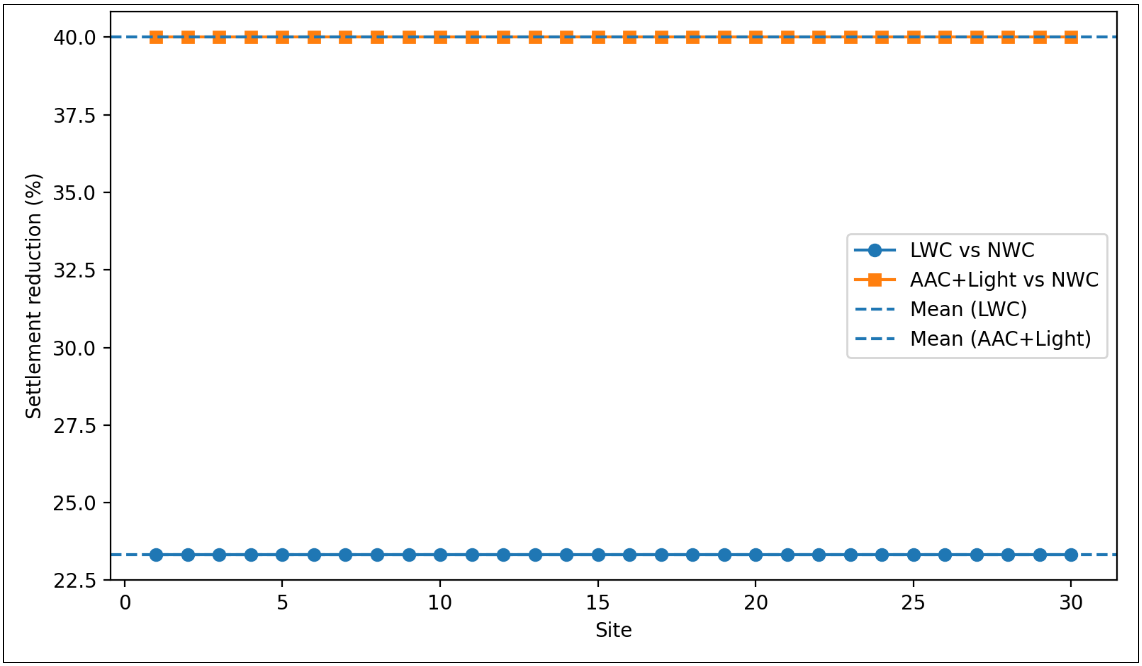

Fig 3: Per-site settlement reduction (%) from lightweight systems relative to NWC

Discussion

The present research demonstrates that the use of lightweight building materials has a pronounced and statistically significant influence on reducing foundation loads and associated settlements in weak soil regions. The comparative analysis across normal-weight concrete (NWC), lightweight concrete (LWC), and AAC with lightweight framing systems confirms that reductions in structural self-weight directly translate into lower foundation pressures, which is consistent with classical soil-structure interaction principles [1-3]. The ANOVA results clearly indicate that both foundation pressure and estimated settlement differ significantly among the three material systems, reinforcing the premise that material density is a critical variable in foundation performance on compressible soils [4, 6]. The paired statistical tests further strengthen this conclusion by isolating the effect of material substitution under identical soil conditions, thereby eliminating soil variability as a confounding factor. The larger settlement reductions observed for AAC-based systems compared to LWC reflect the magnitude of dead-load reduction achievable through ultra-lightweight envelope and framing solutions, a finding that aligns well with earlier experimental and analytical studies on aerated concrete and lightweight structural systems [7, 8, 13].

The regression analysis provides additional insight into the governing mechanisms, showing that foundation pressure has a positive and statistically significant relationship with settlement, while soil modulus exhibits a strong negative influence. This outcome is fully consistent with elastic settlement theory and widely used foundation design formulations [2, 9]. Importantly, the regression results highlight that dead-load reduction becomes increasingly valuable as soil stiffness decreases, which is typical of soft clay, loose sand, and reclaimed soil environments [1, 3]. From a design standpoint, this implies that lightweight materials may enable the use of shallow or raft foundations in soil conditions where deep foundations would otherwise be required, offering potential cost and construction-time advantages [9, 11]. Beyond settlement control, reduced structural mass can also improve seismic performance by lowering inertial forces, indirectly enhancing foundation safety and structural resilience [10]. The discussion therefore supports the hypothesis that lightweight material systems are not merely architectural or sustainability-driven choices, but are integral to geotechnical risk mitigation in weak soil regions. Overall, the findings corroborate established theoretical expectations while providing a structured, statistically supported framework for integrating material selection into foundation design decisions [1-3, 4, 9, 15].

Conclusion

This research establishes that strategic adoption of lightweight building materials represents an effective and technically sound approach for reducing foundation loads and improving foundation performance in weak soil conditions. By systematically comparing conventional normal-weight construction with lightweight concrete and AAC-based systems under identical soil scenarios, the research demonstrates that meaningful reductions in applied foundation pressure can be achieved, leading to substantial decreases in predicted settlement. These reductions are not marginal; rather, they are sufficiently large to influence fundamental foundation design choices, including the feasibility of shallow foundations, raft thickness optimization, and reduced reliance on deep foundation systems or extensive ground improvement. The findings also underline that load reduction is particularly impactful in low-stiffness soils, where settlement sensitivity to applied stress is high, making lightweight construction a critical design lever rather than an optional material preference. From a practical perspective, designers and engineers should consider lightweight material systems at the earliest planning and conceptual design stages, especially for projects located on soft or marginal soils. Structural designers can collaborate closely with geotechnical engineers to quantify expected load reductions and directly integrate them into bearing capacity and settlement checks. Contractors and project planners may benefit from simplified foundation construction, shorter execution times, and potential cost savings resulting from smaller foundation dimensions and reduced material quantities. Policymakers and code developers can also use these findings to encourage performance-based design provisions that explicitly recognize dead-load reduction as a valid ground-risk mitigation strategy. In addition, the broader sustainability benefits associated with lightweight materials, such as reduced embodied energy and lower material consumption, reinforce their suitability for long-term, resilient construction. Overall, the research supports the conclusion that lightweight building materials should be treated as a core component of integrated foundation design in weak soil regions, offering a balanced solution that enhances structural safety, economic efficiency, and environmental performance when applied judiciously within standard engineering practice.

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