SUSTAINABLE CONCRETE TECHNOLOGY ADOPTION

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Concrete is one of the most widely used materials in construction, yet its production accounts for nearly 7 % of all anthropogenic CO2 emissions (Pellegrino 107). As concerns over climate change increase, the construction industry faces pressure to adopt sustainable alternatives. This paper explores the research question: How do existing sociotechnical systems facilitate or hinder the adoption of sustainable concrete technologies? Using the Social Construction of Technology (SCOT) framework, the study examines how various social groups shape and negotiate the implementation of innovative concrete materials. Through a literature-based methodology, this research draws on peer-reviewed journal articles, case studies, and technical reports to analyze the development of sustainable concrete technologies, including 3D Concrete Printing (3DCP), recycled aggregates, and low-carbon cement alternatives. The keywords in this study are Concrete, Sustainability, Carbon Emissions, and Recycled Materials. The analysis follows case studies and stakeholder perspectives and highlights the role of social negotiation in technology adoption. The paper concludes with the findings and reflects on how sociotechnical dynamics can support the broader integration of sustainable materials in construction.

Background Information

Concrete's dominance in the construction industry stems from its durability, affordability, and ability to be locally sourced. However, Portland cement, a concrete ingredient, is one of the most carbon-intensive materials in the world, accounting for approximately 8% of global CO_2 emissions due to the high energy demands of clinker production and the release of carbon dioxide during calcination (López-Malest et al., 2024). As concerns over climate change intensify, the need to shift toward more sustainable construction materials becomes increasingly urgent.

The adoption of sustainable concrete technologies, such as 3D Concrete Printing (3DCP), geopolymer concrete, and recycled concrete aggregate (RCA), is not simply a matter of technical performance but is heavily shaped by the interpretations, interests, and interactions of various social groups. Among these alternatives, 3D Concrete Printing (3DCP) is often considered one of the most promising due to its potential to reduce labor requirements, material waste, and greenhouse gas emissions. Its ability to fabricate complex geometries without formwork makes it attractive for customized, efficient construction. However, despite its advantages, 3DCP remains constrained by several systemic barriers, including high capital investment for equipment, a lack of universally accepted performance standards, and its limited compatibility with traditional building codes (Nan et al., 2025). These factors make it a risky choice for most commercial builders. While high-profile case studies, such as the 3D-printed villa in Beijing and affordable housing prototypes in Russia, have demonstrated its technical feasibility, such projects often rely on unique funding models, regulatory waivers, or experimental permits that are not scalable in conventional markets (Sanjayan et al., 2019). Moreover, cultural resistance within the construction industry, rooted in long-established craft traditions, further complicates its adoption, as some stakeholders view automation as a threat to skilled labor and craftsmanship.

Geopolymer concrete, another innovative solution, addresses sustainability by replacing Portland cement with industrial byproducts like fly ash, slag, or silica fume materials that would otherwise contribute to environmental pollution. By eliminating the need for clinker production, geopolymer concrete significantly lowers embodied carbon while maintaining comparable structural properties to traditional concrete mixes (Munir et al., 2024). Nevertheless, its adoption has been slow and fragmented. Concerns persist around long-term durability, as the material's behavior under different environmental exposures is less well understood than that of Portland cement. Additionally, its chemical composition and curing processes deviate from established practices, making it difficult to integrate into conventional design codes and construction workflows. Engineers and regulators may hesitate to endorse it without decades of performance data, which delays its normalization. Furthermore, the availability and quality of precursor materials vary greatly by region, making standardization difficult and introducing uncertainty in supply chains. This variability undermines the scalability of geopolymer concrete, particularly in areas lacking consistent industrial byproduct streams or infrastructure for material processing. As a result, while geopolymer concrete holds clear environmental benefits, its diffusion into the mainstream remains hindered by both technical uncertainties and institutional inertia.

Recycled Concrete Aggregate (RCA) is a third alternative that addresses both carbon emissions and the growing challenge of construction and demolition (C&D) waste management. RCA is produced by crushing and processing debris from demolished structures, allowing it to replace a portion of virgin coarse aggregates in new concrete mixes. Its environmental benefits are twofold: it reduces the demand for natural resource extraction and diverts large volumes of waste from landfills. Studies have confirmed RCA's suitability for structural and non-structural applications, especially when proper cleaning and grading methods are used to control impurities (Makul, 2023; Roque et al., 2022). However, practical barriers persist. Contractors often express concern about the variable composition and mechanical performance of RCA, particularly when it comes from mixed or poorly sorted sources. Contamination from gypsum, wood, or residual steel can impact strength, durability, and workability. These quality inconsistencies lead to hesitance among engineers and developers, especially on projects where performance risk must be minimized. Additionally, skepticism is reinforced by aesthetic concerns and the lack of widespread certification protocols, making RCA less appealing in markets driven by perception and liability avoidance. Without consistent regulatory frameworks or client demand, RCA remains underutilized despite its accessibility and sustainability benefits.

Research by Papadikis et al. (2019) emphasizes the importance of life cycle assessments (LCA) in shifting construction decisions toward more environmentally responsible alternatives. LCAs allow stakeholders to evaluate the full environmental footprint of materials, including raw extraction, production, transportation, usage, and end-of-life scenarios, rather than relying solely on initial costs or short-term performance metrics. In the context of RCA and other sustainable concretes, LCA tools provide compelling data that challenges the assumption that greener materials are inherently less efficient or more expensive. However, the integration of LCA into project planning is still emerging and is often limited to government-led or LEED-certified developments. Broader adoption will require education, policy mandates, and tool standardization to make LCA assessments a routine part of material selection.

Sajid et al. (2024) further underscore the climate mitigation potential of sustainable concrete technologies, particularly when paired with modular construction systems. By combining low-carbon materials with prefabricated building methods, developers can minimize on-site waste, optimize material use, and reduce energy consumption during construction. Modular systems also lend themselves to better quality control, which can help alleviate some concerns about performance variability in alternative concretes. This synergy between material innovation and construction methods suggests a path forward for sustainable building practices. However, realizing this potential will require not only technical refinement but also a shift in industry culture—where long-term environmental performance is given weight equal to cost and speed. Ultimately, tools like LCA and design-for-environment frameworks can serve as catalysts for more holistic, future-oriented decision-making, but only if they are supported by institutional incentives, training, and a broader shift in construction values.

STS Framework

This research aims to analyze how different groups negotiate, resist, or facilitate the adoption of sustainable concrete solutions. Emphasizing that barriers are not solely technical but rather rooted within broader systems that influence material choices. Contractors prioritize cost-efficiency and construction timelines, often resisting unproven technologies due to perceived risks. Engineers emphasize structural integrity and compliance with building codes, requiring extensive testing and validation before approving new materials. Policymakers influence adoption through regulations, incentives, and sustainability mandates. Finally, consumers and developers drive demand by prioritizing green building certifications and long-term cost savings (Pellegrino, 2016).

The Social Construction of Technology (SCOT) framework is particularly relevant to sustainable concrete because it highlights the interpretive flexibility surrounding each innovation. For example, 3DCP may be framed by engineers as a breakthrough in automation and sustainability, yet viewed by contractors as unreliable and expensive (Sanjayan et al., 2019). Geopolymer concrete is praised by environmentalists for its reduction in embodied carbon but remains suspicious to regulators and developers due to its unconventional chemistry and curing behavior (Munir et al., 2024).

What makes SCOT valuable for this research is its capacity to go beyond technical analysis and unpack the societal, economic, and cultural dynamics that can determine an outcome for sustainable innovation. Stabilization of a technology occurs when relevant social groups resolve their disagreements and converge on a shared meaning or function for it. This was the case with fly ash, which, after years of performance data and regulatory support, gained widespread approval as a supplementary material (Wesche, 1991). As a result, understanding these types of negotiations is essential for identifying where interventions can help transform emerging sustainable concrete technologies from experimental concepts into widely accepted construction standards.

Makers interpret sustainable concrete technologies through different lenses, shaped by their professional priorities and experiences. For instance, some engineers and developers regard 3D concrete printing (3DCP) as a transformative solution for sustainability and efficiency, while others perceive it as costly, unreliable, or lacking in regulatory clarity (Sanjayan et al., 2019). Geopolymer concrete faces similar tensions, that is admired for its low-carbon profile yet questioned for its long-term durability and compatibility with existing standards (Munir et al., 2024).

Technologies like fly ash gained industry acceptance only after years of performance validation and regulatory support (Wesche, 1991), illustrating how consensus must emerge for widespread adoption to occur. Many sustainable concrete alternatives remain in a state of interpretive flux, and understanding these ongoing negotiations is essential for identifying where targeted interventions, such as policy incentives and education campaigns, can shift perceptions and transform these innovations into industry norms.

Methods

This research approach uses literature reviews and case study analysis to examine the sociotechnical factors shaping sustainable concrete adoption. The study will analyze industry policies and academic publications to identify technological acceptance and resistance.

Additionally, case studies of successful and unsuccessful sustainable concrete applications will illustrate how social groups interact with these innovations. The findings will inform strategies that would aid in facilitating the adoption of low-carbon concrete solutions in the construction industry.

The analysis includes both successful and unsuccessful case studies involving 3DCP, geopolymer concrete, and RCA to demonstrate how technology adoption is mediated by social context rather than solely by technical merit. Each material presents a different set of opportunities and challenges, shaped by how stakeholders interpret its performance, risks, and relevance. For instance, while 3DCP is celebrated in academic and media circles for its automation potential and sustainability, it is often viewed with skepticism by practitioners due to a lack of code integration and high equipment costs. Similarly, RCA is environmentally beneficial and readily available in many regions, but lingering doubts about its strength and uniformity limit its structural applications. Geopolymer concrete offers an innovative replacement for Portland cement, yet it faces regulatory and supply-chain hurdles. Using the Social Construction of Technology (SCOT) framework, this study dissects these differing perspectives to reveal how stakeholders' values, knowledge bases, and institutional constraints shape the trajectory of each material. Thematic analysis was used to group recurring concerns, such as durability, constructability, or economic feasibility, within stakeholder narratives, linking individual interpretations to broader sociotechnical structures and trends.

Regulatory agencies play a critical gatekeeping role in determining which materials can be legally and safely incorporated into the built environment. Their standards and codes reflect a preference for time-tested practices, resulting in an institutional bias toward traditional concrete. Because current building codes were largely developed around cast-in-place Portland cement concrete, newer technologies like 3DCP or geopolymer mixes often do not fit neatly within existing prescriptive frameworks. For example, 3DCP structures, which rely on digital fabrication rather than manual formwork, typically require case-by-case approval or performance-based evaluations, which introduce delays and additional costs (Nan et al., 2025). This procedural ambiguity increases perceived risk for developers and deters widespread adoption. Furthermore, code officials themselves may lack the training or resources to evaluate unconventional materials, leading to more conservative rulings. As a result, even promising technologies may be relegated to demonstration projects or niche applications until formalized pathways are established for approval and oversight.

The lack of unified global standards for sustainable concrete technologies compounds the issue of regulatory inertia. While some countries have begun integrating sustainability metrics into their building codes, there is no consistent international framework that supports the scaling of experimental materials like 3DCP or geopolymer concrete. Batikha et al. (2022) note that the absence of standardized testing protocols, material classification systems, and performance benchmarks contributes to legal ambiguity and deters investment in production infrastructure. This regulatory fragmentation creates a patchwork of localized rules that developers and manufacturers must navigate, adding to project complexity and cost. Without harmonized standards or inter-agency cooperation, adoption will likely remain sporadic and geographically constrained. Moreover, innovation-friendly policies such as provisional approvals, third-party certification, or fast-track pilot programs are often lacking, especially in regions with under-resourced permitting offices. Addressing these regulatory bottlenecks is essential to moving sustainable concrete solutions from the periphery of the industry into the mainstream.

Contractors often frame new materials through a lens of cost, constructability, and liability. Many view innovations like 3DCP or geopolymer mixes as high-risk investments due to the need for specialized training, equipment, and workflow adaptation (Sanjayan et al., 2019). Transitioning to these technologies often demands upfront capital, prolonged learning curves, and new coordination protocols with suppliers and engineers. For example, the use of geopolymer concrete may require rethinking batching processes, curing conditions, and quality control methods—all of which deviate from established norms and introduce uncertainty into already tight project schedules. Additionally, there is concern over warranty issues, as contractors may be held liable if non-standard materials fail in the future. Even when sustainable alternatives meet performance benchmarks, contractors may still resist if switching involves retraining crews, adjusting insurance coverage, or revising procurement and bidding strategies. These concerns are compounded on fast-track projects, where introducing unfamiliar systems is seen as an unnecessary risk.

Interpretive flexibility is evident in how firms perceive the same material differently depending on their size, specialization, and market position. One builder may embrace 3DCP as a cutting-edge tool that reduces formwork labor and speeds up production, viewing it as a strategic advantage in a competitive market. Another may see it as a disruptive threat to the value of traditional skilled labor, particularly among unionized trades or legacy crews. This divergence highlights the fragmented nature of construction culture and the importance of trust and familiarity in shaping adoption decisions. Furthermore, smaller contractors may lack the financial resources to experiment with emerging technologies, making them more risk-averse than larger firms with dedicated budgets. Without economic incentives, client mandates, or strong evidence of return on investment, adoption remains limited to niche applications or flagship demonstration projects. Widespread implementation will require technological refinement and cultural and economic alignment within the contracting community.

Engineers are evaluators of material performance, they also shape technology adoption through their interpretations. For a material like geopolymer concrete to gain acceptance, engineers must conduct durability studies, develop design models, and integrate the material into structural software (Munir et al., 2024). Their focus on data and validation reflects the SCOT principle that stabilization occurs only after all interpretive conflicts are addressed. When engineers endorse a material, it gains credibility across the construction network. The opposite is also true, when materials lacking sufficient test data or design guides are quickly dismissed as unreliable.

Banks and insurers contribute to the social construction of sustainable concrete by defining what is financially viable. As Wang and Tang (2022) explain, sustainable materials are often viewed as risky due to limited data on lifecycle performance. This risk aversion reinforces the dominance of conventional materials and limits experimentation.

Finally, end users and developers shape adoption by demanding or resisting green alternatives. While environmental awareness is rising, skepticism remains about the long-term safety and aesthetics of alternative materials. López-Malest et al. (2024) highlight that public interest in sustainable housing is growing, but not yet strong enough to drive market transformation alone. Media portrayals and demonstration projects are crucial for reshaping public narratives. For example, high-profile 3D-printed homes have helped reframe the technology as practical and affordable. Still, SCOT serves as a reminder that such shifts require broad engagement, not just publicity.

While the SCOT framework allows for rich theoretical analysis, future research should incorporate empirical data through interviews with contractors and developers to capture real-time negotiation processes. Additionally, research should investigate adoption patterns in lower-income regions where resource constraints and informal practices may produce different sociotechnical dynamics. Ultimately, deeper interdisciplinary collaboration is needed to guide the construction industry toward truly sustainable and socially accepted concrete solutions.

Conclusion

The adoption of sustainable concrete technologies is shaped as much by social dynamics as by technical performance. Through the Social Construction of Technology (SCOT), it becomes clear that differing interpretations among engineers, end users, and others either accelerate or impede the integration of innovations like 3D concrete printing, geopolymer concrete, and recycled aggregates. These findings emphasize that advancing sustainable materials requires more than technical innovation. It demands alignment across regulatory frameworks, financial models, and public perception.

Understanding these sociotechnical negotiations allows stakeholders to identify targeted interventions that can transform experimental materials into accepted industry standards. As the construction sector faces mounting pressure to reduce its environmental impact, this research underscores the need for collaborative strategies that support both innovation and systemic change. It is crucial to address these barriers through targeted strategies that promote awareness, standardization, and regulatory support. With collaboration among all parties and emphasizing successful case studies, the construction industry can enhance the acceptance of sustainable concrete solutions. Ultimately, this will not only contribute to environmental sustainability but also pave the way for a more resilient and responsible built environment.

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