Lightweight High Strength Concrete For Use in a Concrete Canoe

Reducing Concrete's Carbon Footprint: Strategies for Sustainable Construction

A Thesis Prospectus

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By

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On my honor as a University of Virginia 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 and cement production is the single greatest polluter on earth. Cement production contributes to 8% of all emissions worldwide and to accelerating the pace of global warming. (Zhang, 2024) This pollution also leads to more acute environmental problems, such as nitrification and acid rain, both of which are secondary environmental effects caused by the burning of fossil fuels to stoke the massive kilns required to turn limestone into cement.

The concrete canoe competition came about due to the proliferation of concrete as material. What started as a joke among college students has become an important part of ASCE's competition roster. This competition forces students to research and develop innovative new concrete mixes that satisfy a large list of requirements published in the RFP (request for proposal) which is unique to each year.

The concrete canoe ethos is three pronged, to make the strongest, lightest, most environmentally friendly concrete possible while staying within the confines of the competition. Lightweight concrete requires less material to support its own weight. Stronger concrete requires less material overall to generate the same supporting strength. Environmentally friendly concrete has a much lower GWP (global warming product) per cubic yard as opposed to more traditional materials such as Portland cement and the additions of secondary cementous materials further decreases this GWP. These three prongs work together for designs that use less overall concrete while resulting in concrete that is better for the environment. My technical report looks at how we as engineers can reduce concretes carbon footprint without sacrificing strength or workability. My STS report will explore ways to reduce the carbon footprint of concrete and examine the impact of these changes on stakeholders in the construction industry. Key stakeholders include construction companies, their clients, the surrounding communities, and, most importantly, the environment.

Technical research portion: lightweight high strength concrete for use in a concrete canoe

Lightweight, high-strength concrete represents a unique opportunity to innovate within both competitive and sustainable engineering applications. Concrete remains one of the most extensively used materials globally, yet its environmental impact necessitates significant advancements in production and application. Developing a functional concrete canoe using lightweight concrete serves as both a technical challenge and an opportunity to push the boundaries of material science and environmental responsibility. Tasked by the Concrete Canoe Design Board, our team has undertaken the development of a canoe that meets strict guidelines for strength, replicability, and sustainability, all while maintaining the capacity for mass production.

The scope of this project focuses on three interconnected areas: the concrete mix, the design of the hull, and the construction methodology. These components must work harmoniously to achieve a canoe capable of performing effectively in competition while serving as a model for environmentally conscious design. The goal is to establish a process that can be scaled to produce up to 100 identical canoes using consistent methods and molds. Beyond meeting these requirements, the project strives to advance sustainable practices in lightweight concrete application.

In developing the concrete mix, our research has concentrated on achieving a balance between reduced weight and high structural strength while ensuring the material is suitable for 3D printing. Preliminary tests have yielded promising results, with one mix exceeding strength expectations even when utilizing suboptimal materials. Building on this, additional designs incorporating advanced admixtures have been proposed by members of the general concrete canoe team as well as by the team captains These admixtures improve the workability of the mix without compromising strength. Our Research has further refined optimal fiber content, identifying 1.5% by volume as ideal, while aggregate gradations are being optimized to balance density and strength. Efforts have also been directed toward enhancing mixing techniques to improve consistency and homogeneity, which are critical for reliable results across different batches.

The hull design process has utilized advanced 3D modeling software to develop an optimized shape for the canoe. This design balances hydrodynamic efficiency with structural durability, ensuring that the canoe performs effectively in water while remaining robust under stress. Initial design iterations have provided a foundation for detailed structural calculations, which will be refined once the final mix design parameters are established. Advanced simulations, including Finite Element Analysis, are planned to further analyze stress distribution and ensure the hull meets the necessary standards for strength and reliability.

The construction methodology for the canoe has explored innovative approaches to mold and assembly design. Current evaluations include male molds, female molds, and a mold-free printing method. Each approach is being tested for its compatibility with 3D printing and its ability to incorporate steel cabling for post-tensioning. This cabling system, combined with plastic tubing, will ensure the structural integrity of the canoe's sections while maintaining a seamless appearance. Early testing of these systems aims to identify the most effective method for mass production, aligning with the broader project objectives.

The project follows a structured timeline, beginning with initial research and preliminary testing of materials and designs. The development phase focuses on finalizing the mix design and hull geometry while selecting the preferred construction method. These efforts will culminate in the production of a scale-model prototype, which will be thoroughly tested for its structural and hydrodynamic performance. The project will conclude with a detailed report documenting the process, findings, and recommendations for future work.

This initiative not only aims to meet the specific requirements of competitive concrete canoe design but also seeks to establish new standards for sustainability in lightweight concrete applications. By combining advanced material science, innovative design techniques, and environmentally conscious practices, the project sets a precedent for the future of concrete engineering. The success of this endeavor will highlight the potential of lightweight high-strength concrete to revolutionize both niche applications, like competitive canoes, and broader construction industries seeking sustainable solutions.

STS Research portion: Reducing Concrete's Carbon Footprint: Strategies for Sustainable Construction

Introduction

How can the concrete industry reduce its carbon emissions while meeting the demands of modern infrastructure? Concrete, a cornerstone of urban development, is integral to the construction of cities, transportation systems, and industrial facilities. However, it is also a significant contributor to climate change. Cement, the binding agent in concrete, accounts for approximately 8% of global carbon dioxide (CO_2) emissions due to the energy-intensive production process and the chemical reactions involved. (Zhang, 2024) As global urbanization accelerates, the demand for concrete will rise, exacerbating its environmental impact. (Belaïd, 2022)

This research explores the intersection of technology, policy, and societal norms to investigate how the concrete industry can transition toward sustainability. By analyzing the mutual shaping of technological advancements, social expectations, and government regulations, this paper identifies pathways to reduce concrete’s carbon footprint while supporting sustainable development.

Background/context

Concrete's pervasive role in modern society is deeply embedded in cultural and economic systems. Its durability and affordability have made it the default material for infrastructure, embodying societal values of permanence and progress. However, these norms come at a steep environmental cost. Cement production, which involves heating limestone and clay at high temperatures, releases CO_2 both through fossil fuel combustion and the chemical breakdown of limestone. Each ton of cement produced generates approximately 600 kg of CO_2, contributing to the material's substantial global carbon footprint (Brogan, 2021).

Historically, the concrete industry prioritized performance and cost over environmental concerns. More recently, however, rising environmental awareness has spurred efforts toward greener practices. Public campaigns and certifications like LEED have encouraged architects and engineers to explore low-carbon alternatives (Liu, 2022). Yet, the ingrained cultural associations of concrete with reliability and permanence remain significant barriers to widespread change.

This research seeks to understand how emerging technologies, evolving societal norms, and government interventions can collaboratively reduce concrete's environmental impact. It bridges the gap between technological possibilities and the social and regulatory acceptance required for systemic change.

Use of literature

This project draws on interdisciplinary literature to frame its analysis. Environmental studies document the scale of emissions from cement production and the efficacy of low-carbon alternatives, such as carbon neutral cements and carbon absorbing cements (cooper, 2021)

Technological studies highlight innovations like 3D printing and supplementary cementitious materials (SCMs) that reduce reliance on traditional cement. Social science research examines public perceptions of sustainability and the role of cultural norms in shaping consumption patterns. Policy analyses explore the impact of carbon pricing, green infrastructure mandates, and international agreements, like the Paris Accord,on the construction industry.(Hart, 2024)

By synthesizing these perspectives, this research identifies gaps in the current understanding. While significant work has been done on individual solutions, little attention has been paid to the co-production of technology, policy, and social values needed for systemic change. This paper aims to fill this gap by analyzing how these factors interact to drive sustainable practices in the concrete industry.

Conceptual Framework

This research is grounded in Science and Technology Studies (STS), particularly the concepts of mutual shaping and socio-technical systems. It views the concrete industry as a socio-technical system in which technology, policy, and societal values co-produce each other. For instance, the adoption of low-carbon concrete technologies is not only determined by their technical feasibility but also by social acceptance and regulatory incentives (Hart, 2024).

Additionally, theories of innovation diffusion inform the study, offering insights into how sustainable practices spread within the construction sector. The research investigates barriers to adoption, such as cost, scalability, and entrenched norms, and identifies strategies to overcome them. Framing the issue through these STS lenses highlights the interconnectedness of technological, social, and regulatory change.

Methods & Evidence

This project aims to address the research question by conducting a detailed analysis of case studies focused on carbon-curing concretes. These materials represent an innovative approach to concrete production, utilizing CO_2 gas during the curing process. This method not only enhances the concrete's properties but also permanently sequesters CO_2 within its matrix, significantly reducing the material's overall global warming potential (GWP). To comprehensively explore this topic, the project will analyze infrastructure projects that have adopted carbon-curing technologies, assessing their successes and challenges.

The evidence collected will include technical performance data (e.g., material strength and durability), environmental impact assessments (e.g., GWP reductions), and documentation of social and regulatory factors (e.g., stakeholder acceptance, policy compliance, and industry adoption). Data will be sourced from project reports, peer-reviewed studies, and regulatory documents.

The analysis will focus on identifying key factors that affect the use of carbon-curing concrete, such as its technical performance, environmental benefits, and how it is influenced by regulations and public acceptance. By looking at patterns in the data, the research will aim to understand what drives or hinders the adoption of this technology in construction

Innovations for a Sustainable Future

Technological advancements are pivotal in reducing concrete's carbon footprint. Researchers are developing carbon-zero and carbon-negative concretes that absorb more CO_2 during curing than they emit during production (Singh, 2022). Supplementary cementitious materials (SCMs), such as fly ash and slag, can replace a significant portion of cement in concrete mixtures, reducing emissions by up to 50% (Chen, 2024).

Conclusion

Concrete is essential for infrastructure but its environmental impact, particularly from cement production, is a major challenge. The technical project on lightweight high-strength concrete for a concrete canoe demonstrates how innovation can reduce concrete's carbon footprint without sacrificing performance.

The STS research highlights how technological, policy, and societal changes can drive sustainability in the concrete industry. By advancing sustainable concrete technologies and fostering collaboration, industry can meet modern infrastructure demands while reducing its environmental impact. A balanced approach involving technology, policy, and social values is key to creating a sustainable future for concrete

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