[3D Printing Sustainable Concrete Canoes]

[Decarbonizing Concrete and The Push for Clean Energy]

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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 construction materials in the world, but also has some of the most environmentally damaging processes used during its creation and usage. The capstone team has been tasked by the Concrete Canoe Design Board to design a sustainable concrete mixture and process for mass manufacturing canoes without altering structural integrity. The design must be replicable and able to create 100 canoes using the same methods and mold. By researching construction, hull, and mix designs the team will develop a sustainably 3D-printed concrete canoe process. Creating a sustainable concrete canoe design involves not only engineering a strong, durable canoe but also using materials and methods that reduce the carbon footprint of concrete production. The mix planned for the 3D-printed canoe uses fly ash using fly ash can reduce total concrete emissions by 13 to 15% (Flower & Sanjayan, 2007). Through research, it will be necessary to address the addition of different aggregates to help decarbonize concrete production and determine its effects on local communities and global markets while creating a push for clean energy sources. The technical dimensions of the research question focus on decarbonizing concrete with the inclusion of new aggregates while also focusing on the emergence of clean energy sources and their effects on global markets. The human/social dimension focuses on how politics and communities have benefitted from lower emissions in the concrete industry, the inclusion of clean energy sources, and the reduction of climate change factors positively affecting the Earth and coastal communities.

On a larger scale, the shift toward sustainable concrete mixes can drive demand for low-carbon construction materials. This push not only supports the clean energy transition by reducing reliance on fossil fuels in manufacturing but also encourages research and development of alternative materials. As industries and governments see the economic and environmental benefits, it can lead to wider adoption of green technologies in construction and related sectors, amplifying the impact of this single design approach across global markets and supporting a more sustainable infrastructure for the future. Innovating sustainable concrete production by using alternative, low-carbon materials and processes can drive positive environmental, economic, and social impacts.

3D Printing and Manufacturing of Concrete Products

3D printing of concrete builds structures layer by layer from digital models such as CAD models. A specially formulated concrete mix flows through a nozzle, setting quickly to support additional layers with reusable molds or no mold at all. The concrete mix used in 3D printing is optimized for flowability and typically hardening, and it includes binders, accelerators, and sometimes fibers or additives to enhance its strength and ensure each layer connects well to the next. Strong layer adhesion is crucial for creating a durable, cohesive structure, which is achieved through precise cabling, optimized mixes, and bonding additives that strengthen inter-layer connections. To further enhance durability, reinforcement materials like tensioned cables, mesh, or fibers are sometimes incorporated. In the planned 3D-printed canoe a cabling system will be introduced which can enhance strength by up to 300% (Fanning, 2001). The design flexibility of 3D printing also allows for optimized shapes—like complex canoe curves—that reduce material use while maintaining structural integrity. These factors ensure that 3D-printed concrete can meet or exceed the durability standards of traditional construction and mixing practices while efficiently and sustainably manufacturing products.

The process of 3D printing concrete addresses several critical problems in traditional construction, notably issues related to efficiency, waste, labor shortages, and environmental impact. Traditional concrete construction requires complex formwork, significant manual labor, and extensive material use, all of which contribute to high costs, slow project timelines, and increased waste. Additionally, the construction sector is a major contributor to global CO_2 emissions, largely due to cement production, energy-intensive transportation, and inefficient material use. Cement production accounts for 74% to 81% of the total CO_2 emissions in typical concrete mixes with coarse aggregates making up 13 to 20% and fine aggregates making up 30 to 40% of these emissions (Flower & Sanjayan, 2007).

3D printing concrete provides a streamlined solution by enabling the precise, layer-by-layer deposition of material, which reduces or eliminates the need for formwork and minimizes waste. By directly printing only what is needed, the process reduces excess material use and significantly lowers waste, contributing to a more sustainable building practice. The accuracy of 3D printing also allows for the creation of complex designs and geometries that are difficult or impossible to achieve with conventional methods, offering more efficient and structurally optimized designs that can use less material overall. The choice of 3D printing the canoe challenges previous years' design and production processes as portrayed by the Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions (Norman et al., 2006). Additionally, 3D printing addresses labor shortages in the construction industry by automating much of the building process, reducing reliance on manual labor. This automation not only speeds up construction timelines but also allows for safer job sites by reducing the need for workers to perform dangerous or repetitive tasks.

On a broader scale, the potential for sustainable and locally sourced aggregates in 3D-printed concrete mixes further reduces the carbon footprint of each project. Sustainable resources also known as recycled concrete aggregates (RAC) including fly ash and many types of fibers reduce the need for the virgin extraction of materials ultimately reducing CO_2 based on life cycle assessment models (Mcintyre et al., 2009). RAC can attain compressive strengths ranging from 70% to 100% of conventional concrete, elastic modulus values of 60% to 90%, flexural strengths of 80% to 100%, and splitting tensile strengths of 70% to 90%, depending on the quality and treatment of the recycled aggregates (Xie et al., 2018). When combined with renewable energy sources to power 3D printing machinery, this process aligns with global goals to reduce CO_2 emissions and build greener, more sustainable infrastructure. The focus on reducing CO_2 emissions challenges engineers' perspectives as they have previously designed for strength and durability. As strength and emissions are optimized for non-traditional materials such as concrete, a more efficient push for green infrastructure and clean energy sources can erupt.

Society, Economics, and A Clean Energy Push

In this research prospectus on reducing carbon emissions in concrete and promoting renewable energy, I will begin by collecting data from multiple sources, including industry reports, scientific studies, government policies, and case studies from concrete manufacturing companies focused on low-carbon innovations. For data analysis, I'll employ both qualitative and quantitative methods: qualitatively, I will analyze industry and policy documents for recurring themes related to emission reduction strategies and energy transitions; quantitatively, I will examine carbon emissions data to identify trends and assess the impact of renewable energy integrations in concrete production. To interpret the results, I'll compare these findings with existing literature on clean energy advancements and carbon-neutral strategies in industrial processes, drawing insights on how emerging technologies and policy measures can drive carbon reduction in the concrete industry and accelerate the shift towards renewable energy.

The research aims to explain how the addition of different aggregates helps decarbonize concrete production and how it positively affects local communities and global markets while creating a push for clean energy sources. This is crucial because it addresses the urgent need to reduce carbon emissions in the construction industry, a significant contributor to global greenhouse gases. It also promotes environmental sustainability and supports economic growth and community well-being, driving the global transition towards clean energy sources. From an STS perspective the incorporation of alternative aggregates, such as recycled materials and industrial by-products, reduces the carbon footprint of concrete production by lowering the demand for virgin raw materials and decreasing greenhouse gas emissions. Advances in 3D printing concrete technology enable the precise use of diverse aggregates, enhancing the material’s performance and durability while promoting sustainable construction practices. Utilizing local and recycled aggregates supports local economies, reduces waste, and fosters global market shifts towards sustainable materials, driving the adoption of clean energy sources and benefiting communities worldwide.

Choi et al. (2016) highlight the environmental, economic, and social implications of highway concrete rehabilitation alternatives. The study emphasizes that sustainable concrete practices can reduce environmental degradation and promote economic efficiency by minimizing resource consumption and waste. This not only benefits local ecosystems but also reduces costs associated with raw material extraction and waste management, thereby positively impacting local economies. Spahr et al. (2021) discuss public attitudes toward green stormwater infrastructure, which often incorporates sustainable concrete solutions. The study reveals that communities value the nonmonetary benefits of green infrastructure, such as improved aesthetics, enhanced recreational spaces, and better air quality. These benefits contribute to higher property values and improved quality of life, fostering community support for sustainable practices. Communities adopting sustainable practices experience improved quality of life through better air quality, enhanced recreational spaces, and increased public health. Bennett et al. (2020) explore the predictors of renewable energy penetration in communities. The study finds that socioeconomic factors, such as income levels and political leanings, significantly influence the adoption of renewable technologies. As communities become more aware of the environmental and economic benefits of sustainable practices, there is a growing demand for clean energy solutions, which in turn drives market shifts towards renewable energy. Sakellariou and Mulvaney (2013) discuss the challenges and opportunities faced by engineers in the renewable energy transition. The authors argue that a multidisciplinary approach, incorporating social and environmental dimensions, is essential for a successful transition. This includes developing policies that support sustainable concrete practices and incentivize the adoption of clean energy technologies. The Inflation Reduction Act and Bipartisan Infrastructure Law have driven significant investments in clean energy, totaling $421 billion in domestic, utility-scale clean energy production since August 2022 (Bird & Womble, 2024).

Exploring the significant progress the United States has made in transitioning to cleaner energy, will create a focus on the key drivers behind this shift. For example, the country has seen substantial growth in solar and wind energy capacities, supported by legislative measures like the Inflation Reduction Act and Bipartisan Infrastructure Law. These policies aim to reduce emissions and promote carbon-free electricity generation. Additionally, examining how the adoption of low-emission materials and sustainable practices has positively impacted various aspects of society will contribute to the STS framework of this paper. This includes economic benefits such as cost savings in construction and manufacturing, support for local economies through the use of local and recycled materials, and improved quality of life in communities embracing sustainable practices. The overall analysis of the question takes into account science, technology, and society to better understand how advanced processes and reductions in CO_2 emissions from new concrete technologies affect the global economy, local communities, and renewable energy development.

Conclusion

The capstone team aims to use a repetitive process such as 3D printing to develop a canoe that floats and is made of low-emission concrete with materials such as fly ash and blast furnace slag. A post-tensioning cabling process will be used for added bonding and strength of the concrete. Research areas include mix-designs using different aggregates; hull curves and shapes; calculations of stress, buoyancy, and strength; and construction of a mold and 3D printed design. From an STS perspective, the cleanest material composition of concrete will be developed along with its respective CO2 reduction measurement. The more socially focused aspects of this research focus on the economy around concrete and construction practices, quality of life in communities affected by production practices or clean energy practices, and a larger societal push for clean energy sources and carbon emission cuts. Once completed, the 3D-printed canoe project will lead the way in developing printing practices for the construction industry while the research paper will back many of the quantitative properties of the process including carbon emissions, stresses and strengths of concrete, and monetary savings with renewable energy. However, the qualitative aspects such as the effects this project has on society, the economy, and the environment will demonstrate the need for new ideas in the construction industry. If carbon emissions can be lowered in construction practices, other industries can follow.

This capstone project will have a tangible deliverable with a canoe that is durable, floats, and releases less carbon into the atmosphere. The canoe is evidence that environmentally friendly practices can be incorporated into any sector of business without hindering its functions. The STS paper will provide how this is possible, why it is beneficial to start incorporating these practices into the everyday lives of all people, and why it is important to start the transition today.

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