DEVELOPMENT OF 3D CONCRETE PRINTING FOR SUSTAINABLE CONSTRUCTION

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Abstract: This study emphasizes the need for sustainability in the construction sector by examining the environmental impact of a specific 3D printing technique. Drawing from an engineering-focused 3D printing project, it explores various scenarios and performs a cradle-to-gate life cycle assessment (LCA) using SimaPro 9.5.0 software. The findings highlight the advantages of a mix design utilizing fly ash and furnace slag as binders, which demonstrate reduced environmental impacts across multiple categories. However, the use of silicate in geo-polymer concrete poses ecological challenges due to its high energy demands during production. Additionally, replacing sand with sawdust significantly decreases CO2 emissions, showcasing the environmental benefits of integrating by-product materials into construction practices.

Keywords: life cycle assessment; additive manufacturing; sustainability; green concrete; environmental footprint; geo-polymer (GP) concrete.

1. Introduction

The growing concerns over increased energy consumption and rising CO2 emissions have heightened attention to environmental challenges, particularly within the construction sector. Responsible for approximately 35% of global energy use and carbon dioxide emissions [1], the construction industry faces mounting pressure to adopt energy-efficient and sustainable practices. Traditional building methods, such as timber construction, on-site concrete casting, and brickwork, remain prevalent despite challenges related to waste generation and quality control. This emphasizes the pressing need for innovative, eco-friendly construction approaches that address the socio-economic and environmental demands of modern infrastructure [2].

3D printing, or additive manufacturing (AM), has emerged as a transformative technology within Industry 4.0, offering promising solutions to these challenges [3]. Its design versatility, material efficiency, and streamlined manufacturing processes are proving advantageous across numerous industries [4]. Specifically, 3D concrete printing (3DCP) is gaining recognition for its potential to significantly reduce the physical and functional energy demands of construction, thereby lowering carbon footprints [5].

A notable example is the Tecla project by WASP (World's Advanced Saving Project) and Mario Cucinella Architects. Located in Massa Lombarda, Italy, Tecla features 3D-printed structures designed for effective insulation and ventilation, utilizing the Crane WASP 3D printer. Launched in 2021, this system demonstrates efficient and sustainable construction techniques, using local materials to minimize CO2 emissions [6]. While the project underscores the sustainability benefits of 3DCP, it also raises critical questions: What environmental impacts might arise from the use of a validated concrete mix in 3D printing? And can emissions be further reduced through adjustments to mix designs?

This study aims to address these questions by evaluating the ecological effects of various mix designs used in 3D concrete printing. Building on insights from the Tecla project, it examines four distinct mix designs, analyzing energy and material inputs and their corresponding environmental impacts. By investigating these variables, the research seeks to provide a comprehensive understanding of how mix design choices influence the sustainability of 3DCP, contributing to the broader goal of eco-friendly construction practices.

2. Life Cycle Assessment

This study employs the Life Cycle Assessment (LCA) methodology, adhering to ISO standards 14040-44, to assess environmental impacts. By utilizing SimaPro software in conjunction with the Ecoinvent database, the LCA evaluates the environmental effects associated with processes and products throughout their life cycle. The approach includes defining the study's goal and scope, setting system boundaries, identifying the functional unit for analysis, and evaluating various environmental impact categories.

2.1. Goal, Scope, Functional Unit, and System Boundary

This study aims to evaluate the environmental impact of a 3D-printed house using four design scenarios (A, B, C, and D) in Attawapiskat, a community selected due to its ongoing housing crisis【8】. The functional unit for the analysis is a 130-square-meter house constructed using the Crane WASP 3D printer. This size was chosen as a reference, considering that the average house size in Canada is approximately 181 square meters【9】, with variations influenced by factors such as province, house type, personal preferences, lifestyle, and budget.

In Attawapiskat, where the average household consists of 3.7 individuals【10】, the recommended living space per person typically ranges from 18.58 to 65.03 square meters. For a family of this size, the suggested total living area would be between 68.74 and 240.52 square meters. The study employs a cradle-to-gate system boundary to frame its assessment.

2.2. Life Cycle Inventory

The selection of mix designs in this study is informed by their prior application in 3D printing research and their use of geo-polymer materials such as fly ash and blast furnace slag. The goal of using geo-polymers is to adopt a proven mix design that incorporates industrial by-products, thereby reducing environmental impact. Mix designs for the 3D-printed concrete scenarios were adapted from materials commonly referenced in the literature.

An experimental approach was undertaken, substituting sand with sawdust in the concrete mix. In Scenarios A and B, 50% of the sand was replaced with sawdust, while in Scenarios C and D, sand was entirely replaced with sawdust (100% substitution). Incorporating sawdust into concrete and cement-based composites represents an innovative method for sustainable waste management. Lightweight concretes (LWCs), as explored by Mehdi et al. in 2023, offer benefits such as cost savings, improved handling, and enhanced performance. Replacing natural aggregate with sawdust decreases compressive strength by 35%, but improves sound absorption by 38% and reduces thermal conductivity by a factor of approximately 4.5.

Additional key data for the life cycle assessment model were derived from the Tecla project. For example, energy consumption of the 3D printer was calculated based on parameters from Tecla's data and tailored to a 130 m^2 structure. The Tecla project reported a printing duration of 200 hours with an average electricity consumption of less than 6 kW. Scaling these parameters for the current study, using the Crane WASP 3D printer, it is estimated that printing a 130 m^2 house would require approximately 13 kW and take around 433.3 hours. Table 1 provides a detailed breakdown of these calculations.

However, direct use of sawdust in concrete ink requires size reduction for printability. While sawdust is a by-product, the process of reducing its size involves energy consumption, which adds to its environmental footprint.

Table 1. Crane WASP 3D printer features for Tecla and Attawapiskat projects.

Features	**Tecla Project**	**Attawapiskat Project**
Size of house	59 m^2	129 m^2
Material usage (18 mm nozzle)	39 m^3	82.34 m^3
Printing time	199 h	443.3 h
Electricity consumption	5.9 KW	14 KW

Table 2 summarizes the life cycle inventory for the 3D printing scenarios, detailing key parameters such as energy consumption during construction, electricity requirements for 3D printing, material quantities required for constructing the house, and transportation data. The latter includes the estimated distances from potential material sources to the construction site in Attawapiskat, providing a comprehensive overview of the resources and logistics involved.

Table 2. Life cycle inventory for 3D printing scenarios.

Items	Unit	Scenario A	Scenario B	Scenario C	Scenario D	Distance t* km
Fly ash	kg	13,638.90	49,805.13	13,638.90	49,805.13	0.955
Slag	kg	-	8788.41	-	8788.41	0.955
Sand	kg	51,290.53	43,946.19	-	-	0.683
Na_2SiO_3	kg	-	14,498.56	-	14,498.56	1.336
NaOH	kg	-	11,869.98	-	11,869.98	1.336
Water	kg	19,177.12	4882.73	19,177.12	4882.73	0.100
Cement	kg	47,860.14	-	47,860.14	-	0.683
Sawdust	kg	51,290.53	43,946.19	102,581.06	87,892.38	0.100
Silica fume	kg	6860.78	4882.73	6860.78	4882.73	0.955
Electricity	MJ	21,293.99	21,148.57	22,309.54	22,018.71	-

2.3. Life Cycle Impact Assessment

This study employs the Recipe Endpoint H method for several key reasons, primarily to evaluate the ecological impacts of the construction process at the endpoint level, where Recipe provides detailed emissions data. While methods like Traci and LIME are often chosen based on the specific depth of analysis required, Recipe remains a preferred approach in this research domain. It offers a comprehensive assessment of diverse environmental categories, including global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, fine particulate matter pollution, terrestrial acidification, freshwater and marine eutrophication, terrestrial and aquatic ecotoxicity, human carcinogenic and non-carcinogenic effects, land use, mineral and fossil resource depletion, and water consumption.

3. Finding and Interpretation

The data highlight key factors influencing the environmental impact across the evaluated scenarios. Cement emerges as a significant contributor in Scenarios A and C, while transportation and sodium silicate dominate in Scenarios B and D. These results align with findings from other studies. For instance, research by Mohammad et al., Abdalla et al., and Sambucci et al. reported cement's environmental contributions at 78%, 97%, and 92%, respectively. Cement and concrete production are consistently identified as major environmental contributors. Similarly, sodium silicate, particularly in its production process, is recognized for its substantial ecological impact. Yao et al. demonstrated that reducing silicate content in geo-polymer formulations effectively mitigates environmental effects in 3D concrete printing.

Scenario Comparisons

A comparison of life cycle environmental impacts among the four scenarios emphasizes the role of different materials. Scenario A records the highest environmental impact across several categories, including climate change, photochemical oxidants, particulate matter formation, terrestrial acidification, freshwater eutrophication, and natural land transformation. In contrast, Scenario B shows the greatest impact on ozone depletion, human toxicity, terrestrial ecotoxicity, freshwater and marine ecotoxicity, agricultural and urban land occupation, metal depletion, and fossil resource depletion. Scenario C demonstrates the lowest impact on agricultural land occupation and ozone depletion, while Scenario D has the least environmental effect on natural land transformation, terrestrial acidification, and climate change.

Scenarios B and D are associated with substantial impacts due to the sodium silicate manufacturing process. However, incorporating sawdust as a sand replacement in 3D printing mix designs significantly reduces emissions across all categories. For instance, complete sand substitution with sawdust in Scenarios 1 to 3 led to a decrease in CO2 emissions from 47.57 tons to 44.81 tons. Similarly, in Scenarios 2 to 4, emissions dropped from 24.31 tons to 21.95 tons.

4. Conclusions

This research underscores the importance of sustainability in the construction industry, focusing specifically on the advancements in 3D printing technologies. By analyzing the environmental impacts of various material combinations and mix designs, it highlights the potential for reducing carbon footprints through the use of sustainable binders such as fly ash and furnace slag. Utilizing life cycle assessment methodologies, the study emphasizes the need for comprehensive evaluation of the environmental impacts associated with construction processes. Through the investigation of different mix designs and scenarios (A, B, C, and D), the research provides valuable insights into promoting eco-friendly practices and minimizing environmental impacts in the sector. Adopting sustainable strategies, including innovative materials and cutting-edge technologies like 3D concrete printing, represents a promising step toward fostering a more environmentally responsible and sustainable construction industry.

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