Reducing Carbon Emissions in 3D Printed RCC Slabs

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Abstract

Concrete 3D printing offers significant potential to revolutionize construction through improved efficiency and cost-effectiveness. However, high cement content in 3D printable mixes raises questions about the environmental sustainability of this technology. This study proposes an automated methodology for 3D printing Reinforced Cement Concrete (RCC) filler slabs using compressed polyethylene (PE) waste to reduce the carbon footprint. A gantry-style 3D printer with integrated pick-and-place functionality is designed to position recycled plastic fillers, reducing raw material consumption and emissions. A cradle-to-gate life cycle assessment is employed to compare three scenarios: conventional slabs, filler slabs with clay pots, and filler slabs with PE waste. The results show that the proposed method significantly reduce material use and carbon emissions, while mitigating the environmental impact of polyethylene waste mismanagement. This study demonstrates the potential of integrating 3D printing and automation to advance sustainable construction practices and lower the carbon footprint of RCC slabs.

Keywords – Concrete 3D printing, filler slabs, carbon footprint, carbon emission, automation, sustainable construction, recycling, polyethylene waste.

1 Introduction

Concrete 3D printing has potential to transform the construction industry in terms of productivity, cost effectiveness and environmental sustainability. 3D printing can help construction industry by improving productivity, overcoming skilled labor shortages [1–3], and increasing safety at off-site plants and on-site construction. 3D printing also eliminates the need for formwork, offering geometric flexibility and enabling significant material savings through structural optimization [4, 5]. Though Concrete 3D printing has various potential benefits, challenges like limited automation and dependency on manual labour, insufficient research on structural elements like slabs, and high cement content in 3D printable mixes persist.

The construction industry accounts for around 39% of global energy-related CO2 emissions, a figure expected to rise with urbanization [6]. Concrete, the second most used material worldwide due to its affordability and compressive strength [7], significantly contributes to this footprint, with cement production alone responsible for 5-8% of global CO2 emissions [8]. While concrete 3D printing reduces material waste and eliminates formwork, its high binder content elevates the carbon footprint, leaving its sustainability performance inconclusive. [9–11] have conducted studies to establish the sustainability performance of Concrete printing but they are limited to the non-structural components. The calculations for environmental impact in these studies lack consideration of electricity consumption and transportation of the materials. Inclusion of these aspects would give a clearer aspect on the sustainability performance of Concrete 3D printing process.

In flexural members like slabs and beams concrete tension zone has only one function to connect the concrete in the compression zone to the rebars in the tension zone, thereby facilitating shear transfer. This provides an opportunity to reduce the consumption of concrete in this region. Filler slabs reduce concrete usage in the tension zone by incorporating elements like clay pots and tiles between rebars, decreasing concrete consumption by 25-30%. While this lowers carbon emissions, the benefits are offset by the significant emissions from manufacturing these fillers [12]. Additionally, filler placement is time-intensive and requires meticulous supervision, inadequate oversight or poor workmanship can cause reinforcement bars to contact fillers, increasing the risk of corrosion. The world produces around 2.01 billion tons of solid waste, with 33% poorly managed and 11% incinerated, resulting in significant carbon emissions [13]. Waste management contributes 5% of global GHG emissions [14]. Using mechanically compressed plastic waste as fillers can mitigate emissions from clay pot and tile production while reducing those from incineration and mismanagement of polyethylene waste.

Most reported applications of concrete 3D printing focus on architectural elements or compression members [15]. To maximize its benefits, efforts are now directed toward printing structural elements capable of resisting tension and flexure [16]. While concrete 3D printing can reduce labour and enhance productivity, reliance on manual tasks such as reinforcement placement and curing may undermine efficiency and compromise the benefits of automation. As structural slab casting is labour-intensive process, concrete 3D printing integrated with automation for ancillary works can help reduce the requirement for manual labour and improve efficiency of the process.

This study proposes a methodology to leverage the benefits of concrete 3D printing, automation and filler slabs to reduce the carbon footprint of the RCC slab. A gantry-type 3D printer integrated with a robotic gripper is proposed to automate the precise placement of filler elements and reinforcement cages and casting of filler slabs. The system's environmental performance is assessed through cradle-to-gate life cycle carbon emission assessment of a case study comparing embodied carbon emissions for different scenarios of a 6 m × 4 m RCC slab. Mechanically compressed polyethylene (PE) waste is proposed as a filler material to overcome the limitations of clay pots.

2 Materials and Methods

2.1 Slab Design & Mix Design

As an illustrative case study, an RCC slab of width 4 m and length 6 m is designed. The design follows the Indian Standard Code for Plain and Reinforced Concrete [14]. Assumptions made for the design are mentioned in Table 1.

Table 1 Assumptions for the design of RCC Slab

Design Parameters	Unit	Value
Grade of Concrete	N/mm^2	35
Reinforcement Grade	N/mm^2	415
Live Load	kN/m^2	2
Floor Finish	kN/m^2	1.5
Exposure Conditions	N/A	Mild
Support Condition	N/A	Simply Supported

The design summary is presented in Table 2.

Table 2 Design Summary

Design Parameters	Unit	Value
Thickness of the Slab	mm	250
Rebar Diameter	mm	10
Main Rebar Spacing	mm c/c	150
Distribution Rebar Spacing	mm c/c	180
Cover Provided at the Bottom of the Slab	mm	20
Neutral Axis Location considered from the bottom of the slab	mm	130

The mix design [17] and the material usage detail are presented in Table 3 and Table 4 respectively.

Table 3 Mix proportion for OPC + 30% LC2 concrete design.

Material	Quantity (kg/m^3)
Quartz Sand	1206
Cement	575
LC2 (Limestone Calcined Clay)	246
Water	288

Table 4 Detail of material usage in conventional and filler slab

Material	Unit	Filler	Conventional
Total Volume	m^3	4.37	6
Printable Concrete (tension zone and boundary of compression zone)	m^3	1.63	3.26
Conventional M35 Concrete (used in compression zone)	m^3	2.74	2.74
Volume of Voids	m^3	1.64	-

2.2 Proposed Concrete 3D Printing Setup

A gantry 3D printer with a robotic gripper is proposed for slab printing, comprising three main components: a printing head with dual nozzles a pneumatic gripper for pick-and-place operations, and a motion control system. Concrete is pumped from the mixer to the printing head, where an auger mechanism ensures controlled extrusion. The dual nozzles handle 3D printable mix and regular concrete, respectively. The gantry operates in the x-y-z plane, facilitating rebar cage and filler element placement, with a workspace of 8 m × 8 m in the x-y plane and 1 m in the z direction. Workspace and the 3D printer is shown in Figure 1 and Figure 2 respectively. An early prototype of the design integrating 3D printing with robotic pick and place features is shown in Figure 3.

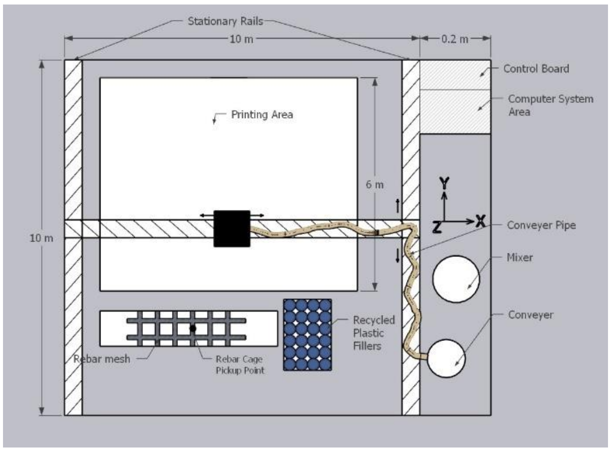

Figure 1 Plan view of the 3D printing system integrated with automated pick and place function.

The process flow is illustrated in Figure 4.

2.3 Filler Slab Printing Process

The slab is assumed to be printed as 6 panels, each 5m long and 1m wide. The printing has been carried out in three parts: cover layers, compression zone, and tension zone printing Figure 5.

The filler and rebar placement settings are shown in Figure 6. “2w” and “2b” are the main and distribution bar spacings, “G+a” indicates the distance between filler pickup point and the first void. The movement in the z-direction is assumed to be 100 mm per pick and place operation.

2.4 Life Cycle Assessment

The LCA used in the study is based on ISO 14040/44 [18, 19] guidelines. The consequential LCA (CLCA) approach is used to show the change in carbon emissions by adopting the proposed concept.

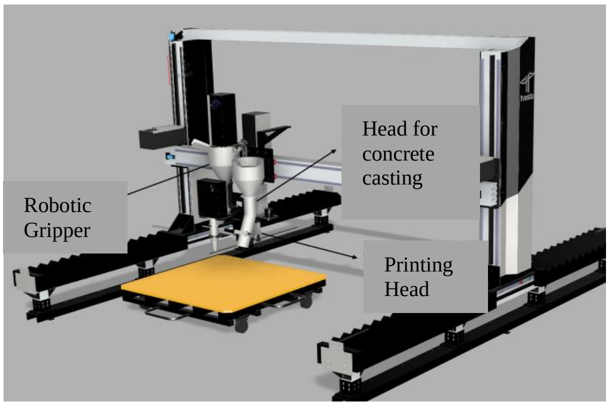

Figure 2 Plan view of the 3D printing system integrated with automated pick and place function.

Figure 3 An early prototype of the design integrating 3D printing with robotic pick and place features

2.4.1 Goal, Scope and System Boundary

This study aims to quantify the reduction in carbon emissions by adapting the proposed method of printing filler RCC slabs using recycled PE as fillers, compared to conventional slab printing. The results provide new insights for the industry and research community, promoting the integration of robotics, concrete 3D printing, and waste recycling to develop sustainable construction alternatives. The recyclable waste used is polyethylene (LDPE or HDPE), the most consumed plastic, with a gantry-type concrete 3D printer integrated with a gripper for pick-and-place operations employed in the process.

The functional unit in this study is the concrete 3D printing 1 m^3 volume of a 250 mm thick structural slab spanning 6 m X 4 m to allow comparisons between different printing scenarios.

Case-1: 3D printing of 6 panels of 4 m length and 1m width for a 6 m X 4 m RCC slab without any fillers.

Case-2: 3D printing of 6 panels of 4 m length and 1m width for a 6 m X 4 m RCC slab with clay pots as fillers.

Case-3: 3D printing of 6 panels of 4 m length and 1m width for a 6 m X 4 m RCC slab with Recycled PE waste as fillers.

Case-1 is considered the base case for the comparing the carbon emissions. The system boundary used for conducting LCA in this study is shown in Figure 7.
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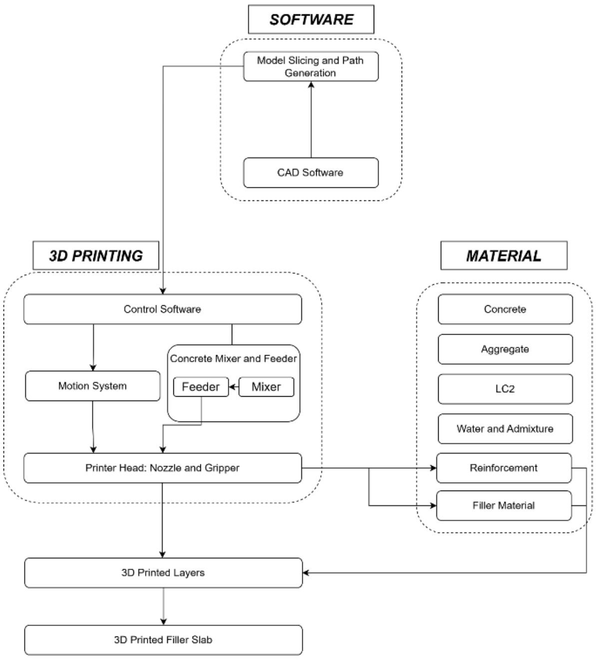

Figure 4 Process flow for 3D printing of filler slab

2.4.2 Life Cycle Inventory

Concrete production emissions are based on design mix [17] and carbon emission study of concrete printed mix [9]. Plastic waste recycling involves motors for washing, drying, and compressing PE waste, with emissions calculated from electricity use (Ecoinvent v3.9), the power calculation for washing and drying has been done based on study by [20], a 5 HP motor is assumed to compress 1 ton of waste in 10 seconds.

Clay pot production emissions is taken from [12] market data is used for volume to weight calculation, assuming 1 litre. pot weighs 1kg. Transportation emissions are calculated for a 10 km local distance using a 3-ton vehicle with 6 km/L mileage and Ecoinvent v3.9.

3D printing emissions account for electricity consumption, while avoided emissions are based on the incineration of PE waste which is calculated using data from Ecoinvent v3.9. Only 11% of the waste used as filler is assumed to be incinerated.

This study employs CML v4.8 2016 to assess life cycle carbon emissions, focusing on the reduction of cement and concrete content and related carbon emissions, as required by the baseline impact category.

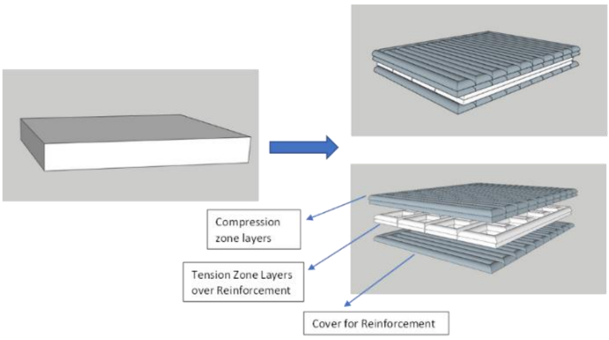

Figure 5 Representation of a Conventional Slab (Left). 3D printed slab (Right Top). Different layers of 3D printed slab (Right Bottom)

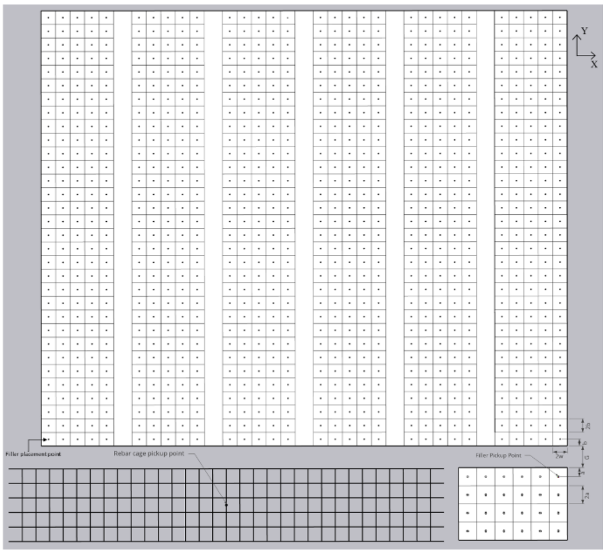

Figure 6 Plan for placement of fillers and rebar cage

3 Results and Discussions

3.1 Concrete 3D Printed Slab Output

The printing path and the placement of the filler are shown in Figure 8. The size of filler material for one void is 140 mm by 110 mm cross-section and 110 mm deep. Figure 9 shows a cross-section view of the 3D printed elements for the case of conventional printing and printing with fillers.

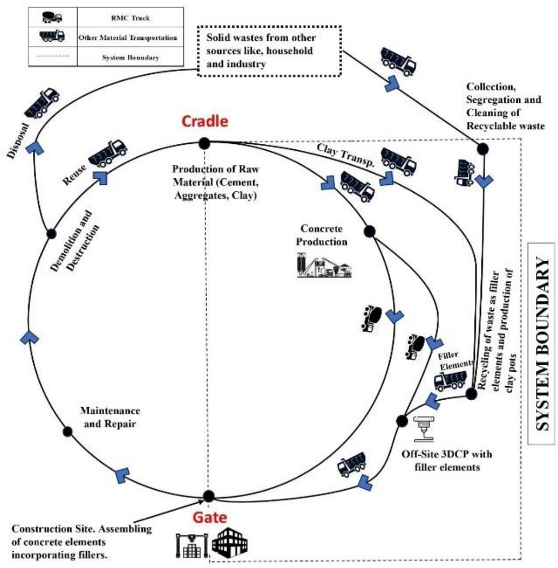

Figure 7 Schematic for life cycle assessment of concrete filler slab

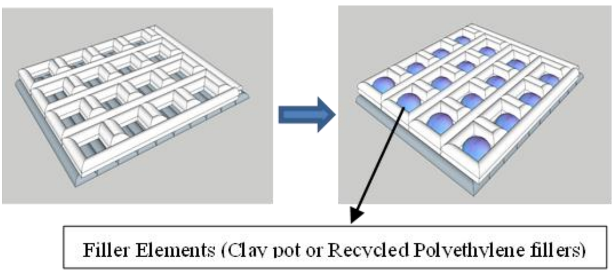

Figure 8 Printing path over rebars in tension zone (left), placement of fillers in voids (right)

3.2 Carbon Emission Assessment

3.2.1 Filler Production

As per the assumptions stated in section 2.4.2 the carbon emission assessment for clay and recycled PE filler production is mentioned in Table 5 and Table 6.

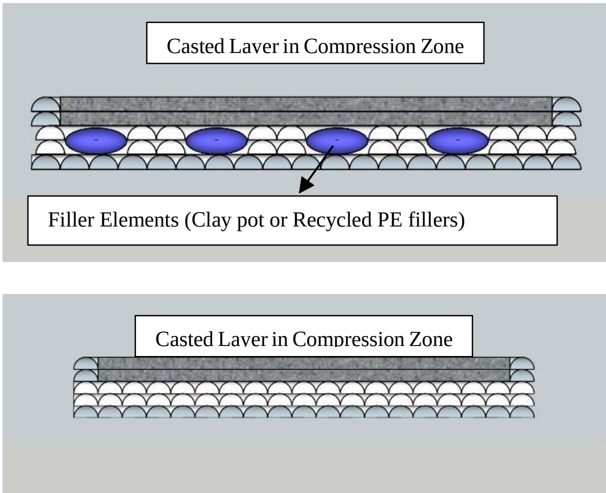

Figure 9 (a) Cross Sectional View of Slab in Scenario Case-1 and Case-3 (b) Cross Sectional View of Slab in Scenario Case-1

Table 5 Emissions generated due to the production of clay pot fillers.

Description	Unit	Value
Weight of the Clay Pots Required	kg	1636.4
Carbon emissions per kg of unit produced	$kgCO_2$ eq.	1.91
Total Carbon emissions for clay pots required	$kgCO_2$ eq.	3125.53

Table 6 Emissions generated due to the production of recycled plastic fillers.

Process	$kgCO_2$ eq. emissions
Transportation from scrap dealer to MRF	12.20
Washing of waste PE	4.07
Transportation to the 3D printing facility	12.20
Compaction using Automatic Baler	16.24
TOTAL	44.70

Using recycled polyethylene fillers reduces emissions by 98%. Additionally, the weight of the recycled polyethylene filler slab (total weight of PE fillers used is 2.08 tonnes) is 6% lower than the clay pot filler slab and 60% lower than the conventional slab, reducing the slab's dead load. This reduction helps minimize material consumption in the substructure.

3.2.2 Electricity Consumption in Printing the slab

The printer head operates at an assumed speed of 80 mm/s in both the x and y directions. For movement in the z-direction, rather than calculating the total distance, the number of layers is considered, with each layer transition taking approximately 1 second. The gantry system employs 1 kW, three-phase motors for the x, y, and z axes. The electricity consumption is determined by multiplying the power rating of the motors by the total operational time. The pump used for extruding concrete has a power rating of 5.5 kW.

The total electricity consumption for printing the filler slabs is presented in Table 7.

Table 7 Total Electricity Consumption for printing slab

Description	Filler Slab	Conventional Slab
Printing Process	36.62	57.48
Filler Placement	37.30	-
Rebar cage placement	0.28	0.28
Pumping Concrete	183.08	287.40
Total Electricity Consumption in kWh	257.28	345.16

3.2.3 Embodied Life Cycle Carbon Emission

Two concrete mixes were used to produce printed slabs. An M35 mix [21] with 30% Class F Fly Ash replacement, emitting 289 kg CO_2/m^3, was used for casting the compression zone, while an OPC-LC2 mix [17] was used for printing the cover, tension and boundary zones, with emissions data sourced from [9]. CO_2 emissions from plastic waste incineration and electricity consumption were derived from Ecoinvent v3.9 [22]. The emission assessment results are summarized in Table 8.

The table reveals that using recycled plastic waste as filler elements reduces carbon emissions by 37%. Conversely, clay pot filler slabs increase emissions by 55% due to the high carbon footprint of clay pot production (3125 kg CO_2 eq.), despite reduced material usage. Case 3 demonstrates the lowest emissions, attributed to avoided emissions from repurposing waste plastic. This highlights that filler material selection is crucial, as the production emissions can offset the benefits of reduced raw material consumption, as seen in Case 2.

Table 8 Life cycle carbon emission comparison for the three scenarios

Description	Case-1 (kgCO2 eq.)	Case-2 (kgCO2 eq.)	Case-3 (kgCO2 eq.)
Concrete Production for compression zone (M 35-35% fly ash replacement)	790.76	790.76	790.76
Concrete Production for tension zone (OPC+30% LC2)	2153.5	694.74	694.74
Production of Filler Element	-	4221.5	49.7
Electricity Consumption in 3D Printing	531.54	396.21	396.21
Avoided Emissions	-	-	-120.48
NET EMISSIONS	3475.78	5385.95	2189.64
NET EMISSIONS PER m^3	579.29	897.65	364.94

4 Conclusion

Concrete 3D printing has significant potential to transform the construction industry, but its full realization is hindered by challenges such as limited automation, minimal application in printing structural elements like slabs and beams, and the high cement content of 3D printable mixes. Hence, developing techniques to reduce raw material consumption is essential to minimizing the carbon emissions associated with production of concrete 3D printed elements. This study proposes an automated methodology for 3D printing RCC filler slabs using compressed polyethylene (PE) waste as an alternative to clay pots. A case study of a 250 mm thick slab spanning 6 x 4 m is analyzed to evaluate the carbon footprint of 3D printing a RCC slab.

Following are the major findings of the case study:

- The findings suggest that the proposed 3D printing methodology can effectively reduce material usage and carbon emissions, offering a cleaner and more sustainable construction alternative. In the case study, utilizing polyethylene waste as a filler material decreased concrete consumption by 27% and carbon emissions by 37% compared to the baseline scenario of 3D printing slabs without filler elements.
- The lower carbon emissions in filler slabs with recycled PE waste, compared to those with clay fillers, are primarily due to the significantly reduced emissions from producing recycled PE fillers, which are 98% lower.
- Also, Recycling PE waste into slab fillers prevents the emissions that would have resulted from the incineration of plastic if the waste had not been recycled.
- Slabs with recycled PE waste as fillers have a lower dead load compared to those with clay pot fillers or no fillers, further contributing to material and carbon emission savings in substructure construction.

The study has assumed various transportation distances which may not be the real scenario. The equipment production related emissions were ignored in the calculation of carbon footprints because the equipment being used in all the three scenarios mentioned is same. Also, a cradle to gate approach for carbon emission assessment was used, because the main objective of the study was to compare the scenario in production phase. In future other phases like operational and demolition phases can also be studied. Also, the study demonstrates the potential using a single slab case, in future the results will be generalized using different cases and structures.

Nevertheless, these findings offer a path toward utilizing the advantages of concrete 3D printing and automation for sustainable construction. Automating tasks such as placing rebars and fillers reduces the risk of human error, addressing one of the key drawbacks of the conventional filler slab technique.

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