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Review of recycled materials relevant for 3D printing habitats

A. Aslaminezhad
University of Antwerp, Antwerp, Belgium
Heriot-Watt University, Dubai, United Arab Emirates

P. Lee
Delft University of Technology, Delft, The Netherlands

H. Bier
Delft University of Technology, Delft, The Netherlands
University of Sydney, Sydney, Australia

M. Rinke
University of Antwerp, Antwerp, Belgium

ABSTRACT: Advancements in 3D printing technology facilitate the implementation of innovative building processes. When combined with circular approaches in particular the use of recycled materials, significant reduction of environmental impact is expected. This paper presents an investigation into the potential of recycled materials for 3D printing habitats. The study's main objective is to assess two recycled materials, concrete and sandstone, which are suitable for 3D printing. Through comparative analysis, the research aims to demonstrate the environmental impact and process feasibility of each material in the context of 3D printing. The methodology involves the evaluation of recycled concrete and sandstone regarding material properties and overall environmental footprint by comparing building components such as columns. The energy use and carbon footprint in 3D printing are evaluated with the goal to minimize waste and contribute to a closed-loop approach. One of the fundamental aspects of this assessment involves quantifying and comparing the carbon dioxide (CO2) emissions associated with each material at some stages of its life cycle, i.e., from material extraction to assembly. Consequently, by analyzing quantitative data, a basis for a more environmentally friendly circular approach for printing habitats is determined.

Keywords: Habitats, Recycled Materials, 3D Printing, Circular Design, Sustainability

1 INTRODUCTION

With the construction industry, being the fifth largest emitter of CO2, the imperative to advance sustainable construction methods is at the foreground. Buildings are currently responsible for 39% of global energy-related CO2 emissions: 28% from operational emissions, from the energy needed to heat, cool, and power them, and the remaining 11% from materials and construction (World Green Building Council, 2019). Circular construction strategies are becoming essential to reduce CO2 emissions and mitigate climate change. Furthermore, technological advancements in 3D printing have enabled improvements in the creation of complex structures with optimized material usage and reduced printing times (inter al. Bier et al. 2018).

Using waste materials, recycled concrete aggregates, and geo-polymers in 3D printing offers a promising approach to advancing circular construction (Tu et al. 2023). The presented study

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evaluates material properties and overall environmental impact by integrating life cycle analysis (LCA) into design considerations. In this context, both challenges and opportunities are examined. Some of the major challenges involve concerns about the compatibility of materials and the actual impact of the recycling process on CO2 emissions. However, there are significant opportunities identified with respect to innovative design alternatives and the potential for increased resource efficiency and CO2 emission offsets.

2 STATE-OF-THE-ART

Due to its large CO2 emissions, the construction industry demonstrates the necessity for sustainable construction methods. This research explores the reduced energy consumption using recycled materials in 3D printing. To meet the target of Net Zero Emissions by 2050 the construction industry must fast-track the utilization of renewable materials and efficient technologies (International Energy Agency, n.d.). The use of recycled materials as a means of achieving lower CO2 emissions has increasingly been adopted (Dixit et al. 2012). For instance, recycled concrete, obtained from demolished structures, is expected to reduce the consumption of natural resources and decrease construction waste. Recycled sandstone mixed with calcium carbonate (CaCo3) is also considered a sustainable alternative to natural raw materials in the 3D printing process. Adopting these materials helps to conserve natural resources, decrease the costs of construction, and improve the sustainability of construction projects (Nething et al. 2020). However, the general effectiveness of the CO2 emission reduction depends on the source of the aggregates, transportation distance, and the manufacturing process. Studies have revealed that the application of recycled concrete decreases the usage of natural mineral resources and demolition waste (Silva et al. 2019). Nevertheless, the total environmental impact involving energy consumption and global warming potential, may vary depending on specific project conditions and transportation distances (Marinković et al. 2010). In the presented study, Life Cycle Analysis (LCA) is employed to compare the environmental load of various materials, i.e. crushed sandstone, recycled sand and recycled aggregate.

In terms of 3D printing, ICON (Dezeen, 2022), develops technology for printing terrestrial and extraterrestrial habitats. It allows fast production of simple housing units. It also facilitates the production of intricate and complex structures with minimal waste and energy use, thus contributing to the reduction of CO2 emissions (Anton et al. 2021, Tay et al. 2017). 3D printing significantly reduces the carbon footprint by minimizing resource and energy consumption when using recycled materials. (Bos et al. 2016).

2.1 *Recycled concrete*

Although recycled concrete offers environmental benefits depending on cement usage, transportation distance, and type of concrete (Marinković et al. 2010), substituting natural concrete with recycled concrete could reduce environmental impact by up to 70% (Knoeri et al. 2013). The study investigates two types of 3D printing recycled concrete. One involves the use of Recycled Sand (RS) and the other explores the use of recycled aggregate, comparing them with non-recycled concrete mix made from crushed sandstone (Anton et al. 2021).

Previous research (Ding et al. 2020) shows that with the use of RS in 3D printed concrete, compressive strength lowers compared to Natural Sand (NS) while tensile splitting and flexural strength remain consistent. Early-age specimens showed more lateral deformation and plastic behavior, becoming more rigid as the concrete aged and RS improved peak load and buildability.

Replacing NS with RS decreases initial fluidity in printing mortar, increasing loss rate and shortening the printability window. However, when sodium gluconate is added, it meets printability requirements and maintains higher green strength, enabling continuous 3D printing with lower initial fluidity (Zou et al. 2021).

The application of RS in 3D printing cementitious composites shows that the increased replacement level of RS decreases the fluidity and compressive strength, whereas the tensile strain and flexural toughness increase with more fibers. Hence, RS-enhanced 3D printing is an environmentally friendly approach especially in 3D printing concrete (3DPC) construction (Bai et al. 2023).

2.2 *Recycled sandstone*

The substitution of Portland cement with microbially based bio-cement to produce construction materials is another emerging sustainable approach. Bio-cemented building components can be fabricated where bacteria-containing aggregates solidify when treated with a cementation solution. Research shows that urease-active CaCO3 powder with its property of residual activity, helps to fix the bacteria in the sand, while the amount of powder affects the mechanical strength and cementation depth (Nething et al. 2020).

The influence of Nano CaCO3 (NC) on the performances of 3D printing cementitious materials with limestone powder (LS) identifies that NC accelerates the hydration reaction of Portland cement through nucleation, whereas LS increases fluidity and vertical displacement but decreases the yield stress and green strength of fresh state 3DPC (Yang et al. 2021).

2.3 *Contribution*

The presented study contributes to the advancement of circular approaches in 3D printing by evaluating recycled concrete and sandstone with respect to their material properties and overall environmental footprint by comparing printed building components such as columns.

3 APPROACH AND METHODOLOGY

The methodology relies on examining a 3D printing column (Anton et al. 2021) and its CO2 emissions using the LCA framework (Lee et al. 2024). The study further speculates on the environmental impact and feasibility of printing similar hypothetical columns using recycled concrete and sandstone, respectively. This approach examines the amount of CO2 emissions involved in the recycled materials and compares it with the emission levels in the original case study to quantify the potential carbon reductions and evaluate the effectiveness of using recycled materials in the 3D printing process.

In this analysis, the raw materials used for concrete production include Calcareous Crushed Sand (CCS), recycled sand, and aggregates recycled from concrete, which are used in three combinations:

- Calcareous crushed Sand Concrete (CSC): CCS and other additives (Anton et al. 2021).
- Recycled Sand bio-cement Concrete (RSBC 1.5%): Bio-concrete containing 100% recycled sand from crushed concrete with 1.5% urease active calcium carbonate powder (UACP), urea and calcium chloride (CaCl2) solution, without cement (Nething et al. 2020, Deng et al. 2021).
- Recycled Aggregate Concrete (RAC): Concrete made from 100% fully recycled aggregates derived from crushed concrete and other admixtures; this mix is intended to replicate the CSC ratios with minor adjustments (British Standards Institution, BS EN 933-1, 2012).

Table 1 illustrates the material composition for each concrete mix and the ratio of materials used relative to sand or aggregate**.** To compare the columns made with each material, an examination of the life cycle stages of each 3D printed column relevant for assessing their environmental impact is studied.

Table 1. The material composition for each concrete mix.

Materials	CCS ~ 0-2 mm	RSBC 1.5% RS ~ 63-250 μm	RAC
Cement (OPC)	35.00%	–	39.00%
Micro silica	2.80%	–	3.12%
Limestone	5.25%	–	5.85%
Water	14.95%	8.00%	18.68%
Superplasticizer	0.25%	–	0.41%
Accelerator (CAC)	3.50%	–	3.90%
Retarder	0.04%	–	0.04%

(*Continued*)

Table 1. (*Continued*)

Materials	CCS ~ 0-2 mm	RSBC 1.5% RS ~ 63-250 μm	RAC
Thickener	0.04%	–	0.04%
Urease active calcium carbonate powder	–	1.50%	–
Urea for Cementation solution (750 mmol)	–	0.36%	–
CaCl2 for Cementation solution (750 mmol)	–	0.67%	–

3.1 *Case study*

Column C7 (Figure 1) has been selected to demonstrate LCA calculations for comparing different material formulations using recycled materials. Among the 12 printed columns, C7 is the most successful example in the Concrete Choreography project, reaching a height of 2.75 meters and a concrete volume of 264.3 liters. It featured intricate surface tectonics and utilized high-precision 3D printing technology. Printing using CCS mortar, LCA calculations for Column C7 will consider comparable formulations that replace natural aggregate concrete (NAC) with RAC and RSBC.

The column consists of two layers: an external shell with varying surface tectonics ranging from 250 to 600 mm, and an internal core with a cylindrical shaft with a diameter of 250 mm. This shaft serves as a permanent mold for placing the reinforcing rebar cage and fresh concrete.

Figure 1. Left: 3DPC columns with column C7 in the middle. Right: 3DPC component details and material tectonics (Anton et al. 2020).

3.1.1 *Calcareous Crushed Sand Concrete (CSC)*

The concrete mix includes CCS (0-2 mm), and ordinary Portland cement (OPC), with a water-to-cement ratio of 0.4, 15% limestone powder, and 8% micro silica replacing some of the cement. To enhance extrudability and bonding, a liquid superplasticizer (0.7% of cement weight) was used, along with a sucrose solution to extend the material's open time to 8 hours. A commercial thickener improved workability, and accelerators at the nozzle tip ensured quick hardening of the concrete to prevent deformation of subsequent layers during printing.

3.1.2 *Recycled Sand Bio-cement Concrete (RSBC)*

The use of bio-based materials like urea in construction is of relevance because of its potential for reducing CO2. Urea acts as a carbon source for bacteria, facilitating chemical bonding in the sand. This process gradually transforms the sand into hard, durable material. Adding nanoparticles such as NC enhances the structural properties of the material by accelerating the hardening process (Zhang et al. 2023).

The compressive strength of this material is adequate, which makes it a suitable alternative to traditional materials relying on Portland cement. Additionally, the material demonstrates stability in diverse environmental conditions, including heat and moisture.

Despite the sand and urea composite proving to have higher thermal conductivity, it has the potential to minimize CO2 emission in construction when compared to concrete. The process of cement manufacturing involves the use of substantial energy and releases large amounts of CO_2, on the other hand, urea is derived from biological sources and its manufacturing involves the use of less energy.

In this study a bio-concrete with 1.5% (w/w) UACP, using a 750 mm solution of $CaCl_2$ and urea at 4°C is considered. This ratio has a greater cementation depth and more homogeneous cement compared to the other ratios (Nething et al. 2020).

3.1.3 *Recycled Aggregate Concrete (RAC)*

Recycled Aggregate Concrete contributes to the efficient use of natural resources and minimization of construction waste, beneficial for the management of waste and decreases the cost of disposal (Thomas et al. 2013). However, using recycled materials in the concrete mix, especially if a high percentage of recycled materials replaces natural aggregates, reduces the compressive strength (Piccinali et al. 2022). Despite these various studies show that recycled concrete is effective in handling tension and bending, often showing little difference from natural concrete. This is essential for 3D printing, where more complex structures are considered. Since cement production is a major source of CO_2 emissions in construction, by partially replacing cement with recycled materials, these emissions can be reduced.

4 LIFE CYCLE ANALYSIS (LCA)

The LCA followed the European Norms EN 15804 and Swiss Norms SIA 2031 as methodological guidelines. A1-A3 is identified as the production stage, A4-A5 the construction stage. B1-B5 the embodied use stage, B6-B7 the operational use stage, and C1-C4 the end-of-life (EOL) stage. In addition, module D is defined to account for potential circular strategies such as reuse and recovery. For this study, A1-A5 is used for the comparisons of various concrete compositions at component scale. Considering the production of recycled materials derived from the demolishing and reprocessing of materials in use, the LCA calculation accounts for the following stages:

- Material extraction (A1): Crushing concrete process and extracting recycled materials from it.
- Materials transportation (A2): Transportation of natural and recycled materials to the factory and project site. In this study, transportation distance is assumed to be 5 kilometers.
- Remanufacture (A3): Including mortar production for 3D printing (a) and component fabrication of the column (b).
- Component transportation (A4): Transportation of column component to project site. In this study, transportation distance is assumed to be 5 kilometers.
- Assembly (A5): Including the production and installation of reinforced steel (c) and new concrete (d) for the inner core.

For all these stages, the data is collected from various scientific sources (Küpfer et al. 2023) and standard databases (KBOB 2022, NSSGA 2021). At each stage, CO_2 emissions related to transportation, production, and processing of raw materials as well as energy consumption in various processes have been calculated. For instance, CO_2 emissions of cement are first calculated from the cement's amount per cubic meter through the mix design. Subsequently, the total CO_2 has been calculated based on production data of each kilogram of cement along with the CO_2 emission in production process collected from standard references as well as emission factors related to transportation of cement from factory to the construction site. The same process was applied for other components of concrete mix including aggregates, water, and additives.

5 RESULTS AND DISCUSSION

The findings of this study show that although there are not significant differences of CO_2 emissions in the early stages of life cycle such as concrete demolition and transportation, considerable differences arise in production and installation stages.

The overall emission of CO_2 for the concrete mix with CCS is calculated at 199.66 kg CO_2eq, for the bio-concrete, RSBC 1.5%, the amount is 142.2 kg CO_2eq, and emission of 195.7 kg CO_2eq is calculated for RAC.

According to the results, the lowest rate of CO2 emission is related to the bio-concrete, RSBC 1.5%, and the highest is related to the CSC in minor differences with RAC. The variation in emissions is thus a reflection of the proportions of material incorporated in its mix design. The amount of CO2 emitted cumulatively at each of the five stages (A1 to A5) for each of the three types of concrete is presented in Table 2.

Table 2. Comparative cumulative CO2 emission allocation with total CO2 emission per column in kgCO2eq.

	A1	A2		A3		A4	A5		
	Material Extraction	Materials Transportation		Remanufacture		Component Transportation	Assembly		
	Recycled Material Extraction	Raw Materials	Processed Materials + Debris	3DPC Mortar Production (a)	3D Printing (b)	Column Transportation	Reinforced Steel (c)	Cast Concrete + Construction (d)	Total CO2 emission
CSC	0	0.3	0.38	100.62	3.13	0.46	39.32	55.46	199.66
RSBC 1.5%	3.66	0.04	0.68	39.46	3.13	0.44	39.32	55.46	142.20
RAC	2.26	0	0.53	93.96	3.13	0.4	39.32	55.46	195.07

According to Table 2, the A3 and A5 stages contribute the most to CO2 emission. Since the final stage for all the columns is to be poured and installed in similar circumstances, the assembly stage is viewed as equal for all the columns. The highest variation of CO2 emission contributes to the 3D printing materials in remanufacture stage.

It might appear that some components such as aggregates and sand that constitute a significant percentage of the composition of all three types of concrete should equally contribute more to CO2 emissions. Nevertheless, the largest contribution to CO2 emissions of both CSC and RAC comes from cement and accelerator, respectively, while in the bio-concrete (RSBC 1.5%), it stems from activated CaCo3 which consists of urease active calcium carbonate (UACP). It has been observed that despite having a very less weight proportion of UACP compared to other materials in the mix design, the 1.5% proportion significantly reduces carbon dioxide emissions.

As a result, a lower value of CO2 emission for the RSBC 1.5% is evident due to lower value of UACP and substitution of cement with UACP and Urea and Calcium Chloride Solution. This finding is supported by earlier studies that have stressed utilization of recycled material in concrete and replacing cement with other chemicals in concrete production for environmental advantages (Jin et al. 2024, Yousaf et al. 2024, Kushwah et al. 2024).

5.1 *Sensitivity analysis*

Two sensitivity analysis scenarios have been demonstrated to examine the impacts of geographical locations, i.e. raw material sources and plants on the CO2 emissions. In scenario 1, all the transportation routes are assumed to be a single route. This means that the distance of both the transportation route for the material from mines to the plants and from project site to the plants and vice versa is calculated as one path. In scenario 2, variables are left constant with the distance from the plants to the project site set at 5km, while the distance from the raw material mines to the plants is changed. In particular, the transportation route of the raw material from mine to the plant is evaluated to determine the optimal means while the remaining routes are irrelevant.

Results show that the higher the distance of transportation, the higher the carbon emissions for all categories of concrete. The carbon emission of RSBC 1.5% is the lowest among all types of concretes and it rises with distance however, the rise is almost invariant with distance and can thus be regarded as highly sustainable.

The CSC ranks highest in carbon emissions, which rises with distance. RAC's carbon emission remains relatively stable due to the minimal use of natural raw materials. The findings shown in Figure 2 suggest that minimizing the use of extracted materials and optimizing transportation distances can substantially decrease CO2 emissions.

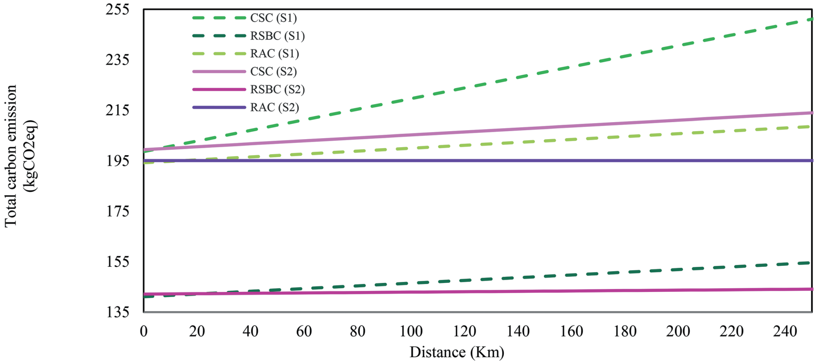

Figure 2. Sensitivity analysis: Scenario 1 in dashed lines, Scenario 2 in solid lines.

6 CONCLUSION

This study explores assessing the environmental performance of three different materials for 3D printing of concrete habitats by studying a single component, i.e. column. The findings emphasize the potential of recycled materials, especially RSBC with urea additive, to significantly reduce the carbon footprint of construction. Sensitivity analyses underline the importance of considering transportation distances in material selection and construction planning.

The bio-concrete, RSBC 1.5%, in comparison to the other materials studied, has the least CO2 emission in its lifecycle. This material has the highest environmental efficiency compared to the other two concretes, in projects where the transport is relatively short. The location of raw materials mines plays an important role in emissions of CO2. Transportation distances of 100 km or more make the use of concrete from CCS less environmentally friendly.

Among all the parameters, the concrete mix design has the most significant potential to minimize the environmental effects of both recycled and normal concrete. Reducing the amount of cement in CSC and RAC and UACP in RSBC contributes to decreasing the emission of CO2. Hence, reduction in cement content and the utilization of optimized additives remain a priority.

Although the main objective of this study is to assess the environmental impact of recycled materials, structural performance is also an important consideration. Future research will consider including in the LCA other factors such as structural performance, water consumption, and waste production. Furthermore, streamlining the data and the LCA methods for 3D printed habitats will enhance the reliability of the assessment.

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