Life Cycle Assessment of 3D Printed Recycled Concrete

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Abstract. As an advanced construction technology, 3D printed concrete (3DPC) currently faces challenges such as high cement consumption and stringent aggregate quality requirements. Using recycled aggregates (RA) from crushed and screened waste concrete to produce recycled 3DPC can help government manage significant amounts of construction and demolished waste and conserve natural resources. By replacing 30% and 50% of natural aggregates (NA) with RA, the study reveals that incorporating RA reduces the strength of 3D printed concrete while increasing its anisotropy. This study also uses the Life Cycle Assessment (LCA) method to analyze the environmental impact during the production stage of RA. The results show that producing RA has a significantly lower environmental impact compared to the production of natural sand. The transportation distance is a crucial factor and the transportation distance should not be longer than 25 km.

Keywords: 3D printed concrete; Recycled aggregate concrete; Life cycle assessment; anisotropic properties.

1 Introduction

With the rapid development of the global economy, many countries are experiencing a demographic shift where population growth is reversing. Civil engineering is facing challenges in many countries, including labor shortages and increased labor costs. 3D printing has become a research hotspot due to its rapid construction, cost savings, and formwork-free method [1]. However, compared to the traditional concrete, 3D printed concrete ink faces issues like high cement consumption and stringent aggregate quality requirements [2]. Therefore, its low-carbon attributes have become a key research focus under the trend of global warming.

In 2023, the generation of CDW reached 3 billion tons in China. Simple stacking or land-filling of these CDW has led to the environmental and safety issues. CDW can potentially be repurposed by crushing and screening to produce recycled aggregates (RA) [3]. Some researchers suggest that replacing 30% of natural aggregates (NA) with RA does not significantly affect the mechanical strength of concrete [4].This study will

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focus on the mechanical properties of 3D printed concrete (3DPC) with added RA [1]. Finally, it will use the Life Cycle Assessment (LCA) method to evaluate the environmental impact of RA from production to application, quantifying whether RA contributes to environmental improvements in 3D printing ink, thereby supporting the usage of 3D printing technology in the industrial application.

2 Materials and Methodology

2.1 Materials

The cement used is Portland 42.5 cement, which complies with GB 175. The particle size distribution of NA and RA ranges from 0.075 to 1.18 mm. Compared to natural aggregates, recycled aggregates contain more fine particles, and their D50 is slightly smaller than that of natural aggregates. Additionally, due to the high water absorption rate of recycled aggregates, the saturated surface-dry moisture content was determined using the saturated surface dry test mold (as shown in Fig. 1a), with a saturated surface-dry water absorption rate of 15.2%. This study considers two mix proportions replacing NA with 30% and 50% RA as shown in Table 1. The quantity of superplasticizer is updated on the same fluidity.

2.2 Testing Methodology

Regarding the mechanical strength of 3DPC, this study measured the flexural and compressive strengths of 3D printed concrete in the X, Y, and Z directions. After testing the mechanical strengths along the X, Y and Z directions, the anisotropy parameter (Ia) will be determined by $I_a = \frac{\sqrt{(f_x-f_c)^2+(f_y-f_c)^2+(f_z-f_c)^2}}{f_c}$. Finally, this study quantified the environmental impact of 3DPC through LCA method. The specific system boundary is from gravel to gate, and the transportation distance from NA to concrete plant is 13 km, from RA to concrete plant is 19 km and distance from concrete plant to construction site is 7 km.

Table 1. Mix design of 3DPC

Group	Cement	NA	RA	Water	Extra water	SP
NA	1	1.43	/	0.36	/	0.001
RA-30	1	1	0.43	0.36	0.065	0.0012
RA-50	1	0.715	0.715	0.36	0.11	0.0015

2.3 Sample Preparation

The study utilized a gantry-style printing device, as illustrated in Fig. 1b. Since 3DPC needs to meet the requirements of pumpability and printability. Pumpability ensures the material flows smoothly from the printing nozzle, while printability ensures each printed layer maintains its shape to prevent distortion of the overall structure. The pumpability of the printing material was evaluated using the flow table test (Fig. 1c), and printability was measured by the height of the printed layer (Fig. 1d). The printing ink can meet both pumpability and printability requirements when the flowability is 170 mm and the consistency is 49 mm.

Fig. 1. Machine and testing methods of 3DPC (a. Saturated surface-dry test mold; b. 3D printing machine; c. Flow table; d. Printability test)

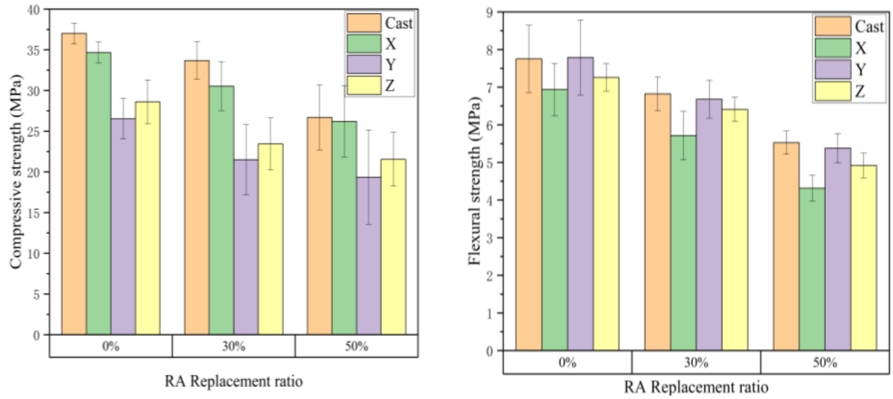
3 Results and Discussion

3.1 Mechanical Properties of 3DPC

The mechanical properties of 3DPC are illustrated in Fig. 2, it shows a gradual decline in strength for both cast and 3D printed specimens with the addition of RA. When 30% RA incorporation, flexural strength decreases by 12.1%, and compressive strength decreases by 9%. However, with a 50% RA replacement ratio, flexural strength decreases by 28.7%, and compressive strength decreases by 27.9%. The compressive strength of 3DPC follows the trend X > Z > Y, while flexural strength shows Y as the highest and X as the lowest, with Y and Z being similar. The lower layers are more compressed than the upper layers, creating a denser structure. Consequently, when compressed in the Y direction, the upper part fails first, causing the entire structure to fail [5]. The addition of RA increases the anisotropy of 3DPC (seen in Table 2). High content of RA can reduce the strength and narrow the difference between cast and 3DPC, thus the anisotropy of 3DPC is reduced. Additionally, the increased variance in compressive strength of 3DPC with 50% RA replacement indicates greater fluctuations in the strength of 3D printed specimens.

Table 2. Ia of the studied 3DPC

Group	NA	RA-30	RA-50
Ia of f_f	0.123	0.175	0.246
Ia of f_c	0.369	0.481	0.336



(a) Compressive strength of 3DPC (b) Flexural strength of 3DPC

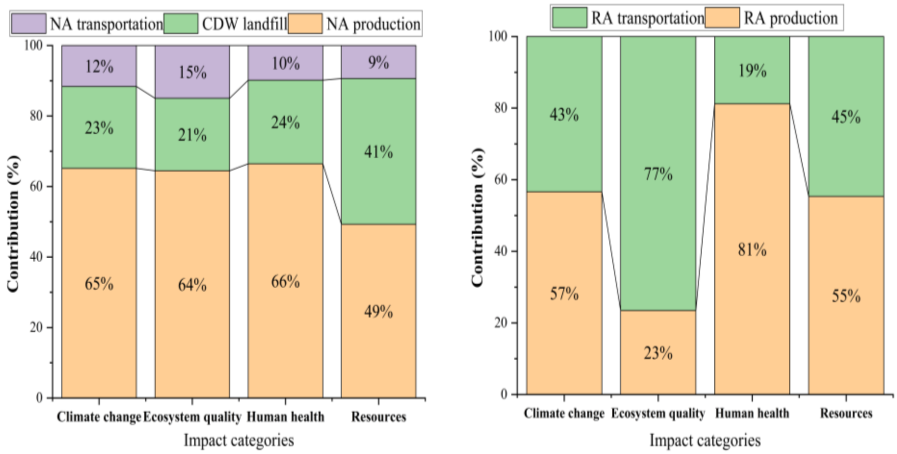
Fig. 2. Mechanical properties of 3DPC

3.2 LCA of RA

This study's LCA is divided into two parts. This section covers the environmental impact of the recycled aggregate production process, with a focus on the eco-friendly attributes of the recycled aggregates. By modeling system boundary of NA&RA, Table 3 summarized the environmental impact of NA and RA. LCA shows that RA offer significant environmental benefits over NA. These benefits are clear in impact categories of climate change, ecosystem quality, human health, and resource consumption. The key contributing steps of each production stage are analyzed as shown in Fig. 3, where transportation contribute over 40% to the total impact [6]. The contribution of RA to climate change, ecosystem quality, and resource consumption are 43%, 77%, and 45%, respectively. Therefore, further analysis was conducted on the transportation distance and its impact. The results indicated that transportation distance (D) has a quadratic relationship with its contribution (T%) written as $T\% = -0.003D^2 + 0.0247D + 0.06$. In that way, when the distance exceeds 24.8 km, the transportation's contribution will surpass RA production. Hence, the operational radius for RA should be kept within 25 km.

Table 3. Environmental impact of NA and RA

Impact categories	Climate change	Ecosystem quality	Human health	Resources
NA	0.00180	0.00073	0.00444	0.00242
RA	0.00070	0.00020	0.003440	0.00074



(a) NA (b) RA

Fig. 3. Contribution analysis of NA and RA

3.3 LCA of 3DPC

Fig. 4 compares the environmental impact of 3DPC containing RA with conventional 3DPC, using the impact of conventional 3DPC as a baseline to quantify the percentage reduction in various environmental impacts. The comparison shows that the reduction in climate change is minimal, which decrease about 3%. Cement is the main CO_2 contributor of concrete production [7]. However, using recycled aggregates is highly effective in addressing land occupation issues, reducing the land occupation impact by 33.8%. Additionally, 50% addition of reduced the total impact of human health by 15.1%. Therefore, the promoting policy of RA should focus on addressing land occupation problems and benefiting human health.

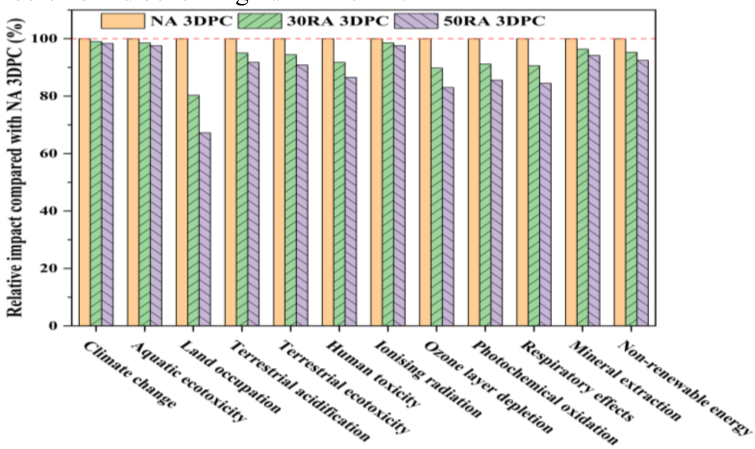


Fig. 4. Environmental impact of 3DPC

4 Conclusion

The effects of recycled aggregate on the 3DPC is evaluated in this study, The main conclusions can be drawn as follow:

(1) Using RA in 3DPC reduces mechanical strength, 30% RA replacement and 50% RA replacement reduce the compressive strength by 9% and 27.9% respectively. The compressive strength of 3DPC follows the order of X > Z > Y.

(2) Transportation distance has a substantial environmental impact (over 40%) on production of RA, which follows $T\% = -0.003D^2 + 0.0247D + 0.06$. It is recommended that the operational radius for RA be within 25 km.

(3) In terms of reducing carbon emissions, recycled concrete contributes only 3%, but it plays a significant role in addressing land occupation (reducing 33.8%) and benefiting human health (reducing 15.1%).

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