# Transforming Construction Waste into Resources for 3D Printed Concrete

**Ekaterina Kravchenko[1]*, Muhammad Huzaifa Raza[2], Svetlana Besklubova[2], Georgy Lazorenko[3]**

[1] *Southern Federal University, Rostov-on-Don, Russia*
[2] *Department of Data and Systems Engineering, The University of Hong Kong, Hong Kong*
[3] *Novosibirsk State University, Pirogov Street, 2, Novosibirsk, Russia*
Emails: ekakra@sfedu.ru; huzaifa@connect.hku.hk; lanabess@hku.hk; glazorenko@yandex.ru
*Corresponding author

**Abstract**

**The construction sector faces significant challenges in balancing environmental sustainability, economic feasibility, and compliance with required strength standards. This study investigates the potential of recycled materials, specifically waste concrete fine aggregates (WCA), for use in geopolymer mortar for 3D concrete printing as a sustainable alternative to conventional construction methods. The research examines the fresh and hardened properties of 3D-printed geopolymer mortar. Experimental results demonstrate that WCA-based mixtures achieve superior compressive strength and dimensional stability compared to natural fine aggregates (NFA). Life cycle analysis (LCA) further highlights the environmental benefits of WCA-based 3D mixture, showing a 3.4% reduction in global warming potential (GWP) and a decrease in terrestrial acidification compared to NFA. The study also underscores the importance of orientation in 3D printing, with significant improvements in compressive strength observed in all tested directions: perpendicular (64.2%), lateral (77.2%), and longitudinal (57.7%). This research emphasizes the promise of 3D concrete printing with recycled materials as a transformative approach to sustainable construction, reducing environmental impacts while maintaining structural performance.**

**Keywords – Waste concrete; Geopolymers; Life cycle analysis; Environmental impact.**

## 1 Introduction

The construction sector is undergoing a transformation driven by the integration of technologies, with 3D concrete printing emerging as a revolutionary approach to construction processes [1]. This method allows the direct conversion of digital building models into physical structures, eliminating the need for labor-intensive and resource-demanding formwork [2]. The advantages of 3D concrete printing include faster project completion, reduced material waste, and the ability to create intricate geometries with precision and minimal labor costs [2].

In addition to improving construction efficiency, 3D concrete printing presents an opportunity to incorporate recycled materials, such as fly ash (FA) [3], ground granulated blast furnace slag (GGBS), and waste concrete-based recycled fine aggregates [4,5]. These materials not only mitigate environmental issues associated with industrial and construction waste disposal but also reduce dependency on traditional resources like Ordinary Portland Cement (OPC). The use of OPC is a significant contributor to carbon emissions and resource depletion, necessitating sustainable alternatives [6]. According to an estimate, the manufacture of each ton of OPC requires the mining of 1.5 tons of limestone and releases around 0.5 tons of $CO_2$ into the atmosphere [6]. OPC production accounts for 5-7% of overall greenhouse gas emissions, making it the fourth most major source after petroleum, coal, and natural gas. [7] Moreover, the use of OPC in 3D concrete printing technique has a variety of constraints due to its setting characteristics. These environmental and technical challenges highlight the need for alternative low-$CO_2$ binders. In this context, geopolymers have emerged as a promising solution, as they can be formulated using industrial by-products [3], thereby reducing waste disposal in open environments and mitigating carbon emissions.

In recent years, the recycling of construction and demolition waste, such as recycled concrete, crushed brick, and ceramic aggregates, has gained significant research interest. Utilizing waste concrete as a substitute for natural resources has led to the development of recycled aggregate concrete, a sustainable product addressing both resource scarcity and waste disposal challenges [8]. Ding et al. [9] investigated recycled fine aggregates in 3D-printed concrete, reporting slightly lower compressive and flexural strengths compared to natural sand, with significant anisotropy in mechanical properties. Panda and Tan [3] conducted a study on fly ash-based geopolymer mortar for 3D concrete printing and found that the mixture with a sand-to-binder ratio of 1.5 exhibited the best extrudability with a yield stress of 0.6 kPa. The optimal open time for printing was 15–20 minutes, preventing deformation of the lower layers. The mixture was successfully used to print a 60 cm model in 20 minutes with good interlayer adhesion. In 3D printing processes, the integration of FA, GGBS and WCA presents unique challenges and opportunities. Unlike standard concrete, 3D printing requires precise control over rheological properties, buildability, and layer adhesion, which necessitates a more tailored approach to mix design. The ongoing research in 3D printing is focused on optimizing these supplementary materials to ensure printability without compromising mechanical performance or sustainability benefits. While FA, GGBS, and recycled aggregate are already used in traditional concrete, their adaptation to 3D printing remains an evolving area of study aimed at maximizing their potential in automated construction processes.

This study investigates the application of geopolymer binders and WCA in 3D concrete printing, focusing on their fresh and hardened properties, environmental impacts, and compliance with strength standards. By evaluating the performance and sustainability of these materials, this research aims to demonstrate the viability of integrating recycled resources into 3D concrete printing as a pathway toward more sustainable and resilient construction practices.

# 2 Materials and Research Methodology

### 2.1 Materials and Methods

Class F fly ash, adhering to the ASTM C618 standard, and GGBS, conforming to the C989 standard, were utilized as precursors. Industrial-grade sodium hydroxide pellets were used as the alkaline activator for the binder. Silica sand with an average particle size of 0.5 μm served as the natural fine aggregate, while recycled fine aggregate derived from waste concrete (WC), with a similar particle size, was employed as a replacement for the natural fine aggregate.

The mix design for the two samples, 3D-NFA (natural fine aggregate) and 3D-WCA (waste concrete aggregate) is as follows: For the 3D-NFA sample, the binder consists of 60 g of FA, 25 g of GGBS, and 15 g of sodium hydroxide. The aggregate used is 100 g of natural fine aggregate, with no recycled fine aggregate included. The water-to-binder ratio is 0.20, and no admixture is added. For the 3D-WCA sample, the binder composition remains the same, with 60 g of FA, 25 g of GGBS, and 15 g of sodium hydroxide. However, the aggregate used consists of 100 g of recycled fine aggregate, with no natural fine aggregate included. The water-to-binder ratio is increased to 0.25, and 0.1 g of sucrose-based admixture is added. The mix composition for the two specimens was determined through preliminary laboratory experiments, optimizing the water content and sodium hydroxide dosage based on the findings of these tests.

The printing experiments involved producing a slab measuring 200 mm × 100 mm × 100 mm and a hollow cylinder with a diameter of 100 mm and a height of 200 mm, using both natural and recycled fine aggregates. The layer height and width were set to 10 mm and 30 mm, respectively. The material extrusion rate during the printing process was maintained at 0.55 $m^3/h$, and the printhead speed was consistently set to 30 mm/s. The printed sample using geopolymer binders with waste concrete and fly ash is presented in Figure 1.

To evaluate the anisotropic behavior of 3D-printed mortars, specimens were tested under perpendicular, longitudinal, and lateral loads relative to the printing direction. The printing orientation was defined as the longitudinal direction. Compression tests were conducted at a strain rate of 1 mm/min, with each test repeated three times to obtain average compressive strength values.

### 2.2 Life cycle analysis

To evaluate the environmental impact of materials and construction methods, a comprehensive life cycle analysis (LCA) was conducted in accordance with ISO 14040 and 14044 standards. The analysis was performed using OpenLCA 2.0.3 software, with the Ecoinvent 3.9.1 database serving as a reliable and compliant data source. The cradle-to-gate approach was adopted for the LCA, covering the production processes of key raw materials. The analysis applied the ReCiPe 2016 midpoint (H) method, focusing on critical environmental impact categories such as global warming potential (GWP), stratospheric ozone depletion, terrestrial acidification, freshwater eutrophication, fossil resource scarcity, water consumption, and fine particulate matter formation, as recommended by the Product Environmental Footprint Category Rules (PEFCR).

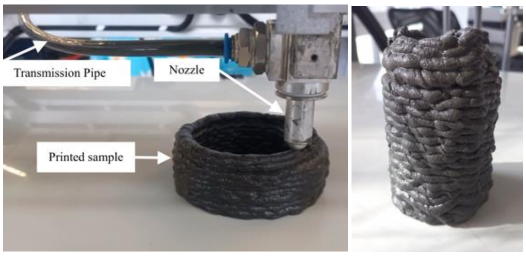
Case study data for LCA are summarized in Table 2.

To assess the environmental impact of recycled concrete aggregates in construction, the performance of concrete containing recycled aggregates was compared to that of concrete using NFA.

Table 2. Case study data for LCA

| Parameters | Value and unit |
|---|---|
| Printing speed | 250 mm/s |
| Printing time | 1.381 h |
| Printer power | 19.06 |
| Mixing time | 1.547 h |
| Mixer power | 9 kW |
| Pumping/flowing time | 8.738 h |
| Pump power | 22 kW |

Figure 1. 3D printed sample using geopolymer binders with waste concrete and fly ash.




## 3 Results and discussion

The fresh property results showed that the slump flow and spread diameter for mixtures with NFA were 14.3 mm and 138.2 mm, respectively. In contrast, replacing natural aggregates with WC aggregates increased these values to 14.5 mm and 143.2 mm, respectively, indicating reasonable flowability for all mixtures.

The maximum number of layers printed was 28 for the mixture with NFA and 24 for the mixture with WC aggregates. The Vicat value for the mixture with natural aggregates ranged between a lower limit of 5±1.5 mm and an upper limit of 21±6 mm, whereas for the mixture with artificial aggregates, the upper limit was slightly higher at 24±6 mm. These results are consistent with those previously presented in the work by Papachristoforou et al. [11].

Figure 2 presents the compressive strength results for two different mixtures (3D-WCA and 3D-NFA) tested along three principal directions: perpendicular, lateral, and longitudinal. The results reveal a significant influence of the material’s extrusion process and orientation on its compressive strength. The specimens 3D-WCA and 3D-NFA exhibited higher strength values of 5.9 MPa and 3.7 MPa, respectively, along the longitudinal direction. This increase in strength can be attributed to the extrusion process, where the material is compacted and densified as it is pushed through the nozzle to print the layers. This densification leads to enhanced bonding and material integrity along the longitudinal direction, resulting in higher compressive strength. When tested in the perpendicular direction, competitive compressive strength values of 5.9 MPa and 3.5 MPa were observed for 3D-WCA and 3D-NFA, respectively. These results suggest that the material's structure in this orientation maintains a significant level of bonding and compaction. The introduction of waste concrete aggregate place as a replacement for NFA further contributed to an overall improvement in strength in this direction. In contrast, the lateral direction exhibited the lowest compressive strength among the three tested orientations. This can be explained by the lower pressure exerted during the extrusion process in this direction.

In general, when using natural aggregates, particularly sand, the printed material tends to expand and settle more freely, resulting in weaker bonding and a less compacted structure, which subsequently leads to reduced strength. A comparison of the results shows a clear trend: replacing natural aggregates with WC has significantly improved the compressive strength in all tested directions. Specifically, the compressive strength in the perpendicular direction increased by 64.2%, while the lateral and longitudinal directions showed enhancements of 77.2% and 57.7%, respectively. These improvements highlight the potential of WCA to enhance the mechanical performance of 3D-printed concrete, particularly by improving bonding and compaction in critical load-bearing directions.

The pumpability results showed a significant difference between the two mixtures. The average pumpability for 3D-NFA was 1580 $mm^3$/sec, whereas for 3D-WCA, it was lower at 1400 $mm^3$/sec. This indicates that incorporating waste concrete aggregates may reduce the ease of material flow through the pump. The lower pumpability of 3D-WCA can be attributed to the higher water absorption and irregular shape of WCA particles, which increase friction and resistance in the pumping system. Moreover, the rough texture and porosity of WCA may lead to greater water demand, affecting the overall workability of the mixture. While WCA enhances compressive strength, these findings suggest that adjustments in mix design, such as optimizing aggregate gradation, increasing superplasticizer dosage, or modifying water-to-binder ratios, may be necessary to improve pumpability and ensure smooth extrusion in 3D printing applications.

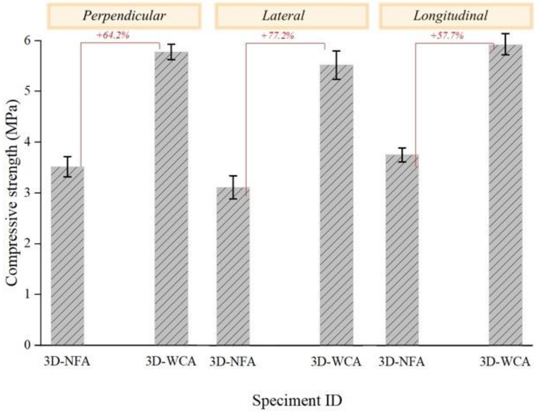



Figure 2. 7-day compressive strength of 3D printed specimens using NFA and WCA.

In LCA, GWP quantifies the amount of infrared radiation absorbed by greenhouse gases over a specified time, referenced to 1 kg of $CO_2$ equivalent. It measures heat trapped by greenhouse gases, which contributes to rising temperatures, extreme weather, sea-level rise, and shifting climate patterns. Analysis reveals that incorporating recycled WCA reduces GWP by 3.4% in 3D printing (Fig. 3), consistent with findings by Habibi et al. [10]. Sodium hydroxide significantly contribute to GWP due to their energy-intensive production processes.

Terrestrial acidification, another critical impact category, reflects emissions that acidify soils through the deposition of compounds like NOx, $NH_3$, and $SO_2$, evaluated relative to $SO_2$. These emissions lower soil pH, release heavy metals, and reduce buffering capacity, negatively impacting plants and animals. The analysis shows that using NFA results in the highest acidification potential (3.63 kg $SO_2$ eq), which decreases to 3.45 kg $SO_2$ eq when replaced with recycled aggregates. The NFA extraction process, involving blasting and quarrying, directly and indirectly, releases acidifying compounds through fossil fuel combustion, contributing more to acidification than recycled aggregates.

Despite the promising results obtained in this study, certain limitations should be acknowledged. One of the primary challenges in evaluating the fresh and hardened properties of 3D-printed concrete is the influence of the extrusion process on the material's structural integrity. Variability in extrusion pressure and nozzle geometry may introduce inconsistencies in layer bonding, potentially affecting compressive strength, particularly in the lateral direction. Additionally, while the substitution of NFA with WCA demonstrated improvements in compressive strength, further investigation is required to assess its long-term durability.

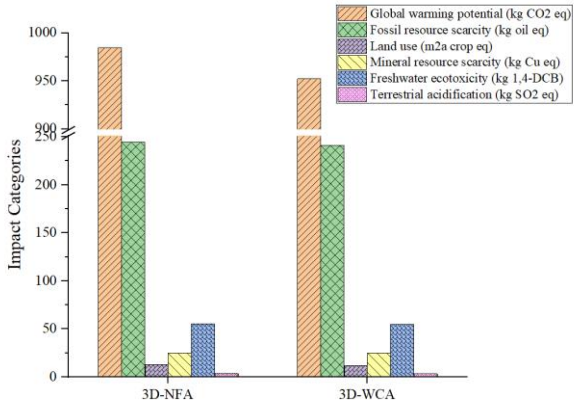



Figure 3. Comparative analysis of life cycle impact categories for 3DP-NFA and 3DP-WCA.

## 4 Conclusion

This study demonstrates the potential of recycled waste concrete for sustainable 3D concrete printing. Experimental results confirm that replacing NFA with waste concrete fine aggregate improves the hardened properties of the mixtures. The compressive strength showed significant improvements in the perpendicular (64.2%), lateral (77.2%), and longitudinal (57.7%) directions when the recycled aggregates were applied.

The LCA highlighted the environmental benefits of recycled fine aggregates, including a 3.4% reduction in global warming potential compared to natural aggregates, as well as lower terrestrial acidification potential. The reduced environmental impacts are attributed to the minimized reliance on resource-intensive natural aggregate extraction and the effective reuse of waste materials. Additionally, 3D concrete printing with waste concrete fine aggregates eliminates the need for formwork, further reducing material consumption and environmental burdens. These findings underscore the feasibility of integrating recycled materials into 3D concrete printing to achieve sustainable construction practices, offering a pathway to reduce carbon emissions, resource depletion, and environmental degradation. Future research should explore optimizing material compositions and scaling up 3D-printed structures to further validate their environmental and structural performance.

The authors acknowledged the support by the Ministry of Science and Higher Education of the Russian Federation (grant No. FSUS-2024-0027).

## References


[1] B. Sun, Q. Zeng, D. Wang, & W. Zhao. Sustainable 3D printed mortar with CO2 pretreated recycled fine aggregates. *Cement and Concrete Composites*, 134, 104800, 2022.

[2] S. Besklubova, N. Spicek, R.Y. Zhong, E. Kravchenko, & J. Miroslaw. A framework for the acceptance of 3D printing technology in construction. *International Journal of Applied Science and Engineering*, 21(4), 1-25, 2024.

[3] B. Panda, M. Tan. Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing. *Ceramics International*, 44(9), 10258-10265. 2018.

[4] Y. Han, Z. Yang, T. Ding, & J. Xiao. Environmental and economic assessment on 3D printed buildings with recycled concrete. *Journal of Cleaner Production*, 278, 123884. 2021.

[5] G. Lazorenko, E. Kravchenko, A. Kasprzhitskii, & E.H. Fini. An evaluation of the environmental impact and energy efficiency of producing geopolymer mortar with plastic aggregates. *Resources, Conservation & Recycling Advances*, 22, 200216. 2024.

[6] Huntzinger, D. N., & Eatmon, T. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *Journal of cleaner production*, 17(7), 668-675. 2009.

[7] Heath, A., Paine, K., & McManus, M. Minimising the global warming potential of clay based geopolymers. *Journal of Cleaner Production*, 78, 75-83. 2014.

[8] Kravchenko, E., Lazorenko, G., Jiang, X., Leng, Z. Alkali-activated materials made of construction demolition waste as precursors: A review. *Sustainable Materials and Technologies*, e00829. 2024.

[9] Ding, T., Xiao, J., Zou, S., Wang, Y. Hardened properties of layered 3D printed concrete with recycled sand. *Cement and Concrete Composites*, 113, 103724. 2020.

[10] Habibi, A., A.M. Ramezanianpour, and M. Mahdikhani, RSM-based optimized mix design of recycled aggregate concrete containing supplementary cementitious materials based on waste generation and global warming potential. *Resources, Conservation and Recycling*, 2021. 167: p. 105420.

[11] Papachristoforou, M., Mitsopoulos, V., Stefanidou, M. Evaluation of workability parameters in 3D printing concrete. Procedia Structural Integrity, 10, 155-162. 2018.