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3D printed concrete as a source of recycled aggregates: potential for multi-recycling and CO_2 sequestration

Hormigón impreso en 3D como fuente de áridos reciclados: potencial de multireciclaje y secuestro de CO_2

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Abstract

Additive manufacturing of concrete (3D printed concrete, 3DPC), is an emerging technology with numerous possible applications and benefits for the digital transition of the construction industry. At the same time, there remain open questions about the environmental suitability of 3DPC. One such aspect is its circularity, i.e. recyclability. Therefore, in this study, the viability of recycling 3DPC is studied on normal- and high-strength 3DPC concretes produced with 0–100% of fine recycled aggregate (fRA). After testing for basic mechanical properties, the specimens were crushed and new (2nd generation) fRA were obtained and tested. The results point to a high potential for recyclability of 3DPC and fRA conducive to multi-recycling and CO_2 uptake through carbonation.

Keywords: Additive manufacturing; multi-recycling; density; water absorption.

Resumen

La fabricación aditiva de hormigón (hormigón impreso en 3D, 3DPC), es una tecnología emergente con numerosas posibles aplicaciones y beneficios para la transición digital de la industria de la construcción. Al mismo tiempo, aún quedan dudas sobre la idoneidad medioambiental del 3DPC. Uno de esos aspectos es su circularidad, es decir, su reciclabilidad. En este sentido, este estudio se evalúa, la viabilidad del reciclaje de 3DPC en hormigones 3DPC de resistencia normal y alta, elaborados con 0-100% de agregado fino reciclado (fRA). Después de realizar pruebas de propiedades mecánicas básicas, las muestras se trituraron para obtener y probar nuevos FRA (segunda generación). Los resultados apuntan a un alto potencial de reciclabilidad de 3DPC y fRA el cual favorece el multireciclaje y la absorción de CO2 mediante carbonatación.

Keywords: Fabricación aditiva; multi reciclaje; densidad; absorción de agua.

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1. Introduction

The construction sector is a crucial part of economies around the world, just in the European Union (EU) accounting for 9% of employment and 5.5% of gross domestic product (GDP) (EUROSTAT, 2024). Nonetheless, the sector is facing several challenges related to the so-called Twin (green and digital) transition, its ageing workforce and difficulties in attracting young workers with advanced digital skills. The shortage of construction workers is a driver for the automation of construction processes (Kasztler et al., 2016), including the additive manufacturing of concrete, or 3D printed concrete (3DPC).

In parallel, the sector needs a rapid and radical shift towards sustainability and circularity due to the ever-increasing construction demands. Construction accounts for over 33% of all waste generated, 40% of all energy consumed and 5 to 12% of all greenhouse emissions (European Commission, 2020). While the industry is making efforts in this regard as well, especially in closing the material loop through recycling, a synthesis and synergy of digital and green technologies is still lacking.

In the last decade, 3DPC has drawn significant attention for its potential to transform the concrete industry and help alleviate the housing crisis in the coming decades (Ahmed, 2023). One of the most common and cost-effective techniques for 3DPC is layered extrusion (Buswell et al., 2018), where cement-based materials are extruded in linear filaments and deposited layer by layer through digitally controlled nozzles, eliminating the need for formwork (Wolfs et al., 2019). This is a key advantage of 3DPC, as formwork costs can account for 50% to 80% (Schipper and Grúnewald, 2014) of the direct expenses in conventional concrete construction. Beyond the cost reduction, 3DPC offers numerous benefits compared with traditional concrete construction. For instance, it can minimize injuries, accelerate construction timelines, reduce material waste, and provide greater architectural freedom (Bhattacherjee et al., 2021); (De Schutter et al., 2018); (Mohan et al., 2021). These benefits mean that 3DPC can potentially cut costs, waste, and time of construction by up to 80%, 60%, and 70%, respectively ((Ahmed, 2023); (De Schutter et al., 2018); (Wangler et al., 2019); (Nodehi et al., 2022). However, 3DPC is still a new technology and many aspects of it need to be thoroughly investigated before it can be widely used in construction.

Even though 3DPC offers significant advantages in terms of cost savings, reduced waste, and faster construction time, it requires nearly twice as much cement as traditional concrete to achieve the necessary workability (De Schutter et al, 2018); (Han et al., 2021). This raises concerns about the environmental impact of 3DPC, as increased cement usage leads to higher CO_2 emissions (Monteiro et al., 2017). Additionally, although natural aggregate is typically preferred for its ability to ensure consistent quality, the growing demand for this resource is depleting global supplies and straining natural ecosystems (Meredith, 2023). In response, several researchers (Bai et al., 2021); (Sun et al., 2022), (Den et al., 2022); (Qian et al., 2022); (Ding et al., 2020); (He et al., 2017) have explored alternative aggregates for producing 3DPC.

Recycled aggregates from construction and demolition waste (CDW) have emerged as a popular and sustainable option due to their widespread availability. Importantly, fine recycled aggregate (fRA, particle size < 4 mm) is still prohibited for use in concrete by numerous standards (i.e., EHE 206) and, hence, without a clear entry point into the circular economy model. At the same time, 3DPC precisely relies on fine aggregate, making it a perfect field of use for fRA. Furthermore, recycled aggregate offers the possibility of CO_2 sequestration through natural or accelerated carbonation making it an even more attractive option for 3DPC (Pu et al, 2021).

Previous studies (Sun et al., 2022); (Zou et al., 2021); (Liu et al., 2023); (Xiao et al., 2021); (Zhang et al., 2024); (Xiao et al., 2022) have investigated the effects of recycled aggregates from conventional concrete on the printability, mechanical performance, and durability of 3DPC. However, there has been limited research on the use of recycled aggregates sourced from 3DPC elements themselves. Notably, Mengistu and Nemes (Mengistu and Nemes, 2024) studied the incorporation of recycled 3DPC aggregates in normal strength concrete production, while (Skibicki et al 2024) studied the use of fine recycled aggregates as a partial cement replacement in 3DPC.

With this in mind, the current paper presents the results of a preliminary campaign on the recycling of 3DPC specimens and the characterization of the obtained recycled aggregates, as well as provides comments on their potential use and benefits.

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2. Materials and methods

2.1 Materials characterization

Type I ordinary Portland cement, conforming to ASTM C150 standards, was used in this study. Additionally, limestone and silica fume were incorporated as supplementary cementitious materials (SCMs) in all the mixtures. The density of the cement and SCMs is presented in (Table 1). A high-range water-reducing admixture (HRWRA), with a specific gravity of 1.05, was added at dosages of 0.5% by cement weight for the normal strength concrete (NSC) mixture and 1.2% for the high strength concrete (HSC) mixture.

Both natural river sand and recycled fine aggregate (fRA) were used as fine aggregates in the 3D-printed elements. The nominal maximum particle size for both aggregates was 2 mm, and their particle size distributions complied with ASTM C33 specifications. The specific gravities of the natural river sand and fRA were 2.69 and 2.41 at the saturated surface dry condition, with water absorption rates of 0.79% and 7.43%, respectively.

2.2 Mixture design proportions

(Table 1) summarizes the mixture design proportions for both the NSC and HSC mixtures with 0% fRA. Each concrete mixture was further evaluated with natural river sand replaced by fRA at levels of 25%, 50%, 75%, and 100%.

Table 1. Mixture design proportions.

	Specific gravity	**NSC (kg/m^3)**	**HSC (kg/m^3)**
Cement	3.05	560	675
Limestone	2.60	240	223
Silica fume	2.20	45	54
Water	1.00	272	233
Natural sand	2.69	1150	1165
HRWRA	1.05	3.08	8.10

2.3 Printing path and compressive strength characterization

Compressive strength development over time was evaluated using 40-mm cubic specimens. For each mixture and level of fRA replacement, nine cubes were cast. The samples were demolded after 24 h and stored in water-filled containers within a curing chamber maintained at 21°C. Compressive strength tests were conducted at 7, 28, and 56 days, with three replicates tested per mixture.

Additionally, for each mixture, a manually printed specimen consisting of eight layers was produced using a rectangular nozzle with a width of 44 mm and a layer height of 10 mm. Immediately after printing, the specimen was wrapped in plastic to prevent water evaporation. At 28 days, three 40-mm edge cubes were cut from each direction of the printed specimen (as shown in (Figure 1)) and tested to determine compressive strength.

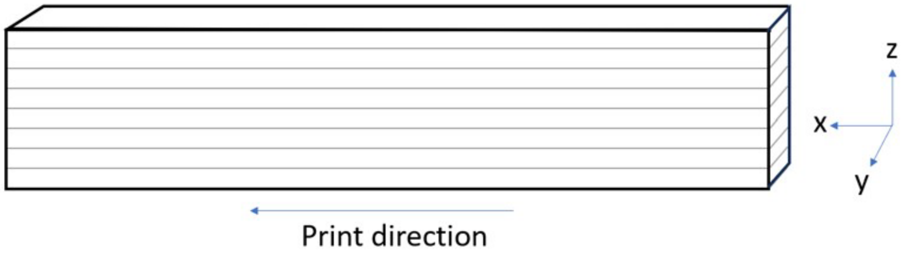

Figure 1. Schematic description of printed specimen and testing directions.

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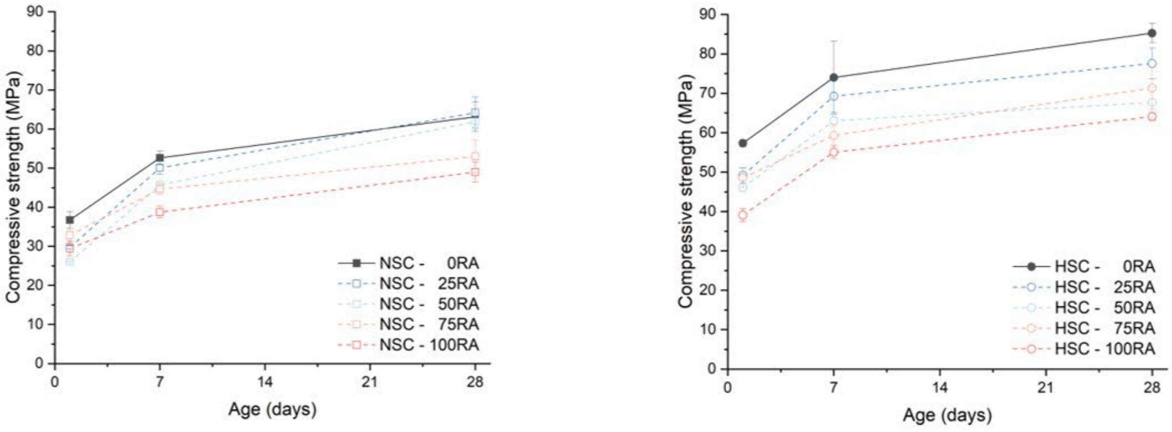
2.4 Aggregate Recycling process and characterization

The samples tested for compressive strength of the printed elements were crushed using a laboratory jaw crusher and sieved to replicate the original particle size distribution of the fRA. The saturated surface dry density and water absorption of the newly produced fRA were then measured according to EN 1097-6.

3. Results

3.1 Properties of 3D printed concrete

(Figure 2a) and (Figure 2b) illustrate the evolution of compressive strength over time for cast samples of normal strength concrete (NSC) and high strength concrete (HSC), respectively. The samples contain varying proportions of fRA as a replacement for natural aggregate.

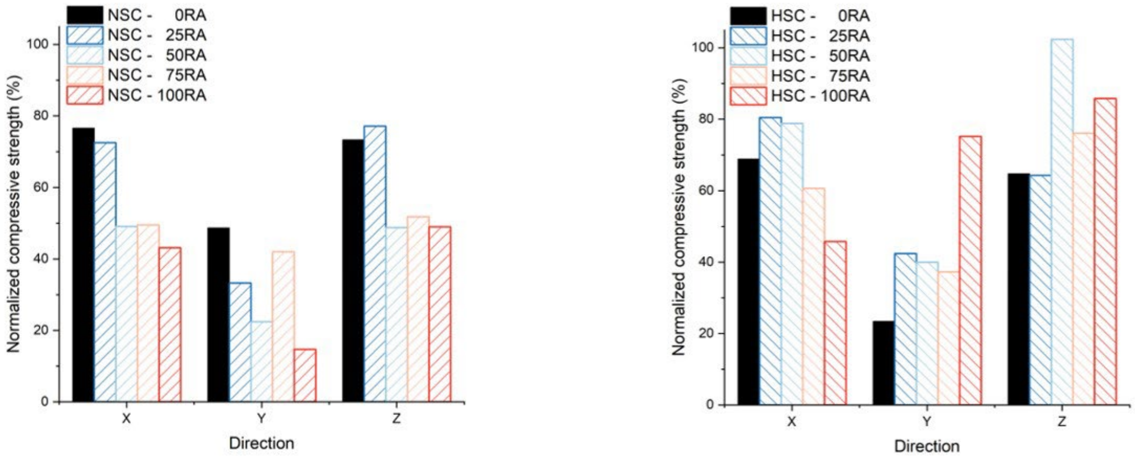


(a) NSC (b) HSC

Figure 2. Evolution of compressive strength over time of cast concrete samples.

The results indicate that for NSC, replacement levels of natural aggregate with fRA below 50% show no significant effect on the 28-day compressive strength (see (Figure 2a)). However, for HSC, replacement levels exceeding 25% result in notable differences in 28-day compressive strength (see (Figure 2b). This suggests that the compressive strength of concrete is more sensitive to fRA content in mixtures with higher compressive strength.

(Figures 3a) and (Figure 3b) compare the compressive strength of printed and cast samples for NSC and HSC, respectively, across all the mixtures tested in the X, Y, and Z directions. The compressive strength of the printed samples is expressed as a percentage relative to the cast samples, with the latter representing 100% of the normalized compressive strength.



(a) NSC (b) HSC

Figure 3. Compressive strength of printed specimens relative to the compressive strength of cast specimens at 28 days.

The results show that the compressive strength of printed specimens was lower than the compressive strength of cast specimens in all the tested mixtures, independently of the original strength of concrete (i.e., NSC or HSC) and the amount of replacement of fRA. In addition, the larger differences are observed in the Y direction, without significant differences between the X and Z direction. This disparity can likely be attributed to the weaker interlayer bonding strength in 3D-printed specimens, a phenomenon corroborated by previous studies (Wolfs et al, 2019); (Babafemi et al., 2021); (Zhang et al., 2022); (Hager et al., 2022); (Niu et al., 2020).

3.2 Properties of recycled aggregates from 3D printed concrete

The saturated surface dry density of the fRA obtained from crushing tested samples of the 3D-printed concrete specimens is 2,195 kg/m³, which is 10% lower than the density of the original fRA used in this study. Additionally, the absorption rate of the fRA from the crushed 3D-printed samples is 13.0%, nearly double that of the original fRA. This difference can likely be attributed to the increased amount of cementitious paste attached to the multi-recycled aggregate.

4. Discussion

4.1 Implications for multi-recycling

This study included the recycling of 3DPC that already contained fRA, hence it constitutes what is in literature called “multi-recycling” (Tošić et al., 2022); (Abreu et al., 2018). While this literature is scarce, the conclusions after 3–4 cycles of recycling typically point to an asymptotic decrease of density and increase in water absorption, as through subsequent cycles of recycling the recycled aggregate approach pure mortar or cement paste particles with no natural aggregate.

Studies done so far on coarse RA (i.e., d > 4 mm) show a similar (10%) decrease in density between cycles 1 and 2, as is the case in this study, whereas absorption typically only increases up to 40–50% [36]. The much higher increase in water absorption (100%) detected in this study is due to the fact that fine RA was tested where reaching a point of pure mortar or cement paste particles is faster than in coarse RA and hence, absorption increases much more rapidly.

This result means that, in the case of 3DPC, properties of the obtained fRA could potentially remain stable after the 2nd recycling cycle. In that case, if techniques are developed to be able to make use of these aggregates in new 3DPC, an “indefinite” recycling of such a material would become possible as the aggregate would always be usable.

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4.2 Implications for CO_2 sequestration

On average, about 850 kg of CO_2 is emitted for each ton of cement produced (UNEP, 2017) with 60% of this amount being emitted from the calcination process of limestone – a chemical reaction in which limestone (which mainly contains calcium carbonate) is converted to calcium oxide and carbon dioxide at high temperatures, named decarbonation ($CaCO_3 + heat \rightarrow CaO + CO_2$) (Marinković et al., 2023).

Subsequently, hardened concrete, when exposed to air, will over time reabsorb CO_2 from the atmosphere through carbonation in a process reverse to calcination ($Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$).

While this process is generally undesirable in reinforced concrete structures as it lowers the pH of the concrete leading finally to reinforcement depassivation and corrosion initiation, in recycled aggregates it is actually a beneficial process which increases their density and reduces water absorption (Sereng et al., 2021), thanks to the $CaCO_3$ and silica gel formed during carbonation, which results in the solid volume increase. Furthermore, recycled aggregate, and in particular fRA, is more beneficial for carbonation due to the larger residual mortar content and specific surface.

Additionally, 3DPC itself can be more conducive to CO_2 uptake through carbonation because of the usually larger surface exposed to the environment, caused by the form of the deposited layers. Finally, being unreinforced, means that carbonation of 3DPC does not pose a risk for generating corrosion.

Limited existing results showed that concretes with 100% of coarse RA, including carbonation of the RA and later of the concrete structure, can reabsorb between 8% and 29% of the CO_2 emissions from cement production (Marinković et al., 2023). In the study by (Sereng et al., 2021) fine recycled aggregate (with maximum particle size 4 mm and water absorption 4–7%) was demonstrated to absorb 1.2–2.2% of CO_2 per kg of aggregate mass. The quantity of fine aggregate used in a typical 3DPC would agree with the previously stated estimation of sequestration of at least 7–8% of emissions associated with the quantity of cement used in 3DPC.

5. Conclusions

In this paper, the results from a preliminary campaign on the recycling of 3DPC are reported. Within the study, 3DPC formulations of normal and high strength were developed with different percentages of fRA, tested for basic mechanical properties and subsequently recycled with the physical properties of the newly obtained fRA being characterized.

Based on the results of the study, the following can be concluded:

- For NSC, the replacement of natural aggregate with fRA up to 50% does not impact negatively compressive strength. For HSC, the limiting replacement level is at 25%;
- The difference in compressive strength between cast and printed specimens (tested in all three directions) is similar between NSC and HSC;
- Recycling a mix of NSC and HSC specimens with 0–100% of fRA produces new (2nd generation) fRA with 10% lower density and almost double the water absorption of the 1st generation fRA. This is in line with results from other campaigns;
- Multi-recycling of 3DPC can be a viable solution as due to the high content of residual mortar, properties of the obtained fRA will tend to stabilize after a lower number of cycles compared with traditional concrete.

This paper only reports preliminary results and identifies the main implications of the results. Further research is needed to analyze in-depth all influencing factors of the studied phenomena.

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