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Concrete construction is one of the largest producers of CO_2 emissions and waste from discarded formwork. 3D printing of formwork using polymer extrusion 3D printing can increase the sustainability of concrete construction by allowing the fabrication of optimized geometry. However, polymer extrusion printed formwork must be discarded after being used several times. Therefore, this paper explores the potential of recycling 3D printed formwork. We describe a workflow in which a formwork is 3D printed, filled with concrete, removed, recycled, and reprinted into a new formwork. Two case studies are presented: filament-printed PET-G formwork for a concrete column, and pellet-printed PIPG formwork for a series of columns. The results indicate that the printing material can be fully recycled for at least one cycle.

Keywords: 3D Printing, Formwork, Recycling, Polymer Extrusion, Digital Concrete

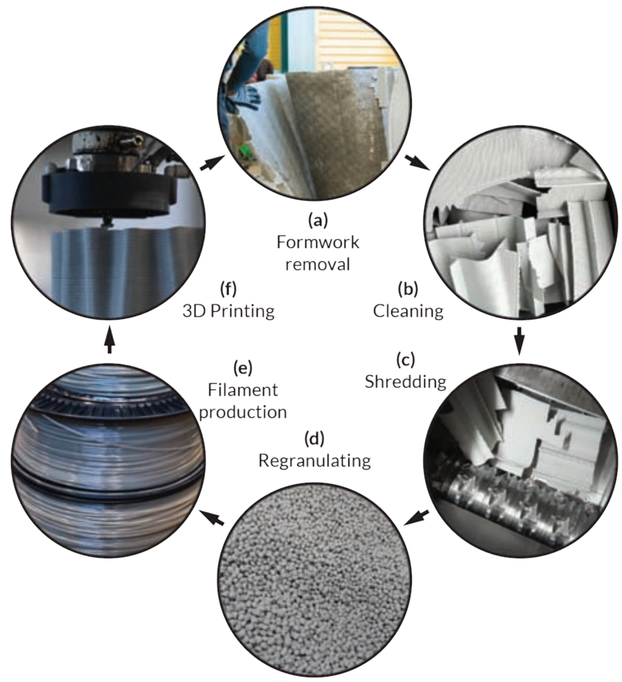
Introduction

Concrete construction dramatically impacts the environment, as it is the most used construction material worldwide (Monteiro, Miller, and Horvath 2017). Not only is cement production responsible for eight percent of all CO_2 emissions, but discarded formwork also significantly contributes to the total amount of waste generated (Cheng et al. 2022). 3D printing of formwork for concrete can improve sustainability in the built environment by enabling the fabrication of nonstandard, material-efficient concrete elements (Meibodi et al. 2018; Gebhard et al. 2021; Burger et al. 2022). Polymer extrusion 3D printing has considerable potential as it is a geometrically flexible, low-cost, scalable fabrication method.

In recent years, polymer extrusion 3D printing has been used to produce a wide range of concrete building elements, such as columns (Leschok and Dillenburger 2019; Murtha 2021), floor slabs (Jipa et al. 2019), staircases (Jipa et al. 2019; Molitch-Hou 2018), façade elements (Roschli et al. 2018; Naboni and Breseghello 2020; Han et al. 2020), and beams (Gebhard et al. 2021). These projects have shown that using polymer extrusion 3D printed formwork can reduce the structural mass of beam and floor slab elements by up to 40%. Additionally, the formwork cost can be reduced by a factor of approximately three using polymer extrusion 3D printed formwork instead of manually constructed timber formwork (Han et al. 2020). For these reasons, polymer extrusion 3D printed formwork has the potential to enable material-efficient concrete structures to be fabricated at a relatively low cost.

It has been shown that polymer extrusion 3D printed formwork can be reused more often than timber formwork. Roschli et al. (2018) showed that 190 pours using a single polymer extrusion 3D printed formwork is feasible, compared to 10–20 pours using a timber formwork (Roschli et al. 2018; Han et al. 2020; Cheng et al. 2022). Still, as the formwork reaches its end of life, the possibility of recycling it arises. As the formwork is made from thermoplastic materials, they have a high potential to be recycled, resulting in a circular process. Circularity contributes significantly to several United Nations Sustainable Development Goals (Schroeder, Anggraeni, and Weber 2019) and is essential to future construction. The polymer extrusion 3D printed formwork must be recycled to realize an environmentally friendly fabrication process.

Therefore, the experiments described in this paper investigate whether polymer extrusion 3D printed formwork can be recycled and reprinted to create new formwork. In particular, this study investigates if the recycling process can be realized for the Eggshell fabrication process, a method for the manufacturing of nonstandard concrete elements using robotically 3D printed formwork (Burger et al. 2020) in combination with Digital Casting Systems, which involves the casting of fast-hardening, set-on-demand concrete (Lloret-Fritschi et al. 2022). Previous studies involving Eggshell have suggested the potential for formwork recycling, but until now, this was not explored experimentally.



◁ Opening Image. Eggshell Pavilion, Vitra Design Museum, Weil am Rhein, Germany, 2022. (Credit: Yen-Fen Chan)

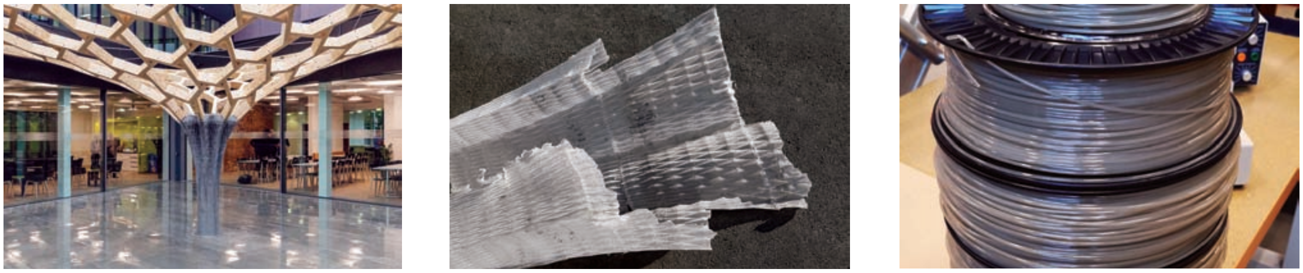
△ Figure 1. Schematic representation of the recycling process. (a) Formwork removal, (b) cleaning, (c) shredding, (d) regranulating, (e) filament production, (f) 3D printing. (Credit: Author for all figures unless otherwise noted)

No published studies (to the best of the authors' knowledge) specifically investigate the recycling of polymer extrusion 3D prints used as formwork. However, since the early 2010s, many studies have investigated the recycling potential of polymer extrusion 3D printing (Keating and Oxman 2013; Baechler et al. 2013; Volpato et al. 2015). A comprehensive review can be found in Cruz Sanchez et al. (2020).

So far, the most used materials for polymer extrusion have been investigated for recycling, such as acrylonitrile butadiene styrene (ABS) (Czyżewski et al. 2018), polylactic acid (PLA) (Cruz Sanchez et al. 2015) and polyethylene terephthalate glycol (PET-G) (Vidakis et al. 2021). This study focuses on PET-G, which is currently the material of choice for 3D printing formwork due to the ease of printing, availability, and improved chemical resistance compared to PLA (Jipa et al. 2022).

Vidakis et al. (2021) showed that PET-G can be recycled and reprinted for up to six cycles. Moreover, they concluded that the recycling process led to stiffening and strengthening after the third and fourth cycles of recycling. Additionally, no degradation occurred up until the fifth recycling cycle. However, after the fifth recycling cycle, the polymer flow significantly decreased. Kováčová et al. (2020) conclude that rPET-G (recycled PET-G) has similar properties to virgin PET-G after one recycling cycle.

Furthermore, the energy use of the recycling process was studied by Kreiger et al. (2014). They conclude that the total energy used for recycled filament production, including shredding,



△ Figure 2. Case Study A. (a) The Future Tree, (b) removed formwork, (c) recycled rPET-G filament.

melting, and extrusion, is about 2.5 MJ/kg. In contrast, the average embodied energy of virgin material is around 80 MJ/kg. Although their study investigates high-density polyethylene (HDPE) material, similar results can be expected for similar thermoplastic materials.

Although the recyclability of PET-G material for 3D printing has been verified by several studies as discussed, this aspect has not been verified for 3D printed formwork. Therefore, this study focuses on verifying the recyclability of formwork 3D printed using PET-G filament and granulate. This study does not aim to provide a rigorous qualitative analysis. Instead, it presents a preliminary evaluation of the challenges and parameters of recycling polymer extrusion 3D printed formwork. The main research question that is answered in this study is: Can 3D printed PET-G formwork be recycled and reprinted as functional formwork?

Section 2 describes the materials and methods used throughout the study. Subsequently, two case studies are presented: Case Study A: Recycling filament-printed formwork to produce formwork prototypes (Section 3) and Case Study B: Recycling of pellet-printed formwork to produce full-scale columns (Section 4). Each case study begins using formwork from previous construction projects, then processed for novel architectural elements. Case Study A provides an initial exploration of the feasibility of formwork recycling. In contrast, Case Study B verifies the use of recycled formwork to produce columns used in a real-world construction project. Although the two case studies cannot be directly compared due to the different geometry and material, each case study provides relevant information for the recycling process. Both filament and granulate are studied, as both are commonly used to produce polymer extrusion 3D printed formwork (Jipa and Dillenburger 2021). Additionally, each case study addresses a different scale: Case Study A investigates the prototypical scale, whereas Case Study B addresses the architectural scale. Lastly, Section 5 contains the discussion and conclusion, Section 6 describes the study's limitations, and Section 7 contains an outlook for future work.

Materials and Methods

The research described in this paper is conducted using a physical-empirical research methodology. Physical prototypes are designed, fabricated, tested, and the results are analyzed. The following sections describe the relevant materials and methods used for the three steps of the process: recycling (Section 2.1), 3D printing (Section 2.2), and casting (Section 2.3).

Table 1. The printing materials used in this study.

Material	Supplier	Type
PET-G	extrudr	filament
rPET-G	-	filament
PIPG	MCPP	pellets
rPIPG	-	pellets

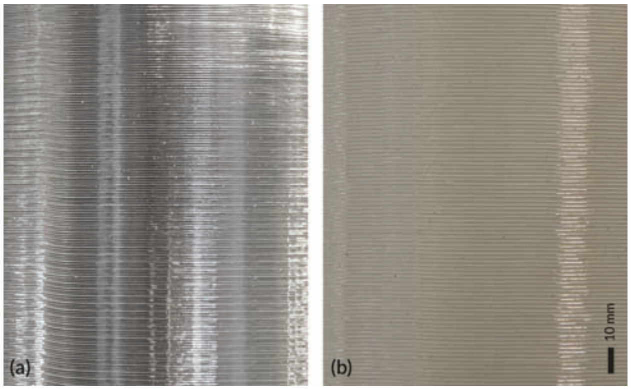
Recycling

Figure 1 shows a schematic representation of the recycling process consisting of the following steps: (a) formwork removal, (b) cleaning of the formwork, (c) shredding of the formwork into granulate, (d) regranulation of the shredded granulate, (e) optional production of filament, and finally (g) 3D printing into new formwork.

First, the used formwork must be removed from the concrete element (a). Depending on the state of the formwork, they can be cleaned of remaining residue (b). The formwork is cut into smaller pieces and fed into a mill that shreds the pieces into a size of around 3–7 mm (0.11–0.27 in.) (c). Then, the shredded granulate can be re-granulated (d). Regranulation ensures that the resulting granulate has a homogenous particle size. The shredded granulate is melted in a corotating twin screw extruder Coperion ZSK 26 Mc with an L/D ratio (process length to screw diameter) of 44 at 230°C (446°F), 400 rpm, and 30 kg/h (66.1 lb./h) throughput. The molten plastic is pushed through a sieve with an opening size of around 375 µm (0.14 in.). Afterward, the molten plastic is pelletized on an Econ EWA 50 underwater pelletizer, where the material is pressed through three nozzles and cut by a rotating knife. Then, the plastic pellets are conveyed in water to a centrifugal dryer and dropped into a container.

The resulting granulate can be extruded into the filament (e) or directly 3D printed (f). In Case Study A (Section 3), the granulate is converted to filament, whereas in Case Study B (Section 4), the granulate is directly 3D printed.

The granulate material is fed into a single screw extruder Collin E P20 heated to a temperature of 230°C (446°F) to produce filament. The molten plastic is extruded through a nozzle into a water bath with a temperature of 85°C (185°F). Then, the filament feeds through a system of rollers that determine the final diameter of the filament. The filament diameter is checked using laser measurements and rolled on spools.



△ Figure 3. Closeup of filament-printed 3D prints. (a) PET-G, (b) rPET-G.

3D Printing

The experiments in this paper use two different 3D printing setups and materials. Case Study A (Section 3) uses a filament extrusion setup, whereas Case Study B (Section 4) uses a pellet extrusion setup. Table 1 shows the materials used throughout this study.

Filament extrusion setup. A self-built filament extruder is used for 3D printing the formwork described in Section 3. The tool has a nozzle diameter of 1.5 mm (0.05 in.) and uses filament with a diameter of 2.85 mm (0.112 in.). The extruder is a slightly modified version (different nozzle diameter) of the extruder described by Burger et al. (2020). The initial filament formwork uses a PET-G filament from the company extrudr for printing. After the PET-G material undergoes one recycling cycle, it becomes rPET-G.

Pellet extrusion setup. The 3D printing of the pellet-printed formwork described in Section 4 uses an E25 Pellet Extruder from the company CEAD. The experiments presented in this paper use a 3 mm (0.118 in.) nozzle.

The material for printing the initial pellet-printed formwork is PIPG from the supplier MCPP. It comprises 70% postindustrial PET-G (PET-G recycled from industrial processes) and 30% glass fiber. The addition of glass fiber in the material increases the stiffness of the printed parts. Before extrusion, the material dries at 50°C (122 °F) for at least two hours. After undergoing one recycling cycle, the PIPG material is denominated as rPIPG.

Casting

Each case study uses a different method of concrete casting. In Case Study A (Section 3), the effect of hydrostatic pressure on the formwork is studied using regular concrete (not a fast setting). The concrete mix design used can be found in Burger et al. (2020). The reason for using regular concrete in Case Study A is to ensure formwork breakage, which provides information on the formwork strength despite the Eggshell process typically relying on fast-setting concrete.

In Case Study B (Section 4), a series of full-scale columns is fabricated, which requires using fast-hardening, set-on-demand concrete, referred to as Digital Casting Systems (DCS). This setup consists of a digitally controlled mixing reactor attached to a six-axis robotic arm. During production, concrete and admixtures are continuously pumped into the mixer, ensuring precise control of the hardening of the material before it is cast into the formwork.

Case Study A: Filament-printed Formwork

This section describes the experiments on filament-printed formwork. The formwork was collected from a previous project and extruded into the recycled filament (Section 3.1). Then, a comparative study compared the recycled filament with the nonrecycled filament. Formwork with different cross-sections is printed from the recycled filament (Section 3.2). Finally, this formwork was cast with self-compacting concrete to assess their behavior under pressure from the concrete (Section 3.3). The results of printing and casting are compared to a previous study (Burger et al. 2021) to evaluate if the formwork from recycled material is suitable for producing architectural elements.

Recycling of Future Tree Formwork

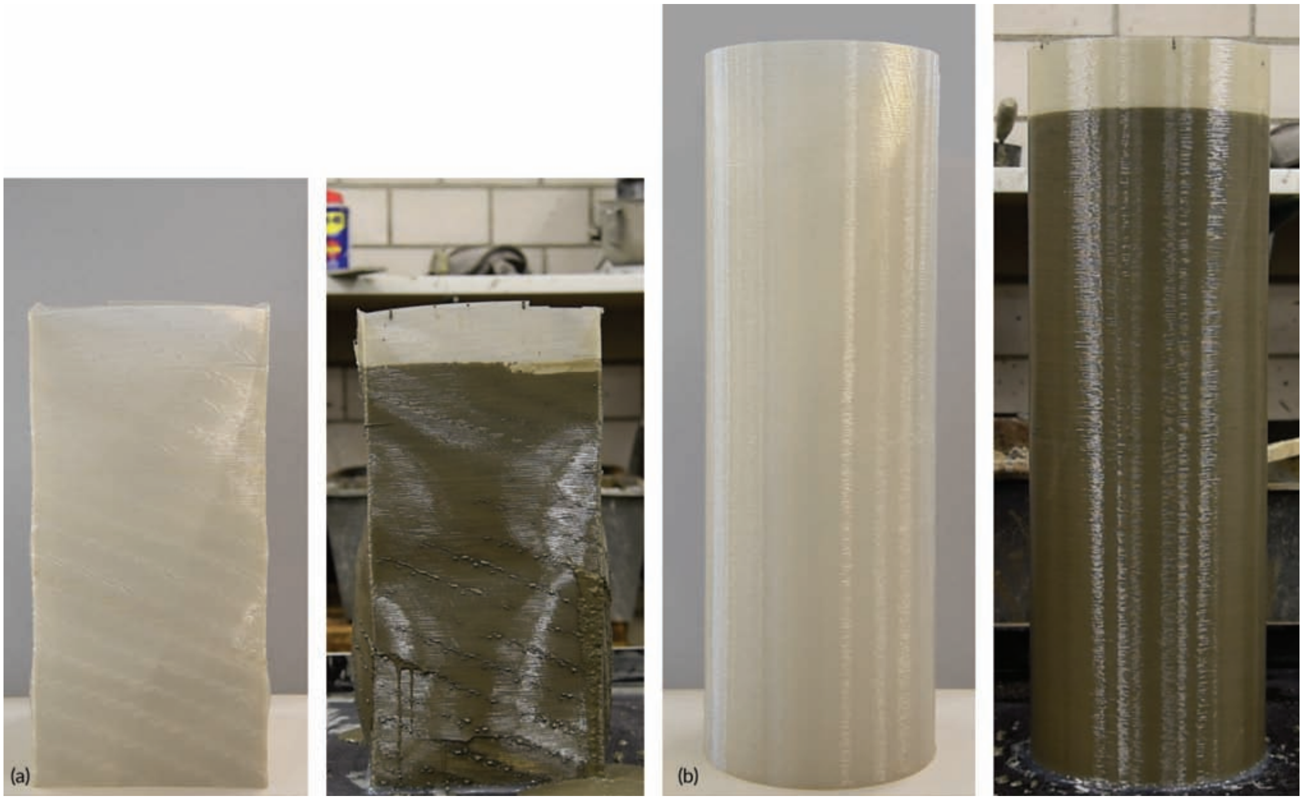
This paper's first set of experiments focused on recycling filament-printed PET-G formwork. Around 26 kg (57.3 lbs.) of used formwork (Figure 2b) was collected from prototypes made for the Future Tree project (Figure 2a). Generally, the recycling process is followed, as described in Section 4.1.

First, the used formwork was inspected for additional materials, during which remains of concrete, duct tape, and hot glue were found. The amount of concrete remaining on the formwork was not accurately quantified, but visual inspection showed that only a small amount of concrete residue remained. The tape and glue were used while casting to attach the formwork to a casting base or fill small holes in the formwork. They were cut away using a knife. The concrete residue remaining on the formwork was left on the formwork as this was deemed to be too cumbersome to remove. Then, the formwork pieces were shredded to granulate.

After the granulate was inspected, some larger concrete particles were found. A method to remove them had to be found as they could cause problems further along the process. Different established methods of separating the concrete particles from the shredded granulate were investigated: (1) sieving, (2) air separation table, (3) roll crusher, and (4) zigzag air sorter. Of these, the zigzag air sorter gave the best results. The zigzag air sorter uses airflow to separate lighter materials from heavier materials. The sorter allowed the separation of the large concrete particles from the granulate. Small (<1 mm) concrete particles were left inside the granulate as these were not expected to cause problems further along the process. Lastly, the granulate was compounded and extruded into the filament (Figure 2c), as described in Section 4.1.

3D Printing of Prototypes

A comparative study investigated if the recycled filament (rPET-G) had similar qualities to the filament (PET-G). Formwork with square and circular cross-sections (Figure 4) was printed as these could be compared with the previous PET-G study, further described by Burger et al. (2021). The formwork was printed from the rPET-G material with a layer height of 1.5 mm (0.05 in.), layer width of 1.8 mm (0.07 in.), and printing speed of 30 mm/s



△ Figure 4. Experiments conducted as part of Case Study A. The left image shows the printed formwork whereas the right image shows the formwork during casting, moments before breakage. (a) Square, h = 700 mm (27.56 in.), (b) circle, h = 1000 mm (39.37 in.).

Table 2. Experimental data obtained during the experiments described by Burger et al. (2021) compared with the results from the experiments described in Section 3.3.

Cross-section	Reference	Circumradius (mm)	Material	Thickness (mm)	Breakage height (mm)
Circle	(Burger et al. 2021)	145	PET-G	1.5	>1000
Square		182	PET-G	1.8	525
Circle		145	rPET-G	1.8	825
Square		182	rPET-G	1.8	470

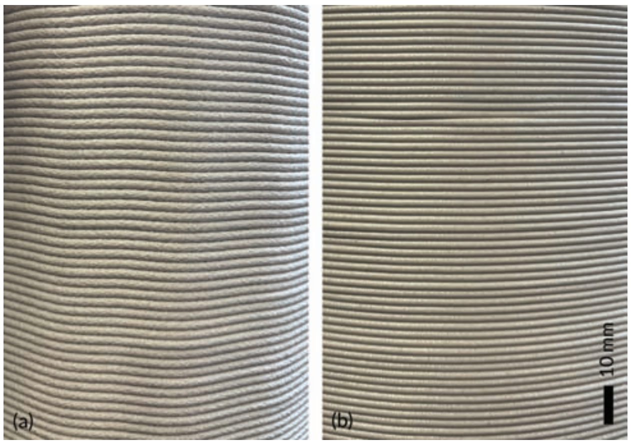
(1.18 in/s). The difference in layer height and layer width compared to the reference study was that the 3D printing extruder had since been modified with a larger nozzle diameter of 1.5 mm (0.05 in.) instead of 1.0 mm (0.03 in.), requiring different printing parameters. Therefore, the square formwork was printed a second time using PET-G as a benchmark to have a directly comparable geometry.

The first printing tests were conducted using the same nozzle temperature used for PET-G (225°C, 437°F). However, this resulted in insufficient layer bonding and print failure. Therefore, the print temperature for the final printed objects was increased to 240°C (464°F), resulting in good print quality. The improvement in print quality with increased temperature is possibly due to the higher tensile strength that results from printing at higher temperatures, as has been previously reported by other studies (Gomes et al. 2022). No other parameters had to be altered between the PET-G and rPET-G material. Visual comparison of the formwork from rPET-G to formwork from PET-G indicated that the rPET-G printed objects are less transparent and yellow (Figure 3). This outcome is an expected result of the recycling process due to the small amounts of pollution (concrete particles, dust, etc.) in the recycled material.

Casting of Prototypes

One of the most critical aspects of the 3D printed formwork is its ability to withstand a certain amount of hydrostatic pressure exerted by the fresh concrete. Other than hydrostatic pressure, the formwork is also strongly negatively impacted by environmental stress cracking caused by the alkalinity of the concrete, as described by Jipa et al. (2022). Therefore, to evaluate the

△ Figure 5. Case Study B. (a) Eggshell benches, (b) removed formwork, (c) recycled rPIPG regranulate.



△ Figure 6. Close-up of pellet-printed 3D prints. (a) PIPG, (b) rPIPG.

behavior of the rPET-G formwork during real casting conditions, self-compacting concrete was cast into the formwork, as was done in a previous study with PET-G formwork (Burger et al. 2021). A layer of concrete corresponding to a height of 100 mm (3.93 in.) was cast into the formwork every 90 seconds. Table 2 shows the experimental data obtained.

The results show that the square formwork with a thickness of 1.8 mm printed with PET-G broke at the height of 525 mm (20.6 in.), whereas the rPET-G formwork (Figure 4) broke at 470 mm (18.5 in.). This result indicates that the rPET-G (Figure 4) material performs less than the PET-G. The circular formwork printed from rPET-G broke at 825 mm (32.4 in.). In contrast, the circular formwork printed from PET-G did not show breakage even when cast to a height of 1000 mm (39.3 in.), despite the PET-G circular formwork having a lower thickness. Therefore, the authors conclude from these experiments that the rPET-G is less performant than the PET-G.

Case Study B: Pellet-printed Formwork

The second case study investigates the recycling and reprinting process of formwork printed using a pellet extruder. Despite its slightly reduced performance, Case Study A (Section 3) has shown the potential of recycled filament for creating formwork. Case Study B additionally investigates the possibilities of directly 3D printing the recycled granulate without processing it into filament using recycled 3D printed formwork to cast full-scale concrete building elements with Digital Casting Systems,

To explore these two aspects, used formwork from a previous project was recycled and reprinted as formwork for several full-scale concrete columns. The columns are part of the Eggshell Pavilion, a concrete pavilion showcasing the possibilities of 3D printed formwork in architecture.

Recycling of Bench Formwork

For this case study, around 245 kg (540 lbs.) of used formwork materials (Figure 5b) were recycled from a previous project, a series of eleven concrete benches with a bespoke geometry fabricated using 3D printed formwork (Figure 5a). The used formwork was printed from PIPG, containing 30% glass fibers. The recycling process followed is described in Section 4.1, except for filament production. Like the experiments in Case Study A (Section 3), the used formwork first had to be cleaned of additional materials. In this case, silicon sealant was used in the bottom of the formwork, which must be manually cut away.

3D Printing of Column Formwork

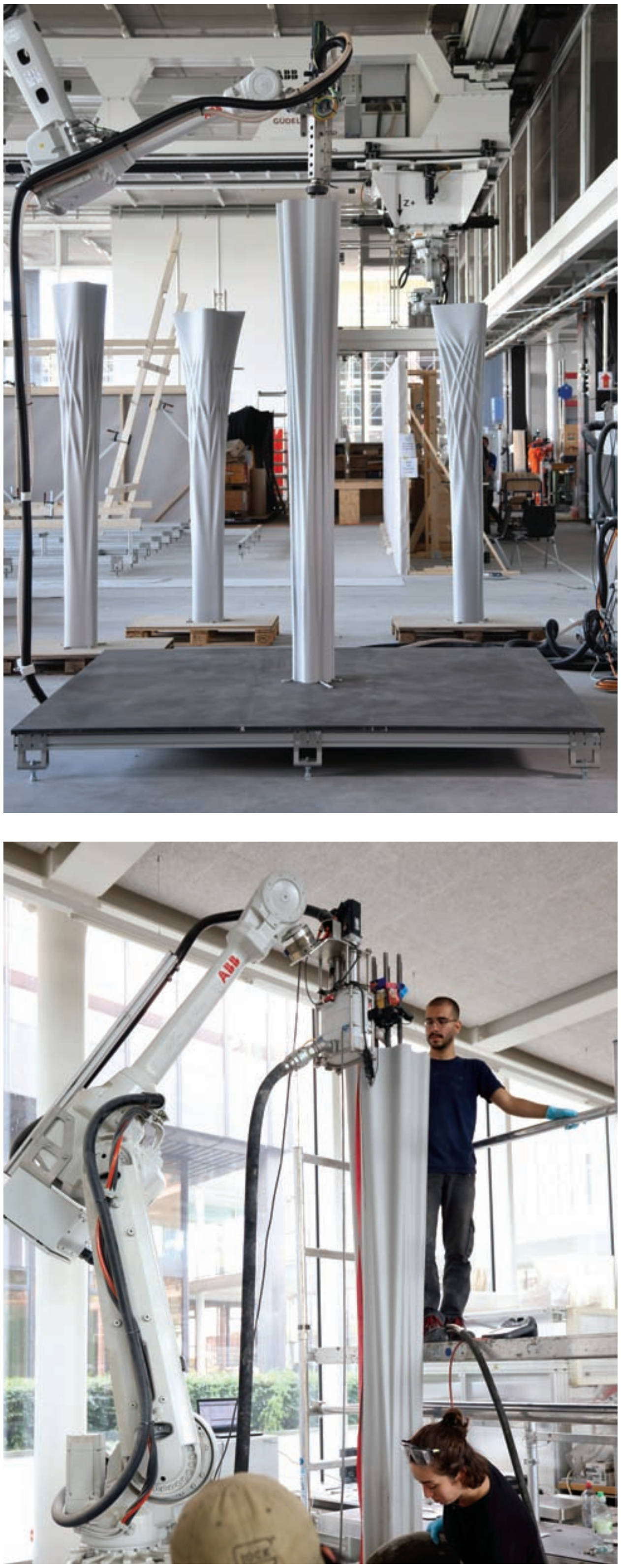
Printing tests showed that the recycled material (rPIPG) could be printed successfully using the same parameters as PIPG: a nozzle temperature of 250°C (482°F), 2 mm (0.07 in.), layer width of 3 mm (0.11 in.), and printing speed of 40 mm/s (1.57 in/s).

However, printing tests showed a difference in surface texture between the PIPG and rPIPG materials (Figure 6b). The PIPG material had a matte texture that showed the glass fibers, whereas the rPIPG material was shiny. This is likely the result of the glass fibers being filtered out in the recycling process, for example, by getting stuck in the sieve during the compounding process. Despite the apparent lack of fibers in the prints using recycled material, the prints look like prints done with PIPG material.

The recycled material was used to print the formwork for four full-scale concrete columns as part of the Eggshell Pavilion to test the recycled material for its applicability as 3D printed formwork. The height of the columns ranged from 2.6–2.8 m (8.5–9.1 ft.), and they were printed using the same parameters as the previously described test samples (Figure 7a).

Casting of Columns

The four column formworks were cast using the digital casting process described in Section 3.3 (Figure 7b). No breakages or other issues were detected in the formwork during casting, and it was possible to fully cast all the columns using the recycled formwork (Figure 8).



△ Figure 7. Fabrication process of the columns. (a) 3D printing process of one of the formworks—the other three formworks can be seen standing in the back, (b) filling the formwork using Digital Casting Systems.

Discussion

Case Study A (Section 3) results indicate that the formwork printed from recycled material was slightly less performant, as the square rPET-G formwork had a breakage height 10% lower than the square PET-G formwork. Furthermore, the rPET-G circular formwork broke at 825 mm (32.4 in.) of cast concrete, whereas the PET-G circular formwork did not show breakage. This result indicates a reduction in mechanical performance, but since only a limited number of tests were performed, this needs validation through further experiments.

The reduction in the mechanical performance of rPET-G compared to PET-G has also been identified by Latko-Durałek et al. (2019). However, others have found the mechanical properties to stay unchanged (Kováčová et al. 2020) or improve (Vidakis et al. 2021). Therefore, no conclusive result can be given on the mechanical performance of the recycled material. Still, the experiments prove that the recycled formwork can resist concrete up to a height of more than 400 mm (15.7 in.), typically enough for the Eggshell fabrication process. Additionally, the printed formwork from recycled material showed good print quality after increasing the nozzle temperature.

This study's formwork printed from recycled material exhibited lower mechanical performance. Still, this reduced performance can be accounted for in the Eggshell fabrication process by either: (1) decreasing the casting rate or (2) decreasing the setting time of the concrete. Both measures would decrease the pressure on the formwork and therefore the mechanical requirements. For that reason, Eggshell is particularly well-suited to use weaker, recycled materials.

Case Study B (Section 4) investigated if formwork printed from recycled material can be used to cast full-scale concrete columns. It proved possible to print rPIPG using the same parameters as PIPG. Possibly the printing temperature did not need to be increased, like with the rPET-G in Case Study A, since the printing temperature was already rather high (250°C, 482°F). The successful fabrication process of the four columns shows that the recycled material is suitable for printing and casting tall elements, despite the apparent reduction of fibers in the recycled material. This result shows that, potentially, the increased stiffness added by the fibers is not required.

Drawing direct comparisons between Case Study A and Case Study B is challenging. The studies were not designed to be compared but to complement each other. However, we can draw some general conclusions. The recycling process is feasible using both filaments and pellets. The recycling process using pellets (Case Study B) is simpler and less energy-intensive, as it avoids the step of filament production. The process could be further simplified by 3D printing the recycled shredded granulate (Section 7).

In all cases, the 3D printed formwork material must stay as pure as possible (meaning no materials other than the thermoplastic). Glue or silicon on the formwork should be avoided, as these must be manually removed before the formwork can be recycled. Instead of glue, screws could fasten the formwork to a casting base.

The results of this preliminary study indicate considerable potential for recycling 3D printed formwork. The successful

△ Figure 8. (a) One of the used column formworks printed with rPIPG, (b) the four cast and demolded columns of the Eggshell Pavilion.

△ Figure 9. The Eggshell Pavilion, Vitra Design Museum, Weil am Rhein, Germany, 2022. (Credit: Yen-Fen Chan).

fabrication of a series of full-scale columns for an architectural project (Figure 9) is a promising step toward circular formwork for more sustainable concrete construction.

Limitations

This study contains potential limitations. Firstly, the sample size of both case studies was small and was limited to a single specimen for each geometry due to the large effort involved in 3D printing and casting each specimen. Furthermore, the material was only recycled for one recycling cycle. Additionally, the energy consumed during the recycling process was not measured. Generally, this is a preliminary study on the possibilities of polymer extrusion 3D printed formwork recycling.

Outlook

Although the presented results give an idea of the potential of recycling 3D printed formwork, additional research is needed before this method can be widely applied. Most importantly, it is crucial to investigate the number of cycles the formwork can undergo before degrading too much to be reprinted as functional formwork. Furthermore, a series of tests with more specimens is required to validate the results.

It would be interesting to explore whether it is possible to directly 3D print the shredded formwork without the additional step of regranulation. This process would remove one more step from the recycling process, making the process more sustainable and cost-effective. So far, this possibility has been demonstrated using PLA, but not yet for PET-G (Alexandre et al. 2020).

One aspect that this paper has not studied is the financial costs related to the recycling process. Although not verified, the manufacturing costs of the recycled material in this study would likely be higher than the cost of producing new material, as this is typically the case for recycled plastic (Hopewell et al. 2009). For recycled plastic to reach mass-market adoption, the costs of recycled material must be competitive with new material. Therefore, efforts should be directed toward the recycling process's cost quantification and optimization. Additionally, the energy consumption of the recycling process must be evaluated to give an insight into the sustainability of the process.

In this study, many of the steps in the recycling process (cutting formwork, feeding machines, etc.) were performed manually. For the proposed method to be applied efficiently at a larger scale, it will be important that both the fabrication and the recycling workflow become increasingly automated. One could imagine a factory-like space in which formwork is 3D printed, filled with concrete, demolded, and recycled continuously. The recycled material could be directly fed back to the 3D printer without human intervention. Although forms of industrialized construction such as this are becoming increasingly relevant (Qi et al. 2021), we are still far from achieving the vision described.

Furthermore, it would be interesting to investigate if the 3D printed column formwork could be reusable for multiple pours for low-volume production. This approach requires creating joints and designing the formwork for demoldability. 3D printed formwork has the potential to be reused a considerable number of times (Roschli et al. 2018), which could be advantageous when creating multiple copies of the same building element.

Lastly, there are still limited examples of polymer extrusion 3D printed formwork applied on a large scale in construction projects. However, one project for the façade of a high-rise building in New York shows the potential for full-scale, high-volume applications (Roschli et al. 2018). In the project, almost 1000 façade panels were made at a formwork cost less than one-third of traditional construction. Although 3D printed formwork might not be suitable for every architectural project, rising costs of labor and materials might make 3D printed formwork more competitive than traditional methods. Future applications must demonstrate if 3D printed formwork can sustainably impact the architecture, engineering, and construction industry.

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Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

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