

# 3DREDO

Development and 3D Printing of Three-Dimensional  
Reinforcement from Waste Composites for Concrete Structures





Peer Reviewed document

## **3DREDO: Development and 3D Printing of Three-Dimensional Reinforcement from Waste Composites for Concrete Structures**

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# 1 Introduction

Concrete remains the most widely utilized construction material worldwide due to its favourable compressive strength, formability, and cost-efficiency; however, its mechanical performance under tensile loading is inherently limited [1]. Concrete exhibits quasi-brittle fracture behaviour [2], low tensile capacity [3], and poor post-cracking ductility [4], making it susceptible to cracking and early structural degradation under service conditions [5]. To mitigate these limitations, steel reinforcement is conventionally embedded within cementitious matrices; yet steel rebars introduce challenges related to corrosion [6], durability [7], and long-term maintenance requirements [8], particularly in aggressive environments where chloride ingress [9], carbonation [10], or moisture exposure accelerate rebar corrosion. The combined effects of material brittleness and reinforcement corrosion significantly impact structural lifespan [11], safety margins, and lifecycle cost [12], prompting ongoing research into alternative reinforcement strategies and material systems that can improve ductility, fracture toughness, and durability.

Alongside structural performance challenges, the construction sector faces increasing sustainability pressures due to the growing volume of discarded polymer and composite materials generated from both household consumption and industrial activities [13]. Common waste sources include packaging films, plastic wrapping, disposable consumer goods, and high-value composite components from the automotive, aerospace, and wind energy sectors [14]. These materials are typically non-biodegradable and difficult to recycle due to their heterogeneous composition and fiber–matrix interfaces, which limit their suitability for mechanical or chemical recycling [15]. As a result, the prevailing disposal routes for these materials remain landfilling and incineration, both of which impose significant environmental burdens [16]. Landfilling contributes to long-term soil and groundwater contamination while occupying critical landfill capacity, whereas incineration releases greenhouse gases and hazardous byproducts that contribute to climate change and air quality degradation [17]. The lack of robust recycling pathways for fibre-reinforced polymer (FRP) waste has therefore emerged as a major bottleneck in advancing circular economy strategies within materials-intensive sectors, highlighting the need for high-value upcycling routes capable of reintegrating these wastes into new industrial applications [18].

Recent advances in additive manufacturing offer promising pathways to engineer new reinforcement geometries for cementitious materials that are not feasible with conventional fabrication methods [19]. In particular, polymer-based material extrusion 3D printing provides the ability to generate complex lattice architectures, helicoidal geometries, and customized rebar-like forms with tailored mechanical responses [20]. Unlike traditional steel rebars, which are predominantly produced in standardized diameters and straight configurations, 3D-printed reinforcements can be designed to enhance crack bridging, energy absorption, and fracture behaviour within cementitious matrices [21]. The geometric freedom associated with additive manufacturing also enables the investigation of cellular structures and topologies that improve ductility and delay crack propagation by redistributing stresses more efficiently during loading [22]. Moreover, polymer-based 3D printing systems are significantly more accessible and cost-efficient than metal additive manufacturing platforms, owing to lower equipment costs, fewer thermal safety constraints, and reduced energy consumption during fabrication [23]. The capability to print reinforcement elements with reduced or zero support requirements further contributes to material efficiency, decreases waste, and simplifies post-processing operations [24]. As a result, additive manufacturing presents a compelling technological opportunity to develop next-generation reinforcement systems for the construction sector and supports the integration of sustainable manufacturing and design principles into concrete reinforcement practices [25].

The integration of waste polymer and composite materials into additive manufacturing offers an opportunity to address both sustainability and performance challenges through high-value upcycling pathways [26]. By converting discarded polymeric and composite waste into filament feedstock for material extrusion 3D

printing, waste streams that otherwise accumulate in landfills or undergo incineration can be reintegrated into productive value chains [27]. Recycled polymer filaments have been successfully produced from polypropylene, polyethylene, PET, ABS, and mixed waste streams, demonstrating mechanical properties suitable for structural or semi-structural applications when printing parameters are optimized [28]. Moreover, the incorporation of short carbon or glass fibres derived from composite scrap can enhance stiffness, strength, and thermal stability, enabling the fabrication of reinforcement elements with improved load-bearing capacity [29]. The incorporation of reinforcing fibres has been widely demonstrated to significantly enhance the mechanical performance of additively manufactured polymer and composite systems. Fibre reinforcement improves stiffness, strength, and load-bearing capability primarily through efficient stress transfer from the matrix to the reinforcement phase, with performance strongly dependent on fibre type, orientation, and volume fraction. Continuous fibre reinforcement typically provides the greatest improvement, often outperforming short-fibre and particle-reinforced systems due to improved load alignment and reduced stress concentration effects. Quantitatively, studies report increases in storage modulus and complex viscosity with fibre addition, reflecting enhanced stiffness and structural integrity during both processing and loading. For example, carbon fibre additions have been shown to increase rheological moduli and improve shear-thinning behaviour, enabling improved mechanical performance while influencing processing parameters such as extrusion pressure and filament stability. Additionally, fibre volume fraction plays a critical role, with mechanical performance generally increasing with reinforcement content up to an optimal threshold, beyond which defects such as void formation and reduced interfacial bonding can decrease strength. These findings highlight the importance of reinforcement architecture and fibre–matrix interaction in achieving high-performance additively manufactured composites, including systems derived from recycled or waste materials. Unlike conventional mechanical recycling, which often downcycles plastics into low-grade products, filament fabrication represents a form of upcycling by generating higher-value functional products that can directly contribute to engineering applications such as reinforcement in cementitious materials [30]. This approach aligns with circular economy principles by reducing virgin material consumption, minimizing landfill demand, and promoting the recovery and reuse of industrial and post-consumer waste [31]. As additive manufacturing continues to expand within the construction sector, recycled and fibre-reinforced filaments present a promising material platform for developing sustainable reinforcement systems and reducing the environmental footprint associated with both polymer waste and conventional concrete reinforcement practices [32].

The convergence of sustainable materials engineering, additive manufacturing, and circular economy strategies presents an opportunity to develop next-generation reinforcement systems that simultaneously enhance structural performance and reduce the environmental footprint of construction materials. Leveraging recycled polymer and composite waste as feedstock for 3D-printed reinforcement elements has the potential to overcome the brittleness of conventional cementitious matrices while addressing critical waste management challenges and reducing dependence on virgin raw materials. This dual-benefit pathway reflects broader industrial and research trends toward low-carbon construction technologies, resource-efficient design, and improved durability across the built environment.

3DREDO is an initiative that aims to harness this opportunity and develop three-dimensional reinforcement systems using the 3D printing technique from recycled polymer and composite waste. The broad objective is to improve the ductility, fracture mechanics, and strength properties of the cementitious matrix while following the circular economy and the Ireland National Research Centre for Construction Technology and Innovation themes (Figure 1).

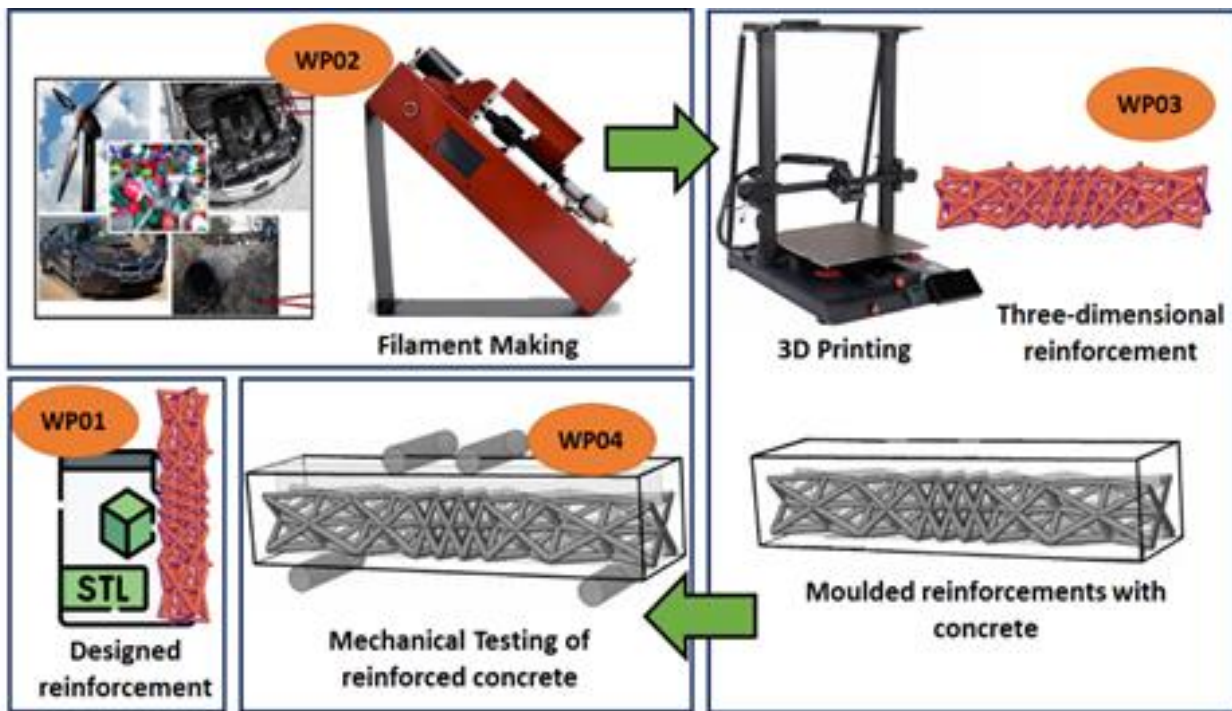


Figure 1. 3REDO project Work packages

Through a combination of design optimization, filament production from waste composites, additive manufacturing, and experimental testing, the project explores how architected reinforcement geometries and upcycled material systems can contribute to more resilient and sustainable construction practices. In doing so, 3DREDO aligns with national and international sustainability targets, promotes innovation within Ireland’s construction sector, and supports the transition toward more circular, durable, and environmentally responsible cementitious infrastructure systems.

## 2. Filament Manufacturing and Material Selection

### Materials and Filament Development

Two types of thermoplastic matrices for 3D printing are to be studied: Polypropylene (PP) and High-Density Polyethylene (HDPE). Both polymers are chosen because of their established usage in several applications, including consumer and industry-based items, thereby creating huge amounts of waste, and also because of their established compatibility with material extrusion 3D printing techniques. In terms of sustainability, PP and HDPE are important components of circular economies because although these are discarded frequently, their potential for re-use as high-quality material is high.

However, they have lower stiffness and tensile strength as a neat material. In pursuit of more functional materials, chopped carbon fibres were used as the reinforcing material. Carbon fibres are preferred because they have higher specific stiffness and strength, as well as stability during the manufacturing process, compared to other materials. Secondly, they can work well with a thermoplastic matrix. Notably, chopped fibres were used as opposed to continuous fibres to ensure that they can be easily processed using a

standard filament extrusion as well as material extrusion-based 3D printing techniques.

A set of composite filaments with systematically varying proportions of carbon fibres was prepared, with the aim of establishing the relationship between the proportions and the mechanical and processability properties. The proportions included in the experiments were:

- PP with 0, 2, 5, 8, 15, and 25wt% chopped carbon
- HDPE with 0, 2, 5, 8, 15, 30, and 45 wt% chopped carbon fibre

The goal of the filament production was to achieve a consistent diameter, a uniform dispersion of the fibres, and the necessary flexibility to ensure that the filaments could be fed through the three-dimensional printer without breaking. Figure 2 illustrates the procedure of filament making and 3D printing of recycled polypropylene and short fibres. The filaments produced needed to be mechanically tested in terms of tensile strength to determine their suitability for producing the three-dimensional reinforcement structures. The preparation and mechanical testing of tensile and flexural specimens were conducted in accordance with relevant ASTM standards to ensure consistency and reproducibility of the experimental results. Tensile testing of the polymer-based filaments and printed composite specimens followed ASTM D638 (Standard Test Method for Tensile Properties of Plastics), which specifies specimen geometry, loading rate, and data acquisition procedures for thermoplastic materials fabricated through extrusion or additive manufacturing. Flexural testing of cementitious specimens was performed following ASTM C348 (Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars) for prism-based bending evaluation, while general flexural testing procedures and loading configurations were aligned with ASTM C1609/C1609M where applicable to reinforced cementitious systems. These standards provide controlled methodologies for specimen preparation, loading configuration, and failure assessment, ensuring that the reported mechanical performance can be directly compared with established literature.

The tested filaments underwent quality checks to determine the diameter and to examine the surfaces in terms of smoothing. Average diameters were measured using a digital calliper, while the examination to check the surfaces for any irregularities was done by visual checks. It was difficult to consistently vary the diameter as the proportion of carbon fibres in the filaments changed. The average diameters of the filaments, depending on the fibre weights, changed as follows: Those with fibre weights of 0 wt% and 2 wt% had an average diameter of 1.45 mm, whereas increasing the fibre weights to 5 wt% and 8 wt% caused the diameter to reduce to 1.40 mm. Finally, with the high weights of 15 wt% and 25 wt%, the diameter decreased to 1.35 mm. It can be stated that the addition of carbon fibres influences the flow properties in the extrusion process such that there is a reduction in the swell portion with the resulting consolidated composite filaments being smoother.

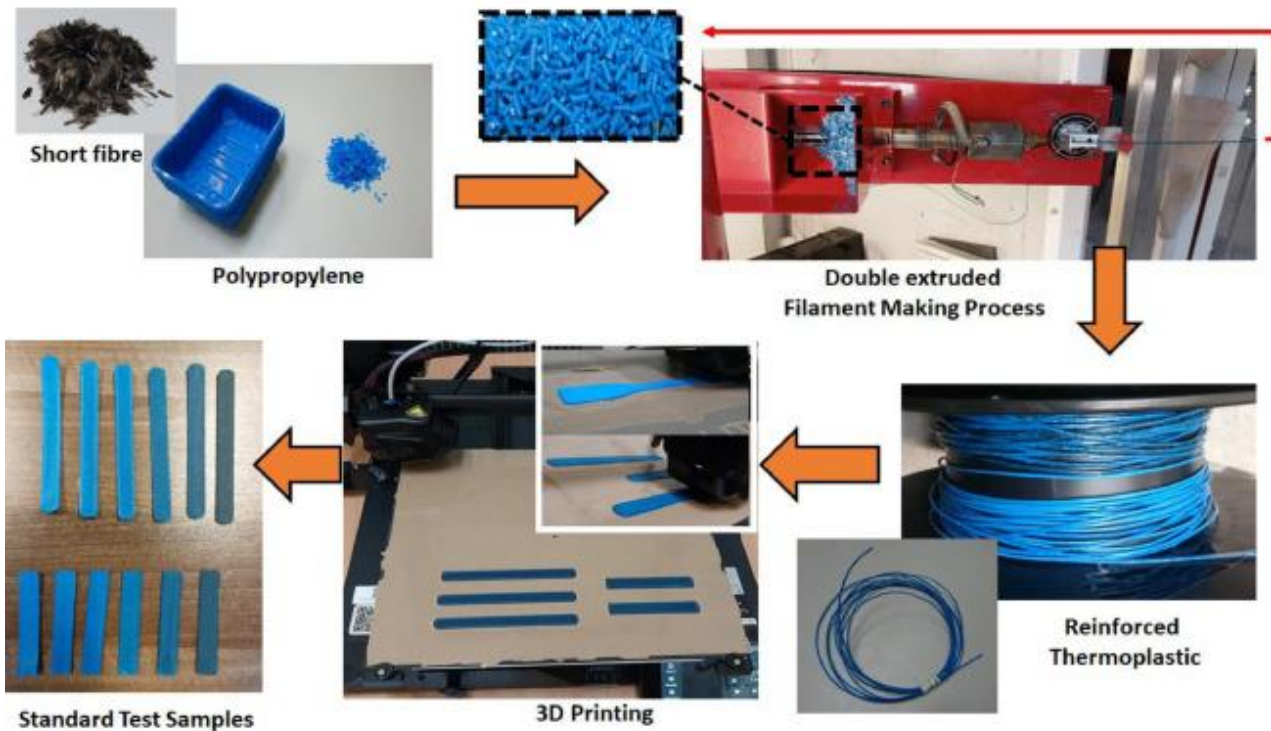


Figure 2. Filament making and 3D printing of recycled polypropylene and short fibres.

The challenge of ensuring that there is an optimal attachment of the printed material and the surface of the bed remains a challenge in material extrusion (MEX) printing of polypropylene (PP). In the cases described below, it was clear that conventional attachment methods had not succeeded. The fact that rafts had to be used to improve material attachment may not solve the attachment of the material to the bed (though now it is between two materials), which may cause print failure too. The brim effect, which is an attachment at the bottom of the print, may not optimize the attachment of material on the build plate either.

Moreover, the use of adhesive specifically for the PP filaments did not provide a satisfactory result when applied to recycled PP (Figure 3). Overcoming the aforementioned issues related to adhesion is important for the successful three-dimensional printing of polypropylene materials. Finally, the phenomenon of “warping” in three-dimensional printing, which lifts the corners away from the build plate, is attributed to the shrinkage of the materials. The polymers/composites experience expansion followed by shrinkage, with the former being more extreme, resulting in “bending away from the plate” as the corner lifts up. To minimize warping, it is crucial to ensure good bonding of the 3D print with the build plate. After a wide variety of adhesion methods had been tried, the successful method consisted of applying 3–4 layers of polypropylene packing tape on the bed, using optimized effective parameters.

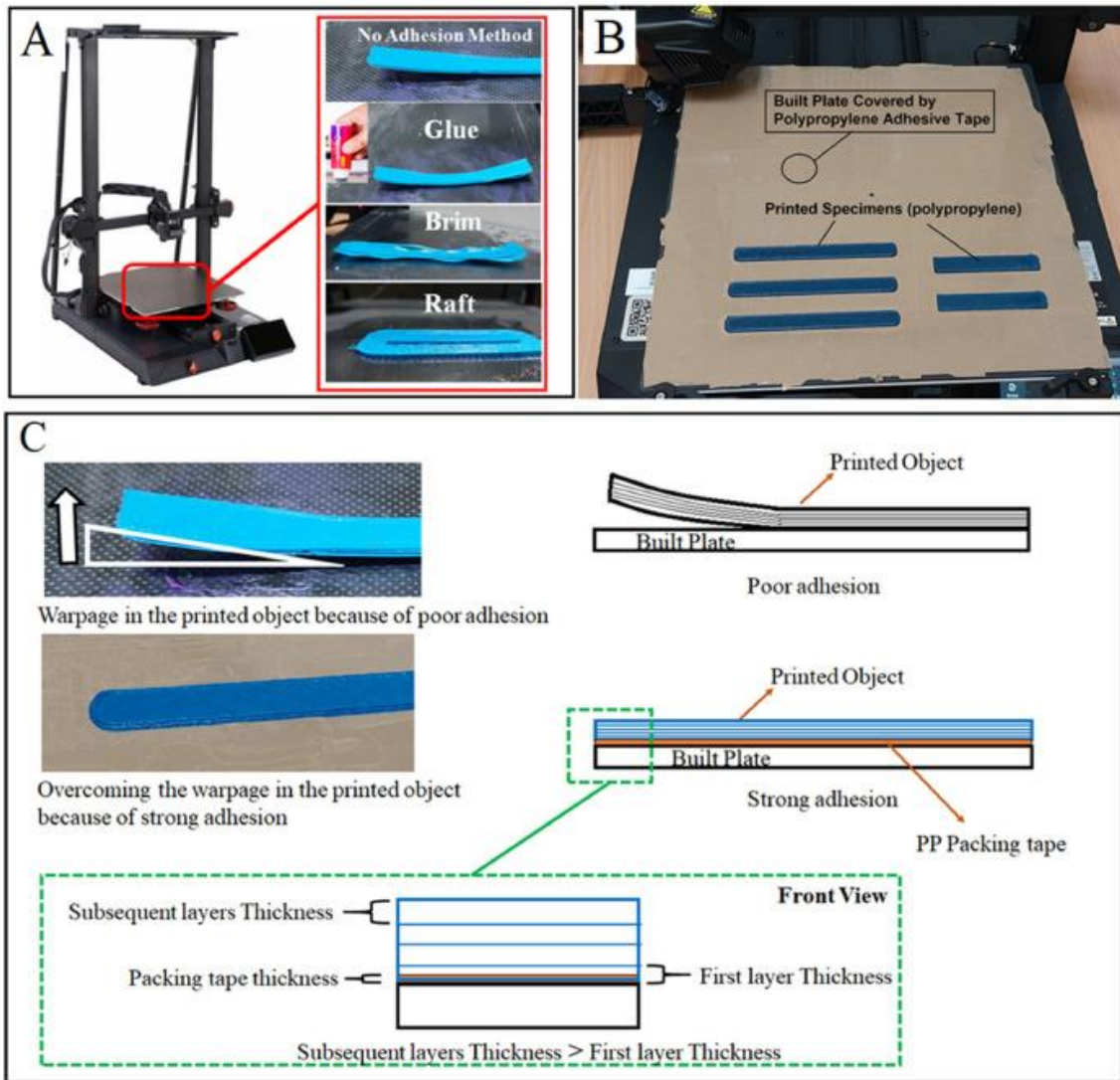


Figure 3. A) Different scenarios to enhance the adhesion of printed object to the built plate, No adhesion method, apply printing glue, add raft and brim (Unsuccessful) B) Use of packing tape to enhance adhesion of printed specimens to the built plate (Successful). C) Polypropylene packing tape used to enhance the adhesion between the printed object and the built plate.

## Tensile Performance of PP–Carbon Fibre Filaments

The neat PP had a tensile strength of about 31.8 MPa at the base, representing typical values for unfilled polypropylene that has been processed by extrusion. Chopping carbon fibre resulted in a steady improvement in tensile strength with increasing fibre content, which suggested that there was active load transfer between the polymer matrix and the reinforcing fibres during low to moderate fibre loadings.

Within the carbon fibre content from 2 to 8 wt%, tensile strength gradually increased from about 42.0 MPa to 52.6 MPa. This represents the increasing contribution of the fibres to the overall load-bearing capacity of the filament and sufficient fibre dispersion with continuity in the polymer matrix. At 15 wt% carbon fibre, there was a pronounced improvement in tensile strength to approximately 80.1 MPa, an increase of over 150% relative to neat PP and showing the strong reinforcing effect accomplished at this fibre content.

A further increase in the carbon fibre content up to 25 wt% resulted in a significant decrease of tensile

strength, with the values declining to approximately 59.9 MPa. This reduction is attributed to certain limitations associated with processing at high fibre loadings, including conditions for fibre agglomeration, poor wetting of polymer, and the induction of stress concentrations inside the filament. Such effects have been considered to reduce the efficiency of the process of transferring stress and promoting early failure of these samples. An increase in the standard deviation with an increase in fibre content further suggests poor reproducibility and enhanced sensitivity to localized microstructural variations.

Among these, PP reinforced with about 15 wt% of chopped carbon fibre exhibited the best compromise between mechanical improvement and material homogeneity. This formulation combines a high tensile strength value with acceptable scatter, thereby making it the optimal PP-based filament for the subsequent 3D printing of reinforcement structures.

## Tensile Performance of HDPE–Carbon Fibre Filaments

Neat HDPE presented a base value for tensile strength of about 27.9 MPa, lower than that of neat PP, due to its molecular structure, which is more ductile. However, adding the chopped carbon fibre has brought about a very significant and consistent enhancement of the tensile performance across the investigated fibre content.

This effect was especially strong at low fibre contents. While the addition of 5 wt% carbon fibre increased the tensile strength by more than twofold, up to about 59.4 MPa, further increases in fibre content resulted in good further improvements to about 66.1 MPa for 8 wt% and 88.0 MPa for 15 wt% carbon fibres. Efficient stress transfer and good fibre-matrix interaction are indicated by this within the here-presented composition range.

This was done at 30 wt% carbon fibre, where a maximum tensile strength of ~95.8 MPa was reached. Such a formulation showed a relatively high standard deviation, which can give evidence of bigger scatter in filament quality and a possibility of problems regarding fibre dispersion and extrusion stability. When the fibre content is too high (45 wt%), the tensile strength decreases to ~79.8 MPa. The excessive load of fibres in the filaments compromised their integrity due to probable poor interfacial bonding and increased densities of defects.

Accordingly, from both a mechanical performance and manufacturability perspective, HDPE reinforced with 15–30 wt% chopped carbon fibre emerged as the most promising range. While ensuring reliable filament feeding, consistent extrusion, and reproducible printing of complex lattice geometries, the 15 wt% HDPE–carbon fibre formulation was pinpointed as the most balanced and robust option concerning reinforcement fabrication.

## Selection of Optimal Filament Systems

The choices of the final compositions of the filaments to be used in the fabrication of the reinforcement structures through material extrusion in the 3D printing process were based on a combination of their tensile properties, variability, and expected printability in the printer. It was apparent that the higher the content of the fibres in the material, the higher the tensile strength, although it was prone to variability in the printing process, which was not desirable in the fabrication of lattice structures with geometric complexity and minimum support.

Based on these considerations, the following filament compositions were selected for subsequent

reinforcement printing and concrete integration:

- **PP + 15 wt% chopped carbon fibre**
- **HDPE + 15 wt% chopped carbon fibre**

These formulations showed a significant improvement in tensile strength compared to the neat polymers. However, they ensured that the mechanical properties remained consistent and the processing was possible. The choice was also based on a balance that met the project's sustainability and circular economy criteria.

## 3. Lattice Structure Design, Printing, and Cementitious Testing

### PLA-Based Lattice Structures

Prior to the fabrication of the reinforcement structure based on the composite filament produced from waste materials, the screening phase based on polylactic acid (PLA) was used. This selection and use of PLA were based on the excellent printability, dimensional stability, and minimal processing variability to ensure the independence of the results from the effects of lattice geometry when considering the behaviour of PLA, and the results would reflect the influence of lattice topological parameters, cell dimensions, and strut thickness.

This approach ensured that the optimal reinforcement morphologies could be determined before the reinforcement filaments introduced the complexities that come with the use of recycled polymer-carbon fibre composites.

Three lattice structures have been chosen due to their extensive usage in lightweight structures and their potential to improve crash resistance capacity as well as to bridge cracks in cementitious materials:

- **Body-centred Cubic (BCC):** Involving a central point in the cubic structure for providing the best combination of strength and ductility.
- **Face centred Cubic (FCC) :** Nodes residing on the faces of the cells, commonly observed in cells with higher connectivity.
- **Fluorite:** This structure incorporates the characteristics of BCC and FCC lattices in a more complex manner that provides higher connectivity between nodes.

These structures were modelled in nTop software, and their CAD files were generated in (.STL) format to be sliced for 3D printing. The unit cell of each structure are illustrated in Figure 4.

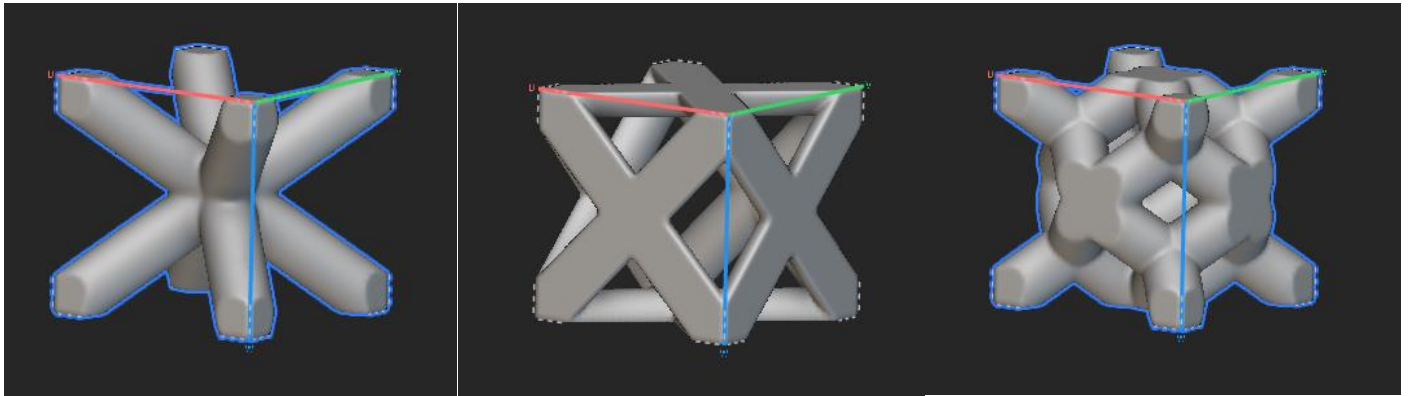


Figure 4. Unit cell of lattice structures for A) BCC, B) FCC, and C) Fluorite

The Fluorite lattice differs topologically from conventional BCC and FCC structures primarily in terms of nodal connectivity, strut orientation, and load-transfer pathways. The BCC lattice consists of nodes located at the cube corners with a single central node connected through diagonal struts, resulting in relatively low nodal coordination and load transfer dominated by diagonal compression members. The FCC lattice includes additional nodes at the face centres, increasing nodal connectivity and enabling more distributed load paths through both edge-aligned and face-oriented struts. In contrast, the Fluorite topology combines features of both BCC and FCC arrangements by introducing additional nodal connections that increase coordination number and structural redundancy. This results in a more interconnected network with multidirectional strut orientations, promoting improved stress redistribution, enhanced stability under complex loading, and potentially greater resistance to localized failure. The increased connectivity of the Fluorite lattice leads to higher relative stiffness and improved energy absorption compared to simpler cubic-based architectures.

A different lattice topology was produced with two sizes of cells (20mm and 30mm) and two strut thicknesses (2mm and 3mm). This parametric variation allows the assessment of the relative density, stiffness, and manufacturability, thus providing a full matrix of different lattice structures.

## 3D Printing of PLA Lattice Structures

PLA lattice structures are produced by material extrusion 3D printing (Figure 5). The parameters of the material extrusion 3D printer are optimized to guarantee stable extrusion and an accurate representation of the geometry of the lattices with a limited geometric distortion during the process. A special emphasis during the preparation of the material extrusion 3D printer was on the stable extrusion of unsupported or merely supported struts, because the availability of the first mentioned property can be considered to be important in the future application of the lattices on the composite filaments derived from wastes.

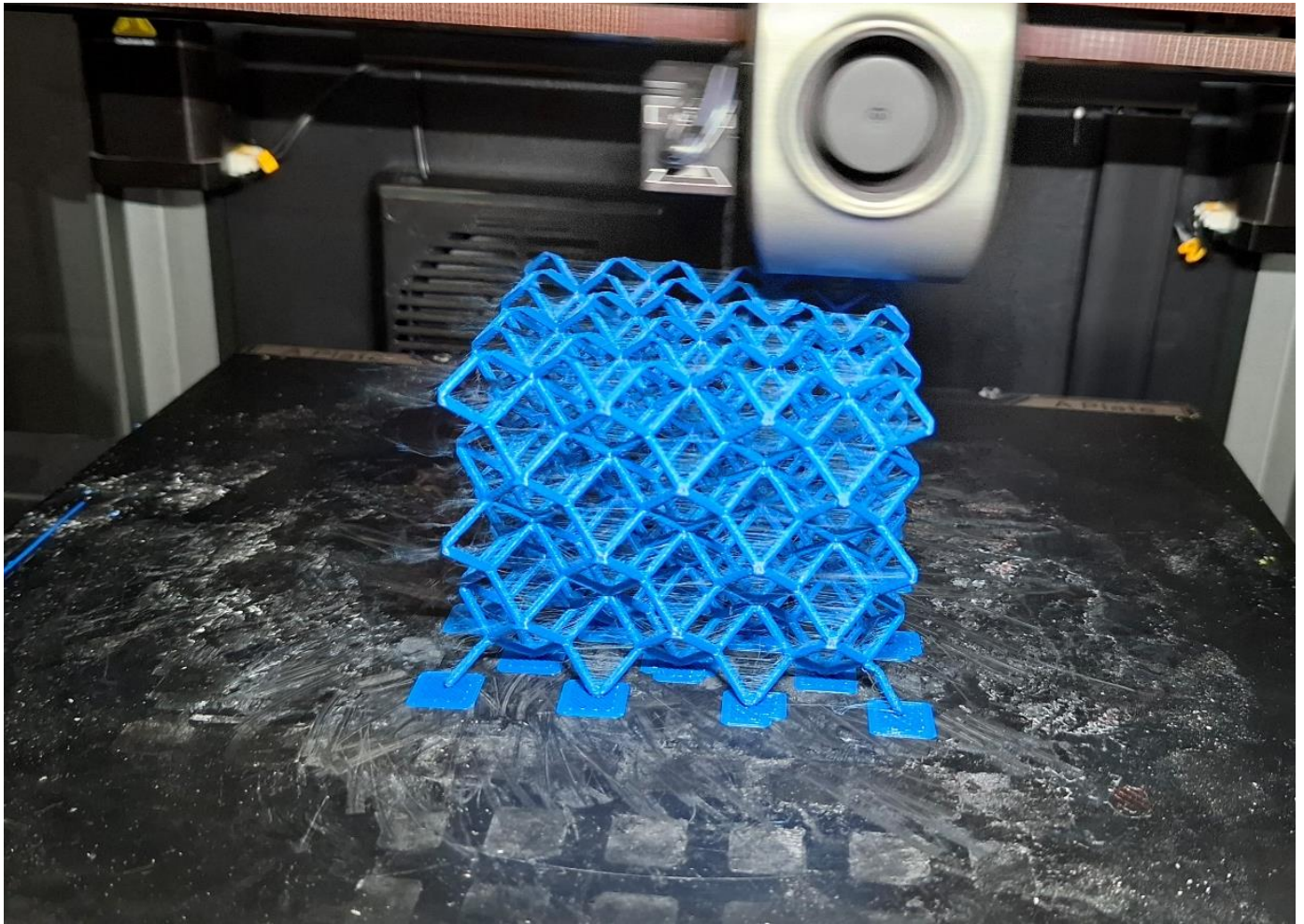


Figure 5. 3D printed lattice structure.

All lattice geometries were printed with controlled layer height and temperature to promote as much inter-layer bonding as possible. Visual checks have revealed good geometric consistency throughout the vast majority of geometries, although larger cell size and thinner struts tended to approach the bounds of unsupported printing, especially with more complex geometries.

Minor imperfections like local sagging and mild thickening of struts at nodes were noticed in highly porous lattices. These are believed to be caused by the influence of gravity during the deposition process. However, it should be noted that the integrity of the printed lattices is not compromised, since there are no failures in the complete struts. Figure 6 illustrates some of the PLA lattice structures printed as the reinforcement.

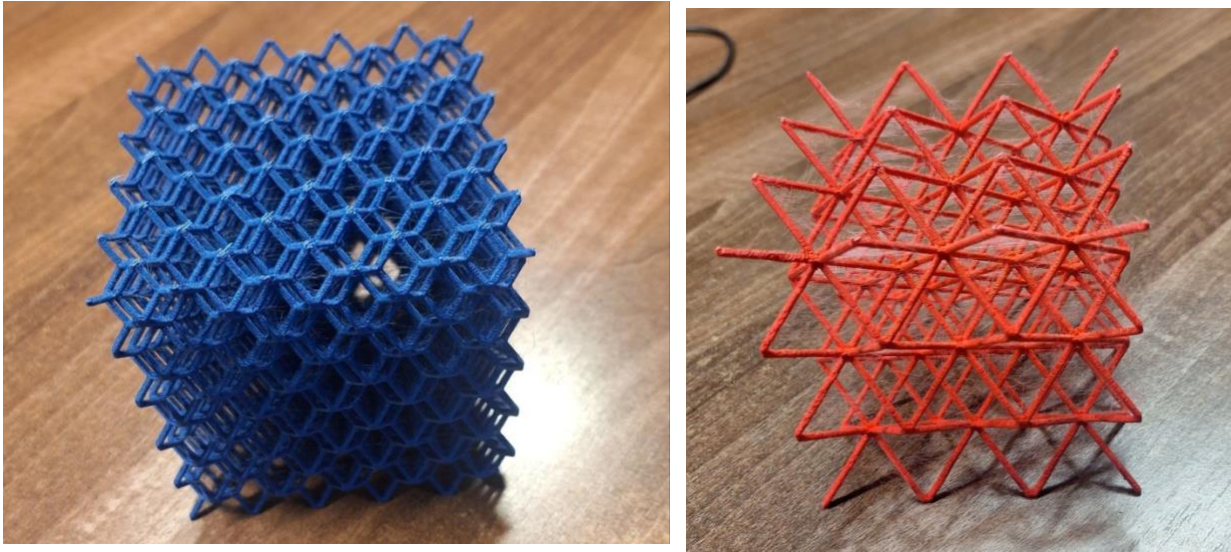


Figure 6. Some instances of the lattice structures printed as the reinforcement

The ability to create these geometric patterns successfully does serve as an important benchmark that can now be used against which future attempts at lattice structure creation from sustainable composite materials must be judged, where working with composite filaments containing recycled or waste material may limit movement of material through the nozzle even further due to higher viscosity and less material flow homogeneity. Nevertheless, this effort does show that material extrusion does have potential applicability in lattice structure creation.

## Moulding of PLA Lattice-Reinforced Cementitious Specimens

After the fabrication process, the PLA lattices were placed inside the moulds and encapsulated in concrete material. The concrete mixture was prepared with Kilsaran KPRO Crete and fine sand in a ratio of 3:1 for cement and sand, respectively, and was mixed as per the manufacturer's instructions. Care was taken to ensure that the lattices were placed in the correct position and were completely encapsulated by the concrete matrix (Figure 7).



Figure 7. The process of moulding of PLA lattice-reinforced cementitious specimens

There were two specimen geometries tested for the various mechanical behaviours:

- Flexure-dominated specimens: 45 mm x 45 mm x 160 mm
- Compression Specimens: 100mm x 100mm x 100mm

Although vacuum-assisted casting techniques can enhance matrix infiltration and reduce entrapped air, conventional staged pouring with light mechanical compaction was selected in this study to replicate practical casting conditions commonly used in construction applications. The relatively open lattice geometries and controlled concrete rheology enabled adequate penetration of the cementitious mixture without the need for vacuum assistance. Visual inspection during demoulding confirmed complete encapsulation of the lattice structures with no observable macroscopic voids. Additionally, avoiding vacuum-assisted casting minimized process complexity and ensured that the evaluated reinforcement behaviour reflects realistic implementation scenarios in standard construction practices.

As show in Figure 8, during the casting process, the cementitious material was poured in a staged manner and lightly compacted in order to allow for the diffusion of the material into the lattice structure. A visual inspection performed during the demoulding of the samples confirmed the desired positioning of the lattices within the cementitious material. No voiding was observed.

After casting, the specimens were cured under controlled conditions to promote equal hydration and material development before conducting the mechanical tests. Curing was chosen to represent common procedures for cementitious materials and to prevent decay of the lattices of the embedded polymer due to the high moisture content. The specimens were all subjected to the tests at the same age to offset the effect of the curing time difference.



Figure 8. Moulded lattice structure.

## Mechanical Testing and Performance Evaluation

The PLA lattice-reinforced samples were subjected to mechanical tests, the purpose of which was to investigate the effects of the lattice topology and geometry parameters on the properties of concrete. The tests done under flexural loading, in turn, aimed to investigate the load-displacement relation, the onset and propagation of cracks, and the load-carrying capacity after cracking, among other parameters, compared to the unreinforced samples.

The influence of the PLA lattice reinforcements demonstrated clear improvements with regard to the control and post-peak performance, as the specimens with reinforcements showed better energy absorption and resistance to catastrophic failure. With regard to the performance under bending loads, the crack growth in lattice-reinforced specimens appeared stable and maintained loading after initial cracking.

Under compressive loading, the reinforced specimens showed limited improvements in stiffness and peak load for some configurations and a more progressive failure response compared to the brittle crushing observed in the control specimens. There were distinct differences between the lattice topologies, underlining the role of nodal connectivity, strut orientation, and relative density in dictating reinforcement efficiency. Lattices with higher connectivity and favourable load-aligned strut arrangements showed improved stress redistribution and damage tolerance.

These findings indeed reveal that the architected polymer lattices can serve as a potent form of internal reinforcement for the cementitious matrix, notably improving post-cracking performance. These findings also emphasize how lattice architecture can be designed to yield targeted mechanical responses, and thus lay the foundation for future efforts that incorporate composite filaments comprising recycled or waste material, in which geometry-driven reinforcement can compensate for inherent reductions in material strength.

Lattices with high crack-bridging performance, higher ductility, and stable post-cracking behaviour from the mechanical test results were selected. The outcome revealed that the influence of the lattice structure topologies and strut thicknesses had been more critical than cell sizes, especially in circumstances concerning the flexibility of the results, in which successful force transmission and energy absorption were highly reliant on the nodal connections.

A critical aspect provided by the PLA screening phase was the relationship between manufacturability and

performance, offering the ability to determine the lattice structure geometry that could provide the best results with respect to the balance between mechanical property and printability performance, while at the same time consuming the least amount of material when realized within cementitious matrices.

The chosen lattice structure design was later used to manufacture the optimised PP-carbon fibre and HDPE-carbon fibre filaments. This shift in material type from PLA filaments to waste-derived composites is a major step in the project. This is because the new material uses the established geometric principles and at the same time exploits the benefits of working with composites. This is a challenge in the production of composites because of the issues of higher viscosity, fibre dispersion, and temperatures.

According to Table 1, compression testing results demonstrate a clear dependence of mechanical performance on both lattice topology (pattern type) and geometric scale (cell size). The highest compressive capacities were obtained for Pattern 1 specimens with large cell size (30 mm), where maximum loads reached approximately 300 kN and compressive strengths approached 30 MPa. This indicates that the structural architecture of Pattern 1 provides effective load transfer pathways and efficient stress redistribution under compressive loading.

Table 1. Summary of maximum load and compressive strength for lattice-reinforced specimens				
Specimen Name	Pattern	Cell Size	Maximum Load (kN)	Compressive Strength (MPa)
P1LARGE1	Pattern 1	Large (30 mm)	300.346	30.035
P1LARGE2	Pattern 1	Large (30 mm)	299.482	29.948
P1LARGE3	Pattern 1	Large (30 mm)	87.929	8.793
P1SMALL1	Pattern 1	Small (20 mm)	254.643	25.464
P1SMALL2	Pattern 1	Small (20 mm)	229.143	22.914
P1SMALL3	Pattern 1	Small (20 mm)	257.929	25.793
P2LARGE1	Pattern 2	Large (30 mm)	228.786	22.879
P2LARGE2	Pattern 2	Large (30 mm)	183.286	18.329
P2LARGE3	Pattern 2	Large (30 mm)	247.071	24.707

### **Influence of Cell Size**

Within Pattern 1, large-cell specimens generally exhibited higher compressive strength compared to small-cell specimens. While small-cell configurations achieved strengths between approximately 22.9 MPa and 25.8 MPa, the best-performing large-cell specimens exceeded these values by a noticeable margin. This behaviour suggests that larger unit cells may allow improved alignment of struts along primary load paths, reducing stress concentration at nodal intersections and enabling more efficient load distribution throughout the cementitious matrix.

However, one large-cell specimen (P1LARGE3) displayed significantly lower performance compared to the others. Such deviation likely reflects experimental variability or localized geometric or manufacturing defects, highlighting the sensitivity of lattice-based reinforcement systems to fabrication precision and structural consistency.

### **Influence of Lattice Pattern**

Comparing Pattern 1 and Pattern 2 specimens with similar cell size (30 mm) reveals that topology plays a dominant role in compressive behaviour. Pattern 2 specimens showed lower maximum loads (approximately 183–247 kN) and compressive strengths (18–25 MPa) relative to Pattern 1. This indicates that Pattern 1 likely provides more favourable nodal connectivity or load-bearing strut orientation, enabling enhanced stiffness and resistance against compressive failure.

These findings support the concept that architected reinforcement efficiency depends primarily on topology-driven stress pathways rather than simply geometric scale. Lattice designs with optimized connectivity can improve load transfer between the reinforcement and surrounding cementitious matrix, leading to improved structural response.

## **4. Printing of Optimised Composite Lattice Structures and Cementitious Testing**

As follows the completion of the PLA-screening phase, a geometry with an optimal trade-off among the three factors took precedence in the fabrication stage using composite filaments derived from waste materials: PP with 15 wt.% cut carbon fibres, and HDPE with 15 wt.% cut carbon fibres. The reason for their selection is their high tensile strength and ability to be fed well in the ME 3D printing process.

Lattice structures were created through material extrusion, with process variables being optimized, taking into consideration the effects of the elevated viscosity and the heterogeneous flow properties of the aforementioned composite filaments. Parameters pertaining to the printing process included layered height, printing temperature, and printing speed. Particular focus was placed on the unsupported or minimally supported struts, where the preservation of integrity is of prime importance for the application of mechanical load in the cementitious matrix.

The composite lattice-reinforced samples undergo flexure as well as compressive tests to determine the effect of the lattice structure as well as filament materials on cementitious behaviour:

- Flexural Testing: Observed the load-displacement response, the formation and growth of cracks, and cracking load support. Both the Polypropylene-carbon fibre (PP-CF) and HDPE-CF lattice structures showed better control over cracks, higher energy absorption, and resistance to failure compared to the unreinforced specimens. The reinforced specimens showed steady loading transfer beyond cracking.
- Compression Testing: Stiffness, peak load, and failure mechanism investigated. There was a modest improvement in peak load performance and a progressive failure mechanism, rather than the brittle failure typical of the controls, for the composite-reinforced samples. Topology, orientation, and relative density played highly significant roles in stress redistribution.

The comparison revealed that the PP-CF lattices had a slightly higher stiffness and peak load, and the HDPE-CF lattices demonstrated improved ductility and energy-absorbing capacity. This is because the two matrices possess different properties.

## 5. Conclusion

This research demonstrates the applicability and potential of utilizing 3D printed polymer composite lattices as internal reinforcing materials in cementitious composites, offering an environmentally friendly alternative to steel reinforcements conventionally being utilized. In the process, several major variants have also been established:

Polypropylene (PP) and high-density polyethylene (HDPE) reinforced with 15 wt% chopped carbon fibres were found to be the best optimized materials based on the tensile strength, printability, and processability criteria. Adding carbon fibres to these materials improved the tensile strength considerably, while the extrusion and feed flow of the materials for 3D printing processes remained feasible. Results showed that HDPE CF was more ductile, while PP CF was slightly stiffer with greater peak load support based on the material properties.

The screening phase enables the identification of the optimal lattice structures and strut sizes before moving on to the production of the composite filaments. The lattice structure, especially the connectivity options and the strut thickness, is more significant than the cell size in terms of the efficiency of crack-bridge, post-cracking properties, and the energy absorption. The architected lattices with greater connectivity options and load-oriented strut patterns provide efficient stress redistribution.

When compared to the unreinforced specimens, the addition of the PP-CF and HDPE-CF lattices to the cementitious matrices resulted in improved flexural and compressive strengths. This was evident through the better control of cracks, energy absorption, and failure modes of the reinforced specimens compared to those without reinforcement. While the stiffness and maximum load were enhanced by the use of the PP-CF lattices, the use of the HDPE-CF lattices showed better ductility and load

This work has shown that the polymeric and composite materials that have been in abundance in landfills all along, in the form of discarded PP, HDPE, or short carbon fibres, can now be transformed into high-quality reinforcement threads for concrete. This is in line with the concept of the circular economy.

In summary, this study provides the groundwork for the incorporation of architected, waste-sourced composite lattices in structural systems. By virtue of lattice optimization along with the utilization of recycled polymer-composite filaments, the ductility, resilience to branch fracture, and energy absorption capacities of concrete

can be improved. Future research directions can investigate the scalability of these systems to larger structural components, formulation improvements for the filaments, and the utilization of more sources of recycled composites, thus opening the avenue to the production of sustainable, high-performance, 3D-printed structural systems for the future.

## 6. References

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