Thermoplastic Composites by 3D Printing and Automated Manufacturing to Extend the Life of Transportation Facilities

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Design and Manufacture of Precast Concrete Formworks Using Polymer Extrusion-Based Large-Scale Additive Manufacturing and Postprocessing

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ABSTRACT
Large-scale thermoplastic polymer extrusion-based additive manufacturing (AM) has been used to fabricate precast concrete formworks. There are some limitations inherent to the large-scale AM process that need to be overcome to design complex, multipart additively manufactured formworks to be used for precast concrete. This research work uses a large-scale polymer composite AM process to manufacture two-part formworks. Postprocessing was used to repair imperfections, create smooth casting surfaces, achieve precise dimensional tolerance, and incorporate assembly mechanisms for multipart formwork. Two biodegradable polymer composites (wood-fiber polylactic acid and wood-fiber

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amorphous polylactic acid) and a conventional polymer composite (carbon fiber acrylonitrile butadiene styrene) were selected to manufacture four sets of two-part formwork. Design details, including the cellular infill pattern, continuous toolpath, and layer time selection, are presented. Postprocessing and repairs performed on the manufactured formworks to get the required dimensional tolerance and surface smoothness are discussed.

Keywords

large-scale additive manufacturing, formworks, precast concrete, PLA, ABS, postprocessing

Introduction

The extrusion-based additive manufacturing technology of thermoplastic polymers has advanced in recent years. The major advancements include scaling up to large build volumes and the use of reinforcement. The build envelope of polymer extrusion-based additive manufacturing of the thermoplastic polymer ranges from a few hundred millimeters for a small desktop 3D printer to several meters for large-scale machines.[1–4]

Different materials, including concrete, metal, clay, and fiber-reinforced polymers, have been used for large-scale 3D printing for construction applications. Buchanan and Gardner[5] reviewed the use of metal 3D printing in construction. Zhang et al.[6] reviewed the application of 3D-printed concrete for construction applications. 3D-printed concrete can offer geometric freedom, rapid automated construction, cost savings, formwork-less printing, and low waste. Jipa and Dillenburger[7] reviewed the state of the art, opportunities, challenges, and applications of 3D-printed formworks. Thermoplastic polymer extrusion-based additive manufacturing of formworks also offers geometric freedom, cost savings, and low waste via recycling. Anderson[8] studied the recycling of 3D-printed polylactic acid (PLA) at a small scale and found small significant changes in tensile strength but no significant change in the stiffness of recycled PLA. Lanzotti et al.[9] compared the bending strength of 3D-printed virgin PLA and PLA recycled for multiple cycles and found recycling viable. Gomes et al.[10] reviewed different recycling studies on 3D-printed polymers and discussed several methods to mitigate the reduction in mechanical properties. Additionally, thermoplastic polymer extrusion-based additive manufacturing of formworks allows the continued use of existing technology and infrastructure for concrete casting operations. This study uses thermoplastic polymer composites for manufacturing 3D-printed formworks.

Short carbon fiber, short glass fiber, and natural fibers are the most common fiber reinforcements that have been introduced to feedstock polymers.[11] Ajinjeru et al.[12] studied the influence of carbon fiber reinforcement on the dynamic rheological properties of polyetherimide used for large-scale extrusion-based additive manufacturing. Duty et al.[13] discussed the effect of the reinforcing fibers on the viscosity of the feedstock and the impact of reinforcing fibers on the extrusion pressure.[13] Pappas et al.[14] carried out a comparative study of pellet-based extrusion deposition of short, long, and continuous fiber-reinforced polymer composites for large-scale extrusion-based additive manufacturing. The study found that the polymers with longer fibers exhibited better mechanical properties of the printed part, although the longer fibers resulted in lower impregnation with the polymer and worse wetting. Love et al.[15] found that the addition of carbon fiber to the polymer in additive manufacturing causes an increase in strength and stiffness, as well as a reduction in distortion and warping. Other research work also found a similar increase in the mechanical properties of the manufactured parts and a reduction in the coefficient of thermal expansion as a consequence of adding carbon fibers to the polymer feedstock.[16]

These advancements in large-scale extrusion-based additive manufacturing of thermoplastic composites present a potential for manufacturing complex formworks for casting precast concrete structures. The 3D-printed formworks can shorten the process of prefabricating concrete while offering highly detailed surface finishing and an expanded degree of geometric freedom.[17] Combining 3D printing with computer numerically controlled (CNC) machining can synergize the process by complementing the advantages of additive manufacturing and postprocessing.[18]

Large-scale polymer extrusion-based additive manufacturing has been used for a variety of applications, including tooling for automotives,[19] automotive bodies,[20] boat hull molds,[21] transportation structures,[22,23] and precast concrete formwork.[24,25] The advancements in large-scale extrusion-based additive manufacturing of thermoplastic composites present a potential for manufacturing complex formworks for casting precast concrete structures. The 3D-printed formworks can shorten the process of prefabricating concrete and offer highly detailed surface finishing and an expanded degree of geometric freedom.[17]

3D-printed formworks have been used for manufacturing precast concrete structures for architectural purposes. Roschli et al.[24] used large-scale 3D-printed short carbon fiber-reinforced acrylonitrile butadiene styrene (CF-ABS) formworks for casting architectural concrete window panels. The 3D-printed formworks were 20 times more durable than traditional wooden formworks and therefore were significantly more cost-effective based on a life-cycle analysis.

The cost of the 3D-printed formworks can be further reduced by using biobased environmentally friendly polymers. This study investigates the manufacturing and postprocessing of 3D-printed biobased polymer composite formworks and compares them with the conventional CF-ABS 3D-printed formworks.

Materials and Methods

The Ingersoll Masterprint large-format 3D printer was used for manufacturing the formworks. This 3D printer has a build envelope of 18.2 m (60 ft.) in length, 6.70 m (22 ft.) in width, and 3.05 m (10 ft.) in height. The extruder can deposit at a rate of 68 kg/h (150 lb/h). Figure 1 shows the Ingersoll Masterprint large-format 3D printer in the Advanced Structures and Composites Center at the University of Maine.

FIG. 1 Ingersoll Masterprint large-format 3D printer.

The formworks were designed to manufacture a precast concrete parking garage wall system, Litewall, with a patented design from Unistress Corporation. Figure 2 shows the Litewall system and the essential features required in the formworks for casting the features present in the Litewall system. Figure 2*A* shows the Unistress Litewall system in a parking garage wall structure. The formworks are designed for casting the window openings with an embedded metallic mesh for parking garage structures. The typical precast concrete wall structure is 10.0 m (32.8 ft.) long, 6.0 m (19.7 ft. high), and 0.304 m (1.0 ft.) thick with seven openings per wall. A two-part form assembly with bolted connections is required for each opening to cast the concrete wall. The openings are 1.60 m (5 ft. 3 in.) high and 0.914 m (3 ft.) long. The manufactured formworks have some essential features needed for casting the concrete wall. Figure 2*B* shows the essential features in the bottom wall of the two-part formworks system. Three sides are sloped at 1/12, and one side is sloped at 1/3. The sloped sides enable ease of demolding of the concrete part from the formwork. Notches need to be placed on the formworks for embedding the metallic wire mesh.

Three different polymer composite materials were selected for manufacturing the formworks.

Two sets of formworks were manufactured using WF-PLA (biobased material system with conventional semicrystalline PLA polymer). Another set of formworks was manufactured using WF-aPLA (biobased material system with a novel amorphous PLA polymer). The fourth set of formworks was manufactured using CF-ABS (a conventional 3D-printing material system that has been used before for precast concrete forms). Table 1 lists the mechanical properties provided by the material suppliers for the feedstock materials used in the study.

FIG. 2 Unistress Litewall system. (*A*) Unistress Litewall window screen system. (*B*) Essential features for casting the Litewall system.

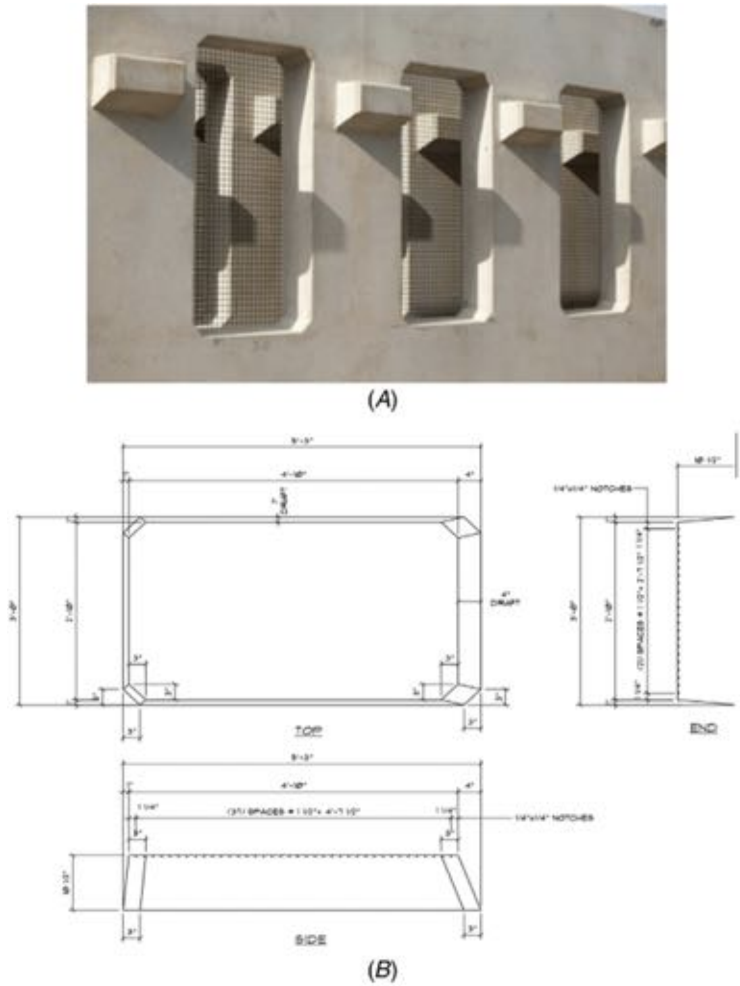


TABLE 1 Thermomechanical properties of feedstock materials

	WF-PLA	WF-aPLA	CF-ABS
Reinforcement (% wt.)	20.0	20.0	20.0
Tensile strength along bead (MPa)	55.8	58.2	89.6
Tensile modulus along beads (GPa)	5.65	4.90	12.4
Flexural strength (MPa)	93.1	94.6	143
Flexural modulus (GPa)	5.31	4.46	12.1
Processing (melt) temperature (°C)	160–190	N/A	260–293

A cellular design was adopted for the bottom formwork. The cellular structure minimizes material usage and reduces print time. Figure 3 shows the 3D model of the bottom formworks designed with a cellular structure for 3D printing. The distance from the inner wall to the outer wall in the cellular structure is 0.210 m (8.25 in.).

Surface models were used for the slicing process instead of the solid models. The surface models allowed for more precise control of the deposition toolpath. Using the surface model, a continuous toolpath was generated for the layers to minimize the seams. The toolpath has a single point for the start and the stop in each layer. The 3D-printed parts were designed to be slightly oversized than the final dimensions. The increased dimensions in the near-net-shape model compensate for the shrinkage of the material during cooling and allow machining to create a smooth concrete casting surface. The printing parameters used for different polymer systems are listed in table 2.

CNC machining was carried out to generate the net shape with precise dimensions and to create a smooth surface finish. CNC machining was also used to cut out the notches on the bottom formworks for embedding the wire mesh and to drill the holes for threaded inserts. The threaded inserts were placed on the bottom formworks. The top formworks and the bottom formworks were assembled using six hex bolts, four at the corners and two at the centers of the 1.60 m (5 ft. 3 in.) sides.

FIG. 3 3D model for bottom formwork.

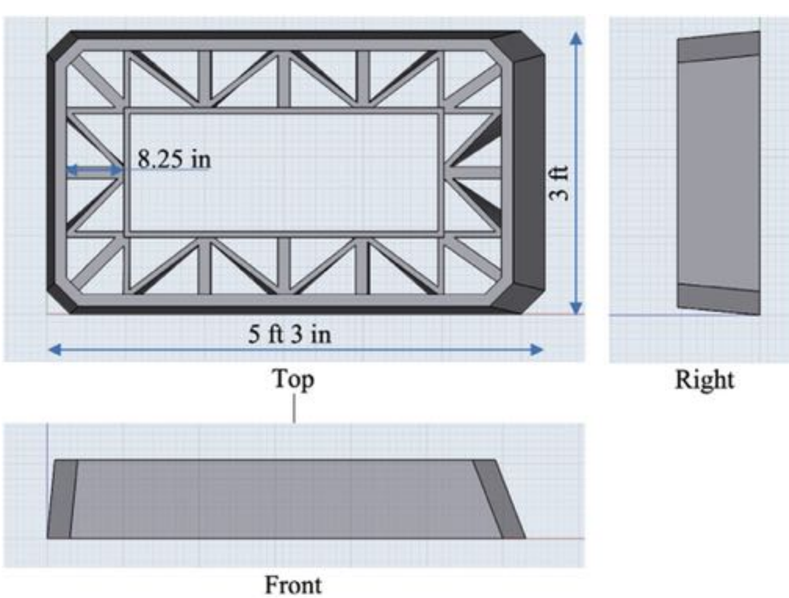


TABLE 2 Printing parameters for different polymer systems

Parameters	Values
Bead width	19.1 mm (0.75 in.)
Bead thickness	5.08 mm (0.20 in.)
Extrusion rate	
WF-PLA	25 kg/h (55 lb/h)
WF-aPLA	25 kg/h (55 lb/h)
CF-ABS	39 kg/h (85 lb/h)
Extrusion temperature	
WF-PLA	207°C
WF-aPLA	210°C
CF-ABS	240°C

Discussion of Results

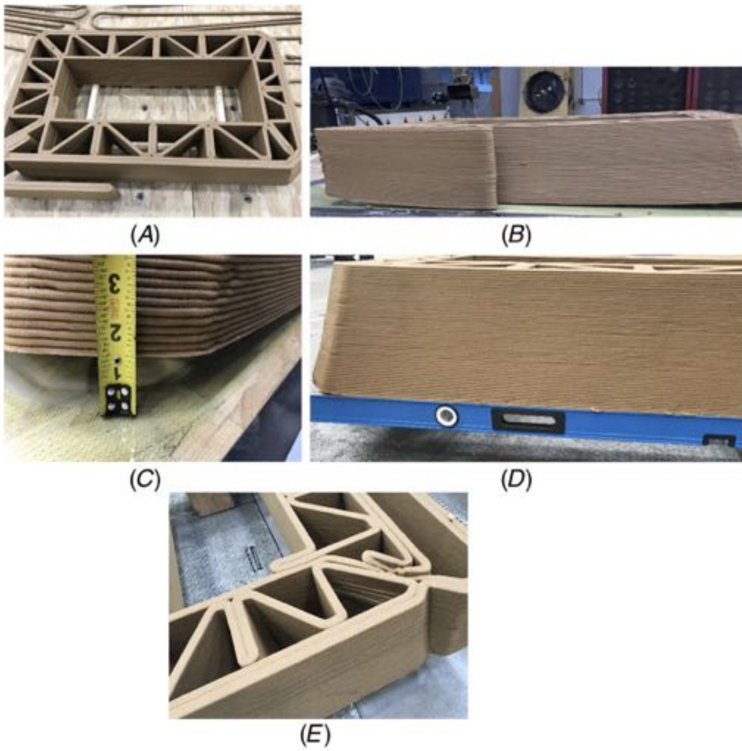
The slightly oversized near-net-shape parts were 3D-printed using the three material systems selected. Figure 4 shows the 3D-printed WF-PLA and WF-aPLA bottom forms. Figure 4*A* shows the near-net-shape 3D-printed WF-PLA bottom form. The printed forms had a single continuous toolpath per layer, minimizing the number of seams that are formed at the start and end points of the extrusion toolpath. The WF-PLA forms underwent significant shrinkage and warping during 3D printing.

Figure 4*B* and *C* shows the warping of the 3D-printed WF-PLA forms at the corners. The 3D model used for slicing was oversized by 25.4 mm (1 in.) in height to compensate for the warpage. However, the warpage was higher than expected and reached up to 38.1 mm (1.50 in.) at one of the corners.

The 3D-printed WF-aPLA forms did not show any noticeable warpage of the parts. However, at layers above half the height of the part, in regions of deposition that were three or four bead widths thick, the collapse of the walls was observed. Figure 4*D* and *E* shows the 3D-printed WF-aPLA bottom form. The bottom form was checked for warping with I-beam level equipment, and no significant warpage was observed in the form. The thicker walls retain heat longer because the thick regions have a lower surface area to volume ratio. As the thicker walls cool slower, they undergo higher viscous deformation due to the loads from layers deposited above. Consequently, the layers in the region of the thick walls collapsed. The phenomenon of layer collapse in extrusion-based additive manufacturing of polymer composites has been discussed by Duty et al.[13] The oversized near-net-shape CF-ABS forms were 3D-printed without any observable issues.

The 3D-printed forms were machined to a smooth surface finish using CNC machining. Notches were carved out for embedding the metallic mesh.

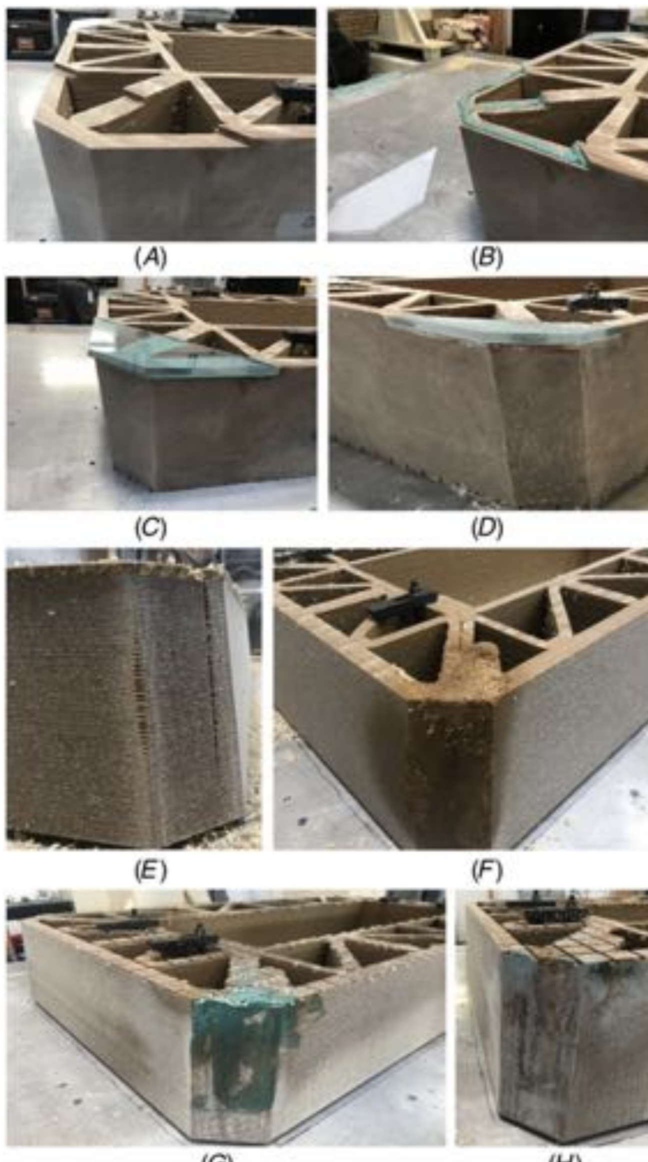
FIG. 4 3D-printed WF-PLA and WF-aPLA bottom forms. (*A*) Near-net shape 3D-printed WF-PLA bottom form. (*B*) Warpage of bottom forms (WF-PLA). (*C*) Warpage measurement (WF-PLA). (*D*) Bottom form with I-beam level (WF-aPLA). (*E*) Collapse of thick walls (WF-aPLA).



The 3D-printed WF-PLA and WF-aPLA were repaired during postprocessing. Figure 5 shows the repair process for the 3D-printed WF-PLA and WF-aPLA forms. Figure 5*A*–*D* shows the process of repairing the warpage of the 3D-printed WF-PLA forms. The 3D model for the bottom form was designed 2.54 mm (1 in.) taller than the required final dimensions. After machining the bottom form, a cutout was made at the corners where repair work was planned. Pliogrip two-part polyurethane adhesive was applied to the freshly cut surface, and a polycarbonate (PC) sheet was bonded to the 3D-printed part. The adhesive was allowed to cure for 2 h. The PC sheet was trimmed to the final dimensions by CNC machining.

The 3D-printed WF-aPLA forms were also repaired. Figure 5*E*–*H* shows the steps for repairing the WF-aPLA forms. The two major issues observed with the 3D-printed WF-aPLA forms were the collapse of the layers in the region with thick walls and the interbead voids that were exposed after machining of the outer surface.

FIG. 5 Repairing WF-PLA and WF-aPLA bottom forms. (*A*) Cutout for placing the PC sheet. (*B*) Polyurethane adhesive applied to the cutout. (*C*) PC sheet bonded with the 3D-printed form. (*D*) PC sheet trimmed to final dimensions. (*E*) Interbead voids exposed after machining. (*F*) Layer collapse and the interbead void filled with molten WF-PLA. (*G*) Polyurethane adhesive applied to the repaired surface. (*H*) Final machined surface.



WF-aPLA bits produced during the CNC machining were melted using a heat gun and applied to the damaged area. The repaired WF-aPLA was machined after it was allowed to cool down for 1 h. Smaller voids that were not properly filled up by molten WF-aPLA were plugged using a polyurethane thermoset polymer.

Threaded inserts were embedded into the bottom forms for assembling the two-part formworks. Figure 6 shows the threaded insert in the bottom form and the assembly using six hex bolts. Figure 6*A* shows the threaded insert embedded in the bottom form. Figure 6*B* shows the top and bottom form assembled using the hex bolt and the threaded insert. The embedded threaded inserts and hex bolts allow for easy assembly and disassembly of the top and bottom forms.

Figure 7 shows the final 3D-printed formworks after postprocessing. Figure 7*A* shows the CF-ABS and WF-PLA forms. Two sets of WF-PLA, one set of WF-aPLA,

FIG. 6 Threaded insert and assembly of the top and bottom forms. (*A*)Threaded insert embedded in the bottom form. (*B*) Top and bottom form assembled using hex bolts.

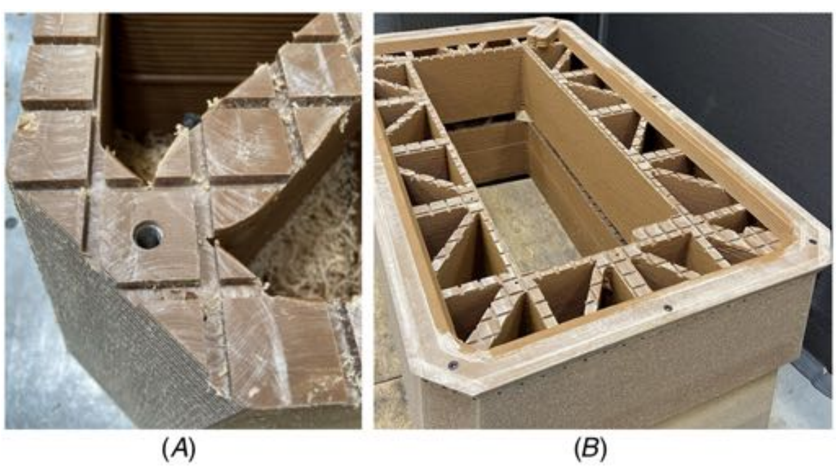


FIG. 7 Final 3D-printed formworks after postprocessing. (*A*) One set of CF-ABS and two sets of WF-PLA forms. (*B*) WF-PLA form with embedded mesh.

and one set of CF-ABS forms were manufactured using large-scale 3D printing and postprocessing. Figure 7B shows the WF-PLA form with embedded mesh.

Conclusions

The following conclusions were drawn from the research work:

1. Large-scale 3D printing in combination with CNC machining can be effectively used to manufacture relatively complex formworks for concrete casting operations.
2. The design of a continuous extrusion toolpath for the cellular infill pattern is required to minimize the number of seams in the formwork.
3. The parts additively manufactured using WF-PLA bio-based polymer composite exhibited excessive warping. The parts additively manufactured using WF-aPLA biobased polymer composite underwent excessive deformation in regions where more than two beads were laid adjacent to each other. The postprocessing repair methods presented can correct these manufacturing defects.
4. Parts manufactured using CF-ABS polymer had relatively fewer defects and required minimal postprocessing for repairs.
5. Postprocessing is necessary to achieve the dimensional tolerance and surface smoothness required for casting precast concrete structures.

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