Longevity of extrusion-based 3D printed polymer composite materials for culvert diffuser application

Prabhat Khanal, Department of Civil and Environmental Engineering, University of Maine

PI: Roberto Lopez- Anido, Co-PI: Sunil Bhandari

Introduction

Culverts are installed in highways to control water flows. Culverts deteriorate with age due to corrosion and cracking and need repairs.

Current culvert retrofit technology: Use of slip-liners.
Problem: Reduction of cross-section and hence the capacity of the culvert.
Solution: Culvert outlet diffuser technology.
Large-scale polymer extrusion-based 3D printing allows for rapid prototyping and cost-effective manufacturing of customized culvert outlet diffusers.
Impact of 3D printed diffusers

- Improved asset performance: The 3D printed diffuser system can increase the capacity of the culvert by about 40%, eliminating the need for replacement of the existing pipe.
- Environmental benefit: The diffuser and outlet weir serve as an effective energy dissipator, addressing environmental concerns related to outlet scour and downstream sedimentation.
- Ease of installation: The 3D printed diffuser system can be installed by a maintenance staff without creating traffic disruption.

- ❑ A 3D printed diffuser prototype was temporarily deployed in an operational environment in Thorndike, ME to assess hydraulic performance.
- ❑ A second 3D printed outlet diffuser was designed and manufactured using large format 3D printing for a 42-in CMP liner and inlet upgrade project, Rocky Hill Brook at NH 85/Newfields Rd, in Exeter, NH. Installed on: August 2023 (In collaboration with NHDOT).

Figure 1: 3D printed culvert diffuser in working condition.

Figure 2: 3D printed witness panel installed at site for real exposure to moisture.

Location: Exeter, NH
Photo Source: TIDC (Sunil Bhandari, Aaron Schanck)

Objective of the research:
Previous research work showed that exposure to moisture and freeze thaw cycles can reduce the strength of 3D printed polymer composite materials. The objective of this research work is to understand the longevity of 3D printed polymer composite materials for culvert diffuser applications. The change in mechanical properties with time for different accelerated environmental exposures are evaluated experimentally.

Expected derivable of project:
Predict longevity.
Determine reduction in mechanical properties with time.

Materials

The composite materials selected for this project are:

- Biobased Material- WF-aPLA (Wood fiber – amorphous Polylactic Acid)
- Synthetic Materials:
  - CF-ABS (Carbon fiber - Acrylonitrile Butadiene Styrene)
  - GF-PETG (Glass fiber - Polyethylene Terephthalate Glycol)

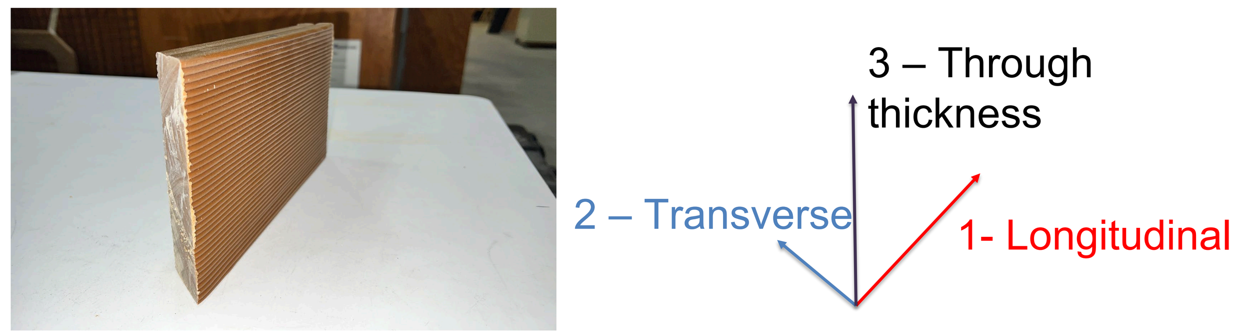

Figure 3: Printing directions considered for large-scale 3D printed specimens

Manufacturing

GF-PETG WF-aPLA CF-ABS

Figure 4: 3D printed hexagons.

Hexagons were printed in the lab and cut into plates which were cut into specimens for different exposure conditions.

Methodology-Environmental Exposure

Accelerated environmental exposure – accelerated ageing of materials in lab conditions was done.
Tests were conducted in accordance with ASTM standards to generate material properties.
Mechanical property retention after accelerated exposure times was evaluated to characterize the longevity of the materials.
The material's longevity is evaluated using retention of mechanical properties after accelerated exposure.

Moisture Exposure:
Standard Adopted: ASTM D5229-14 Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials.
Method: Specimens were conditioned at the elevated temperature of 40 degree Celsius in an oven and were tested after 30,60 and 90 days of exposure.
Exposure to Freeze-Thaw cycles:
Standard adopted: ASTM D7031-11 Standard Guide for Evaluating Mechanical and Physical Properties of Wood Plastic Composite Products.
Method: 1 hygrothermal cycle comprises of specimens submerged underwater for 24h (at room temperature), in a freezer at -20° F (-29° C) for 24h, returned to room temperature for 24h.
Specimens were conditioned and tested after 3,6, and 9 hygrothermal cycles.

Test Methods

Mechanical Testing:
•Tensile Test was conducted for the evaluation of the material's mechanical properties.
•The material properties determined are ultimate tensile strength, ultimate strain, modulus of elasticity and Poisson's ratio.

Figure 5: Conduction of Tensile Test to evaluate material properties.

Results and Discussions

- Stress vs strain curves were generated.

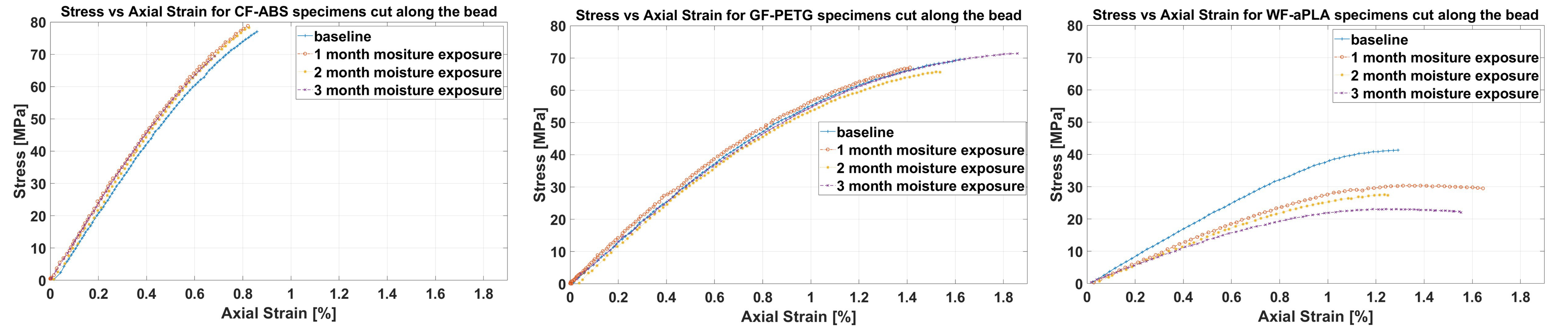

Figure 6: Stress vs axial strain curve for CF-ABS, GF-PETG and WF-aPLA specimens for baseline condition and after 1,2, and 3 months of moisture exposure at elevated temperature of 40 ℃.

- Moisture Absorption property (Sorption curves) of polymer matrix composite materials was generated.

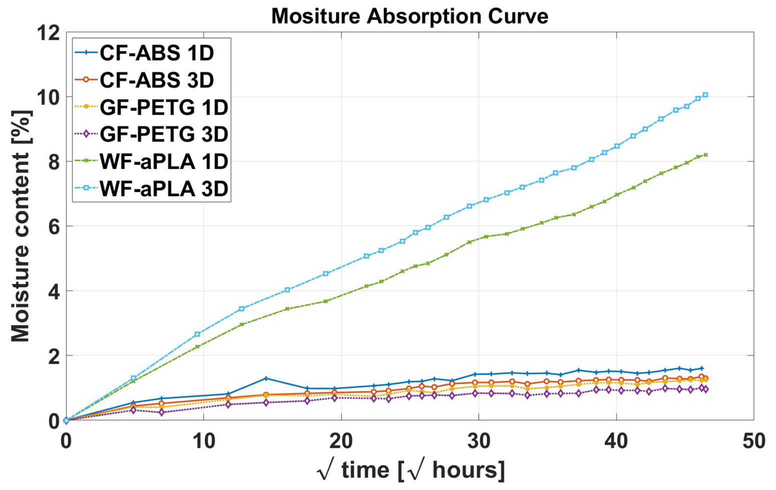

Figure 6: Moisture Absorption curve for CF-ABS, GF-PETG and WF-aPLA specimens at an elevated temperature of 40 ℃.
(1d means specimens cut in printing direction along the length of bead in printing direction and 3d means specimens cut through thickness perpendicular to the printing direction).

	Baseline	1 month exposure	2-month exposure	3-month exposure
Modulus of Elasticity, E [Mpa]	4364	3221	3066	2748
Reduction in E with respective to baseline value [%]		26	30	37

Table 1: Reduction in Modulus of Elasticity of WF-aPLA specimens cut along the bead due to accelerated exposure to moisture.

Discussion:

- There was no significant reduction in mechanical properties of CF-ABS due to moisture exposure.
- There was significant reduction in mechanical properties of WF-aPLA (Modulus of Elasticity was reduced by 37%) after 3 month of exposure to moisture at elevated temperature of 40 ˚C.

Ongoing Research Work

- Accelerated exposure to Freeze-Thaw cycles.
- Actual external exposure of plates.
- Statistical analysis to determine if the change in properties after exposure are statistically significant using ANOVA considering a p- value < 0.05 as statistically significant.
- Matrix dissolution and Scanning Electron Microscope (SEM) image analysis for fiber length analysis.

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