Durability of Large-Scale 3D Printed Materials for Transportation Infrastructure

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Motivation

- Aging and deterioration of highway culverts across the Nation require rehabilitation methods.
- Large-Scale 3D printing of customized culvert outlet diffusers offers a cost-effective solution.

Introduction

Accelerated testing or accelerated conditioning according to Nelson et al [1], consists of a variety of test methods for shortening the life of products or hastening the degradation of their performance.
The materials selected for this research work are Wood Fiber/ Polylactic Acid, (WF/PLA), Wood Fiber/ Amorphous Polylactic Acid, (WF/aPLA), and Carbon Fiber/ Acrylonitrile Butadiene Styrene (CF/ABS).
This research works studies the durability of large-scale 3D printed materials under moisture conditioning and freeze-thaw cycling for WF/PLA and WF/aPLA and UV exposure for CF/ABS. Large-Scale 3D printing is used for precast concrete formworks [2] and for highway culvert rehabilitation [3], it is important to understand how these materials are going to behave under specific site conditions and to contribute to advance in the design of these materials for structural engineering.

Objectives

- Characterize the effects of environmental exposure on mechanical properties of 3D printed polymer composite materials.
- Implement material capacity reduction factors to account for environmental exposure in the structural design of 3D-printed polymer composites.

Research Questions

- How does moisture conditioning affect the hygro-mechanical response on large-scale 3D printed materials?
- Are flexural modulus and flexural strength dependent on specimen dimensions?
- Are flexural modulus and flexural strength dependent on the printing direction?
- Are there any differences in the hygro-mechanical response between machined and as-printed test specimens?
- How to select 3D printing materials based on site environmental conditions?

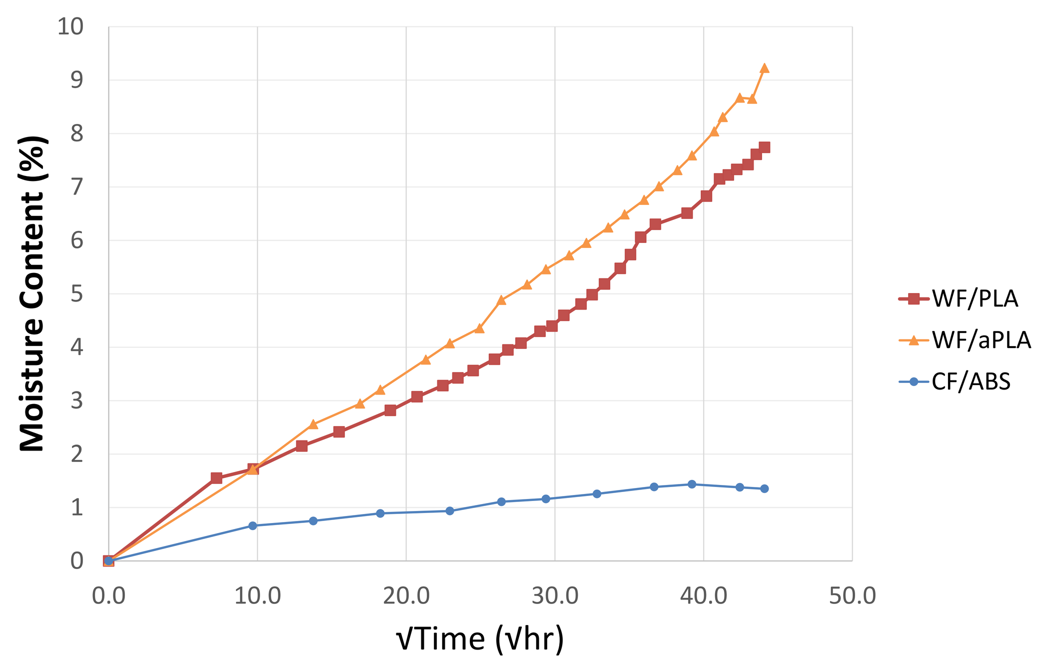

Figure 1: Sorption curves for large-scale 3D printed materials

Research Methods

Flexural properties were selected to assess the durability of the large-scale 3D-printed polymer composite materials. ASTM D7264 standard test method (Procedure B) for four-point bending was adopted. In this test configuration, the central region of the beam is subjected to pure bending without shear.
Flexural modulus and flexural strength were computed from the load cell and non-contact digital image correlation strains. Experimental data is used to determine residual properties after environmental exposure.
Three environmental exposure conditions were adopted:

- Moisture conditioning (ASTM D5229)
- Free-thaw cycling (ASTM D7031)
- Simulated weathering based on Ultraviolet (UV) and condensation cycles (ASTM G154)

Table 1: Coefficient of moisture expansion for large-scale 3D printed materials

Material	β (1)	β (2)	β (3)
WF/PLA-LMP1.5	2.12E-03	2.08E-03	5.57E-03
WF/PLA-aLMP1.5	1.83E-03	3.26E-03	5.58E-03
CF/ABS-LMP1.5	1.62E-03	1.16E-03	4.37E-03

Figure 2: 3D Printed Formwork for Precast Concrete using WF/PLA material

Discussion of Results

After environmental exposures two factors are defined, C_F^i and C_E^i, to account for the retention of flexural strength and flexural modulus, respectively. Superscript i represents the exposure. (M: Moisture conditioning, F: Freeze-thaw cycling)

Moisture Conditioning

- WF/aPLA was the material with the highest moisture content. CF/ABS was the material with the lowest moisture content. As shown in Figure 1.
- The coefficient of moisture expansion (β) is affected by the dimension of the specimens, direction, and surface finishing.
- WF/aPLA has a retention factor C_F^M of 0.31 and C_E^M 0.67 for as-printed specimens, and 0.49 and 0.56 for machined specimens.
- CF/ABS has a factor C_F^M of 0.55 and C_E^M of 0.85 for as-printed specimens.

Freeze-Thaw Cycling

- WF/aPLA and CF/ABS had no significant impact on their mechanical properties.
- WF/PLA has a retention factor C_E^F of 0.87 for as-printed specimens, and C_F^F of 0.79 and C_E^M 0.55 for machined specimens.

UV Exposure

- After CF/ABS is exposed to a cycle of UV light and condensation, damage can be noticed on the surface of the material. Showing discoloration and material loss on the surfaces exposed.
- Contact angle measurement shows that the surface of the material tends to be more water absorbent in early exposures, but less water absorbent for long exposures.

Table 2: Retention factor for flexural strength due to moisture

Retention factor	WF/PLA	WF/aPLA	CF/ABS
C_F^M	-	0.56	0.85
C_F^F	0.55	-	-

Table 3: Retention factor for flexural modulus due to freeze-thaw cycling

Retention factor	WF/PLA	WF/aPLA	CF/ABS
C_E^M	-	0.31	0.55
C_E^F	0.79	-	-

Sustainability Statement

All thermoplastic composite materials investigated can be recycled and reused for 3D printing other products. Two of the materials have both bio-based polymers and reinforcing fibers.

Figure 3: 3D Printed highway culvert diffuser using CF/ABS material

Conclusions and Recommendations

- Surface finishing impacts the material properties, showing that WF/PLA and WF/aPLA flexural properties are 23% and 16% higher for machined specimens than as-printed specimens.
- The hygro-mechanical response evaluated by the coefficient of moisture expansion depends on the dimensions of the specimen, direction, and surface finishing.
- In high moisture and water content environments, research findings show that CF/ABS is the material that retains the lowest moisture content, equal to 1.35%, compared to 7.74% for WF/PLA and 9.23% for WF/aPLA.
- Moisture degrades material properties. The retention factor for flexural modulus and flexural strength are 0.31 and 0.56 for WF/aPLA and for CF/ABS the factors are 0.55 and 0.85, respectively.
- Freeze-thaw cycling only affects WF/PLA, degrading material properties. The retention factor for flexural modulus and flexural strength is 0.79 and 0.55, respectively.
- In environments subjected to freeze-thaw cycles, research findings show that WF/aPLA and CF/ABS have no significant impact on its materials properties.
- Change in surface roughness and contact angle is observed in CF/ABS after UV light and condensation exposure, this should be accounted for if this material is used in environments like the cycle exposure used in this research work. To avoid this, it is recommended to research protective coatings.

Future Work

Future work includes finalizing the data analysis on the specimens under moisture conditioning for all the materials and the characterization of environmental effects. Along with the computation of material capacity reduction factors for environmental exposure, recommendations for the structural design of 3D-printed parts for transportation applications will be drafted.

Baseline flexural material properties

E_x^f: *Baseline flexural modulus*

F_x^f: *Baseline flexural strength*

Exposed flexural material properties

E_{xd}^f: *exposed flexural modulus*

F_{xd}^f: *exposed flexural strength*

$$E_{xd}^f = C_E * E_x^f \qquad F_{xd}^f = C_F * F_x^f$$

→

$$C_E = C_E^M * C_E^F \qquad C_F = C_F^M * C_F^F$$

→

$$E_{xd}^f = C_E^M * C_E^F * E_x^f \qquad F_{xd}^f = C_F^M * C_F^F * F_x^f$$

References

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