Thermo-Mechanical Recycling of 3D Printed Formwork: Characterization of Thermoplastic Composite Rheological Properties

Katie Schweizer, Department of Civil and Environmental Engineering, University of Maine PI: Roberto Lopez-Anido, Co-PI: Sunil Bhandari

Introduction

Large-format additive manufacturing (AM) produces large quantities of solid waste, which can be reduced through material recycling. However, the recycling process can potentially degrade both the fiber reinforcement and the polymer matrix. Changes in rheological properties are key in understanding the processability of the materials in question. The purpose of this work was to monitor the rheological properties following one cycle of thermo-mechanical material recycling.

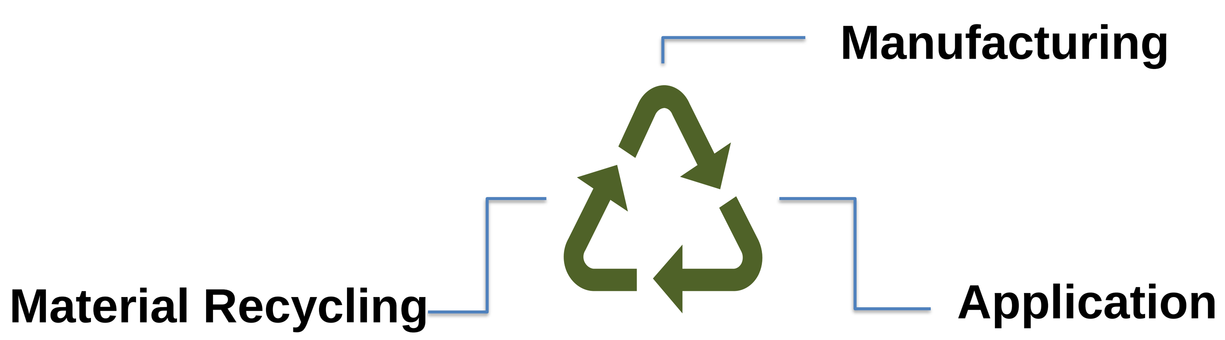

Figure 1: Material's circular life-cycle

Methodology

Recycling Process

Precast concrete formwork manufactured using both bio-based and synthetic materials was recycled using a two step, thermo-mechanical process. The two steps of this process are material shredding and granulate pelletization. Material shredding is a purely mechanical process where formwork parts are ground into granulate material. Granulate pelletization is a thermal process where granulate material is homogenized into uniform feedstock pellets.

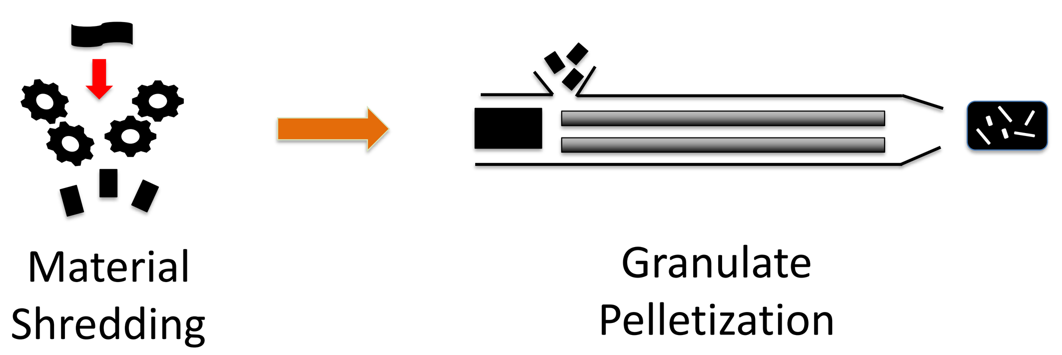

Figure 2: Two-step material recycling process

Rheological Testing

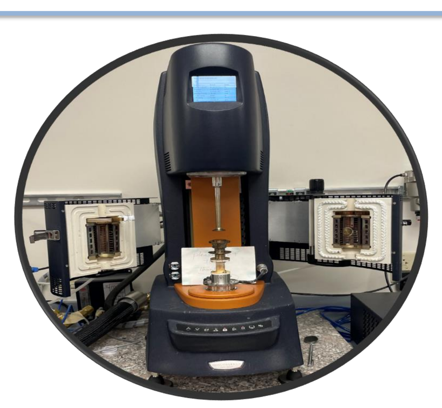

Figure 3: Parallel plate rheometer

Rheologic material properties were measured through oscillatory and shear testing. The oscillatory tests produced experimental values for the complex modulus and complex viscosity. The shear tests experimentally characterized the apparent viscosity. A combination of 8 mm samples and 25 mm samples, prepared using a combination of pressure and temperature, were tested using parallel plates with a 1 mm gap.

Materials

Short carbon fiber reinforced acrylonitrile butadiene styrene (CF-ABS)

Wood flour fiber reinforced polylactic acid (WF-aPLA)

Results and Discussion

Oscillatory Tests

Figure 4 shows results obtained from oscillatory tests conducted on the parallel plate rheometer. Depicted in these figures are the complex viscosities of both the CF-ABS and WF-aPLA baseline, R1 granulate, and R1 pellet.

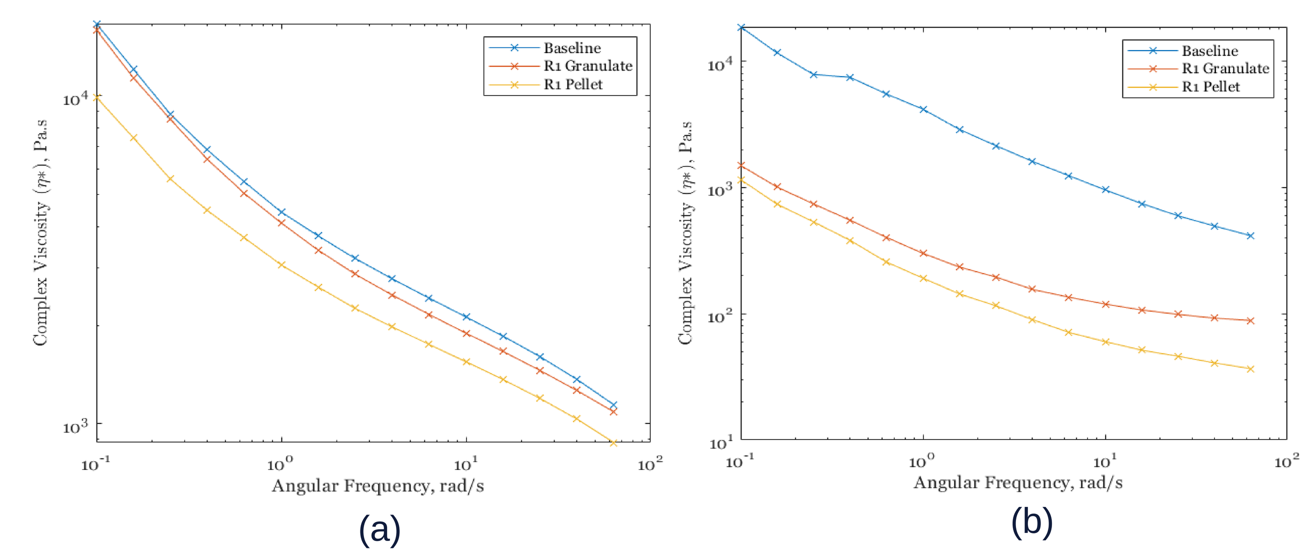

Figure 4: Complex viscosity at different stages in the recycling process: (a) CF-ABS, (b) WF-aPLA

This figure shows that both the CF-ABS and WF-aPLA material systems, at each stage of the material recycling process, are non-Newtonian, shear thinning fluids. Meaning that these materials have decreasing viscosity with increasing shear. Additionally, this figure shows that there are varying degrees of material degradation during the material recycling process. Figure 4a shows that there is very minor degradation between baseline, R1 granulate, and R1 pellet. Figure 4b shows that there is noticeable degradation between the baseline, R1 granulate, and R1 pellet. Similar change is recognized in the complex moduli.

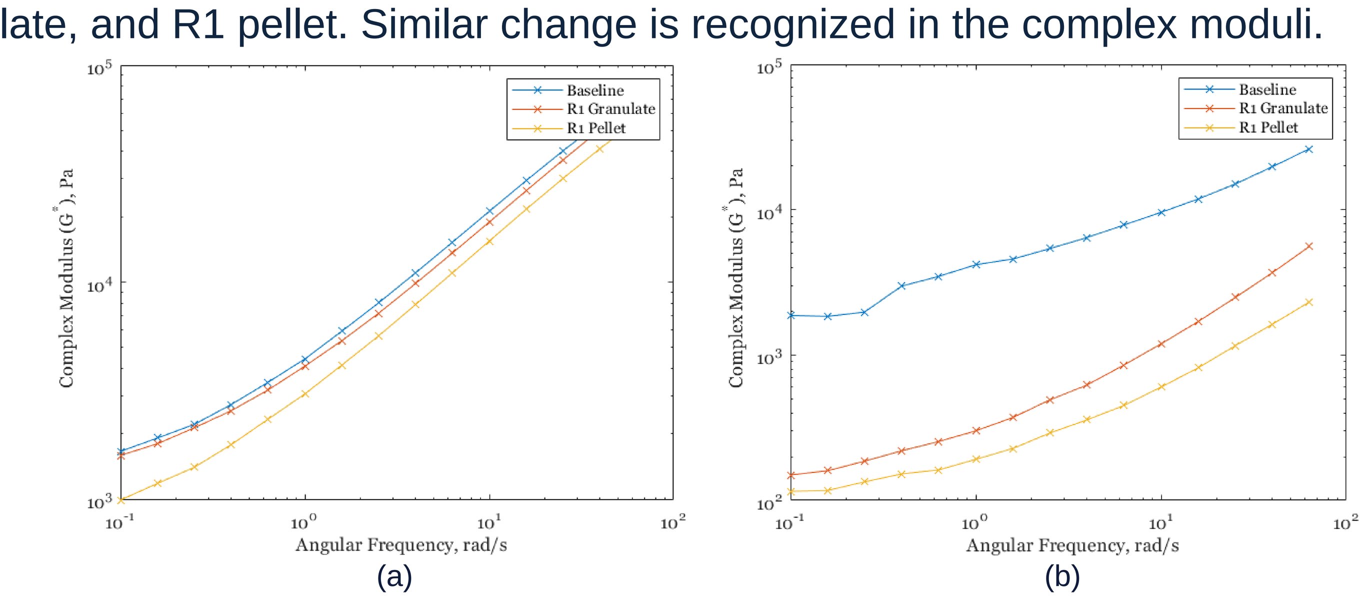

Figure 5: Complex modulus at different stages in the recycling process: (a) CF-ABS, (b) WF-aPLA

Figure 5 also shows the entire viscoelastic behavior of both material systems. Showing that both materials become increasingly more flow resistant with increasing frequency. However, the flow resistance of the materials decreases with additional processing.

The change between the CF-ABS baseline, R1 granulate, and R1 pellet is minimal. Table 1 supports this claim by showing that the calculated p-values for both the CF-ABS complex moduli and complex viscosities are greater than α. Conversely, the WF-aPLA system shows a more significant degradation in complex modulus and viscosity throughout the material recycling process. With Table 1 showing that the decrease in both complex modulus and complex viscosity being statistically significant from the baseline (α > p-value).

Table 1: Significance of material property degradation through one recycling cycle

Material System	Level of Re-processing	Significance Level (α)	Complex Viscosity p-value	Complex Modulus p-value
CF-ABS	Baseline	-	-	-
	R1 Granulate	0.05	0.84	0.85
	R1 Pellet	0.05	0.21	0.51
WF-aPLA	Baseline	-	-	-
	R1 Granulate	0.05	0.005	0.001
	R1 Pellet	0.05	0.004	0.003

Shear Tests

CF-ABS and WF-aPLA both are classified as a viscoelastic materials, meaning they behave between and solid and a liquid; and that they have an apparent yield stress. Where the apparent yield stress of the material represents the amount of stress the material can take before it begins to yield or flow. This point is shown in Figure 6, by the y-intercepts.

The data presented in Figure 6 is representative of the material properties at low shear rates, 0.01/s to 10/s, and non-representative of the shear rates experienced by the material during the AM process (CF-ABS: 72/s & WF-aPLA: 43/s). The Herschel-Bulkley (H-B) model was used to fit the experimental data and obtain the apparent viscosity at the desired shear rates.

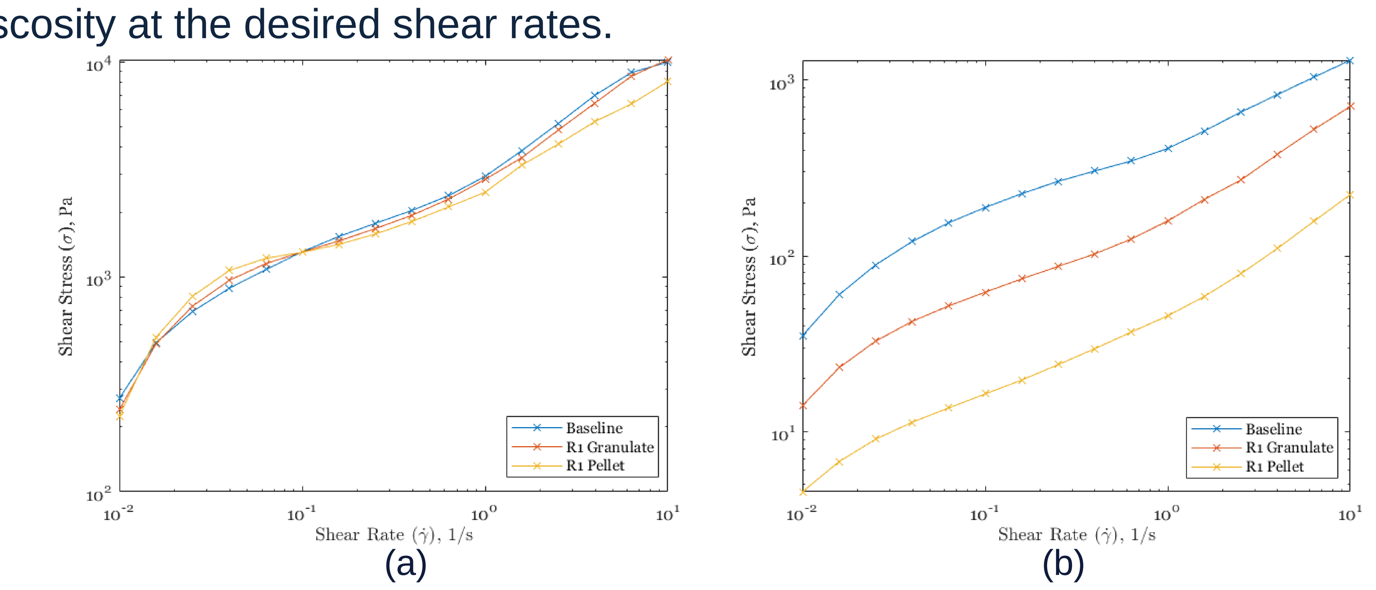

Figure 6: Shear rate vs. shear stress at low shear rates for: (a) CF-ABS, (b) WF-aPLA

The H-B model is presented in Equation 1, where k, σ, and n are fitting parameters.

$$\sigma = \sigma_0 + k\gamma^n \qquad \text{Eq. 1}$$

The shear stress values and fitting parameters were obtained through a least squares curve fit. Apparent viscosity of the material at the nozzle was calculated using Equation 2.

$$\eta = \frac{\sigma_0}{\gamma} + k\gamma^{n-1} \qquad \text{Eq. 2}$$

Table 2 shows that apparent viscosities of each material system throughout the first recycling cycle.

Table 2: Apparent viscosity for each material at the nozzle using H-B model

Material	Level of Re-processing	Apparent Viscosity at Nozzle (Pa. s)
CF-ABS	Baseline	956
	R1 Granulate	791
	R1 Pellet	489
WF-aPLA	Baseline	68
	R1 Granulate	53
	R1 Pellet	17

The CF-ABS has less degradation of apparent viscosity between the baseline and R1 results, when compared to the WF-aPLA. The CF-ABS baseline to R1 granulate has a percent difference of approximately 19% and an approximate difference of 65% between the baseline and R1 pellet. The WF-aPLA baseline to R1 granulate has a percent difference of approximately 25% and an approximate difference of 120% between the baseline and R1 pellet. This decrease in the apparent viscosities of both the CF-ABS and WF-aPLA systems is due to a combination of fiber attrition and polymer degradation.

Future Work

Additional material characterization will be conducted for the R1 material. Additional properties to be characterized include:

- material strength and stiffness
- material glass transition temperature
- material molecular weight
- material purity

Additionally, concrete parts will be cast in the R1 forms.

Following material characterization and concrete casting the forms will enter a second recycling cycle (R2 cycle).

In Collaboration with: Oak Ridge National Laboratory

November 2023 – www.tidc-utc.org

Acknowledgements: Funding for this research is provided by the Transportation Infrastructure Durability Center at the University of Maine under grant 69A3551847101 from the U.S. Department of Transportation's University Transportation Centers Program.