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PROPOSED SIEVING PARAMETERS FOR MECHANICALLY RECYCLED GLASS FIBER COMPOSITES

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ABSTRACT

To achieve lightweight, stiff, large structures such as wind turbine blades for energy generation or waterslides for aquatic recreational parks, Glass Fiber Reinforced Polymer Composites (GFRPC) are frequently used. The disposal at end-of-life of such material has proven to be a difficult task due to the nature of the thermoset resins used. Landfilling of such composite waste poses a growing risk to the environment. One promising alternative is the mechanical grinding and milling of GFRPCs into recyclates to be re-introduced into the Fused Filament Fabrication (FFF) production stream. In this paper, the sieving step of the mechanical recycling strategy was evaluated to increase the yield rate of fine GFRPC recyclates, to be used in filament making. Recyclates produced from decommissioned water slides were processed in a gyratory sieve. Batch size, sieving time, and use of repeated sieving were evaluated. Fiber length distributions were also obtained. Batch sizes of 500g or 750g sieved for 1-2 minutes showed greatest yield rate for a mesh sequence of 840µm-150µm. Total yield of fine recyclates following repeated sieving reached roughly 25%, however the fiber length distribution deteriorated for a repeated sieving operation. Distribution convergence also manifested at 3000 fiber length measurements.

1 INTRODUCTION

As the use of Glass Fibre Reinforced Polymer Composites (GFRPC) has proliferated into major sectors including automotive, aerospace, marine, and recreation, the amount of non-biodegradable waste generated increases at the same time. With production estimated at 8 million tons and wastage estimated at 1.5 million tons annually, the need to develop effective recycling methods has been highlighted repeatedly in the literature [1-5]. However, due to the use of thermosetting resins and their highly stable molecular cross-linking, end-of-life processing is rendered very difficult, limiting the feasibility of commercialized recycling methods [2, 5, 6]. Lab-scale studies on alternatives to the current disposal routes of incineration and landfilling comprises mostly of thermal, chemical, or mechanical methods [2, 5, 7]. The latter approach has been highlighted as the simplest and most cost-effective, with only a few examples of commercialization [4, 7, 8]. Integration of mechanically recycled fiber reinforcements, termed 'recyclates', into thermoplastics for use in Fused Filament Fabrication (FFF) has gained recent attention and shown promising improvements in filament performance [7, 9-11]. Employing multiple size reduction steps such as shredding, milling, and grinding followed by recyclate size screening via sieves, recycling of GFRPCs for FFF has been limited to lab-scale tests [2, 7, 9]. Therefore, the current research is focused on improving the processing speed of the sieving step as well as the quality and quantity of fine recyclate available for filament extrusion. The fiber lengths of the fine recyclate should also not surpass the 3D printer nozzle diameters to prevent nozzle congestion. Various process parameters were evaluated to improve the yield rate of fine recyclate and control the length distributions including sieving time, sieve input commonly referred to as 'batch size', and repeated sieving. This report details the preliminary optimization efforts achieved to date in dry particle screening of ground glass fiber composite.

2 METHODOLOGY

2.1 Material preparation and processing

Decommissioned water slide test panels measuring 30cm by 20cm made from glass fiber reinforced polyester matrix were provided by ProSlide Technology Inc. (Canada). The panels were granulated in a hammer mill grinding machine (ECO-WOLF, INC., Canada). Sample sizes of 250g, 500g, 750g, 1000g, and 1250g were processed in a 15.7in diameter gyratory screening machine fitted with an 840-150µm mesh sequence. The top two output spouts were closed to encourage the extraction of fine powder from the bottom, third layer. The 'fine' fraction (<150µm) collected was weighed at regular time intervals to determine the percent yield and the instantaneous yield rate. Once the change in fine fraction weight achieved less than 1% of input weight, the sieving process was stopped, and the final weight and total sieving time were recorded. The recyclate fraction between 840µm and 150µm, referred to as 'medium' fraction in this report, was used for repeated sieving experiments. Total sieving time for repeated sieving was kept identical to that of first sieving.

2.2 Fiber length distributions

Microscopy (Nikon, Japan) was performed to determine the fiber length distributions of fine recyclates. Individual fibers were manually measured through microscopy software and processed in Excel spreadsheets for analysis (Microsoft, USA). Distribution convergence was determined via calculation of the Standard Error of the Mean (SEM). A target of 3000 length measurements was set to achieve a convergent length distribution. As-ground, single-sieved, and twice-sieved samples were characterized for their length distributions.

3 Results and discussion

3.1 Sieving time

Figure 1 shows the time taken for each batch size to achieve less than 1% weight change in yield of fine recyclate during the sieving process for N ≤ 2 repeats. The total time required were 120, 210, 360, 540, and 825 seconds respectively for 250g, 500g, 750g, 1000g, and 1250g batches. A non-linear increase in material processing time was found. The plot of instantaneous yield rate against the percent yield of fine recyclate for each batch size revealed a decreasing relationship, for example in Figure 2a with a 750g batch size. The rectangular 'area' formed by each of these data points with the axes can be plotted, shown in Figure 2b. The time corresponding to the peak area was considered as the optimal sieving time for a given batch size. This activity was repeated for each batch considered and the corresponding proposed sieving times were plotted in Figure 2c. The latter revealed an exponential increase in sieving time for increasing batch size. In comparison to laboratory procedures [12], these sieving times are considerably lower due to the stopping criterion described in section 2.1. This exponential behaviour also revealed the potential in optimizing the batch size given the current mesh sequence.

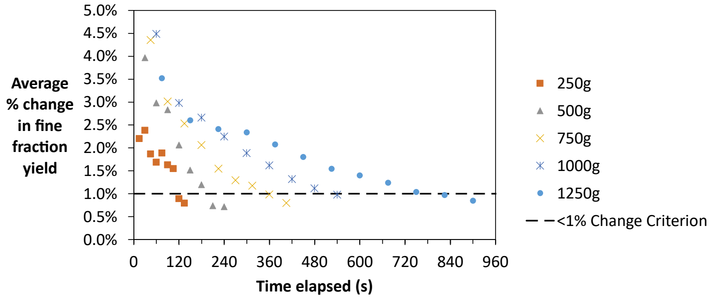

Figure 1. Total sieving time required given <1% change stopping criterion for input masses 250g to 1250g in 250g intervals.

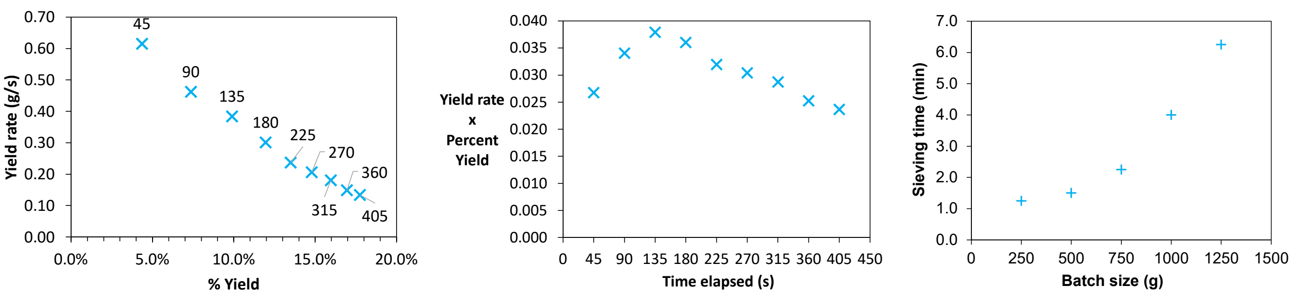

Figure 2. a) Trade-off between yield rate and percent yield for 750g batch with duration labelled in seconds.
b) Yield rate multiplied with percent yield showing optimal sieving time for 750g input.
c) Exponential behaviour was found between the sieving time and the batch size.

3.2 Batch size

Process downtime is undesirable in industrialized applications [13]. Therefore, to determine an optimal batch size, semi-continuous performance was estimated. In detail, the fine recyclate yield data for each batch size was truncated down to the proposed sieving times from section 3.1 and was added sequentially to itself, producing a steadily increasing curve. A linear regression was applied for each batch size and the resulting average yield rates were imposed onto Figure 2c, resulting in Figure 3 where the 500g and 750g batch sizes represent the proposed machine input for semi-continuous operation. The new data points were labelled with percent yield, showing that less than a tenth of the input material would be recuperated using these operating parameters.

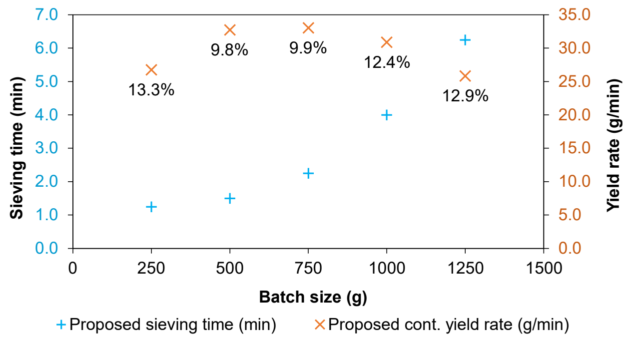

Figure 3. Addition of average yield rate onto Figure 2c. The proposed batch size for the given setup is 500-750g while the corresponding optimal sieving times were around 1.5-2 minutes.

3.3 Repeated sieving

Previously successful [7], repeated sieving was also used here. Figure 4 shows the total fine recyclate yield of around 25%, regardless of batch size, obtained following a 2nd sieving of the medium fraction, with 5-8% yield attributed to the latter. The generation of agglomerates containing both long and short fibers as shown in Figure 5 could explain the much lower yield compared to that found by Rahimizadeh *et. al*. [7] The particle collisions in the vertical throw-action sieve used by the authors could be dismantling clumps as opposed to the vibrations of the gyratory sieve used here [14]. Sealing the top two output spouts also prevented longer, rejected fibers from exiting the machine, potentially worsening the clumping behaviour.

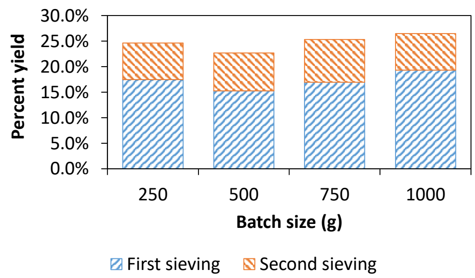

Figure 4. Total fine recyclate yield at the <1% change criterion following a double-sieving process (N ≤ 2 repeats). 1250g was omitted due to lack of data.

Figure 5. Agglomeration of recyclate during repeated sieving. A mix of long and short fibers can be seen in each clump.

3.4 Fiber length distributions

Figure 6 shows the resulting relative frequency distributions obtained following the procedure detailed in section 2.2 of as-ground, single-sieved, and twice-sieved recyclate with 500, 3000, and 1000 fibers measured, respectively. Results highlighted an increase in length variance following a second sieving operation potentially explained by the passing of fibers vertically through the sieve meshes [15]. Considering the 0.4mm and 0.6mm FFF printer nozzles to be used (Original Prusa i3 MK3S+, Prusa Research, Czech Republic), the cumulative frequency of fibers past these lengths was greatest in the as-ground material (24.0%), followed by the twice-sieved material (12.0%), and lastly the single-sieved material (1.6%). Considering the fiber breakage that also occurs during FFF [16], the latter cumulative frequency will undoubtedly near 0% during printing. Therefore, maintaining a single-pass approach could avoid clogging during the 3D printing process. Although the distribution convergence for as-ground and twice-sieved recyclate have not yet been confirmed, as opposed to that of single-sieved recyclate in Figure 7, their respective preliminary length distributions suggested a poor consistency in fiber lengths.

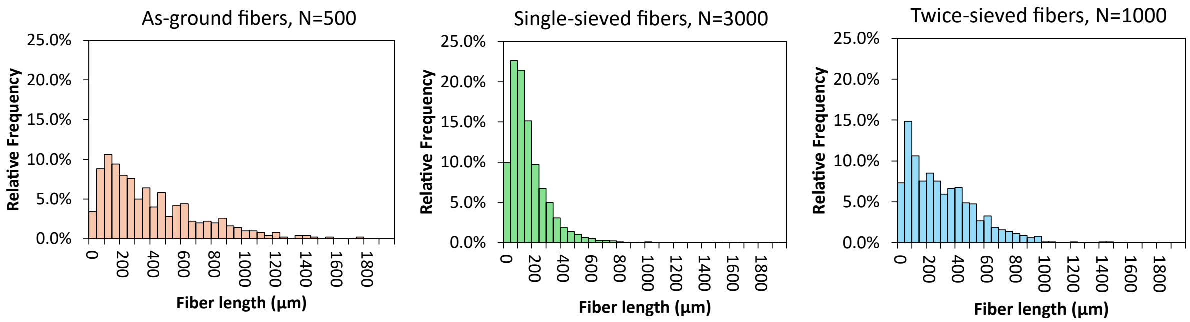

Figure 6. Fiber length distributions for a) as-ground fibers, b) single-sieved fibers, and c) double-sieved fibers.

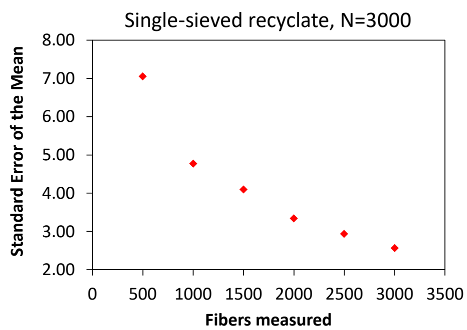

Figure 7. Standard error of the mean for single-sieved fine recyclate.

To summarize, the measurement of fine recyclate yield progression was important in extracting the optimal sieving times and batch sizes. Sieving for 1.5-2 minutes with 500g or 750g batch sizes were found to be optimal. Employing the less stringent <1% change criterion compared to laboratory standards allowed for quicker processing times. Repeated sieving produced excessively long fiber content and agglomerates in the sieve, thus was deemed unproductive compared to previous studies. Finally, 3000 measurements were shown to generate an acceptably converged fiber length distribution.

4 Conclusions

The need to recycle glass fiber composite material has been repeatedly highlighted in the literature. Efforts in mechanically recycling this material were detailed in this report, covering the preliminary optimization achieved to date. Sieving represents a key step in the recycling operation. Optimal sieving times, batch sizes, and sieving repeats were evaluated for the given machine setup and methodology. Results showed that in the context of semi-continuous operation, a sieving time of 1.5-2 minutes for an input mass of 500-750g of ground recyclate in a gyratory sieve fitted with a wire mesh sequence of 840µm followed by 150µm apertures could provide the fastest yield of adequately sized recyclate powder to be used for filament extrusion. Issues with recyclate agglomeration were encountered and were suggested to be affected by the vibration mode and the lack of oversized fiber rejection. Fiber length distribution convergence was also found to be achievable at 3000 measurements. Subsequent work will be focused on minimizing agglomeration and increasing yield through the use of sieving aids, the ejection of oversized particles, and varying the vibration mode.

5 References

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