Reusing Waste Polylactic Acid (PLA) as a Substitute for Concrete Aggregate

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SUMMARY

This experiment sought to analyze the effect of varying sizes of Polylactic Acid (PLA) as a supplement for aggregate in concrete, specifically, the maximum stress and Young's Modulus of a concrete specimen. Young's Modulus is a measure of flexibility and maximum stress measures strength. PLA is a type of plastic that is rarely recycled and is used with increasing frequency. The PLA was sorted into three groups, <2.5mm diameter, 2.5 - 5mm diameter, and 7.5mm diameter, and added to concrete to replace aggregate. The specimen with both the highest Young's Modulus and maximum stress was the control group (stress = 18419.76 kN per m2, Young's Modulus = 12.343 GPa). The specimen with the lowest was the 5 - 7.5mm group (stress = 4975.22 kN per m2, Young's Modulus = 3.02 GPa). The p-value for the stress test was 0.000399 and for the Young's Modulus test was 0.00181, indicating statistical significance. The hypothesis was partially supported, Young's Modulus was reduced in the experimental groups; the trend among the samples was unclear. The maximum stress was reduced in the experimental group. These results show that PLA in concrete could be used when flexibility is more desirable than strength.

INTRODUCTION

While few things are truly set in stone, the reign of concrete as one of the world's most widely used building materials is one of them. Second only to water, concrete is a highly consumed material worldwide (Monteiro, 2017). Concrete is produced by mixing cement, water, and aggregate. Due to its high strength, high durability, and low production cost, concrete is used in everything from skyscrapers to decorative planters. Unfortunately, due to concrete's widespread usage and as a result of mining aggregate, concrete has significant detrimental environmental impacts (Concrete and the Environment, 2001).

Another commonly used material is plastic, which is composed of synthetic polymers and is often produced from fossil fuels. Plastics are widespread throughout society due to their lightweight, flexibility, and durability. Hundreds of millions of tons of plastic are thrown away and relegated to landfills or incinerated each year, causing innumerable adverse effects on the environment through their longevity and toxicity (Andrady, 2009). These include effects such as the Great Pacific Garbage Patch, which is composed primarily of plastics, specifically single-use plastics. In 2022, the OECD released a report showing that only about 9% of plastic is recycled and that the usage of plastic continues to grow each year (OECD, 2022).

One specific type of plastic that is growing in usage is a plastic known as Polylactic Acid (PLA). PLA is broadly used throughout many emerging industries such as 3D printing as well as other consumer products (Naser, 2021). As shown in **Figure 1**, waste PLA is produced in large quantities as a byproduct of the 3D printing process. Nearly 200 thousand tons of PLA were estimated to be produced in 2019, and the total amount of PLA produced is expected to double every three to four years (Naser, 2021). Using plastics as a way to substitute aggregate in concrete is a way to reduce the total greenhouse gas emissions of the concrete while simultaneously providing a productive way to utilize waste plastic (Sharma, 2016). The efficacy of the aggregate replacement is generally measured through the compressive strength of the concrete after it has cured (Khajuria, 2019).

There are numerous factors to consider when substituting any type of plastic for aggregate. The size of the plastic and the amount of plastic added play significant roles in the strength of the final mixture (Lumina, 2022). One study conducted on the usage of PLA in concrete found that the optimal amount of PLA to add was 10% of the total volume of concrete (Patil, 2020). This value was actually found to increase the strength of the concrete over a control. Another critical factor in replacing aggregate in concrete is the size of the plastic particles. A preliminary study found that smaller particles of plastic led to increased strength in the cured concrete (Tamrin, 2020). However, there has been very little published research conducted on the effects of plastic particles smaller than 1 centimeter (cm) in diameter and no published research on the effects of PLA particles that are smaller than 1 cm in diameter. This research serves to fill this gap in the current literature.

Measuring the strength of a cured concrete sample varies. Most research concentrates on the compressive strength or maximum strain of the cured concrete; however, it is possible that adding plastic will affect the “Young’s Modulus,” also known as the modulus of elasticity, or the amount that the concrete deforms when a certain load is applied (Khajuria, 2019). This form of strength is important in construction and provides another measurement to measure the results of the addition of PLA particles. Therefore, this study will measure the maximum strain as well as Young’s Modulus in order to determine the effects of varying sizes of PLA particles as a substitute for some aggregate in concrete. It is hypothesized that the addition of PLA will decrease the Young’s Modulus and decrease the maximum stress of the concrete and that the effects will be more pronounced as the sizes of PLA particles decrease.

RESULTS

After conducting the tests on the concrete samples, data was collected on the force placed on the sample and the change in the length of the sample. Using this data, the maximum force resistance was found for each sample. As shown in **Figure 2**, the control group exhibited the highest maximum stress (18419.76 kN per m2 ± 3366.48), with the 2.5 - 5mm group following at 11386.36 kN per m2 ± 1899.251041, then the < 2.5mm with a maximum stress of 7266.55 kN per m2 ± 3333.15, and finally the 5 - 7.5mm group with 4975.22 kN per m2 ± 942.52. The results of the ANOVA show a p-value of 0.000399. One possible outlier that was identified was the second trial of the <2.5 mm group. This data point had a value of 10599.67 kN per m2 compared to trial 1, which had a value of 5590.27 kN per m2, and trial 3, which had a value of 5609.70064 kN per m2. Additionally, while preparing the samples, the larger plastic sizes made it difficult to properly compact the concrete in the molds, which may have led to additional errors.

In addition to the maximum stress, the mean Young's Modulus for each sample group was calculated. **Figure 3** shows a sample graph of stress and strain for the control group. As stated earlier, a linear regression was applied to an interval of points preceding the yield strength point to find Young's Modulus for each sample. Young's Modulus measures how flexible the sample is, with higher values indicating higher levels of rigidity, and the sample with the highest Young's Modulus was the control group with a mean Young's Modulus of 12.343 GPa ± 3.067. As shown in **Figure 4**, the second most rigid group was the 2.5 - 5mm group with a mean Young's Modulus of 8.654 GPa ± 1.852, and the third most rigid was the <2.5 mm group with a Young's Modulus of 5.23 GPa ± 2.49, and the least rigid group was the 5 - 7.5mm group with a Young's Modulus of 3.02 GPa ± 1.03. The result of the ANOVA conducted on the data showed that the data had a p-value of 0.00181.

DISCUSSION

The hypothesis for this experiment was that the maximum stress of the materials would decrease, and the Young's Modulus would decrease as the size of the PLA particle decreased. This trend was partially observed in the results. All three experimental groups exhibited lower maximum stresses than the control group, but Young's Modulus for all of the experimental groups was lower than that of the control group. Within the experimental groups, the 2.5 - 5mm group had higher maximum stress and Young's Modulus than the other groups, which did not follow the predicted results. The reason for the decreased strength and Young's Modulus was likely due to the incorporation of the PLA particles in the concrete mixture, which caused the mixture to become less stiff at the cost of becoming more ductile and reducing maximum stress due to the increased difficulty the samples became to prepare with the addition of larger PLA particles.

The incorporation of PLA particles is the likely cause of the reduced maximum stress and Young's Modulus in the experimental groups when compared to the control group. The PLA particles negatively affected the ability of the cement to adhere to the aggregate, resulting in a weakened internal structure, which lowered the maximum stress (Luminia, 2022). Additionally, the hydration of the concrete was likely affected by the plastic during the curing process, as observed by a similar study conducted with alternate plastics (Monterio, 2017). This hydration weakened the bond the Portland cement made between the aggregates which allowed the concrete to become more ductile and flexible.

Another cause of the reduced stress and flexibility was because of the increased difficulty of preparing the concrete as the sizes of plastic increased. With the largest size of plastic, the concrete became less workable, and it became difficult to compress the concrete properly into its mold. This likely resulted in a non-homogenous structure inside the concrete, which could have caused reduced maximum stress as the force would not have been evenly distributed throughout the concrete specimen. Similar patterns of stress have been observed in fracture analysis of rocks (Labuz, 2018).

There are numerous limitations to this experiment. One of the largest limitations is the relatively small sample size this study had (n = 3). With the limited number of trials conducted for each group, combined with the high variability in each specimen, it is difficult to definitively draw any conclusions. Additionally, it was difficult to compact the concrete samples fully during the pouring process. This changed the exact structure of each sample and added to the variability. Another limitation was the process through which the plastic was sorted. The plastic was all PLA; however, it may have had different densities or contained resins or dyes depending on the manufacturer of the PLA, which may have affected the final concrete samples. Further research is necessary to determine the impacts of these factors.

Further research may focus on large-scale applications of the findings presented here. Studies could be conducted using larger amounts of concrete or with a larger number of trials for each sample. This research could serve as a template for future research into the viability of recycling PLA as an aggregate supplement in concrete.

Based on this study, the addition of PLA as a supplement for aggregate in concrete shows a significant impact on the maximum stress the concrete can withstand. Additionally, the

PLA reduces the Young's Modulus of the concrete, allowing it to become more ductile and flexible. Because of the limitations associated with using large-sized PLA particles, such as those that range between 5 - 7.5mm, more information is needed to determine if those sizes truly reduce stress and Young's Modulus by the degree present in this study. However, the other study groups show that using medium or small sizes of plastic (< 5mm) could substantially decrease Young's Modulus for concrete, rendering it useful for applications that do not require high maximum stresses. These applications could be similar to those used in Controlled Low-Strength Materials (also known as flowable fill) with use cases such as road backfill or stabilizing or strengthening concrete structures that have degraded over time (Siddique, 2009). Also, supplementing aggregate with PLA would reduce the demand for natural aggregate which currently has several negative environmental impacts due to the mining process. Using more PLA in concrete or similar mixtures could allow for more plastic to be recycled and serve as an efficient use of plastic that would otherwise be degrading in a landfill, while also reducing the demand for natural aggregate.

MATERIALS AND METHODS

Preparation:

In this study, research was conducted into how varying particle sizes of Polylactic Acid (PLA) affected the maximum stress and Young's Modulus of concrete. PLA was collected from waste produced by small, consumer-grade 3D printers. This PLA was reduced to a standard size by grinding it using a grain mill. This mill reduced the size of the PLA substantially. The PLA was then filtered through a series of sieves to the following sizes: < 2.5 mm, 2.5 - 5 mm, and 5 - 7.5 mm. These sizes were chosen based on the particle sizes with the greatest positive effects from other research on other plastics (Sharma, 2016). After filtering, each size of PLA was mixed with sand to form a mixture that comprised 10% PLA by volume. In a 9.5 kilogram concrete mixture, 1.84 kg of PLA was added, replacing an equivalent volume of sand. A 10% by-volume mixture was chosen because of previous research that had determined that 10% by-volume was the optimal amount of PLA to add (Patil, 2020). The sand-PLA mixture was combined with Portland cement and gravel aggregate in an "Oarlike Electric" concrete mixer along with 978 ml of water. These materials were used because of they are the most commonly used in research on concrete (Monteiro, 2017). Because of the hazardous effects of concrete and cement, proper precautions were taken at all times such as wearing appropriate PPE and mixing all samples in a well-ventilated area. The mixture was mixed for 10 minutes until it was homogeneous and then poured into three cardboard cylinders. The concrete was then compacted to ensure it was level with the mold. The cardboard molds were 100 mm diameter x 200 mm tall cylinders and were made from cardboard mailing tubes. This size of the cylinder was chosen because it is a standard size across the concrete testing domain (Lumina 2022). These steps were repeated for each size of PLA particle, including three controls with no PLA added. The concrete was allowed to be cured for ten days. Ten days was chosen to be the cure time because of prior research (Shiuly, 2022). After the curing, the diameters of the sample were measured in order to calculate the cross-sectional surface area of each sample.

Testing and Analysis:

A compression test was performed on the cube concrete samples using an MTS821 machine, as shown in **Figure 5**. The samples were placed in a hydraulic press, and a downward force was applied until the cubes failed under the force. The maximum force was recorded in kilonewtons. The amount of displacement was also measured. This test was chosen to measure the direct effects of replacing aggregate with PLA and follow procedures laid out by similar studies (Tamrin, 2020). The maximum force calculation was converted to a maximum stress measurement by using the following formula: Stress = F/A where F is the maximum force in kilonewtons, and A is the cross-sectional area of the sample in meters squared. The strain was also calculated by using the following formula: Strain = X/X where X is the change in length, and X is the original length (203.2 mm for all samples). Finally, the stress and strain were graphed, and a linear regression was performed to find Young's Modulus for a given interval after the machine elasticity had passed and before the yield strength of the concrete specimen. An ANOVA was performed on both categories of data. This analysis was chosen because it was most prevalent among similar studies (Naser, 2021). The samples were disposed of in accordance with local policies surrounding concrete disposal.

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Figures and Figure Captions

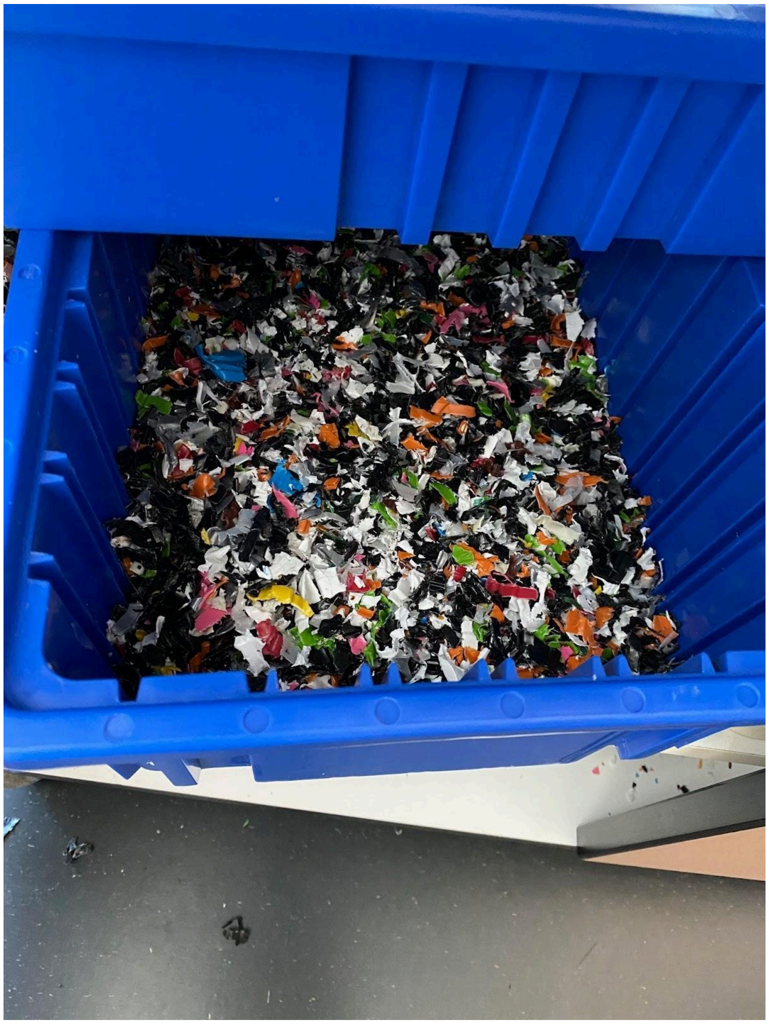

Figure 1. An image of waste Polylactic Acid (PLA) produced as a byproduct of 3D printing. This waste PLA was produced at a local school's design lab and represents a small fraction of the overall PLA disposed of at one institution. *Image by author.*

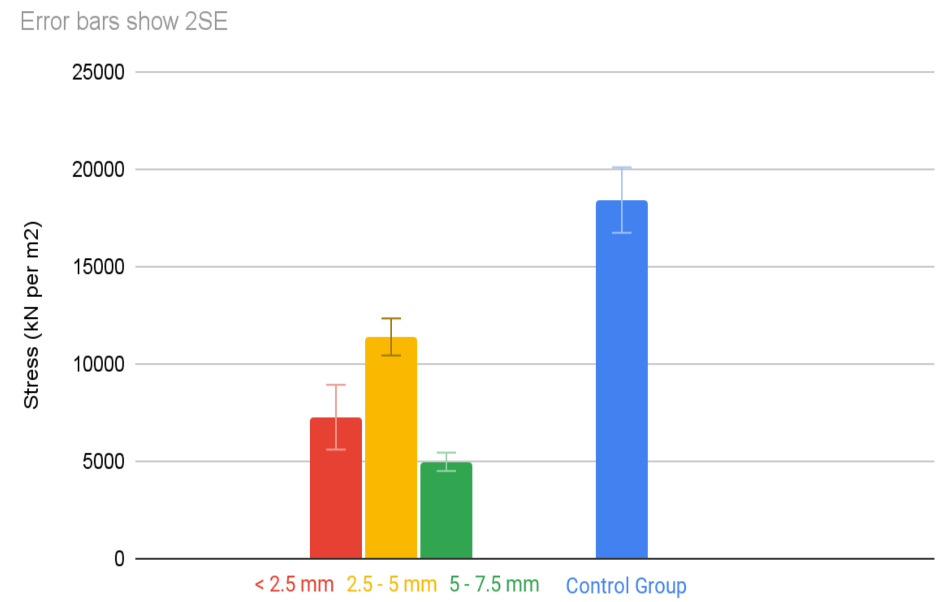

Figure 2. Mean maximum stress before failure. Bar graph showing mean maximum stress for each sample group. Each sample containing varying sizes of PLA, as well as a control, underwent compression testing and the maximum stress value was recorded. (n = 3). One-way ANOVA, $p < 0.001$. *Graph by author.*

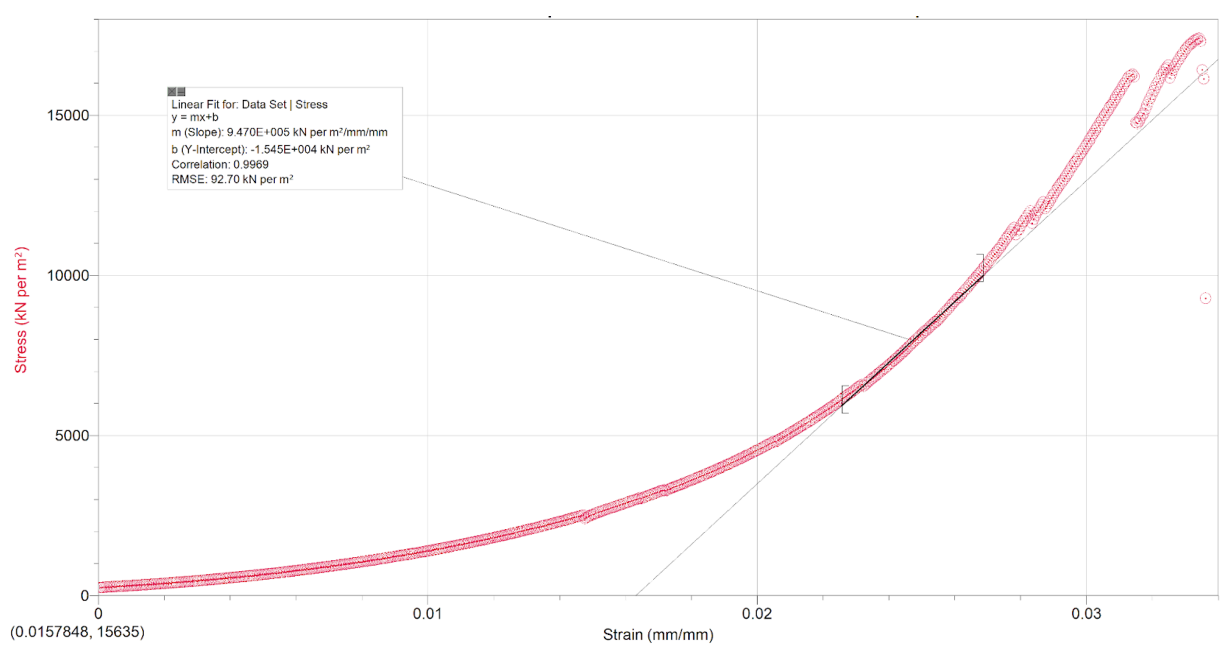

Figure 3. Example stress vs strain graph. This graph shows stress plotted against strain for trial 1 of the control group. The stress and strain were calculated according to the methodology described in the Methods section. This graph serves as one example showing how Young's

Modulus was calculated. One graph was created for each data point to measure Young's Modulus. To calculate Young's Modulus, all data up to the yield strength of the material was included. Then, the data that was shared among all graphs (approximately the bottom third) was discarded as this data is not indicative of the specimen's performance but rather a byproduct of latent load-frame stresses and laboratory conditions. A linear regression was applied to the remaining data (as seen above). *Graph by author.*

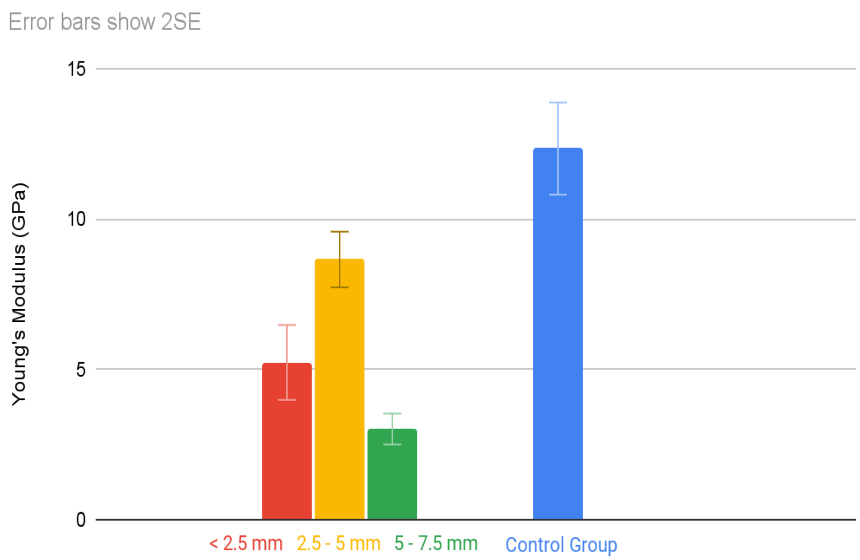

Figure 4. Mean Young's Modulus. Bar graph showing mean Young's Modulus for each sample group. Each sample containing varying sizes of PLA, as well as a control, underwent compression testing and the Young's Modulus was calculated for each sample as described in **Figure 3**. (n = 3). One-way ANOVA, $p < 0.002$. *Graph by author.*

Figure 5. Image of the MTS 810. This image depicts the MTS 810 load frame which was used to test the samples. Also pictured is one concrete sample before any force was applied. Each sample was tested using the MTS and data was collected each second measuring force applied and displacement. *Image by author.*