HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCE

Development of a small-scale plastic recycling technology and a special filament product for 3D printing

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PhD Thesis

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Table of Contents

I. INTRODUCTION, OBJECTIVES

This chapter presents the background and the importance of the study as well as the objectives of the research.

1.1 Introduction

Plastic has long been considered a manmade material with many benefits. It has lightweight properties and is easily shaped to the designer's desires. Its versatile properties have led to its widespread use. Since 2016–2017, plastic consumption has increased from 335 million tons to 348 million tons and reach 370 million tons in 2019 (Rakesh Kumar et al., 2021). This demand is expected to reach 485 million tons by 2030 (EEA Report., 2019).

Nevertheless, regarding quality and the standardization of the finished product, the injection moulding process remains superior to 3D printing. While 3D printing can create roughly 5000 distinct sizes and shapes for components, it is typically used for small production units in competitive settings. The standard practices and technology implemented by a specific organisation or country determine which materials are used for 3D printing. Whether making bottle caps, jugs or plumbing pipes, using HDPE or bottle manufacturing and fiber using PET, plastic wastes are usually recyclable. PET is considered the optimal recyclable material when 3D printing. Prior to the extrusion process, the PET is dried. HDPE, ABS, and PET are moulded into pellets after being shredded when a plastic pellet formation is sought. While sheets are frequently constructed using injection moulds, the creation of 3D printers occurs through laments being formed after additional processing of the pellets. Similar to any manufacturing technology, difficulties and obstacles persist, yet the various methods mentioned to recycle plastics are both affordable and easy to use (Al salem et al., 2009). Through the presence of polylactic acid, losses to the tensile strength were found, yet were negligible after the extruded PET was recycled over 10 times. A marginal loss in the mechanical properties of polypropylene (PP) and polybutylene terephthalate (PBT) was found after mixing the polymers at distinct ratios. Prior to use in component fabrication, the mechanical properties of a 3D printed PET filament remained unaffected after being recycled five times, as per a study in the field. Nonetheless, at the fracture point, a 10% reduction in elongation was observed (Community for plastics professionals., 2020).

Gases are released at high temperatures due to 3D printing thermoplastic. Hydrogen cyanide, carbon monoxide, and other instable organics were identified as outputs when using ABS (ASTM D638-14., 2020). There are potential health risks when using ABS which emits a higher quantity of ultrafine particles than the PET filament. Contaminates and pollutants linked to health risks are a principal cause of this. Prior to further research, these risks should be taken into account. Thus, the process of 3D printing must include an adequate ventilation system to avert these risks. Presently, the next generations of 3D printers may include HEPA filters to mitigate these risks, as these filters are tried and tested within desktops in the current market (R. Joseph et al., 1986).

Sixty percent of plastic materials stemming from synthetic fibers meet the world-wide requirement of 30%. Polyethene (PE) and polypropylene (PP) are the largest usable polymers, while PET comes third, also known as polyester, making up 18% of the global polymer production (Stephens et al., 2013). In

1973, Nathaniel Wyeth removed the patent of the first PET bottle. Solar cells and thin films are additional materials made using PET (Perkins et al., 2020).

The objective of this thesis is to examine the feasibility of utilising recycled polymers for the production of 3D printed components, while also investigating the specific conditions that facilitate this process. Additionally, the study will explore the impact of mechanical qualities on the suitability of these parts for various applications.

1.2 Objectives

I will examine the prior study on the utilisation of ABS filaments in MakerBot 3D printers for filament materials. Additionally, we will provide a portion of the literature review that focuses on the incorporation of particles, resins, and fibres. Firstly, it is essential to thoroughly examine the material properties and production methods used in the sector. Additionally, consider the environmental parameters that influence the selection of a printing mode. Perform an investigation on the various classifications of plastics and the currently available methods for recycling and 3D printing. Formulate a hypothesis and establish a systematic method for analysing and developing recycling technologies. Develop a comprehensive system plan for the advancement of 3D printing filament materials, utilising systems engineering theories to guide technological progress. Finally, conduct field and laboratory testing to assess the physical, mechanical, and application characteristics of the materials.

The aim of this paper is to evaluate the mechanical properties of the samples fabricated from the initial PET filament. The original 3D samples are utilised to fabricate the specimens utilising the PET filament, which are subsequently contrasted with the findings of the study. The recyclability of PET was the determining factor for its selection in this work.
The primary objective of the research is to perform a thorough examination of the utilisation of waste plastic bottles (PET) and tanks (low density polyethylene) as a constituent in concrete, without any additional processing other than grinding. This is done with the intention of reducing the overall cost of the final material.

The specific research aims are as follows:

Researching recycling technologies, materials, and 3D printing technologies.
Examined and investigated the impact of varying waste proportions on the physical and mechanical properties of the novel material, specifically in relation to concrete.
Assessing the mechanical characteristics of samples made from virgin PET filament and comparing them to recycled materials, specifically in relation to their impact on concrete

II. MATERIALS AND METHODS

This chapter presents the materials, procedures, and processes used in the research, including the scientific methods involved in the experimental measurements and the description of the test systems to obtain the set research objectives.

2.1 Small scale recycling technologies

The purpose of this project is to investigate and develop an autonomous recycling station that operates without human intervention. The station will be designed to automatically process plastic waste, with the operator only required to load the plastic into the system and collect the resulting filament at the output.

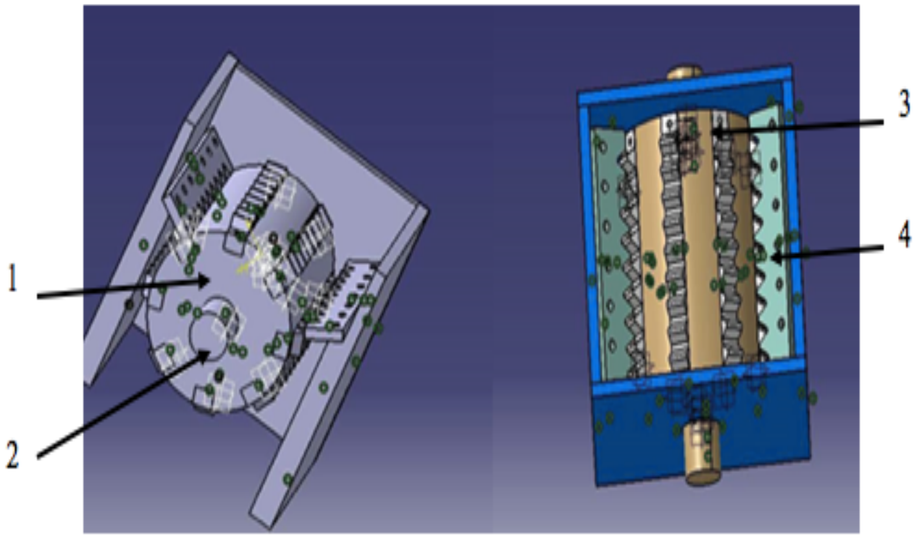

Figure 1 - overview of the crusher (first solution)

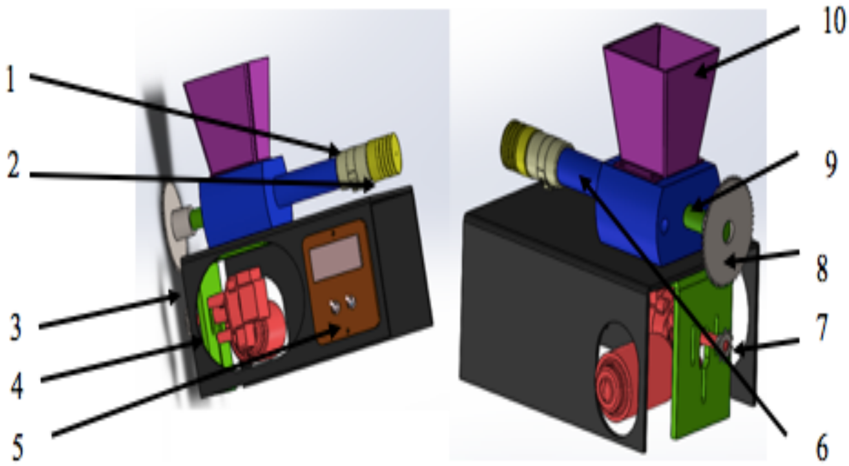

Figure 2 - overview of the extruder (third solution)

2.2 Materials and methods used to prepare filament from recycled and virgin PET

The main production for PET is for the applicability of synthetic fibres (in excess of 60%) with bottle production accounting for around 30% of global demand. In terms of textile applications, PET is generally referred to as simply "polyester". The terminology "PET" is used generally for packaging applications. The polyester industry makes up about 18% of world polymer production and is third largest industry after polyethylene (PE) and polypropylene (PP). (Rahmani et al., 2013).

PET is recycled quite frequently and has the number "1" as its recycling symbol. The first PET was patented in 1941 by John Rex Winfield, James Tennant Dickson and their employer the Calico Printers' Association of Manchester and the PET bottle was patented in 1973 by Nathaniel Wyeth. PET is also used as substrate in thin film and solar cell.(Bornak, 2013).

For the purpose of the experiment, materials made of polyethylene terephtalate that were both coloured and clean were selected

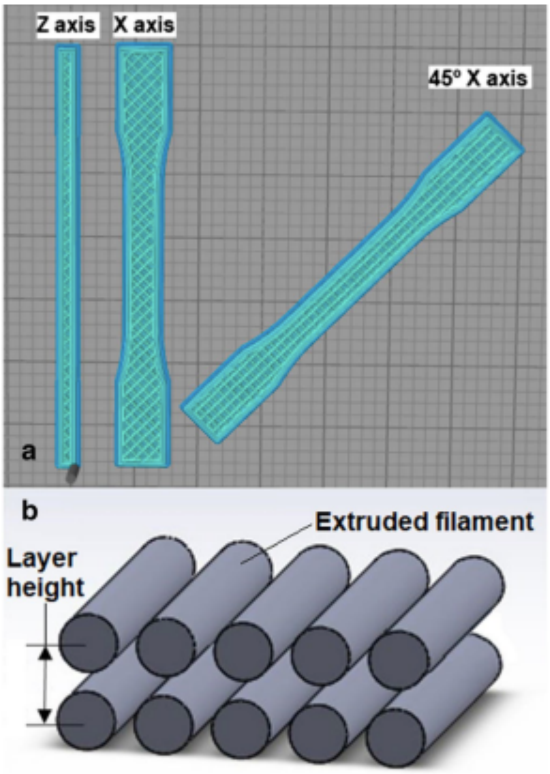

Figure 3 - Geometrical drawing of specimens for tensile test

The specimens that will be tested on the research of this dissertation will follow the parameters from standard test ASTM methods. ASTM are standards to follow on the experimental research to determine mechanical properties of materials. Given material restrictions, for each type of material, there were made three specimens for each printing temperature. There were printed the same number of specimens for each filament for the three mechanical tests such a tensile, deviation and eleasticty.

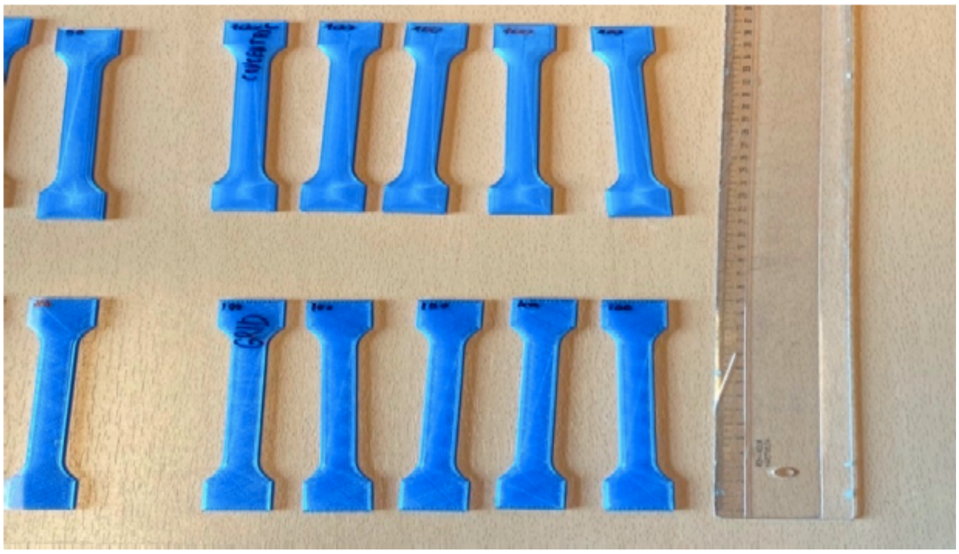

Figure 4 - testing materials standard for the specimens

The virgin materilal PET (not recycled one) filament with a diameter of 1.75 mm enabled the manufacturing of the original test samples. A digital micrometer with 0.01 mm accuracy was used to assess the length and width of the shear specimens after the specimens were generated at 210 celcus degree, with a nozzle of 0.4 mm. At a head travel speed of 5 mm per min, the Testometrinc Zwick/Roel Z100 was used to carry out the tensile testing, as seen in Figure 20 , after the tensile test, a sample of final shape of virgin PET specimens is shown in Figure 19 .

2.3 Polyethylene terephtalate: homogeneous materials after using recycled method

Figure 5 - Sand used during the test

The integration of waste plastic into concrete has emerged as a feasible approach to promote sustainable construction practices. Integrating plastic trash into concrete mixtures offers a hopeful method to alleviate the adverse effects of plastic waste on landfills. This novel technology has the capacity to produce numerous advantages, such as higher mechanical qualities, increased durability, and less environmental effect. Further research and development are necessary to properly address the challenges associated with the processing of plastic waste, ensuring quality, and maintaining the long-term effectiveness of plastic-modified concrete. By implementing this innovative approach, the construction industry has the capacity to significantly contribute to the circular economy and promote environmental sustainability initiatives.

III. RESULTS

The results obtained from the experimentation and the discussions highlighting the new scientific findings. These include the new filaments characteristics

3.1 Results and discussion on the Small scale recycling technologies

Crushers are mechanical apparatuses that are employed to fragment larger substances into smaller particles, rendering them amenable for subsequent processing. The evaluation and configuration of crushers are pivotal factors that have a direct impact on the efficacy and proficiency of crushing procedures. The attainment of precision in the size reduction process is contingent upon the attainment of accuracy in measurement. Additionally, the optimization of the crusher's performance, energy efficiency, and overall productivity is facilitated by the careful consideration of design elements.

During the design phase, we gave each individual component its own distinct design, taking into mind its practicability and the likelihood that it will be able to be manufactured. The components that make up the crusher are as follows: twelve blades, twelve anvil-blades, a right axis, a left axis, a cover, a sieve, fourteen casing spacers, four nuts, two pins, and a crank. After you've finished designing all of the individual components, we'll move on to the Assembly step.

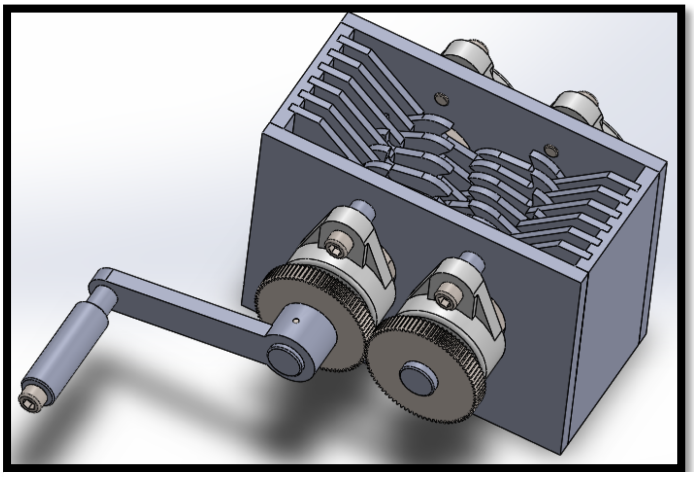

Figure 6 - Overview of the complete design of the crusher

We measured the load that was being applied to the axle by the blades, spacers, and nuts, and then we used the RDM 6 software to distribute that load as a uniform load. You can see this illustrated in the picture below. The following definitions describe the distribution of the load value q:

$$q = \frac{load}{Length} = \frac{mass \times g}{L} = \frac{3{,}42 \times 10}{190} = 0{,}18 \text{ N/mm} \qquad (3)$$

q = 0,18 N/mm

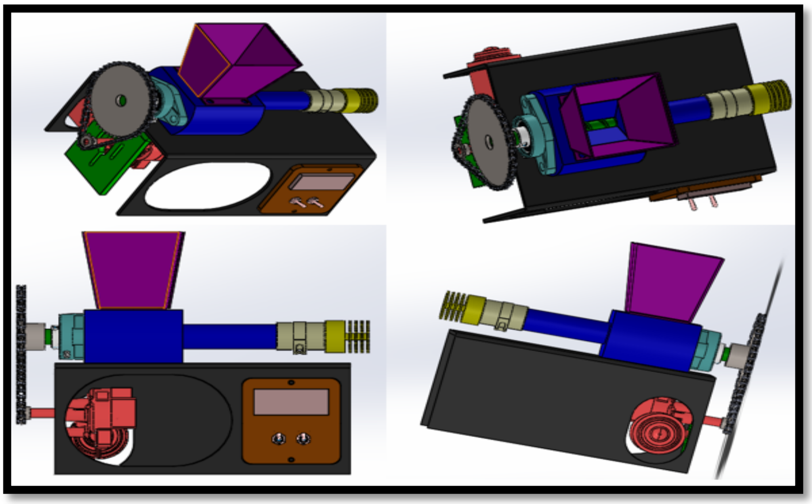

Figure 7 - Overview of the design of the extruder

3.2 Development of 3D printing raw materials (polyethylene terephtalate)

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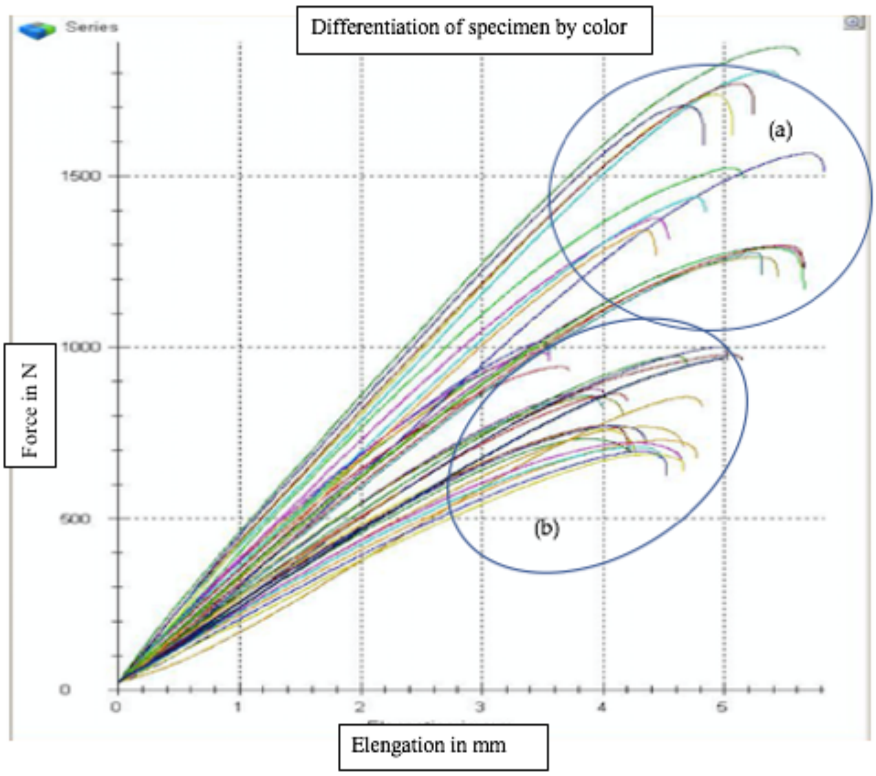

Figure 8 - Tensile Elongation of a recycled (a) and virgin (b) 3D printed PET.

Using stress-strain diagrams, one may also identify the qualities that are wanted, such as the Young Modulus, Yield Strength, and Tensile Strength. The next study will give, for each material, the Stress-Strain curves as well as the tables indicating the mechanical properties that were analyzed based on the three trials that were performed at each printing temperature. These properties were determined by analyzing the results of the trials. Beginning with the PET samples, the Stress-Strain curve that corresponds to the example average of value s gathered is displayed in figure 37. This is done for each printing temperature.

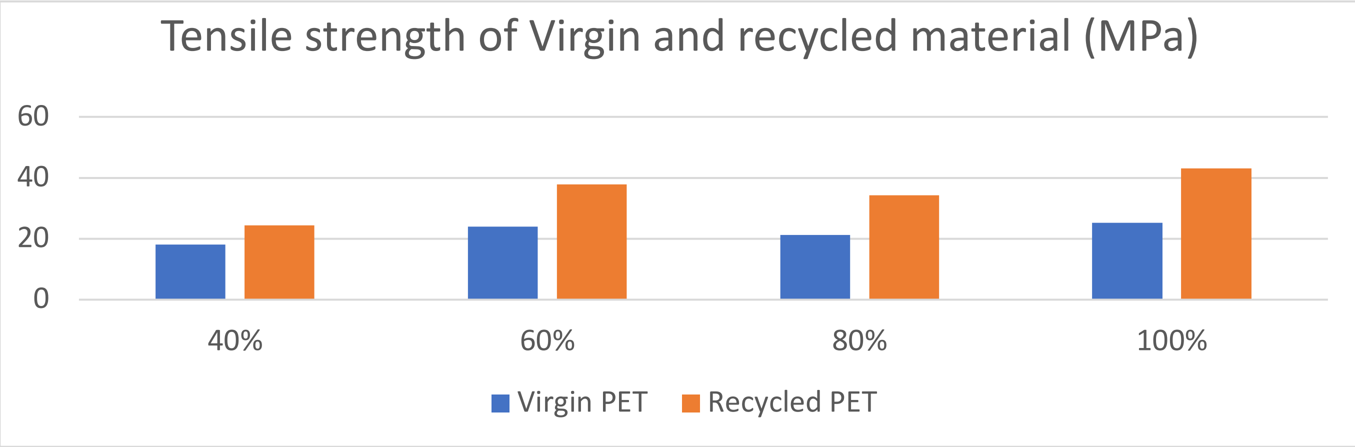

Figure 9 - Tensile strength of a recycled and virgin 3D printed PET.

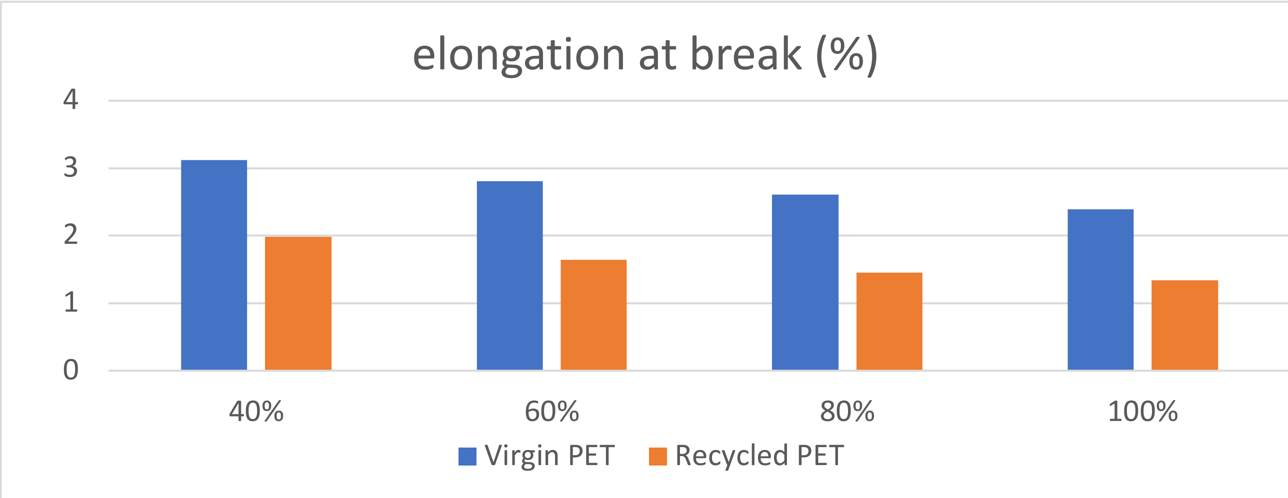

Figure 10 - Elongation at a break of a recycled and virgin 3D printed PET.

Because of the combined effects of a number of different elements, the qualities such as tensile strength and hardness were found to have decreased. This could be due to a deterioration in the qualities of the recycled filament itself, or it could be due to issues that have arisen as a result of the 3D printing process, such as interruptions in the extrusion process or a restriction in the amount of inter-layer adhesion that can be achieved. Because the properties of individual filaments could not be investigated, certain aspects of the system were left out of the study. There were several problems related with using recycled filament, such as the nozzles becoming clogged. Additionally, there were problems with the printing process, which can lead to flaws in the specimens. The fact that the filament re-extrusion was performed without the use of a filter was the primary problem associated with the process; as a result, the filament may have been contaminated with a few minute contaminants.

It was not very logical that the recycled material's average shear strength was around 6.8% higher than that of the virgin material. This was the most important finding. The specimens should have different levels of expansion, and one possible explanation for this is that there was a change in the poison's ratio, which resulted in the specimen being compressed and expanded against the sides of the shear jig. In addition to this, there may have been some microscopic changes in the interlocking of the extruded recycled PET as a result of it being laid down. Working with recycled filament can result in an increase in the amount of ultrafine particle emissions, which would be a potential negative

3.3 Homogenous composite: recycling technologie

Mixing plastic waste in concrete to obtain a homogeneous composite has gained attention as a potential solution for both waste management and improving the properties of concrete.

Plastic waste is crushed or shredded and mixed into concrete during batching. Plastic particles partially replace concrete aggregates or fillers. PET, HDPE, and recycled plastic can be used.

Waste plastic may improve concrete. First, it keeps plastic garbage out of landfills and incinerators. Second, it improves composite mechanical characteristics. Plastic particles reinforce concrete's tensile and flexural strength. Flexibility improves the composite's cracking and impact resistance.

Figure 1 - Homogeneous samples

After conducting an analysis on these curves, we have discovered that the resistances change in accordance with the particle size. The grain size must be narrow for the flexural strength to rise, and the higher the grain size, the thinner the grain must be.

We obtain values of 10 MPa, 15 MPa, and 18 MPa, respectively, for sand with 0.5 d 1, entire sand, and sand with d 0.5 (where D is the grain diameter of the sand).

This shift in flexural strength can be explained by the fact that coarse grains in a mixture encourage contact between grains, which then results in the creation of portions of the material that are fragile.

These figures exceed the requirements of the NBN EN 1339 standard (BNOR, 2004), which calls for a stronger flexural strength of at least 3.5. After that, the use of this material in construction could be advised. It even has a flexural strength that is larger than the compressive strength that was found by the PRSDO-CER project (CIFAL 2011) on a material that was composed of sand and plastic.

Through careful examination of these curves, we have determined that the resistances change in accordance with Figure 42 displays the outcomes of testing conducted on the flexural strengths of recycled PET sand. The addition of PET led to a decrease in the compressive and flexural strengths; the pattern was very similar to that of the compressive strength. At a replacement ratio of 10%, flexural strength reduced by 2.4%, however at a replacement ratio of 40% or 50%, it decreased by 58% or 84.2% respectively at 28 days. During the process of removing the specimens from the mold, one of the PET. 50 samples fractured, which is an indication of the significant drop at this substitution level. 5.92 MPa was the stress level while the replacement ratio was at 30%.

IV. NEW SCIENTIFIC RESULTS

4.1 Modeling recycling machine

In this section, i examine the many sorts of plastics and identify the pollution that is brought on by the former. This project also gave me the opportunity to plan and scale the construction of a recycling station for the conversion of plastic into filaments for use in three-dimensional printers. This station will contribute to the fight against pollution, which is important to us.

The station includes two machines: one for grinding the plastic, and the other for extruding the appropriate filaments. These machines work together to complete the station's functions. Both of these machines were the subject of a theoretical academic investigation, which we also carried out using SOLIDWORKS 2015 as our design software. The theoretical analysis covers everything from the essential mechanical calculations to the design and evaluation of the structure through the application of various techniques.

4.2 Development of 3d raw materials from solid waste

Comparative tests were carried out on the mechanical properties of virgin PET and 3D printed recycled PET to demonstrate that one option for PET recycling is recycling into 3D printing. The comparison found that there is no noticeable difference between the properties of the two types of PET. It was found that the p-value did not exceed 0.003. Achieving a value of 0.003 is the primary result of the study as it proves the validity of the hypothesis made, solid PET waste is suitable for use as raw material for 3D printing.

4.3 Mechanical properties of virgin and recycled polyethylene terephthalate

I have found that the mechanical properties of virgin polyethylene terephthalate (PET) and recycled PET can vary depending on a number of factors, including the conditions under which the PET is processed, the presence of contaminants or additives, and the degree of degradation that occurs during the recycling process. This scientific result summarises the routinely evaluated mechanical properties of virgin PET and recycled PET.

As a result of these tests, it was found that the average shear strength of the recycled material was approximately 6.8% higher than that of the virgin material. The specimens should have expanded to different extents, and one possible explanation for this is that the Poisson's ratio changed, causing the specimen to compress and expand relative to the sides of the shear tool. In addition, microscopic changes in the interlocking of the extruded recycled PET may have occurred as a result of the deposition. Working with recycled fibres may result in an increase in the emission of ultrafine particles, which could be a potential negative.

4.4 FLexural strength on the composite of Waste PET in concrete

Another possibility for PET recycling is the production of PET-concrete composite. To determine the criteria for its applicability, I investigated the flexural strength of the composite for different mixing ratios. The content and distribution of waste PET, the concrete matrix and the waste PET-concrete bonding affect the flexural strength of the waste PET-concrete composite. By analysing standard bending tests, I found that both compressive and flexural strengths decreased with the addition of PET; the pattern was quite similar to that of compressive strength. The flexural strength decreased by 2.4% at 28 days when the replacement ratio was 10%; however, when the replacement ratio was 40% or 50%, it decreased by 58% and 84.2%, respectively, in accordance with the replacement ratio.

4.5 Homogenoous composite – recycling technologies

By examining the curves obtained in the bending tests, I discovered that the resistances vary with particle size. Flexural strength increases in direct proportion to the particle size of the thin layers of material.

For PET sand with a particle diameter of 0.5 mm or less, for all sand and for sand with a particle diameter of less than 0.5 mm, values of 10 MPa, 15 MPa and 18 MPa are obtained.

This shift in the flexural strength can be explained by the coarse grains in the mixture promoting contact between the grains, which then leads to the formation of brittle particles in the material.

These values are higher than the requirements of the NBN EN 1339 standard (BNOR, 2004), which specifies a flexural strength of 3,5 or higher or equivalent. Subsequently, the use of this material in the construction industry is recommended. It has a flexural strength even higher than the compressive strength achieved by the PRSDO-CER project (CIFAL 2011) on a material composed of sand and plastic.

V. CONCLUSION AND SUGGESTIONS

Crushers break big materials into smaller pieces for processing. Crusher evaluation and setup directly affect crushing efficiency. Size reduction precision depends on measurement accuracy. Design factors optimize crusher performance, energy efficiency, and productivity.

We designed each component with practicality and manufacturing in mind. The crusher has twelve blades, twelve anvil-blades, two axes, a cover, a sieve, fourteen casing spacers, four nuts, two pins, and a crank. After you design all the components, we'll assemble them.

Extruders help manufactures manipulate and shape materials. Extrusion efficiency depends on extruder evaluation and configuration. Quantifying key factors and carefully assessing design features ensures product quality, efficiency, and profitability.

After loading the extruder with shredder-crushed plastic, the operator feeds grain plastic into the hopper. The extrusion screw spins and feeds the grain into the extrusion chamber. The plastic will start to sag. As it enters compression, the plastic mixture homogenizes and heats up. Finally, the band heaters soften the plastic mixture, which is blasted out through the nozzle to produce the filament.

3D printing raw materials have helped progress additive manufacturing technologies. Due to their printability, cost, and versatility, polymer-based materials like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyamide (PA) are commonly used in 3D printing. Scholars have developed polymer composites with better mechanical strength, thermal stability, and electrical conductivity for aerospace, automotive, and medical applications.

This thesis evaluates virgin PET filament sample mechanical properties. The PET filament specimens are compared to the study results after recycling the 3D printed samples. This paper chose PET because of its recycled pliancy.

Stress-strain graphs can help highlight desired properties like Young Modulus, Yield Strength, and Tensile Strength. The following study will present Stress-Strain curves and mechanical property tables for each material based on three trials at each printing temperature. Trial results revealed these qualities. Figure 37 shows the Stress-Strain curve for the PET sample average value s. For each printing temperature.

Figure 36 shows that at each printing temperature, PET specimen Yield Strength and Tensile Strength are equal. The specimens printed at 250 degrees Celsius exhibited a higher Young Modulus than those printed at other temperatures, which were similar. The printing temperature of 240 degrees Celsius has higher tensile and yield strengths. However, printing at 250 degrees Celsius increased the Young Modulus. The variation coefficient is minimal for all features when printed at any of the four temperatures. Several methods are available. Tables 12 and 13 show average PET mechanical feature values based on sample data, not printing temperature. These tables include all sample data.

Based on its mechanical properties, ABS can be translated as Young Modulus (792.51 MPa), Yield Strength (18.63 MPa), or Tensile Strength (21.21 MPa). Figure 29 shows the average PET sample stress-strain curve for each printing temperature. PET samples determined these results.

Elongation at break measures how much a material can be stretched before breaking under tension. It shows ductility and suppleness. This academic paragraph discusses the impact of elongation at break on material behavior and its applicability in many industries and applications. Polymers, metals, and composites have tensile characteristics based on elongation at break. It determines material deformation before breaking. "Elongation at break" is the length a specimen has grown before breaking in a tensile test. Elongation at break indicates material deformation resistance. Since the material can be extended before breaking, higher elongation at break values indicate stronger deformation resistance and toughness. Low-elongation materials are fragile and rapidly break under force.

Several approaches reduce plastic-sand segregation in waste plastic-concrete mixtures: Proper Mixing: Mixing evenly distributes plastic particles and sand in concrete. Longer mixing durations, intermittent cycles, and mechanical agitation promote dispersion and reduce segregation.

Gradation control reduces segregation. Suitable plastic and sand particle sizes can increase interlocking and reduce separation.

Viscosity-modifying chemicals and superplasticizers can make waste plastic-concrete more workable and cohesive. These additives reduce plastic-sand segregation.

Curing and compaction ensure homogeneous hydration and consolidation of the waste plastic-concrete mixture. Reduces holes and imperfections that could separate plastic and sand. Quality Control: Quality control during mixing, placing, and curing detects and fixes segregation issues. The product meets standards by monitoring the mixture's workability, uniformity, and homogeneity.

Segregation may occur despite these measures. To reduce segregation, waste plastic, sand, mixing, and curing conditions must be assessed.

In conclusion, nonrecyclable waste plastic in concrete may create plastic-sand segregation. Mixing, particle gradation, admixtures, curing, compaction, and quality monitoring prevent segregation. Evaluating components and process parameters prevents segregation and creates a more homogeneous waste plastic-concrete mix.

Finally, recycling systems mix plastic waste and concrete into a homogenous sample. These methods manage concrete particle size, shape, and distribution and make plastic waste constant. Mechanical blending, extrusion, melt-mixing, and fiber reinforcing are used. These recycling technologies make plastic waste-concrete composites more homogeneous, boosting performance and sustainability.

VI. SUMMARY

A small-scale plastic recycling technique and PET filament for 3D printing provide a sustainable and innovative way to turn plastic waste into useful resources. This academic paragraph discusses crucial factors of developing such a technology and its filament product.

Collecting and sorting plastic waste is the first stage in building a small-scale PET recycling method. PET waste from families, industry, and businesses must be collected efficiently. Sorting PET from other plastics, whether manually and automatically, ensures a clean and consistent feedstock for recycling.

After sorting, PET waste is processed. Shredding or granulating plastic helps in processing. PET waste is cleaned and washed to remove debris, labels, and residue.

The next critical step is turning cleaned and processed PET into 3D-printable filament. A unique extrusion mechanism melts PET flakes or granules from recycling. This extrusion process melts PET and forces it through a die to generate a continuous filament with a particular diameter and shape.

Additives or modifiers can be added during extrusion to improve filament strength, flexibility, or heat resistance. Depending on the required filament properties, these additives may include strengthening agents, colorants, or flame retardants.

To ensure recycled PET filament uniformity and reliability, quality control is conducted throughout development. Mechanical qualities, dimensional correctness, and 3D printing compatibility may be tested. Optimize filament performance by changing process parameters or composition.

3D printing with PET filament is sustainable. Recycled plastic trash reduces the environmental impact of filament manufacture. PET filament works with many 3D printers and may be used to make many products and prototypes.

In conclusion, developing a small-scale PET plastic recycling technology and a 3D printing filament product requires collecting and sorting PET waste, processing and cleaning the plastic, and extruding the recycled PET into filament. Additives and quality control enable high-quality 3D printing filament. This novel technology improves plastic waste management and opens new additive manufacturing applications for recycled PET

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