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Using HDPE waste as a source of recycled material in 3D printing

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ABSTRACT:*A primary objective of this paper is to present the findings of an experimental investigation of the 3D printing conditions of waste material (recycled HDPE). As a first step, we produced filament suitable for 3D printing from recycled HDPE of acceptable and competitive quality. Another step was to determine which bed layer should be used for 3D printing of recycled HDPE materials. The paper examines the impact of recycled HDPE material properties and the production processes of filament production and 3D printing on the final product. Two types of recycled HDPE material were used as input raw materials, namely lids from PET bottles and waste from HDPE injection molding. Researchers aimed to determine the effect of 3D printing parameters (bed temperature, extruder temperature) and the interaction between two recycled HDPE types with the shrinkage of final printings.*

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I. INTRODUCTION

In our economy and everyday lives, plastic plays an influential and ubiquitous role. Plastic's significance and role in our economy have grown steadily over the past 50 years. Our society faces a number of challenges that it helps address through its various functions. The use of lightweight and innovative materials in automobiles and airplanes reduces fuel consumption and CO_2 emissions [1]. There has been a significant increase in the global demand for plastic-based products in recent years. In 2019, Asia accounted for 51% of the world's plastic production, and Europe accounted for 17%. According to PEMRG [2], there were 359 million tons of plastic produced worldwide in 2019. Approximately 4% of the global demand is satisfied by the supply of virgin plastics (1.3 billion barrels per year). There are multiple reasons why polymers used in manufacturing are non-degradable and can last in the environment for several years [4]. Therefore, this type of waste may cause environmental contamination.

Despite these benefits, plastics are currently produced, used, and discarded in ways that harm the environment and fail to maximize their economic potential [1]. We must address the environmental problems that today surround plastic production, use, and consumption as urgently as possible. According to the renewed EU Industrial Policy Strategy [5], increasing the sustainability of the plastics industry can bring new opportunities for innovation, competitiveness and job creation in Europe [6]. As part of the EU Action Plan for a circular economy, the Commission adopted a document in December 2015. Plastics were identified as a key priority and the committee committed itself to "preparing a strategy that addresses the challenges plastics pose within the value chain and takes into account their entire lifecycle".

Plastics can be recycled up to 90%, according to statistics. There is an estimated 80 percent of plastic waste being disposed of in landfills at present, and just a small percentage of plastic waste is being recycled. The most serious problem is the use of polymers like HDPE, LDPE, PP, and PVC plastics in industrial processes. These plastics emit harmful gas emissions into the atmosphere as a result of their widespread use [7]. As a result of its natural roots, pollution arising from PLA is much less of a global problem as compared to other types of pollution, which has a much greater global impact. The disadvantage of this material, particularly the fact that it is less physically stable than most other kinds of materials, makes future producers reluctant to use it more frequently. It should be noted that the biggest disadvantage associated with the use of recycled fabrics, after multiple recycling cycles, is that some of their properties will be lost. As a result, there is an imbalance in the economic system, which can have a detrimental effect on the well-being of the public (8). Implementing the circular economy in production companies is one of the ways for them to be able to ensure that the EU strategic plan is implemented. In contrast to the current economic model - the linear economy - the circular economy, also known as the green economy, is a new economic model [9]. There is no doubt that the current take-produce-throw-away system is profit-driven in large part by the excessive consumption of renewable material as well as non-renewable material, which logically cannot last. Meanwhile, research possibilities for improving product properties are still open for recycled or waste thermoplastics. This system can be considered unsustainable when we factor in other negative factors, including cheap labor from developing countries, a population explosion, an increase in consumption, and adverse environmental effects [9, 10]. In terms of economics, ecology, and society. A circular model, however, is intended to ensure a nation's competitiveness, sustainable economic growth, and environmental health. Using materials, products, and components efficiently is the key to achieving the circular economy's yield. As material flows are constantly closed by their return to the technical and biological cycles, they represent the closure of material flows. New products can be produced with a reduction in waste, material inputs, and energy costs. As part of this concept, renewable energy sources will be used, eco-innovation will be implemented, as well as renting, sharing, and supporting local businesses. Growing concerns about the environment, as well as a growing need for polymer-based materials, have created an ever-increasing interest in waste polymers.

There are considerable benefits to be gained from moving decisively towards a sustainable and prosperous plastics economy. Developing a 'circular' plastics economy in Europe would require a strategic vision that sets out what it will look like in the coming decades [1]. Innovation must be promoted and challenges turned into opportunities as part of this vision. To achieve this vision, the EU will propose concrete measures, but all players in the plastic value chain must take action, including plastic producers, designers, brands, retailers, and recyclers. It is also imperative to note that all the sectors of civil society, the scientific community, the business community as well as local authorities have an important role to play in bringing about positive changes, working closely with regional and national governments to do so.

Plastic circular economy should be facilitated by an innovative, sustainable and smart plastics industry that fully respects reuse, repair, and recycling needs [1, 2]. It has been shown that 3D printing can be used to reuse and recycle waste-based plastics in order to bring about a decrease in plastic waste, decrease the negative impact of plastic waste, and lessen the amount of unnecessary plastic produced [5].

The topic of waste-based materials for 3D printing is a topic of this paper, which presents a research report covering the findings. Several factors have a significant impact on the final printed s quality, including recycled HDPE-based waste, 3D printing conditions, and technology setup. Using waste based plastic materials for 3D printing is the aim of the authors. HDPE waste material applications and production possibilities are very interesting and important as a result of such results. The findings of the research can be very advantageous for the production process using 3D printers and may even add to the possibility of utilizing waste raw materials in the production process as well, thus increasing the environmental responsibility with the company's environmental protection efforts.

II. MATERIALS AND METHODS

This study aims to investigate whether waste HDPE could be used or applied for the purpose of 3D printing in general. It will also investigate possible applications and uses. Keeping this in mind, the review recommended that the experiment be broken down into several phases. Initially, we were trying to prepare HDPE waste into a form that's suitable for being 3D printed, following which it will undergo a processing step. After the initial phase of 3D printing conditions was determined, an investigation was conducted to examine what type of bed layer is used most commonly for 3D printing. A major objective of this study is to determine the effect of 3D printing parameters on the shrinkage of 3D printed pieces in the final printing process. Material type, bed temperature, and extruder temperature are the three most significant factors that influence the extrusion process.

A variety of raw materials were selected and prepared as the basis for the above-mentioned investigation. During the experiment, HDPE 1 (waste from high-density polyethylene called TIPELIN 1108J, which is intended for injection moulding, with a melt index of 8.0 g/10 min) and HDPE 2 (high-density polyethylene derived from PET bottle lids) were used as plastic matrixes. Steps involved in the preparation of samples and the treatment included:

1.) Treatments (separation, disintegration) are based on basic mechanical principles.
2.) Producing filament for 3D printers (filament for 3D printers).
3.) The production of samples (using 3D printing with FDM).

Using Filament Maker, the input raw waste material was disintegrated into smaller particles since a material with the proper shape can be 3D printed. Thus, disintegration and separation processes were employed to obtain the given particle sizes of HDPE waste. Figure 1 shows a cutting mill Retsch SM 300 being used for disintegrating PET bottle lids (Figure 1) and HDPE waste. In order to determine the moisture content before extrusion, Kern MRS 120-3 balances were used. Consequently, a constant weight was determined by heating the raw material (gravimetric method of moisture content measurement) [12]. In an experiment, the moisture content of HDPE 1 and HDPE 2 was measured at 0.2 % and 0.2 %, respectively.

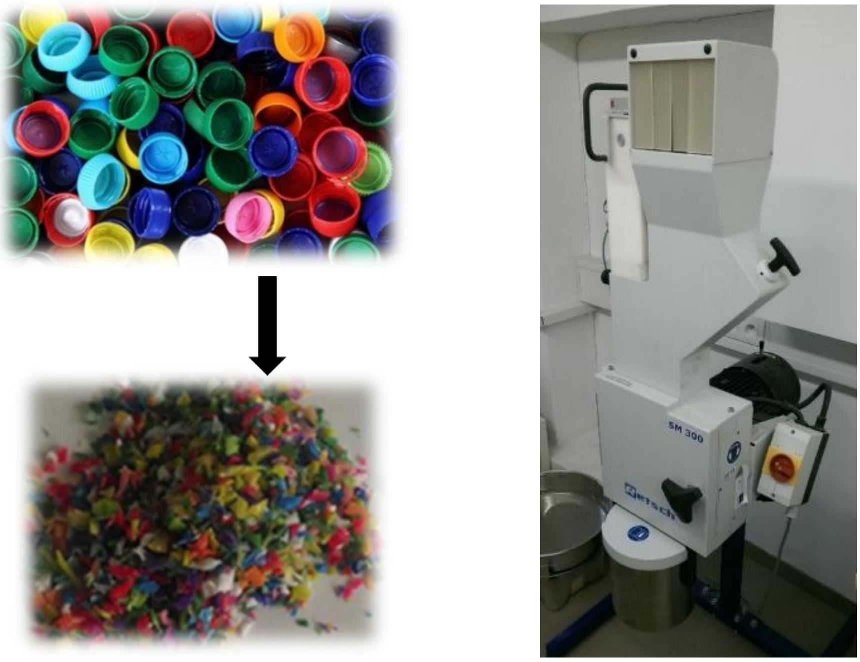

Fig. 1 Disintegration of PET bottles and Retsch cutting mill

Filament needs to be shaped appropriately for 3D printing. With the Filament Maker Composer (Figure 2), filament for 3D printers from recycled HDPE was produced to an acceptable and competitive quality. Both samples of waste-based HDPE were able to be turned into filament with our maximum effort. Material properties required different extrusion parameters for each material sample depending on their extrusion parameters. There were proper output parameters for printing as well as a stable shape and surface of HDPE 1 and HDPE 2 filaments (Figures 3 and 4). A 3D printer appears to use these. According to Table 1, the settings of the filament maker were kept during the extrusion process. 3D printer properties (the output diameter of the printing nozzle is 1.0 mm) and filament manufacturers' properties (the diameter of the filament maker nozzle is 1.0 mm) are used to determine the diameter of filament. There should be an investigation into the extrusion process alone, as the filament maker has its own limitations in terms of increasing extruder speed. It was capable of rotating at 15 rpm at maximum speed. Based on the filament's requirements, we adjusted the extruder speed. It is critical to ensure that the filament is produced without any damage and in the quality needed.

Fig. 2Filament Maker Composer 3devo

Also, the fan output power of the filament maker was adjusted according to the requirement of the filament quality. During production of the filaments the temperature at the beginning of the screw (T1) was constant for both samples of the filaments. But at the end of the screw (T2), it was changing as shown in the below Table 1.

Table (1). Filament production parameters according to the sample.

Sample	HDPE 1	HDPE 2
Extruder speed (rpm)	4.60	7.10
Filament fan power (%)	55	40
T1 (°C)	240	240
T2 (°C)	230	230
T3 (°C)	230	230
T4 (°C)	220	220
Puller speed (rpm)	automatic	14.37

Fig. 3Filament produced from waste based HDPE 1Fig. 4Filament produced from waste based HDPE 2

The difference in temperature at different points has been compared. The puller speed affects both filament shape and quality, and therefore also filament makers' productivity. Depending on the quality of the final filament, this parameter of the filament maker should also be adjusted. Puller speed could sometimes be controlled automatically by the filament maker, without the need for operator intervention.

Acrylonitrile Butadiene Styrene, Polycarbonate, and Polylactic Acid are the most common plastic materials used in FDM technology for plastic part production. It was waste-based HDPE that was used in our case [11], which is generally not designed for 3D printing. The properties of these materials are very important, as they have different processing requirements, such as the temperature required. Because not all FDM devices can process all materials, the type of printing device to use for produced specimens depends mainly on the input material [13]. It is important to keep the temperature at a certain level to melt plastic materials and make layers thick. The filament manufacturer only specifies the range of temperatures that are suitable for their product [14], not the exact temperature. The reason is because different 3D printers use different software and are designed differently, so different temperature settings are necessary, as well as many other parameters.

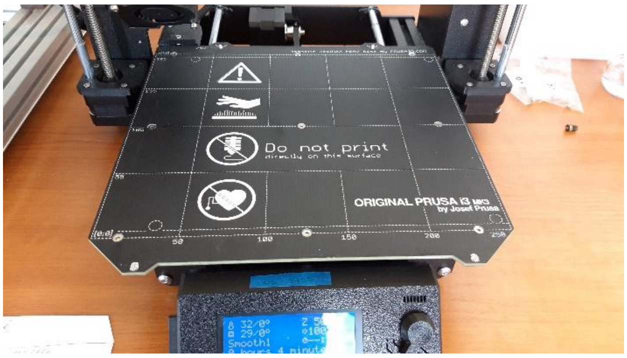

Fig. 5FDM 3D printer used for the experiment

There is a direct link between temperature and the consistency of semi-melted thermoplastic, causing it to flow differently and influencing the diffusion of deposited fibers [14, 15]. Various studies have shown that layer thickness affects dimensional accuracy, so we investigate whether it also influences shape and positional tolerances [15]. The thickness of the layers can be adjusted within the 3D printer, and this can affect the quality of the final product. The specimens that we plan to print will have standardized dimensions for our experiment.

For testing, a number of specimens were manufactured on a Prusa i3 FDM 3D printer (Figure 5).

A 3D printer was used to print the samples after the filaments were prepared. However, we encountered another problem during printing. A key question was which 3D printing parameters needed to be adjusted as a result of the wrong material composition? Consequently, printing processes are influenced by this factor, as well as shrinkage of printings. Shrinkage of printings can be caused by a number of factors, but it is typically caused by bed temperature and bed layer. Due to the limited range of temperature settings in our 3D printer, we can only adjust the temperature up to 120°C during printing. There was also a problem with the adhesion of the printing to the bed layer. Our research is therefore focused on finding the optimal material composition for a bed layer using such an investigated material composition. An increased adhesion force between the printing surface and bed layer was the general goal. A combination of the right bed temperature, extruder temperature, and bed type can accomplish this. Ideally, the bed layer material should be as close to the printed material as possible. Only one setting was selected because there were many choices and for the purpose of obtaining clear results regarding the influence of bed type on adhesion. We have adjusted the 3D printer according to the following technological parameters: 3D printer extruder temperature 190 °C, bed temperature 120 °C, and printing speed 18 mm/s. The following types of bed layer have been used as part of the bed construction:

→ PP base material without additional layer,
→ PVC base material without additional layer,
→ PVC base material with additional 2nd textile layer (rectangle structure),
→ LDPE base material with additional 2nd textile layer (line structure),
→ LDPE base material with additional 2nd textile layer (square structure).

Because of the availability of only a few types of bed layers in this phase of the investigation, only the ones mentioned below were used. Figure 6–8 shows that the majority of bed layers weren't suitable for printing. With the exception of the LDPE tape with the second squared textile structure (Fig. 9), both types of printing materials were suitable for printing. This figure shows that when using HDPE 1 or HDPE 2 as filament, the corner points of printing would shrink. The sample wouldn't stick to the bed during printing on the PP bed layer. Also, similar results were obtained by printing on a PVC bed layer (Figure 7) and on an LDPE (grey) bed layer (Figure 8). A small adhesion was preventing the sample from sticking to the bed since the corners of the printings shrank. As compared to both previous tapes, LDPE appeared to be better. This tape contains a second layer (textile) that contributes to improvement. A lined structure is present in this textile layer.

Fig. 6Polypropylene (PP) transparent bed layer

Fig. 7Polyvinyl chloride (PVC) black bed layer

The final decision was made to use another tape-based LDPE material, however with a different structure in the second layer. On the second (textile) surface of this tape, which is made up of green neon, there was a square design. It was possible to print stable samples with this type of bed layer (Figure 9) with this method. We are going to use LDPE as the main material for the main experimental phase. This will be combined with a second textile layer which will be square shaped as an additional layer on top.

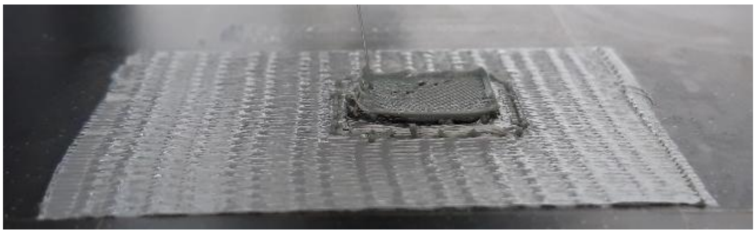

Fig. 8Low-density polyethylene (LDPE) grey bed layer

In 3D printers, there are different settings that can be adjusted according to different parameters. Below are the constant variables that will be used in the model. Our purpose in considering the given variables is to compare the differences in shrinkage of samples based on the existing variables.

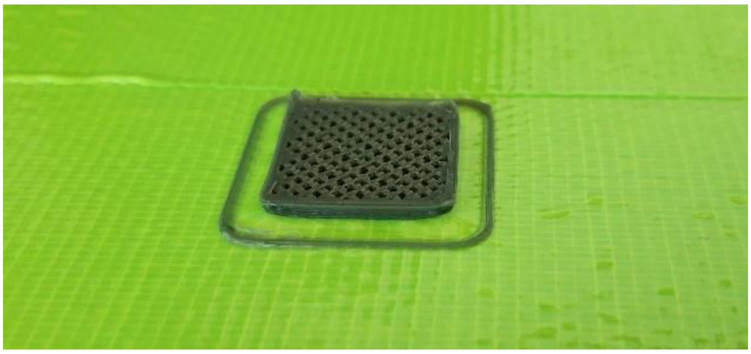

Fig. 9Low-density polyethylene (LDPE) green-neon bed layer

III. RESULTS AND DISCUSSION

During the experimental stage, the main aim of the research is to study the impact of bed temperature and extruder temperature with interaction of type of waste HDPE on the shrinkage of final printed products in the final printing process.

→ length of the printing sample: 100 mm,

→ printing nozzle diameter: 1.0 mm,

→ extrusion coefficient “e”, which means amount of material between the starting point and ending point: 7,

→ printing speed: 20 mm/s.

The influencing parameters (bed temperature and extruder temperature) were changing within the following values:

→ bed temperature: 60 °C, 90 °C and 120°C,

→ extruder temperature: 180 °C, 200 °C, 220 °C and 240 °C.

A comparison was performed between 3D printed lines made from two different types of waste HDPE to determine the final shrinkage after the printing process had been completed. It was necessary to repeat each experimental setting six times in order to eliminate measurement inaccuracies. By evaluating the average of these six repetitions, we calculated the final printing shrinkage. A constant bed temperature of 60°C was used in Figure 10 to extrude HDPE 1 samples at different extruder temperatures. It was determined how much shrinkage had occurred by measuring the change in length of the printed lines. Similarly, in Figure 11, we see samples of HDPE 2, extruded at different extruder temperatures with a constant bed temperature of 60°C. We evaluated shrinkage by measuring the length of the printed lines.

In Figures 12 and 13, you can see the final graphical results. This figure shows how printing shrinkage was related to extruder temperature for waste HDPE samples at various levels of bed temperature. In figure 12, we see the results for waste HDPE 1 samples. The shrinkage decreases as the extruder temperature is increased. By increasing the temperature of the bed, shrinkage can be reduced.

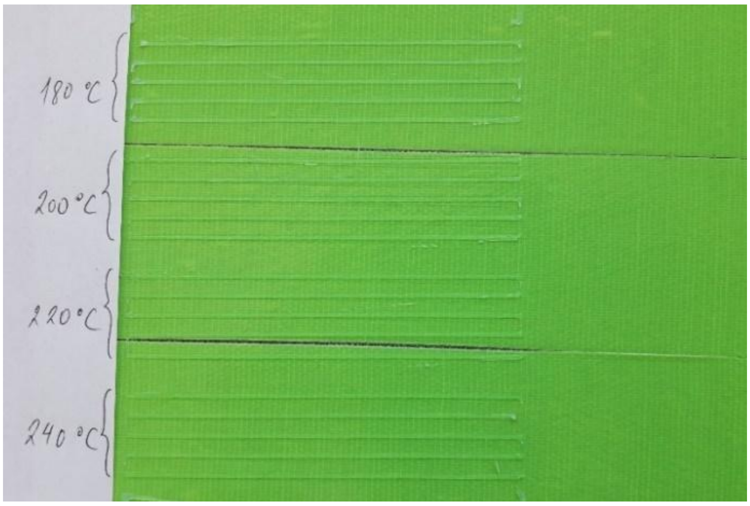

Fig. 10Printed samples-lines from the HDPE 1 material at different extruder temperature

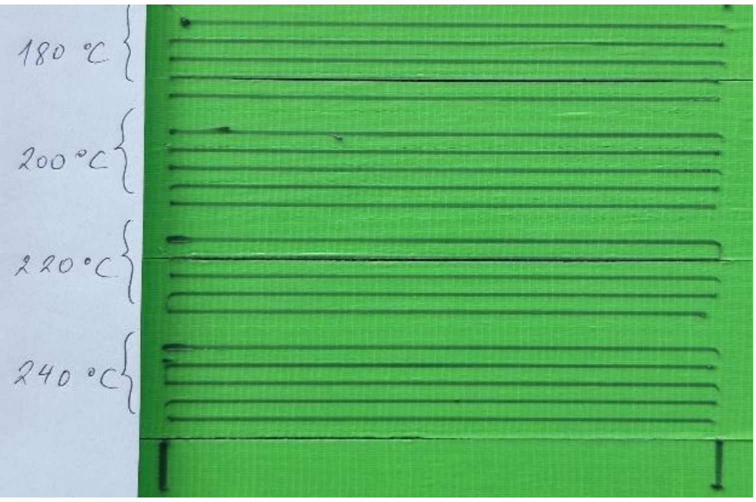

Fig. 11Printed samples-lines from the HDPE 2 material at different extruder temperature

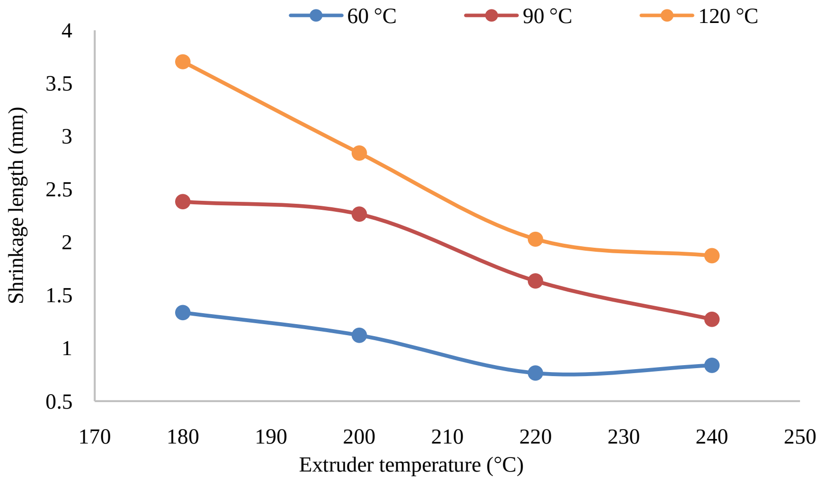

Fig. 12Dependence of printing´s shrinkage on extruder temperature at various levels of bed temperatures for HDPE 1

As can be seen in Figure 13, printing shrinkage is influenced by extruder temperature at various levels of bed temperature for waste HDPE 2 samples. The shrinkage decreases as the extruder temperature is raised. A lower shrinkage rate may also be achieved by increasing the temperature of the bed. It is interesting to note that the dependencies follow a course with a local maximum, so the results are quite similar to those of HDPE 1. The difference is only present with the dependence of 90°C and 120°C, where the dependence character changes when the extruder temperature exceeds 200°C.

For a closer examination of the result comparison between HDPE 1 and HDPE 2, we must take into account the bed temperature at each level separately. A lower shrinkage was observed with waste HDPE 1 samples at a bed temperature of 60°C. A level of 90°C bed temperature had smaller shrinkage in HDPE 2 samples until the extruder temperature exceeded a value of 200°C. The shrinkage of HDPE began to decrease from this point onwards. As bed temperature reached 120°C, HDPE 2 samples shrank less until extruder temperature exceeded 210°C. HDPE 1's shrinkage began to decrease at this point.

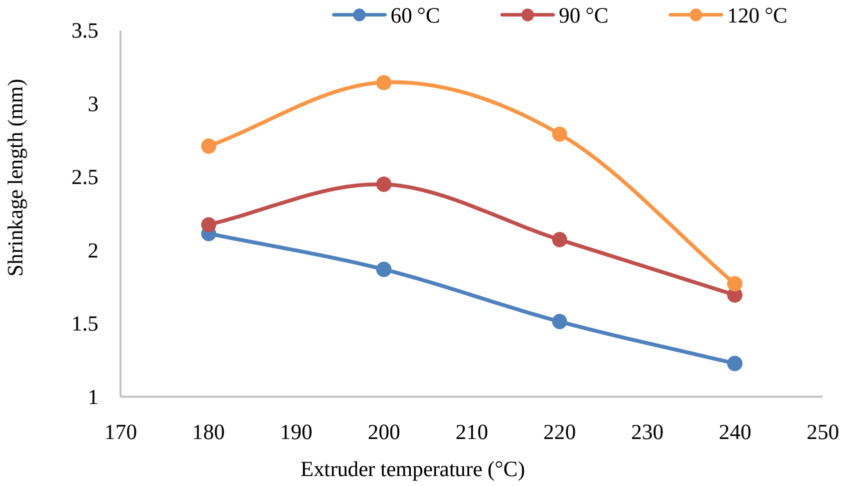

Fig. 13Dependence of printing´s shrinkage on extruder temperature at various levels of bed temperatures for HDPE 2

IV. CONCLUSION

In this study, waste plastic (HDPE) materials were analysed for filament production and 3D printing conditions. These preliminary results discuss the effects of waste-based materials on 3D printing conditions and shrinkage during the printing process.

According to this study, the following conclusions can be drawn:

- The production of filaments can be conducted using HDPE recycled material derived from waste sources.

- 3D printing can be carried out using waste-based recycled HDPE, but under certain conditions,
- Tape-based LDPE can be printed using recycled HDPE materials with a second textile square structure.
- There may be a relationship between bed and extruder temperatures and shrinkage of printing materials.
- We found that shrinkage on printings originating from PET bottles was lower when compared to printings originating from waste-based HDPE.

Acknowledgments

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