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A Study of Repetitive Recycling of Polypropylene Waste: A Quality Evaluation and Economic Assessment

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ABSTRACT

Plastic products play an important role in our daily lives. Many efforts have been directed during the past ten years towards reducing the amount of plastic waste polluting the environment. Mechanical recycling is one of the techniques for disposing of plastic waste. The plastic scrap is first collected, sorted, washed, crushed, and then converted into useful products through injection moulding or any similar primary shaping process. Polypropylene is a common thermoplastic that is listed as a food grade plastic being used to manufacture food containing products. Polypropylene could be recycled more than once without a significant reduction of its mechanical and physical properties. This paper presents a real case study that seeks to evaluate the economic benefit and product quality of repetitive recycling of polypropylene boxes up to five cycles. The results showed a clear reduction of the unit cost of the recycled plastic compared to a new part. The transparency of the recycled boxes decreased but remained acceptable till the fourth cycle. Tests proved that tensile properties were moderately affected by recycling. Hardness and density had slightly decreased at the fourth cycle.

Keywords:

Repetitive recycling; Injection molding; Polypropylene; Durability; Cost benefit; Tensile properties; Hardness

1. Introduction

The municipal solid waste in Egypt including plastics is dramatically growing because less than 20% of it is appropriately disposed of or recycled. This waste is burned in uncontrolled incinerators, which affects health, air and soil [1,2]. The use of plastic materials is increasing worldwide because of their durability, cost-effectiveness, and light weight [3]. Plastic is a polymer that has many types, like polyethylene terephthalate, high density polyethylene (HDPE), polyvinyl chloride (PVC), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), whereas plastic waste can be a mixture of all of them [4].

There are three ways to get rid of plastic waste: energy recovery, mechanical recycling, or landfill [5]. Both chemical recycling and mechanical recycling can be used to reduce plastic disposal in landfills [6,7]. Plastic recycling is a process of recovering plastic wastes or scraps and reusing the solid

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for production of valuable products [8]. The form of useful products can be either similar or different from virgin plastic [9,10]. Secondary recycling or mechanical recycling is the most popular recycling method. It refers to operations that recover plastic solid waste (PSW) via mechanical processes [11-14]. The new recycled material obtained can be converted into new plastic products, replacing virgin polymers or a part of virgin polymer [10-15].

Polypropylene (PP) is a low-density thermoplastic with excellent durability, fatigue resistance, and chemical resistance. PP has a high volume to weight ratio, glossy appearance, good optical properties, high tensile strength, waterproof and extremely resistant to moisture absorption which makes it suitable for packaging many products including food [16,17]. PP contributes to around 10% of plastic municipal solid waste. It can be recycled by mechanical methods after being washed to remove dirt where acceptable washing water quantity is only 1L/100gm of plastic with a duration up to 30 minutes [18].

Plastic injection molding is among the most popular mechanical methods that are used to recycle plastics including PP. This method can fabricate the products at a high production rate, which makes it beneficial to the world economy and industrial ecology [19]. Thermoplastics can be reused or recycled without any limit for several cycles. Earlier studies suggested that recycling is to be limited to twelve cycles. However, the recycled products become fragile and their appearance changes when recycled up to five times [20]. Another study proved that recycling polypropylene could enhance the tensile properties rather than impact properties [21,22]. In addition, it was shown that the quality of raw material significantly influenced the yield strength of the commercial recycled polypropylene [4]. A study investigated tensile properties of fully recycled polypropylene and proved that the yield strength decreased by 1.43% compared with virgin material [23]. In another study on mechanical properties, polypropylene was recycled up to fourteen times using injection molding, and no significance reduction of the tensile strength was reported [24]. In general, the possibility to use recycled materials depends on its mechanical and optical properties [25].

The aim of this study is to evaluate the economic benefit of four recycling cycles of boxes made up of PP, and to assess the effect of the repeated recycling processes on the mechanical and physical properties of the final product. The plastic boxes investigated in this real case study are used to store dry food and salad that are consumed inside an academic campus restaurant located in Alexandria, Egypt. The boxes were received after being collected and sorted by the campus designated staff. First, the boxes were washed using water at room temperature inside a designed washing tank followed by drying using a centrifugal force of a rotating drum. Second the boxes were crushed into small flakes that were then introduced to the third stage which is sterilization using ultraviolet (UV) radiation in the same way it is used for sterilization of food and grain products to control microorganisms [26]. It has been taken into consideration that UV is directed for a short time on small flakes vibrating on a moving conveyor to avoid degradation. In the fourth and final stage the polypropylene flakes are injected into a molding machine to produce recycled boxes. The whole recycling process was performed at the R&D workshops inside the campus.

The remainder of this paper is organized as follows: in Section 2 the methodology is shown including the detailed description of the four-stages recycling process, followed by Section 3 that shows the cost calculations, then Section 4 displays the experimental procedures of the three tests made on the PP boxes. The results of tests and their discussion are provided in Section 5. Finally, the conclusion drawn from this work are pointed out in Section 6.

2. Recycling Processes

PP is listed as a food grade material, so it is used to store food. The product investigated in this case study is a PP box that is used by the campus main restaurant to store dry food and salads. The box is made of two parts, the body, and the cover. After collecting and sorting the waste, the recycling process has been repeated up to four times to evaluate the quality and economic feasibility of recycling. Each recycling cycle is composed of four stages as shown in Figure 1.

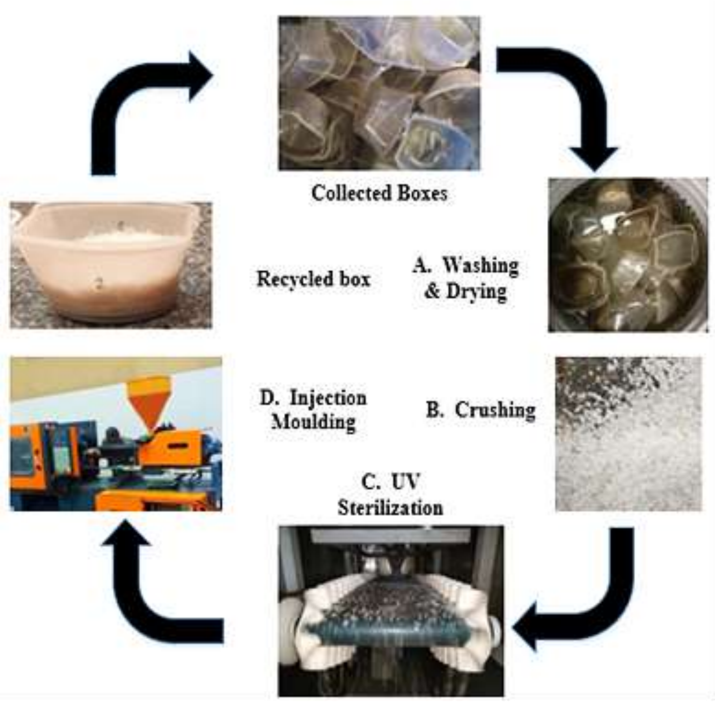

Fig. 1. Stages of the recycling process

2.1 Washing and Drying

The collected boxes are washed in a designed washing machine using water at room temperature, since the contained food is dry and free of fats. The washing capacity is 100 boxes/hr. The washing is followed by drying that is done by the washing drum rotating at 850 rpm. Washing is done before crushing to avoid clogging of washing drum with crushed plastic flakes.

2.2 Crushing

After washing and drying, the boxes are then crushed using a plastic crushing machine (DONGGUAN Machinery) at a rate of 115 boxes/min.

2.3 UV Sterilization

The surface of crushed flakes is then subjected to UV radiation inside a UV unit fully designed and manufactured by the R&D team with specifications previously set by empirical research [26], studying sterilizing grains with similar density and surface area, where surface area and consecutively the conveyor speed and intensity of radiation are among the most important factors. The designed vibrating mechanism in this study ensured a speed of 15 m/min. The intensity of radiation is 245 μW/cm2 to kill surface bacteria and other microorganisms. The unit has a sterilizing capacity of 2 kg/min.

2.4 Injection Molding

The last stage is the injection molding of PP flakes using a molding machine supplied by SWEITH Company. The molding parameters extracted from the machine manual and according to the range mentioned in previous studies [20-24], the temperature was set at 245 °C, and the injection pressure was kept constant at 90 bar. There are two separate dies for both the box body and the cover. The average rate of injection is 40 g/min, which is equivalent to two box bodies per minute.

3. Cost Calculations

To evaluate the cost of applying the repetitive recycling of PP boxes and the cost savings to the campus, an accurate calculation of the labor and equipment used in the recycling process stages, are shown in Table 1. Two recycling cases have been proposed and cost/unit for each case for a different number of recycling cycles are compared to the case of the current situation which is buying PP boxes from wholesalers without recycling as shown in Figure 2.

Table 1
Operating cost of one recycling cycle of 1000 box units

Op operation name	Rate (kg/hr)	Production time (hr.)	Electricity cost (EGP)	Labor cost (EGP)
Washing and drying	1.20	20.83	11.67	1,042
Crushing	138.00	0.18	0.63	9.06
UV sterilization	120.00	0.21	0.05	10.42
Injection moulding of boxes	2.40	8.83	35.25	441.67
Injection moulding of covers	1.00	5.50	21.95	275.00
Sorting and delivery				750
Total cost of one cycle of 1000 units (EGP)				2,528

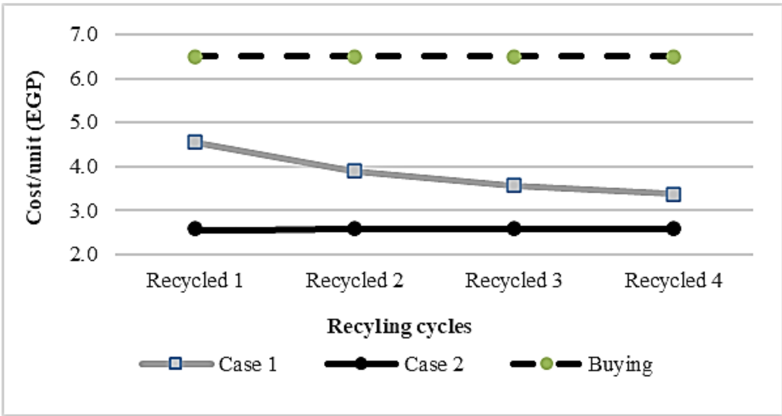

Fig. 2. Cost/unit comparisons between recycling cases and buying at different recycling cycles for 1000 units

3.1 Recycling Case 1

PP boxes will be bought and used by the restaurants then collected by the campus staff to be recycled for four repetitive cycles without buying. The cost of buying the first 1000 unit which is about

6500 Egyptian pounds (EGP) is considered and added to recycling cost. The cost per unit bought is 6 EGP (Figure 2).

3.2 Recycling Case 2

Virgin Material will be bought and injected inside the campus then recycled for four repetitive cycles. The cost of buying and injection of the virgin PP is about 2,573 EGP which is considered and added to the subsequent recycling cost. Cost per unit of virgin material bought and injected is almost kept constant at about 2.6 EGP/unit with different recycling cycles (Figure 2).

4. Methodology

Three tests were carried out to investigate the effect of the four recycling runs of the PP boxes. The PP used is an injection molding grade 1100 Homo polymer, white color, manufactured in Saudi Arabia. The three tests made are tensile test, hardness test, and density measurements.

4.1 Tensile Test

The tensile specimens with dimensions shown in Figure 3 and an average thickness of 0.7 mm were cut out of the box itself using a standard die applying a compression force via a hydraulic rocker pressure tester GT-KD20 as shown in Figure 4(a)

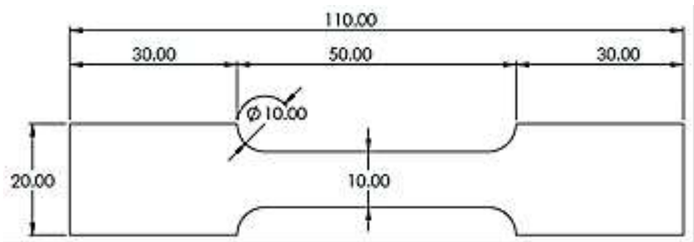

Fig. 3. Tensile specimen dimensions in mm

The tensile test was then performed using a TM2101 tensile machine with a load cell of maximum 50 kgf. The test was conducted at cross-head speed of 100 mm/min with a fixed distance between clamps set at 80 mm. The tensile results, force elongation curves, and stress strain curves are generated using Haida test v1.6 software. Eight samples were tested for each recycling cycle in addition to samples from virgin material. The results were reported and compared.

4.2 Hardness Test

Square samples for hardness test were cut the same way as tensile specimens but using a square die with a side length of 20 mm. The test was carried out using TINIUS OLSEN- FH1 Series universal tester. The hardness test was performed according to Rockwell R scale which is used for testing soft and thin plastic samples, Indenter is a tungsten carbide ball of 12.7 mm (1/2 in) diameter, with a total force applied equals to 588.4 N. Samples from four recycling cycles and the virgin material were tested with an average of ten readings for each sample. A virgin material sample tested for hardness is shown in Figure 4(b).

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4.3 Density Measurements

Density was measured by taking a sample of 10 gm from virgin material prior to injection molding and another four crushed samples from the consecutive recycling cycles. The sample mass was measured using a RADWAG digital balance with an accuracy of 0.01 g. The volume was measured using displacement flask by immersing the crushed sample in ethyl alcohol that is denser than polypropylene as shown in Figure 4(c). Density was then calculated by dividing the mass of the sample by its volume.

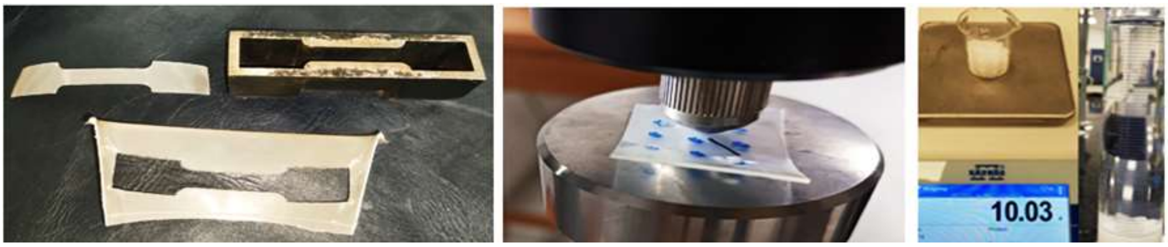


Fig. 4. Tests performed (a) Cutting a tensile sample (b) Hardness test (c) Density measurement

5. Results

5.1 Visual Inspection

The virgin material is semi-transparent, but repetitive recycling of the used boxes caused the box transparency to decrease gradually to an acceptable limit up to the third recycling cycle, the shape and finish is also degraded at the fourth cycle as shown in Figure 5.

Fig. 5. Samples from virgin PP and four recycling cycles

5.2 Tensile results

Tensile test was carried out at room temperature for 40 samples, 8 samples of each of the virgin material product and four recycled cycles products and the average results were calculated. stress strain curve for one of recycled 4 sample as an example is shown in Figure 6. Stress strain curve of one of recycled 4 sample. The tensile data displayed in Figure 7 are ultimate tensile strength, and elongation % at peak.

The results in Figure 7(a) showed that that the average ultimate tensile strength of virgin PP was 27.4 MPa, slightly higher than that obtained by an earlier study [21], but is within the range known for pp tensile strength [27]. After four recycling cycles the tensile strength had decreased by only 13.8 % and elongation % at peak increased by 10.1 % as shown in Figure 7(b).

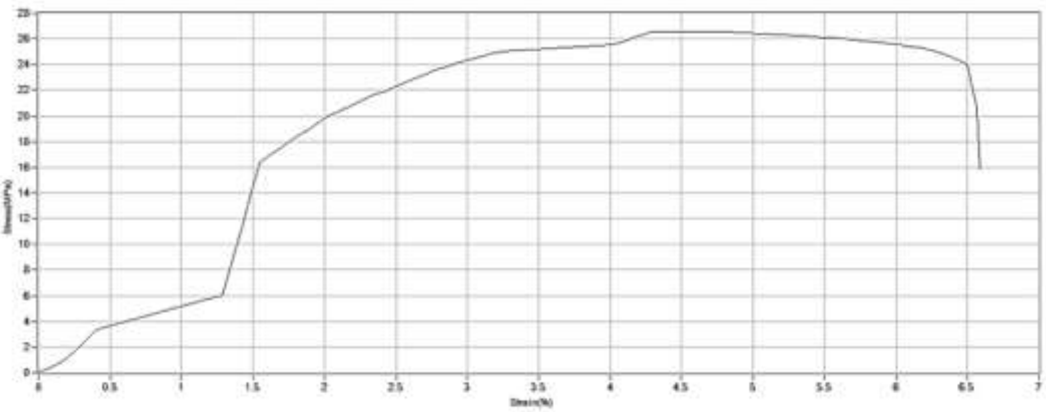
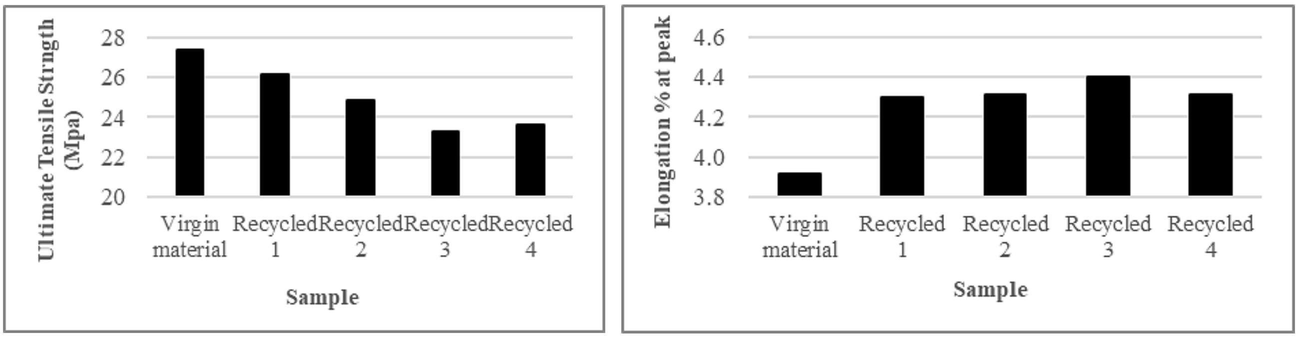


Fig. 6. Stress strain curve of one of recycled 4 sample



(a) (b)

Fig. 7. Tensile results comparison for virgin PP & four recycling cycles (a) Ultimate tensile stress (b) Elongation % at peak

5.3 Hardness results

Indentation hardness reflects the resistance of material surface to deformation [28]. From results shown in Figure 8, the hardness of virgin material product reached 53.7 HRR, the hardness decreased only by 3.4 % at the third recycled cycle but decreased dramatically by 28.2% at the fourth recycled cycle which may be due to effects of consecutive crushing and injection.

5.4 Density Results

Density measured for virgin pellets were 0.91 g/cm3, slightly increased to 1.00 g/cm3after the first cycle and then remained constant for the subsequent cycles.

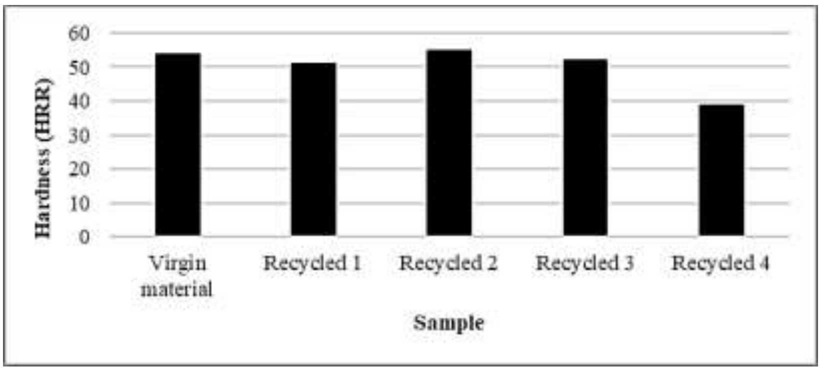


Fig. 8. Hardness results for PP samples

6. Conclusions

This study provides an evaluation of the cost effectiveness and quality of repetitive recycling of PP boxes used inside a faculty main campus. Cost evaluation of two proposed recycling cases for recycling 1000 units proved that case 2 of buying and injecting virgin PP would decrease the unit cost up to 60 % after recycling 3 or 4 times compared to buying wholesaled new boxes. Recycling the wholesaled boxes will only decrease the cost by 48 % after four times recycling. This proves the effectiveness of the recycling process. The visual inspection on transparency and shape proved that only three recycling cycles are enough to keep acceptable quality. Tensile properties are the most affected property after recycling three or four times, but still acceptable as ultimate tensile strength decreased by 15 % and elongation % decreased by 12 %. Hardness and density didn't show any significant change after recycling. Future work can be performed on other types of plastics, Co-polymers from 3D printing waste and biodegradable plastics.

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