Original Article

Louise Pick*, Paul R. Hanna and Luke Gorman

Assessment of processability and properties of raw post-consumer waste polyethylene in the rotational moulding process

<https://doi.org/10.1515/polyeng-2021-0212>

Received July 22, 2021; accepted December 26, 2021;

published online February 7, 2022

Abstract: This paper presents work from an ongoing study into the use of post-consumer waste polymer in the rotational moulding process. Raw plastic recycle, predominantly consisting of polyethylene, was processed into polymer powders containing an additive package suitable for rotational moulding, with and without the addition of a compatibiliser. Rheological studies on the materials showed very high viscosities at low shear rates in comparison with materials typically used in rotational moulding, which has significant implications for melt flow and bubble removal during the process. It was possible to mould the materials successfully, but poor surface finishes were achieved. Impact strength was drastically lower for recycle mouldings compared with virgin material. Tensile strength of the recycle mouldings was reduced compared to virgin polyethylene, but results indicated that optimising the processing conditions could lead to improvements. This work gives some baseline indicators to inform further planned work on optimising processing conditions and identifying viable material compositions.

Keywords: mechanical properties; polymer recycling; post-consumer waste; rheology; rotational moulding.

1 Introduction

Increased focus on sustainability in recent years has aimed to develop clear strategies for dealing with plastic waste, with a particular increase in awareness of the issues relating to single-use plastic products, and of problems in recycling other plastic products at the end of their life-cycles. While recycling schemes have become more common, and sorting of household waste is now widespread, problems remain in being able to fully utilise collected plastic waste [1]. Despite increased separation of domestic waste for recycling many problems remain due to issues such as contamination of waste streams with other materials, solvents or food waste. In addition, recycling often reduces the mechanical or chemical properties of the material and there can be large variations in properties of different recycled batches making quality control difficult.

In the UK, it is reported that in 2018, 4 million tonnes of post-consumer plastic waste was collected ~32% of this was recycled, around 47% was used in energy recovery and around 22% went to landfill. In terms of plastics packaging, 2.3 million tonnes were collected in the same year, with 44% being recycled, 42% being used for energy recovery and 14% going to landfill. While all these figures have shown a positive trajectory in recent years there is still significant scope to increase the amount of plastic material being recycled [2].

The rotational moulding process is a common method used for producing hollow plastic products. Often, it is chosen for large product applications such as water and chemical storage tanks due to the relatively low cost of moulds, good wall thickness uniformity and low residual stresses in the products produced [3]. This common use in large products provides potential for incorporation of high quantities of recycled material into the process, for example storage tanks can often be over 5000 L in capacity, and double-skinned versions can require shot weights in excess of 300 kg. Replacing even a proportion of the virgin material in such products with recycled material can have positive environmental and cost implications.

*Corresponding author: Louise Pick, School of Mechanical and Aerospace Engineering, Queen's University of Belfast, BT9 5AH, Northern Ireland, UK, E-mail: l.pick@qub.ac.uk. <https://orcid.org/0000-0003-0629-4698>

Paul R. Hanna and Luke Gorman, Polymer Processing Research Centre, Queen's University of Belfast, BT9 5AH, Northern Ireland, UK, E-mail: p.r.hanna@qub.ac.uk (P.R. Hanna), lgorman05@qub.ac.uk (L. Gorman)

A review of the literature reveals a very limited number of studies which have been published into the use of raw recyclate or recycled material in rotational moulding. A number of these have concentrated on using materials consisting of a single polymer type, or compatible polymer types. For example, Dou and Rodrigue [4] looked at using recycled HDPE in the rotational moulding process to produce foamed parts and concluded that there was potential in using recycled material for this purpose. However, the material originated from a single source of HDPE bottles so lacks the challenges that are involved in moulding recycled polyethylene containing levels of other incompatible polymers which is typical of post-consumer plastic waste. There was also no comparison to the performance of the material in its virgin form. Another recent study [5] looked at blending virgin LLDPE with recycled HDPE for septic tank applications and found that up to 50:50 blends produced a material with appropriate viscosity and good mechanical properties.

Many more issues are likely to arise with post-consumer waste, as it tends to contain multiple contaminants. A study by Diaz et al. [6] investigated the potential to use the polymeric component of end-of-life cable waste in the rotational moulding process. While this is not post-consumer waste as would be typically found in household recycling, it did nonetheless contain various contaminants including other polymers and even metal residues which constituted up to 16% of the overall content. The study found that reductions in flexural and tensile strength occurred almost linearly with increasing recyclate content, but that a dramatic reduction in impact strength was seen with only 10% of recyclate material.

A WRAP commissioned report [7] investigated potential market applications for waste post-consumer polyethylene film sourced from UK kerbside mixed recycling collection. The report described moulding trials with post-consumer recyclate that were carried out using a variety of processes, including rotational moulding. The rotational moulding studies were carried out on blends of recyclate and virgin MDPE, which were used to produce a range of products. Mouldings of acceptable aesthetic quality were produced, but there was notable deterioration in surface finish and an increase in the number of pinholes in the products as the percentage of recyclate in the material increased. Poor quality of the polymer powder was noted, which was identified as an influencing factor on problems with surface finish. A second milling of the powder to reduce particle size appeared to provide some improvement in surface finish. Only qualitative analysis on the quality of moulded parts was performed with no consideration of the effect on mechanical properties.

Cestari et al. investigated the use of blends of post-consumer and virgin polymer from a range of sources in various processes including rotational moulding [8]. They found decreasing mechanical properties with increasing quantities of recyclate material, but better results were achieved by platen pressing the same materials, suggesting that some process optimisation of the rotational moulding process may lead to improved results.

The objectives of this study are to assess the mouldability and mechanical properties of post-consumer waste plastic in the rotational moulding process, providing baseline data which can then be used in further work to identify optimised processing parameters and material combinations.

2 Materials and methods

2.1 Raw materials

The recyclate material used in this study originated from a mixed plastic post-consumer waste stream which was received by a recycling plant. The material was sorted using a density separation process to separate the mixed stream into individual polymer types. While the aim of the process is to achieve batches consisting of a single type of polymer this is in practice very difficult and batch purity ranges from 70 to 98%. The recyclate material used in this study was a batch predominately consisting of various unknown grades of polyethylene, initially believed to be towards the higher end of the range of purity with around 95% polyethylene content. Testing, however, using differential scanning calorimetry, later confirmed purity to be in the range 57–68% polyethylene. The remaining content is mostly polypropylene but may also include impurities such as pigments, additives, inks, adhesives, and other residual contamination.

Two “baseline” materials were chosen for comparison, these included a natural virgin polyethylene rotational moulding grade (vPE), and reground green pigmented polyethylene which was produced from scrap tanks from a rotational moulding factory (reground green tanks, RGT). The RGT material could potentially consist of one or a mixture of three similar rotational moulding tank grades of polyethylene used in the factory at that time. The RGT material was used to give an indication of the effect of reprocessing, without the additional factors in the recyclate material such as potentially significant contamination, unknown number of grades of materials, a range of processes which have been used to produce the products that have been recycled and unknown use conditions.

2.2 Preparation of polymer powder

The material was supplied as raw chipped flake and therefore required a number of preparation steps to produce a powder suitable for the rotational moulding process. This included a pre-compounding step using a single-screw extruder to produce pellets which could then be ground to a powder and dry-blended with the additives. A further compounding step was carried out using a twin-screw extruder followed by pelletising, grinding and rotational moulding.

Single-screw extrusion was carried out using a Killion 150 KN, 38 mm compounding unit, fitted with a barrier screw to promote mixing of the recyclate material. A single pass through the extruder was used. The barrel temperatures of the single-screw extruder were: 195 °C (die), 195 °C (adaptor), 185 °C (clamp ring), 185 °C (zone4), 180 °C (zone3), 180 °C (zone2), 180 °C (zone1).

The blends were compounded using a Collins ZK 25 co-rotating twin-screw extruder. The die and five barrel heating zones were set to 200 °C with the feed zone set to 180 °C.

Cryogenic grinding (to avoid melting of the PP content in the recyclate) was carried out on a Wedco SE-12-TC pilot plant grinding machine using 12" milling plates with 480 teeth and a gap size of 500 microns. Approximately 2 kg of recyclate pellets were placed in a vacuum insulated stainless steel Dewar flask and liquid nitrogen poured onto the pellets until the liquid level was above the pellet. The pellets were left to soak for approximately 10 min before being manually fed into the grinding machine using a ceramic cup. The resulting powder was collected from the outlet pipe of the grinding head using a pillowcase which allowed the entrained air to escape whilst also capturing the ground powder.

In this study the effect of compounding typical rotational moulding additives as well as compatibiliser (an ionomer of ethylene acid copolymer with a density of 0.94 g/cm³ and an MFI of 1.8 g/10 min) into the material was studied. By way of example, a typical series of material preparation steps were as follows:

- (1) Chipped flake recyclate dried for 72 h in a Jenco, recirculating, hot air, desiccant dryer at 60 °C. The dew point of the dry air was -40 °C.
- (2) Dried flake passed through a single-screw extruder and pelletised.
- (3) Pellets cryogenically ground to produce a powder.
- (4) Ground powder separated into five batches as shown in Table 1.
- (5) Additives (typically incorporated into rotational moulding grades of polymer) were ground using a pestle and mortar and blended into batches of recyclate using a Prism Pilot three high-speed mixer.
- (6) Blends were melt compounded using a twin-screw extruder with the resulting pellets cryogenically ground into a powder.

2.3 Rheology

The rheological properties of the compounded blends and two baseline materials [virgin PE (vPE) and post-industrial reground green tank (RGT)] were determined to assess their likely behaviour during the melting/densification stage of the rotational moulding process. Melt flow index (MFI) testing according to BS EN ISO 1133-1:2011 was initially carried out followed by a more detailed study using oscillatory rheometry according to BS EN ISO 3219:1995, at a temperature of 190 °C. This allowed comparisons to be made between the blends at near zero shear rate which is typical of the rotational moulding process.

2.4 Differential scanning calorimetry

In order to assess the crystallinity of each blend, and to obtain an estimate of the relative percentages of polyethylene and polypropylene within each blend, differential scanning calorimetry (DSC) was carried out according to BS EN ISO 11357-3:2018 on a Perkin Elmer DSC machine. Between 7 and 9 mg of material was used for each sample, and sealed in an aluminium pan. The samples were heated and cooled from 30 to 300 °C, followed by one reheat cycle. The enthalpies of crystallisation of the PE and PP components (ΔH) were determined on reheat, and percentage crystallinity of each component was determined by Eq. (1), with the theoretical enthalpies of crystallisation of polyethylene and polypropylene taken as 293 J/g and 209 J/g respectively.

$$\% \text{ Crystallinity} = \frac{\Delta H_{\text{Measured}}}{\Delta H_{\text{Theoretical}}} \times 100 \quad (1)$$

2.5 Powder quality analysis

In the rotational moulding process, there are several indicators of powder quality which have an influence on powder flow and packing

Table 1: Recyclate batches and baseline materials.

	Material code	Description	Zinc stearate%	Anti-oxidant Irganox B215%	UV Stabiliser Tinuvin 783 FDL%	Compatibiliser%
Recyclate batches	rPE	Recyclate blend with 1 heat history (single round of extruder compounding)	0	0	0	0
	rPE/E	Recyclate blend with 2 heat histories (two rounds of extruder compounding)	0	0	0	0
	rPE/E + A	Recyclate blend with 2 heat histories (with additives ~ antioxidants, zinc stearate and UV stabiliser)	0.1	0.15	0.15	0
	rPE/E + C	Recyclate blend with 2 heat histories (with PE-PP compatibiliser)	0	0	0	10
	rPE/E + A + C	Recyclate blend with 2 heat histories (with additives ~ antioxidants, zinc stearate, UV stabiliser AND PE-PP compatibiliser)	0.1	0.15	0.15	10
Baseline comparison materials	VPE	Matrix revolve 5056 N-307 natural virgin polyethylene	N/A	N/A	N/A	N/A
	RGT	Matrix revolve 5056 N-307 green pigmented post-production scrap tanks	N/A	N/A	N/A	N/A

in the initial stages of processing, bubble removal, final surface finish and mechanical properties [9–15]. The main properties commonly measured are the time taken for 100 g of powder to flow through a standard sized funnel (dry flow rate), the packing of the powder (bulk density) and particle size distribution. Dry flow and bulk density testing were carried out according to standard ASTM D 1895 and particle size distribution analysis according to ASTM D 1921.

2.6 Moulding trials

All recycle and baseline batches were rotationally moulded on a Ferry Rotospeed machine. An aluminium cube test mould (300 × 300 × 300 mm) was used to manufacture parts from which test specimens could be cut. A shot weight of 1.8 kg resulted in a nominal 3 mm wall thickness. The oven set temperature was 300 °C and an arm:plate speed of 8 rpm:2 rpm was used. A datapaq temperature acquisition system was used to measure in real-time the air temperature inside the mould during processing. For each material, two mouldings were produced, one exiting the oven at an internal air temperature of 140 °C and the other exiting at 190 °C. This achieved peak internal air temperatures (PIATs) of approximately 180 °C and 220 °C, respectively.

2.7 Mechanical testing

Tensile testing was performed on a Lloyd LS5 machine according to BS EN ISO 527:2019 at a strain rate of 5 mm/min. Drop dart impact testing was carried out according to BS EN ISO 6603-2:2000 on a CEAST Fractovis falling dart impact testing machine, at both room temperature and –40 °C.

3 Results and discussion

3.1 Rheological properties

The difference in melt flow rate (Table 2) amongst the blends ranged from 2.80 g/10 min for post-industrial waste (reground tank) to 4.14 g/10 min for recycle without additives or compatibiliser. This was encouraging as these were therefore all within a range that would be considered appropriate for use in the rotational moulding process, where typical values range from 2–10 g/10 min [16]. Whilst melt flow rate is a commonly used metric within the

Table 2: MFI testing results.

	MFI (g/10 min)
VPE	3.33
RGT	2.80
rPE	4.14
rPE/E	3.05
rPE/E + C	2.85
rPE/E + A + C	2.81

industry, the rotational moulding process is characterised by very low shear rates and therefore further analysis of the rheological properties was carried out using oscillatory rheometry.

The results from oscillatory rheometry are shown in Figure 1 where it was observed that blends containing recycle exhibited much higher values of zero shear viscosity compared to the two baseline rotational moulding grade powders. This is known to have a major influence on the processibility of the resins by making it more difficult for air molecules within bubbles to dissolve into the viscous polymer melt that surrounds each bubble. The polyethylene contained within post-consumer recycle is likely to contain a high proportion of high density grades with low MFI and therefore it is not unexpected that a more viscous melt would be observed. The longer polymer chains associated with higher viscosity melts resist the diffusion of air molecules through the polymer and therefore reduce the rate at which air molecules can dissolve into the melt across the bubble/melt boundary. This can subsequently have a detrimental effect on mechanical properties, especially impact resistance, as the entrapped bubbles become voids on cooling beneath the melt temperature and act as sites where cracks can initiate and propagate more easily. These bubbles near the outside surface will also result in a lower quality outer surface finish known as ‘pin-holes’. A study by Greco et al. [9] also suggests that sintering in recycled HDPE which is the joining and fusing together of adjacent melting polymer particles will only occur if the viscosity is sufficiently low, which would suggest further that bubbles in HDPE are more difficult to remove from the melt and likely require higher temperatures than typical rotational moulding grades of polyethylene.

3.2 Differential scanning calorimetry

Results from the DSC testing (Table 3) showed that there was a notable variability in the composition of the blends, with the percentage of polyethylene varying between approximately 58–68% compared to 32–42% of polypropylene. This is problematic when trying to develop processing recommendations for inherently non-homogeneous material batches. In addition, the purity of the recycle batches was much lower than expected overall the total crystallinity of the recycle blends slightly increased with a second extrusion pass, and again with the addition of additives of the polyethylene component in the recycle blends as additives were introduced.

Figure 1: Viscosity of blends at low shear rates.

Table 3: Differential scanning calorimetry results.

Batch	PE% crystallinity	PP% crystallinity	Total% crystallinity	Percentage of PE	Percentage of PP
rPE	18.03	10.22	28.25	63.84	36.16
rPE/E	18.67	13.69	32.36	57.70	42.30
rPE/E + C	22.95	10.63	33.59	68.34	31.66
rPE/E + A + C	23.52	11.89	35.41	66.41	33.59
vPE	36.41	0.00	36.41	100.00	0.00
RGT	44.82	0.00	44.82	100.00	0.00

3.3 Powder quality analysis

Table 4 shows the results from dry flow and bulk density testing. The lowest dry flow time is observed for the virgin PE, increasing by 22% for the RGT powder and between 33 and 53% for the recyclate batches. This indicates that flow of the powder within the mould during the initial heating and lay-up stages may be somewhat reduced compared to virgin PE and could have implications for wall thickness distribution. Previous work [3] has indicated that a dry flow time between 20 and 30 s is preferable in rotational moulding with only the rPE/E + C blend being significantly above this at 34.7 s.

The bulk density of the virgin PE and the RGT powders were identical, but recyclate blends showed a reduction in bulk density of 11–17%. This indicates less efficient packing in these powders which can have a direct effect on

Table 4: Dry flow and bulk density results.

Material	Dry flow time (s)	Bulk density (g/cm ³)
vPE	22.6	0.364
RGT	27.5	0.364
rPE	30.0	0.325
rPE/E	30.3	0.301
rPE/E + A	30.5	0.315
rPE/E + C	34.7	0.303
rPE/E + A + C	30	0.364

consolidation of the melt and bubble removal in the rotational moulding process [17].

The particle size distribution of the various blends (Figure 2) are similar for all recyclate batches however these differ significantly when compared with the two baseline materials. The vPE and RGT powders show a distribution that is more in line with those commonly used

Figure 2: Particle size distribution.

in the rotomoulding process, where powders are ground to below 35 mesh size (500 μm maximum particle size) [18]. In contrast, the recyclate powders contained 42.5–55.0% of particles which were greater than 600 μm. This is likely to have a strong influence on powder flow and layup, the

behaviour of the melt, and some influence on the quality of the surface finish of the mouldings produced.

Microscopy of the powder samples (Figure 3) showed that the VPE and RGT powder samples were generally rounded in shape than the recyclate blend samples, which

Figure 3: Microscopy images of powder. Top left to right: VPE, RGT, rPE. Bottom left to right: rPE/E, rPE/E+C, rPE/E+A+C.

tended to consist of sharper and more irregularly shaped fragments. This is consistent with the results from powder quality tests.

The reduction in all three measures of powder quality for the recycle batches are likely to largely be due to the cryogenic grinding process used which causes brittle fracture of pellet fragments. The vPE and RGT batches on the other hand were ground above room temperature where pellets undergo a series of high-speed, shearing, cuts rather than brittle fracture. Micrographs taken of the various powders displayed much more rounded, smooth and more consistently sized particles for the virgin PE in comparison to the recycle powders which are of much more angular shape and a greater range of sizes.

3.4 Moulding trials

Visual inspection of the mouldings showed excellent surface finish for the vPE mouldings but very poor internal surface finish for all the recycle batches. The internal surface was very rough and uneven, and displayed evidence of unconsolidated patches, potentially indicating that not all the material had become molten during the processing stage. The RGT mouldings showed some minor ‘orange-peel’ effect on the inner surface.

The poor surface finish of mouldings incorporating recycle was consistent with the zero shear viscosity results along with the lower powder quality reported above. However, it is likely that there are other factors which have contributed to the extent of the poor surface finish. These could include the inherent incompatibility of any minor polymer components within the melt, as well as the effect of non-polymer contaminants in the blends e.g. inks and glues and non-ideal processing conditions for the particular polyethylene grades within the recycle.

3.5 Mechanical testing

3.5.1 Tensile testing

The two baseline materials which did not contain any PP (vPE and RGT) had very similar tensile strength and tensile modulus (Figure 4) and this was not significantly influenced by internal air temperature at removal from the oven. Much lower values of tensile strength were recorded for all blends containing recycle at approximately 30% of that seen for vPE. The wide range of grades of both PP and PE likely to be contained within the post-consumer recycle used are thought to be major contributing factors to the reduction in tensile strength seen in these tests. It was also

Figure 4: Tensile test results.

observed that both the additive package and compatibiliser used in this study did not appear to significantly improve the tensile strength. In contrast with tensile strength, the Young's modulus of the recyclate mouldings did not show consistently lower values when compared with the vPE/RGT samples; in fact, several of the recyclate mouldings had notably higher modulus values. This is thought to be due to the recyclate containing a proportion of PPs and PEs with much lower (fractional) MFIs that are typical of bottles, tubs and pots. This is supported by the higher zero shear viscosities of recyclate blends observed using parallel plate rheology and reported in Figure 1. When comparing the effect of processing temperature for recyclate mouldings, statistically significant improvements in modulus were seen at an oven removal temperature of 190 °C for all recyclate blends except the rPE/E + C mouldings where no difference was observed (Table 5). Whilst higher processing temperatures in rotational moulding would typically be associated with more bubble removal and better mechanical properties as a result, for recyclate blends, it is possible that the polypropylene content within the recyclate samples, which would have a melting temperature range of approximately 160–170 °C, may not have enough time to fully consolidate in the samples processed with an oven removal temperature of 140 °C (reaching PIAT of approximately 180 °C). This may also help to explain the differences in performance between the samples removed from the oven at 140 °C compared to 190 °C.

3.5.2 Impact testing

The results of drop dart impact testing are presented in Table 6. For all blends incorporating recyclate the impact strength was drastically reduced when compared to the vPE or RGT samples. Peak impact strength for recyclate blends were below 0.5 J/mm and total impact strength below 1 J/mm, for both internal air temperatures at removal from the oven. There are some important points to note

Table 5: *t*-Test showing effect of processing conditions on Young's modulus.

<i>t</i> -test comparing Young's modulus values at two processing conditions of 140 °C and 190 °C oven exit temperature	<i>p</i> -Value	Significant?
rPE	<0.001	Yes
rPE/E	0.036	Yes
rPE/E + A	0.001	Yes
rPE/E + C	0.797	No
rPE/E + A + C	0.004	Yes

Table 6: Average drop dart impact strength.

	Oven pull temperature (°C)	Peak impact strength (J/mm)		Total impact strength (J/mm)	
		20 °C test	−40 °C test	20 °C test	−40 °C test
vPE	140	9.12	9.82	16.33	17.01
vPE	190	9.05	6.57	15.17	7.14
RGT	140	6.62	4.55	11.24	4.89
RGT	190	7.92	6.33	13.33	6.81
All recyclate blends	140 and 190	<0.5	<0.5	<1	<1

regarding the impact results from these “baseline” samples. Firstly, the drop in low temperature impact strength of the samples removed from the oven at 190 °C is unexpected and would indicate suboptimal processing or other factors. For example, drops in low temperature impact can be caused by contamination, or by “overcooking” of the mouldings causing oxidation of the inside surface [19–22], although this would not normally be expected until a higher oven removal temperature. This does however highlight the need to optimise processing conditions to ensure no detrimental effects on any of the mechanical properties.

A second point to note is the clear reduction in impact performance of the recycled green tank (RGT) material compared with vPE. The recycled tanks from which this material came from had been manufactured using a dry-blend of vPE and green pigment which will have had an influence on impact performance. This has been observed by other authors and has been attributed variously to poor dispersion of pigment and in some cases localised nucleation [23–27]. As noted previously, there are also potentially three grades of polyethylene in the RGT material, which may have an influence. These RGT values are important as they indicate the levels of impact strength that are acceptable for certain products and applications within current markets. Additionally, it would seem highly likely that these reduced levels of impact strength would be at the maximum end of what could be expected if blending significant quantities of post-consumer waste into virgin polyethylene, given that unrefined recyclate contains a variety of polymer grades as well as impurities.

4 Conclusions

This baseline work on rotational moulding of plastic recyclate has highlighted several areas that need to be

addressed in further work. Firstly, while MFR testing on recyclate blends sourced from post-consumer plastic waste indicated MFI values that were in an acceptable range for rotational moulding, further rheological testing showed clear evidence that for all recyclate blends there was a very large increase in viscosity at the very low shear rates which are typical of the process. DSC testing also revealed notable variability in the recyclate material, and higher levels of PP contamination than expected. This can have profound implications for the processability of such materials. Work is currently being carried out to better understand the rheological behaviour of these materials and will be reported upon in due course. It will be important to determine how to best process materials which exhibit these high viscosities at low shear rates, and also develop guidelines on acceptable ranges of material compositions received from recycling plants.

Powder quality issues were found when cryogenically grinding the blends, which also can directly impact on powder flow, sintering, bubble removal (densification) and subsequent surface finish and mechanical properties. Rotational moulding trials showed that parts could be successfully manufactured using recycled plastic blends but that their surface finish and quality was not ideal. The suitability of these materials for any given product depends on its design and function as well as the mechanical properties required.

Impact performance was the most negatively affected of the mechanical properties tested, and further work is being designed to assess how to achieve improved impact strength.

Tensile strength of the mouldings produced from recycled material displayed a drop compared to the vPE and RGT samples. Young's modulus for four out five of the recyclate samples showed statistically higher values when the mouldings were processed at the higher temperature. Further planned work will also assess the potential for blending recyclate with virgin material and/or producing multilayer mouldings in order to compensate for the drops in mechanical properties as well as aiming to identify optimum processing conditions.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: None declared.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

1. Hopewell J., Dvorak R., Kosior E. Plastics recycling: challenges and opportunities. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 2009, 364, 2115–2126.
2. Plastics Europe. G. M. R. conversion market & strategy GmbH. *Plastics – the Facts 2020*, 2020.
3. Crawford R. J., Throne J. L. *Rotational Molding Technology*; William Andrew, 2001.
4. Dou Y., Rodrigue D. Morphological, thermal and mechanical properties of recycled HDPE foams via rotational molding. *J. Cell. Plast.* 2021, 1–19; <https://doi.org/10.1177/0021955x211013793>.
5. Chaisrichawla S., Dangtungee R. The usage of recycled material in rotational molding process for production of septic tank. *Mater. Sci. Forum* 2018, 936, 151–158.
6. Díaz S., Ortega Z., McCourt M., Kearns M. P., Benítez A. N. Recycling of polymeric fraction of cable waste by rotational moulding. *Waste Manag.* 2018, 76, 199–206.
7. Freegard K., McCarthy R., McKinlay R., Morrish L. *End Market Applications for Household Polyethylene Film Pellets*; Wrap: Oxon, 2014.
8. Cestari S. P., Martin P. J., Hanna P. R., Kearns M., Mendes L. C., Millar B. Use of virgin/recycled polyethylene blends in rotational moulding. *J. Polym. Eng.* 2021, 41, 509–516.
9. Greco A., Maffezzoli A. Polymer melting and polymer powder sintering by thermal analysis. *J. Therm. Anal. Calorim.* 2003, 72, 1167–1174.
10. Pick L. T., Harkin-Jones E. Effect of mould pressurisation on impact strength of rotationally moulded polyethylenes. *Plast. Rubber Compos.* 2006, 35, 324–330.
11. Spence A. G., Crawford R. J. The effect of processing variables on the formation and removal of bubbles in rotationally molded products. *Polym. Eng. Sci.* 1996, 36, 993–1009.
12. Xu L., Crawford R. J. Analysis of the formation and removal of gas bubbles in rotationally moulded thermoplastics. *J. Mater. Sci.* 1993, 28, 2067–2074.
13. McDaid J., Crawford R. J. Grinding of polyethylene powders for use in rotational molding. In *Annual Technical Conference – ANTEC, Conference Proceedings*, Atlanta, 1998; pp. 1943–1947.
14. Olinek J., Anand C., Bellehumeur C. T. Experimental study on the flow and deposition of powder particles in rotational molding. *Polym. Eng. Sci.* 2005, 45, 62–73.
15. Gogos G. Bubble removal in rotational molding. *Polym. Eng. Sci.* 2004, 44, 388–394.
16. Lyondellbasell. *Guide to Rotational Molding*; LyondellBasell: Houston, 2001; pp. 1–16.
17. Kontopoulou M., Vlachopoulos J. Bubble dissolution in molten polymers and its role in rotational molding. *Polym. Eng. Sci.* 1999, 39, 1189–1198.
18. Throne J. L., Sohn M.-S. Characterization of rotational molding grade polyethylene powders. *Adv. Polym. Technol.* 1989, 9, 181–192.
19. Cramez M., Oliveira M., Crawford R. Optimisation of rotational moulding of polyethylene by predicting antioxidant consumption. *Polym. Degrad. Stabil.* 2002, 75, 321–327.
20. Cramez M. C., Oliveira M. J., Crawford R. J. Optimization of the rotational moulding process for polyolefins. *Proc. Inst. Mech. Eng. B Manag. Eng. Manufact.* 2003, 217, 323–334.

21. Spence A. G., Crawford R. J. Removal of pinholes and bubbles from rotationally moulded products. *Proc. Inst. Mech. Eng. B Manag. Eng. Manufact.* 1996, 210, 521–533.
22. Oliveira M. J., Cramez M. C., Crawford R. J. Structure-property relationships in rotationally moulded polyethylene. *J. Eng. Appl. Sci.* 1996, 31, 2227–2240.
23. Nagy T., White J. L. The effect of colorants on the properties of rotomolded polyethylene parts. *Polym. Eng. Sci.* 1996, 36, 1010–1018.
24. Kearns M. P., McCourt M. P., Ervik R. The effect of pigment on rotomoulded polyethylene powder and micropellets. In *Annual Technical Conference – ANTEC, Conference Proceedings*, Charlotte, NC, 2006; pp. 1963–1967.
25. McCourt M. P., McNally G. M., Kearns M. P., McConnell D. C., Martinez-Cobler M., Murphy W. R. The effect of pigmentation on crystal growth during rotomoulding. In *Annual Technical Conference – ANTEC, Conference Proceedings*, Boston, 2005; pp. 146–150.
26. Hanna P. R., McNally G. M., Kissick J., Kearns M., Murphy W. R. The effect of polyethylene catalyst type and pigment concentration on crystal growth during rotomoulding. In *Annual Technical Conference – ANTEC, Conference Proceedings*, 2006; pp. 1943–1947.
27. Cramez M. C., Oliveira M. J., Crawford R. J. Effect of pigmentation on the microstructure and properties of rotationally molded polyethylene. *J. Mater. Sci.* 1998, 33, 4869–4877.