PIM moulding of post consumer mixed plastics

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Abstract

Post consumer plastics from household are highly mixed and contaminated and are thus particularly difficult to recycle. Although advances in sorting and cleaning technologies for waste plastics have enable the relatively pure and clean streams such as bottles to be recycled, there is a increasing need for processing technologies that can utilise the low grade and mixed plastic residues from the plastics recovery facilities (PRF). In this work, potentials of utilisation of such feedstock in Powder Impression Moulding (PIM), a process capable of fabricating lightweight sandwich structures, are investigated in terms effects of loading and size of flakes from PE-rich mixed plastics in the formulations of the core on flexural properties of the sandwich panels. It was demonstrated that sandwich panels can be made by incorporating about 75 wt% of coarse flakes of a low-grade mixed plastics material directly obtained from a PRF.

Keywords: PIM, recycling, post-consumer, mixed plastics, sandwich panels

1 Introduction

Unlike plastic waste from industrial processes, post consumer plastics from household consist of many different types of plastics and often contaminated and mixed with residues of label, paper and ink etc. This poses great challenges in sorting and cleaning of post consumer plastics for purpose of recycling[1]. In recent years, significant advances have been achieved in plastic waste separation technologies using combination of flotation/sedimentation[2-3], magnetic/optical [4-5] colour and chemical composition[6-7] segregation methods. This, together with the use of extensive cleaning processes, has enabled the "low hanging fruits" – the relatively pure and clean sources of plastics (e.g. HDPE milk bottles and PET drink bottles) to be recycled to food grade[8]. Recently, the UK government has conducted an industrial-scale trial which demonstrated that it is technically and commercially viable to recycle non-bottle post consumer plastics[9]. With each step improvement in purity, however, more complex and expensive systems are required, which results in higher investment and running costs and more material rejection. It is thus highly desirable that novel processing technologies can produce high quality products utilising the relatively low-grade recycled plastics containing considerable residues produced at intermediate stages of a sorting and cleaning line on a plastic recovering facility, PRF. However, recycling of such plastics poses a great challenge. The heterogeneous composition, immiscibility and poor interfacial adhesion between dissimilar plastics may result in poor mechanical properties and poor processability[10]. In conventional mechanical recycling, such feedstock will result materials usable only for low-grade applications such as outdoor bench or drainage pipes.

Powder Impression Moulding (PIM) is designed to mould lightweight panels with solid skins sandwiching a foamed core and possesses great potential for incorporating low-grade and mixed plastics recyclates in powder or flake forms[11]. A thin layer of powder materials is spread on two halves of a heated flat–bed mould and sintered to form solid skin layers and on one of the moulds, powder with blow agent for the core is added. The moulds are then closed and heated to a temperature at which a foamed core is produced and bond to the surfaces. As minimum material flow is required and the non-molten particles (e.g. impurities or contaminants) can be encapsulated by the dominant composition in the material, PIM is much more tolerant to the incorporation of mixed plastics or impurities in the feedstock than conventional extrusion and moulding techniques as means of mechanical recycling. This enables PIM to produce high performance sandwich panels that have found many applications in construction e.g. hauling boards, bathroom wet floor systems and concrete moulds and hybrid structures with embedded pipes or reinforcements[11].

Feedstock in the PIM process is normally pulverised to fine particle powder (~0.5 mm) for adequate flow behaviour and uniformity of structure. Preparation of such fine powder can be energy intensive and thus it is highly desirable to utilise coarse flakes directly produced from a PRF and avoid extensive size reduction.

In this work, a HDPE powder recycled from milk bottles was used for the skin. Coarse flakes of PE-rich mixed plastics obtained from a PRF were prepared to different sizes and incorporated in a LDPE powder for the core. The influences of particle size and loading of mixed plastic flakes on the PIM process and quality of sandwich panels produced are investigated.

2 Experimental details

2.1 Materials

The materials used in this work are listed in Table 1. The rHDPE used to form the skins of the PIM sandwich panels was a food grade recyclate from milk bottles in powder form (particle sizes = 100-400µm). The core contains a combination of 3 materials: a virgin LDPE powder (particle sizes = 100-400µm) for improvement of foamability of the core, a blowing agent, Oxybis Benzene Sulfonyl Hydrazine (OBSH) in powder form for foaming of the core and the rHDPE-mix (a HDPE-rich mixed plastics in flake form without colour segregation) to be incorporated in to the core for recycling.

The as–received rHDPE-mix flakes were in irregular shapes with thickness of 100-400µm and max dimensions up to10 mm (Fig1a). They were obtained from a platics recovery facility (PRF) for sorting post consumer plastics. The composition of the rHDPE-mix (Table 2) was assessed by identifying thermal fingerprints of the flake samples (of about 10 grams) with a DSC (DSC Q2000, TA Instruments). The mix contained mainly HDPE with considerable amount of PP (melting temperature T_m=165°C) and PET (T_m=248°C) and a small amount of unidentifiable residues.

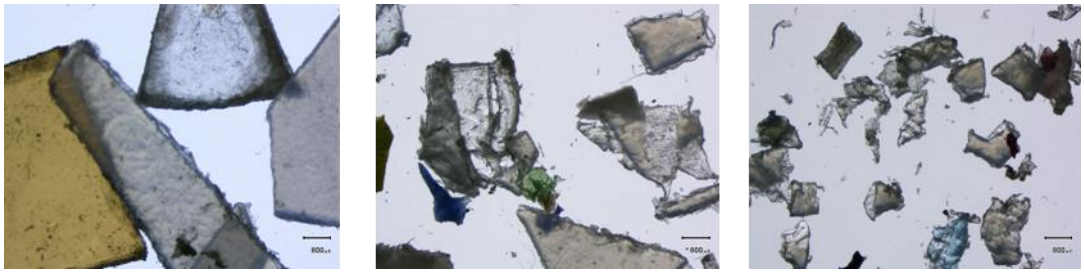
Table 1: Raw material information

Materials	**Supplier**	**Grade**	**Descriptions**	**T_m°C**
rHDPE	Nampak, UK	Food grade	Powder from HDPE bottles	135
LDPE	Exxon, UK	LD362	Virgin powder	115
rHDPE-mix	Severnside Recycling UK	Flakes	PE-rich mixed plastics	-
OBSH*	Celogen, UK	Industrial grade	Blow agent (powder)	-

* OBSH-Oxybis Benzene Sulfonyl Hydrazide with decomposition temperature 158-160 °C

Table 2: Composition of the rHDPE-mix flakes

	HDPE	PP	PET	others
Weight Percentage %	61.8	12.1	25.4	0.6



(a) (b) (c)

Fig. 1: Optical micrographs showing the size reduction of the flakes in the rDHPE-mix: (a) Size 1- as received; (b) Size 2- sieved through 4mm square perforations and (c) Size 3- sieved through 1.5mm conidur perforations.

Size modification of the as-received rHDPE-mix flakes (Size 1 in Fig.1a) was conducted with a cutting mill (SM100, Retsch U.K. Ltd) utilizing two sieves with square perforations of 4.00 mm (Size 2 in Fig.1b) and conidur perforations of 1.50 mm (Size 3in Fig.1c).

Formulations of the core are shown in Table 3.
The rHDPE-mix flakes of 3 sizes (shown as "recycled PE" in the table) were incorporated at 3 levels from 25 to 75 wt% with the remaining as the LDPE. The blow agent OBSH was added at 1.5 wt. % based on total mass of the core materials.

Table 3: Formulations for the cores

Code	virgine LDPE	recycled PE		
	%	size 1	size 2	size 3
R01	75%	25%	0%	0%
R02	50%	50%	0%	0%
R03	25%	75%	0%	0%
R04	75%	0%	25%	0%
R05	50%	0%	50%	0%
R06	25%	0%	75%	0%
R07	75%	0%	0%	25%
R08	50%	0%	0%	50%
R09	25%	0%	0%	75%
R10	100%	0%	0%	0%

2.2 Moulding of the PIM panels

For each formulation in Table 3, sandwich panels were moulded with a purpose–built laboratorial PIM machine. The mould (internal dimensions: 450 x 300 x20mm) was fitted with temperature and clamping force sensors to monitor the changes during moulding. The open mould was preheated to 190 °C using an oil heater. 250g of the rHDPE skin material was applied on each half of the mould and allowed to sinter. 710g of the core material, premixed with a Shaker Mixer (Turbular T10B, WAB), was applied to the lower half of mould. The mould was then closed until clamping force reached it peak (Fig 2). The mould was then brought in contact with a cooling station connected to a chiller to bring the temperature to room temperature. Specimens for flexural tests were cut with a band saw from the moulded panels and left to relax under 50±5% RH and 23±1°C for 3 weeks before testing.

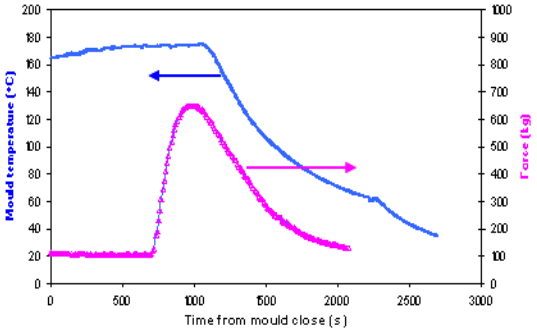


Fig. 2: The temperature and pressure profile during PIM processing.

2.3 Characterizations of the PIM panels

Apparent density of the PIM samples was calculated from mass and volume in accordance with BS EN ISO 854:1995. Three-point bending tests of the PIM samples was performed at 23±2°C in accordance with BS ISO 1922:2001 and ISO 178 with an Instron universal mechanical tester at a crosshead velocity of 10 mm/min. For each composition, 3-5 specimens were tested to obtain averaged results.

The PIM samples were sectioned with a sharp blade at desired positions to assess microstructure with a stereo microscope (SZX16, Olympus).

3 Results and Discussion

3.1 Temperature and pressure changes during PIM processing

Figure 2 shows the typical mould surface temperature and clamping force profiles in a PIM process. The blowing agent started to decompose from about 700 seconds which gave rise to rapid increase in the clamping force. As soon as the force peaks (at ~ 1000 sec) which indicating the completion of foaming, the mould could be cooled to solidify the moulding.

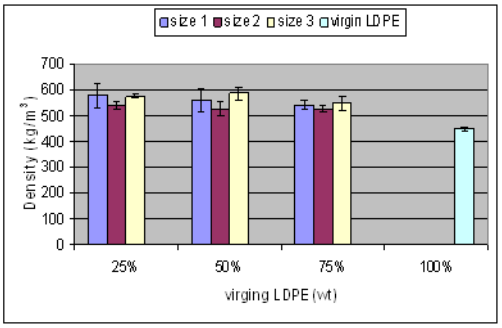


Fig. 3: Variation of densities of the PIM samples with the virgin LDPE content.

3.2 Density of PIM sandwich panels

Figure 3 shows the variation of density of the PIM samples. As a constant mass of materials was used for each panel, density was directly related to the final thickness of the panels and reflects the degree of foaming. LDPE is known to have good foamability and stability during bubble growth attributable to its high elongational viscosity and strain hardening[12-14]. This is supported by the observation that when the core was made from 100 wt% LDPE, the density approached the theoretical value of 450 kgm^{-3} calculated from the mass of the materials and mould cavity. With the reduction of LDPE content (or increase of the rHDPE-mix content), density of the panels increased by about 16 to 25%. This may be attributable to the low elongational viscosity and low strain hardening of the HDPE in the rHDPE-mix which led to bubble claps[12-14] and the non-foamed particles (e.g. the non-molten PET flakes) which restrict bubble formation and growth. As results, the final panel thickness at these compositions was in the range of 17-19mm, lower than the height of mould of 20mm. The effect of particle size on density was not as strong as the LDPE content. The smallest particle size in the rHDPE-mix did seem to lead to slightly higher densities due probably to the restriction of finer non-molten PET particles to growth of bubbles.

3.3 Morphology of PIM structure

Micrographs of the sectioned samples are shown in Fig. 4. Core composition R10 (100% LDPE) resulted in uniformly foamed core with excellent interfacial integration (a0, b0 and c0). At 25 wt % loading of the rHDPE-mix, solid flacks were dispersed and encapsulated within foam regions. The cores were integrated well with the skins and incorporation of finer flakes generated finer structures (e.g. comparing column I with II and III).

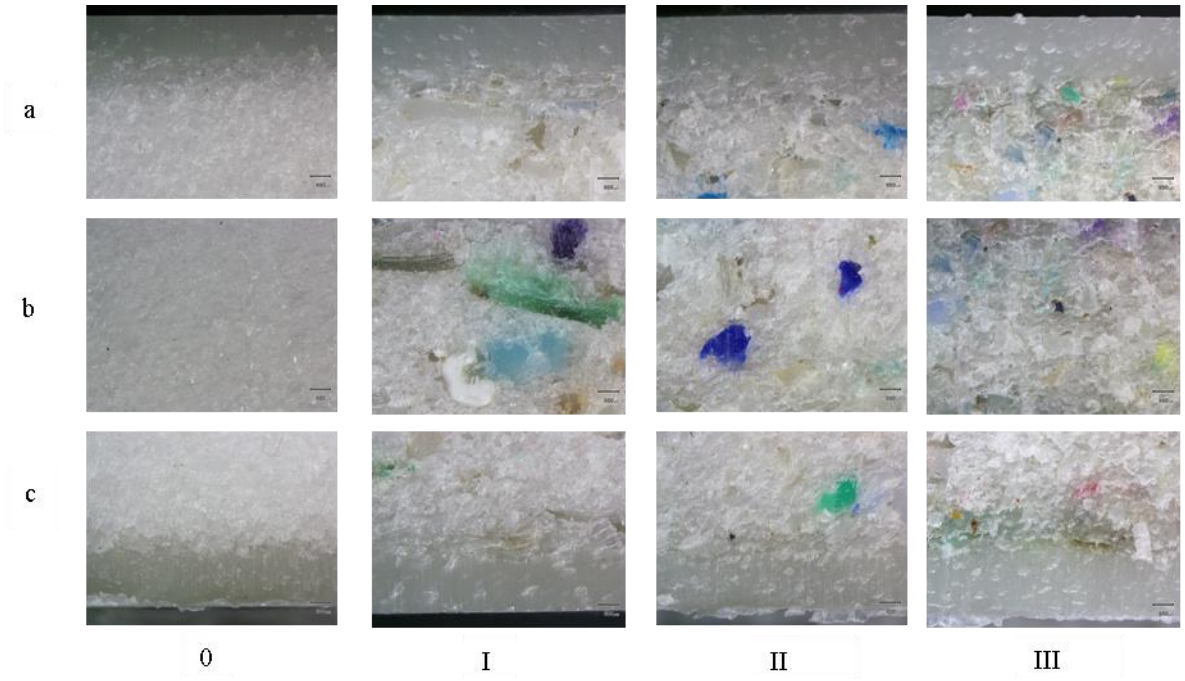


Fig. 4 Optical micrograph of cross sections of the PIM samples showing the regions (a-c) the up skin, core and bottom skin. The compositions of the cores are (0-III) R10, R01, R04 and R07.

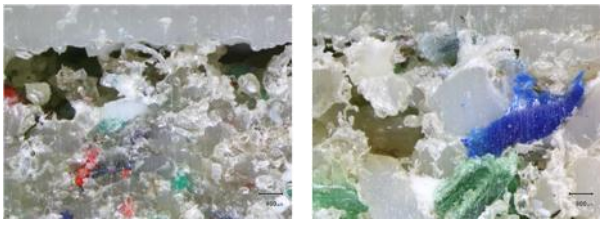
However, addition of the rHDPE-mix reduced foamability of the core as shown in the density results. Apart from HDPE, the rHDPE-mix contains fairly high concentrations of PP and PET (Table 2). The PET flakes would not melt at the moulding temperature and would exist as solid particles. The PP flakes would have melted together with the other polyolefin components (the LDPE and HDPE) and contribute to a potentially foamable molten phase. However, large PP/HDPE flakes were not be able to blend uniformly with the blow agent and thus, although melted, might not be foamed. Despite this, the unfoamed particles, as shown in Fig 5, were well encapsulated by the foamed phase in the core but at the core/skin interface at high loading of the rHDPE-mix could lead to formation of defects due to insufficient foamability of the core (Fig.6a) and/or lack of particle adhesion (Fig. 6b). These defects can be prevented by adjusting the amount of the core material (to compensate the low foamability of the core) and/or adding a layer of LDPE powder at the interface (to enhance adhesion).

(a) (b) (c)

Fig. 5 Optical micrographs of the core containing size 1 flakes at loading of (a) 25 wt%, (b) 50 wt% and (c) 75 wt%

3.4. Flexural properties of PIM panels

Figs. 7 and 8 show the variation of flexural modulus and strength of the PIM samples with loading of the rHDPE-mix and particles size. In general, addition of the rHDPE-mix in the core for 25-50% loading improve both the flexural stiffness (by ~37% max) and strength (by ~53% max) of the panels in comparison with the pure LDPE core and thus stiffer and stronger panels are resulted. With further increase of the loading of the rHDPE-mix to 75 wt%



(a) (b)

Fig. 6 Optical micrographs showing defects near the interface for cores at 75 wt% loading of the rHDPE-mix flakes of (a) size 3 and (b) size 1.

though, considerable reduction in the properties was observed. This can be correlated, as discussed earlier, to the poor particle and interfacial adhesion.

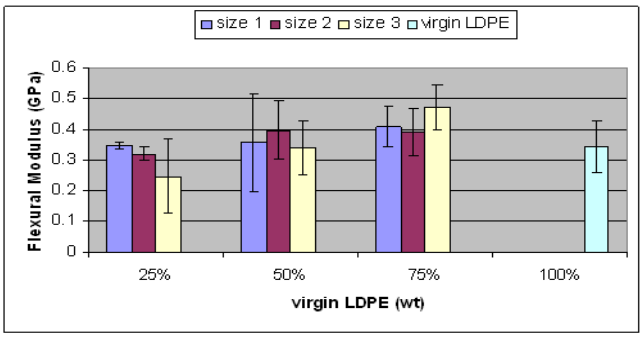


Fig. 7 Variation of flexural modulus of the PIM samples with loading of the rHDPE-mix and particles size.

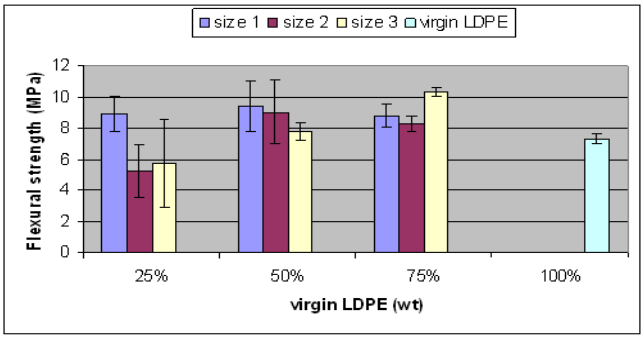


Fig. 8 Variation of flexural strength of the PIM samples with loading of the rHDPE-mix and particles size.

Interestingly, the effect of particle size on the properties is dependant on the loading of the rHDPE-mix. At low loading e.g. 25 wt%, fine particles gave rise to significantly better performances than the coarser particles. This may be attributable to good foamablility of the core with high LDPE content (and hence lower density) and fine solid particles assisted the refinement of the pore structure. When loading increase to 50 and 75 wt % however, the trends were reversed. The fine solid particles might have restricted foaming of the already reduced LDPE phase and the penetration of foamed phase in to the voids between particles, leading poor particle and interface adhesion. Whether to refine size of flakes therefore depends on the priorities: for maximum flexural performance, low loading of the rHDPE-mix (e.g. 25 wt%) and fine particle size should be employed whereas for maximum incorporation of the rHDPE-mix, no refinement is necessary and the coarse flakes such as those received directly from PRF are adequate for direct PIM moulding. Care should be taken though to choose optimum amount of the core materials to compensate its reduction in foamability and it is also desirable to add a layer of LDPE powder on the skins before the core materials is loaded to enhance interfacial adhesion.

4 Conclusions

a) With reference to PIM panel made from rHDPE skins and a pure LDPE foamed core, it is demonstrated that light weight sandwich panels can be made by incorporating about 75 wt% of flakes of a low-grade HDPE-rich mixed plastic material from a PRF.

b) The incorporation of the flakes reduced foamability of the core and resulted in density increases by 16-25% compared with the pure LDPE core and yet remained below 600 kgm^{-3}.

c) The foamed core was able to encapsulate solid flacks and integrate well with the skins resulting in stiffer and stronger panels than that with the LPDE core -flexural modulus and strength of the panels were increased by up to 37% and 53% respectively for 25 and 50 wt % incorporation of the mixed flakes, respectively. Maximum flexural modulus and strength achieved are 500 MPa and 10 MPa respectively.

d) Regarding whether to refine size of the flakes depends on the priorities: for maximum flexural performance, low loading of the rHDPE-mix (e.g. 25 wt%) is recommended and fine particle size may gave rise to additional increase in flexural stiffness and strength. Whereas for high loading of the flakes so as to maximise the use of recycled plastics, flake refinement has advert impact on flexural properties and thus coarse flakes such as those directly obtained from PRF are adequate for direct PIM moulding. Care should be taken though to choose optimum amount of the core materials to compensate its reduction in foamability and it is also desirable to add a layer of LDPE powder on the skins before the core materials is loaded to enhance interfacial adhesion.

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