Novel Reduced Density Materials by Solid-State Extrusion: Proof-of-Concept Experiments*

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ABSTRACT

The feasibility of extruding polymer in a solid phase encapsulated in a lower melting point polymer in a low-temperature extrusion process is demonstrated. Such solid-state extrusion has been accomplished in two different resin systems, using different mechanisms. The first system is based on rigid PVC pellets coated with a plasticizer and dusted with highly plasticized PVC powder. Here, PVC pellets, pre-foamed in a batch solid-state microcellular process, were extruded in a way that preserved the microcellular structure of the individual pellet. In the second system hollow pellets were co-extruded using polystyrene as the core material and encapsulating it with polyethylene and polyethylene methacrylate co-polymer (EMA). During extrusion, the softer, lower melting polyolefins carried the polystyrene through the extruder in the solid-state. The unique feature in both examples is that the polymer to preserved in the solid phase is not melted inside the extruder barrel.

INTRODUCTION

Nature provides many examples of solids made to behave as liquids. Common mud is a prime example of how soil is transformed into a viscous liquid like substance that deforms very easily. When it rains, water falls on the soil that absorbs it like a blotter. Since soil is composed of small solid particles impervious to water, the water must reside between the soil particles. This, in effect, lubricates each of the particles causing them to slide past one another when a load is applied. The soil now can no longer support an applied load as it did before when the frictional forces between each of the particles were greater. Whenever we have attempted to walk on this pseudo-liquid, the end result was at least muddy shoes or in extreme cases much worse.

In this paper we describe two different approaches to achieve the thermoplastic analog to mud in a continuous process. Both approaches provide an end

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product that is realized by extrusion and that contains microcellular foam. Microcellular foam can be produced in a batch process by first saturating the polymer with a non-reacting gas such as carbon dioxide at a high pressure. Bubble nucleation is achieved by introducing a thermodynamic instability either by increasing the temperature(1-5) or rapidly decreasing the pressure(6). Recently, a novel method to induce bubbles by subjecting the gas-saturated polymer to a high compressive stress has been reported(7). In this study PVC and specially prepared PS pellets were first converted into microcellular foam pellets. The foamed pellets were then used as the primary material to be extruded in the solid-state. Different approaches to achieving mud-like conditions inside the extruder are presented.

In the first system pre-foamed and plain PVC pellets were coated with liquid a plasticizer and dusted with flexible PVC powder before extrusion into a rod at very low temperature to preserve the pellet structure. Here the highly plasticized PVC powder served to lubricate and carry the pellets in the extruder.

The second system was based on polystyrene. Special co-extruded hollow pellets were first prepared by enveloping the stiff polystyrene portion with a softer lower melting polyethylene portion. The pellets were foamed and then were successfully extruded into a rod with the foam structure intact. In this case the polyethylene played the role that water plays in the composition and flow of mud.

EXPERIMENTAL

Screw Design

We used a 1:1 compression ratio 1.25" diameter screw used in the extrusion experiments. It is basically a 22:1 L/D ratio feed screw with its feed depth of .24" carried across all 22 flights. With no physical compression resulting from the screw itself, the only compression would be from the viscous drag of material along the extruder and screw surfaces and any back pressure resulting from the exit die. The extruder housing the screw was made at BBS and had no other special provisions different from other similar extruders used in the extrusion lab. The thrust bearing was, in fact, a relatively inexpensive ball bearing type about 3 inches in diameter with a bronze sleeve bearing forward from it and a wall mounted radial ball bearing following it. A three horsepower variable speed AC drive was the power source driving the screw through two spur gears.

Die Design

The die used in these experiments was a simple rod die kept at the same diameter as the extruder barrel and attached directly in line with the barrel without any obstructions. If the extruder was cold and pellets were fed to it, then pellets would emerge from this die. The only back-pressure created would be by friction against the side walls of the die length of 6 inches. Temperature of the rod die was controlled by a thermocouple mounted in the side-wall of the die.

Solid State Extrusion of PVC

Preparing Foamed PVC Pellets

Foamed PVC pellets of 0.63-0.67 g/cc density were made from a proprietary rigid formulation containing very little plasticizer using the batch microcellular process described in [4]. The pellets were saturated with CO_2 at 5 MPa for three days and foamed in hot water at 70 C.

Coating the Pellets

The foamed pellets were weighed out into a 5 gal. pail with wooden tumble slats attached to the wall. This was all inserted into a cement mixer drum prepared to receive it. The pellets were blended with 1% K-Flex DP plasticizer from B.F. Goodrich for 15 minutes to wet the surface of each pellet. Then, a highly plasticized flexible PVC powder (40 pph) was added at varying levels from 1 pph to 6 pph. The PVC powder and plasticizer coated pellets were then tumble-blended for an additional 15 minutes. When the powdered PVC became adhered to each plasticizer-wetted pellet, the prepared pre-foamed pellets were ready for extrusion.

Solid-State Extrusion

As a control, un-foamed rigid PVC pellets were also prepared with plasticizer coatings and flexible PVC powder adhered to them. Table 1 gives the extrusion conditions for each of the rigid pellet compositions and samples produced. Following the extrusion of rigid pellets, foamed PVC pellets coated with PVC powder as described above were extruded at different processing conditions described in Table 2.

Table 1 Rigid PVC Pellet Extrusion Conditions

	1	**2**	**3**	**4**	**5**	**6**
Pellet Coating Ratio						
Wt. rigid pellets:	100	100	100	100	100	100
Wt. plasticizer:	1	1	0.5	1	1	1
Wt. flexible powder:	1	3	1	4	4	4
Extrusion Conditions						
Rod Die:	343F	343F	343F	365F	365F	365F
Forward Barrel:	250F	250F	250F	260F	260F	260F
Mid Barrel:	230F	230F	230F	240F	240F	240F
Rear Barrel:	200F	200F	200F	200F	200F	200F
Hopper Cooling:	OFF	OFF	OFF	OFF	OFF	OFF
Screw RPM:	13	13	13	13	13-18	28
Sample #:	2	3	4	5	6	7
Surface Condition:	poor skin		better skin		poorer skin	

Table 2 Foamed PVC Pellet Extrusion Conditions

	1	**2**	**3**	**4**	**5**
Pellet Coating Ratio					
Wt. rigid pellets:	100	100	100	100	100
Wt. plasticizer:	1	1	1	1	1
Wt. flexible powder:	4	4	6	6	4
Extrusion					
Rod Die:	368F	380F	380F	380F	380F
Forward Barrel:	255F	250F	255F	255F	255F
Mid Barrel:	230F	235F	225F	225F	225F
Rear Barrel:	200F	210F	200F	200F	200F
Hopper Cooling:	OFF	OFF	OFF	OFF	OFF
Screw RPM:	13	28	28	41	41
Sample #:	8	9	10	11	12
Surface Condition: All surfaces were rough from foam					

Solid State Extrusion of Polystyrene

Hollow Pellet Preparation by Co-extrusion

The special equipment for making the co-extruded rod is now described along with the co-extrusion conditions used to make the hollow pellets. In trial 1, EMA encapsulated PS pellets were used, while in trial 2, a polyethylene outer layer was used, and a higher amount of PS was introduced.

Rod Co-extrusion Die

The Modular Disk Die(8,9) was used to co-extrude the hollow rod that was chopped into pellets. The module defines the co-extruded structure. It is assembled separately from the die using disks to form a cell and arranging cells to accept pre-selected inlet melt streams. Each cell defines the composition of each layer and its position within the structure.

A Standard Cell, consisting of 4 disks, spreads the melt by simple division to 8 points and from there into a layer. Some materials are prone to show melt join lines as optical defects so there are also two melt spiral overflow designs as well. The first is a single Floating Spiral and the other is a double Floating Spiral Maze for maximum material randomization. Each of the spirals is designed to float within its own overflow melt to avoid hang-up that normally occurs within spiral overflow channels or grooves in conventional dies. For the pellets prepared for this study the standard 4-disk cell was used to co-extrude the individual layers because superior optical qualities were not needed.

Trial 1: EMA/EMA/PS/EMA/EMA Hollow Pellets

Pellet Co-extrusion

A General purpose grade of polystyrene and Exxon TC 221 EMA were co-extruded into a hollow rod which was then palletized. The 5 layer hollow rod, EMA/EMA/PS/EMA/EMA, was created using a module consisting of 5 cells and 21 disks. The mandrel tip was 0.5 in. (12 mm) in diameter and the exit annulus had a .050 in. gap. The polystyrene layer was extruded from a 1.25 in. extruder fitted with a 3:1 compression ratio 22:1 L/D screw. All 4 of the EMA layers which were split from 2 melt streams within the module were fed by two 0.75 in. extruders fitted with 28:1 L/D ratio 2:1 compression ratio screws. The three extruders were all commonly driven at a fixed ratio using spur gears from a 3 HP AC Variable Drive. The output rate was therefore in the ratio of 20/20/60 for the two 0.75 in. and 1.25 in. extruders respectively regardless of output rate.

The 5-layer rod was extruded downward into a small hot water cooling bath and then carried directly into the pelletizer. Startup temperature conditions shown in Table 3. Conditions 1 were at first too cold for polystyrene in extruder A. Also, having polystyrene in extruder C made a rod that was too stiff and brittle. The 2:1 compression ratio screw also in this extruder caused partially melted polystyrene pellets to pass through the die. Switching to condition 2, however, produced good hollow rod that could be pelletized especially when air was allowed to vent through the opening provided by the hole through the mandrel.

Screw and Die for Solid-State Extrusion

The same rod die and the 1:1 compression ratio 1.25 in diameter screw used in the PVC experiments were used here.

Solid-State Extrusion

The extrusion conditions for the hollow PS pellets with EMA outer layers are given in Table 4. The pellets were placed in a porous cloth bag and held in a pressure vessel at 5 MPa CO_2 pressure for 2 days to saturate the polystyrene portion of the pellets. They were removed just prior to extrusion and were fed continuously to the extruder hopper. While the barrel was maintained at 200F or below to foam the saturated pellets in the extruder and cause them to sinter together, the die was gradually raised in temperature to reduce the back-pressure. Finally the screw speed was raised during condition 3.

Trial 2: PE/EMA/PS/PS/EMA/PE Hollow Pellets

Pellet Co-extrusion

The water quench system used in Trial 1 did not permit as much polystyrene as desired because the hollow tubing was quenched below the Tg of polystyrene and the rod became brittle. Air-cooling was now substituted for the water. Another 1.25 in. extruder was added to the original triplex extruder used to make pellets for Trial 1 in order to add significantly more polystyrene to the co-extruded pellets. Polyethylene was also added as an outer layer to avoid tacky pellets from the EMA surfaces that had previously created a feeding problem at the extruder. Table 5 shows the conditions used. As can be seen, addition of extruder D extruding at 28 rpm added much more polystyrene to the pellets.

Table 3 Conditions for making co-extruded hollow pellets

A. Extruder: 22:1 L/D 1.25" 3:1 Compression Ratio screw with a Breaker Plate, .375" ID extensions directly to die		
	1	2
Forward Barrel:	390F	450F
Mid Barrel:	370F	465F
Rear Barrel:	330F	460F
Hopper Cooling:	on	on
Screw RPM:	9.5	9.5
Material:	PS	PS
B. Extruder: 28:1 L/D 0.75" 3:1 Compression Ratio Screw; No Breaker Plate; .375" ID extension to die		
	1	2
Forward Barrel:	390F	390F
Rear Barrel:	310F	310F
Hopper Cooling:	on	on
Screw RPM:	10	10
Material:	EMA	EMA
C. Extruder: 28:1 L/D 0.75" 3:1 Compression Ratio screw; No Breaker Plate; .375" ID extension to die		
	1	2
Forward Barrel:	450F	420F
Rear Barrel:	400F	385F
Hopper Cooling	on	on
Screw RPM:	10	10
Material:	PS	EMA
Die: .5" Die with B/C/A/C/B structure from a module having .125" star spreader disks, .125" Cap Disks 1& 2; .125"Distribution Disks		
	1	2
Die Lip Temperature:	406F	395F
Module Temperature:	450F	410F
Rod Draw Speed (FPM):	21	21

Table 4 Hollow pellet extrusion conditions

Extruder: 22:1 L/D 1.25 in 1:1 Compression Ratio screw without a Breaker Plate and a 1.25 in ID rod die			
	1	2	3
Rod Die:	140F	160 F	190- 270F
Forward Barrel:	190F	200F	200F
Mid Barrel:	170F	170F	170F
Rear Barrel:	150F	130F	130F
Hopper Cooling:	yes	yes	yes
Screw RPM:	34	34	48
Material:	CO_2 Saturated	EMA/EMA/PS/ EMA/EMA pellets	
Samples	1,2	3,4	5,6

Table 5 Conditions for making co-extruded hollow pellets with larger amount of polystyrene and PE outer layer

A. Extruder: 22:1 L/D 1.25" 2:1 Compression Ratio screw without Chopper Mixing tip but with a Breaker Plate, .375" ID extensions directly to die	
Forward Barrel:	420F
Mid Barrel:	420F
Rear Barrel:	360F
Hopper Cooling:	on
Screw RPM:	28
Material:	PS
B. Extruder: 28:1 L/D 0.75" 2:1 Compression Ratio screw without Chopper Mixing tip; No Breaker Plate; .375" ID extension to die	
Forward Barrel:	410F
Rear Barrel:	340F
Hopper Cooling:	on
Screw RPM:	10
Material:	PE

Table 5 Continued

C. Extruder: 22:1 L/D 1.25" 3:1 Compression Ratio screw without Chopper Mixing tip but with a Breaker Plate, .375" ID extensions directly to die	
Forward Barrel:	420F
Mid Barrel:	410F
Rear Barrel:	370F
Hopper Cooling	on
Screw RPM:	9
Material:	PS
D. Extruder: 28:1 L/D 0.75" 2:1 Compression Ratio screw without Chopper Mixing tip; No Breaker Plate; .375" ID extension to die	
Forward Barrel:	340F
Rear Barrel:	280F
Hopper Cooling	on
Screw RPM:	10
Material:	EMA
Die: .5" Die with B/D/A/C/D/B structure from a module having .125" star spreader disks, .125" Cap Disks 1& 2; .125"Distribution Disks	
Die Lip Temperature:	400F
Module Temperature:	413F
Rod Draw Speed (FPM):	28-30
Material Description:	a. polystyrene (General Purpose grade) b. EMA Exxon TC 221 c. PE (E4%VA, 2 MI) Rexene

Solid State Extrusion

Co-extruded Hollow Pellets

Experimental conditions for extrusion of plain pellets are shown in Table 6 along with the rod sample numbers that were collected for density measurement.

Table 6 Unfoamed hollow pellet extrusion conditions

Extruder: 22:1 L/D 1.25" 1:1 Compression Ratio screw without a Breaker Plate and a 1.25" ID rod die							
	1	2	3	4	5	6	7
Rod Die:	140F	160 F	190-270F	309F	309F	309F	309F
Forward Barrel:	190F	200F	200F	170F	200F	250F	300F
Mid Barrel:	170F	170F	170F	180F	210F	260F	315F
Rear Barrel:	150F	130F	130F	160F	160F	230F	280F
Hopper Cooling:	yes	yes	yes	yes	yes	yes	yes
Screw RPM:	34	34	48	21	21	21	21
Material:	Plain	PE/EMA/PS/PS/EMA/PE	pellets				
Samples	1, 2	3, 4	5, 6	7, 8, 9			
Density, g/cc	.73	.85	.99	1.0			

-extruded Foamed Hollow Pellets

he same pellets that were extruded above were pre-foamed by subjecting hem to CO_2 in a pressure vessel at 5 MPa for 2 days. After saturation, the ellets were immersed in water at 93 C for 2 minutes where they immediately amed. On cooling and drying the bulk density of the pellets was measured be 0.25 g/cc. The foamed pellets were extruded at conditions given in table Samples 1-6 were collected at approximately 15-minute intervals and their ensity was measured the next day after they had cooled.

Table 7 Foamed hollow pellet extrusion conditions

Condition	1	2	3	4	5	6	7
Forward Barrel	190F	190F	190F	190F	190F	190F	190F
Mid Barrel	175F	175F	175F	175F	175F	175F	175F
Rear Barrel	155F	155F	155F	155F	155F	155F	155F
Die	180F	190F	200F	210F	220F	230F-330F	330F
Screw RPM	30	30	30	30	30	30	30
Sample	1	2	3	4	5	6A skin forms	6B
Density, g/cc	0.61	0.70	0.63	0.59	0.65	0.61	0.61

RESULTS

Solid-State Extrusion of PVC

The objective of the experiments was to determine if the prepared plain and foamed PVC pellets could be fused together during extrusion without melting them and destroying the pellet structure. Coating the rigid PVC pellets with plasticizer and flexible (40 pph plasticized) PVC powder was expected to provide a softened tacky adhesive surface to the pellets to accomplish fusion. Figure 1 shows a rod being extruded from pre-foamed pellets. The surface is seen to be rough due to ruptured foam bubbles. The un-foamed pellets overall had a smoother surface finish.

Rigid Pellet Extrusion

Table 1 gives the extrusion conditions for each of the rigid pellet compositions and samples produced. Samples 2 - 4 were collected using plain PVC pellets coated

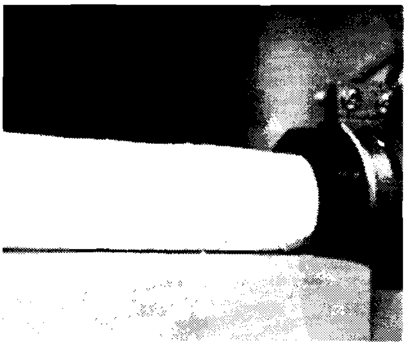

Figure 1 PVC solid state extruded rod from pre-foamed pellets. The die was heated to melt temperature to form a skin, while the barrel temperatures were kept low so as not to melt the foamed pellets

with 1 pph plasticizer having varying amounts of 40% plasticized PVC powder adhered to the wetted surface. At the data conditions stated, 1.25" rod was extruded with melted skins of varying degrees of smoothness. The interior of the rod was essentially fused pellets. These probably continued to fuse still further during the slow air-cooling of the rod as it was extruded and collected. Samples 5-7 were extensions of sample 3 at higher amounts of the flexible PVC powder. The rod die temperature was also raised to 365F and screw speed was varied from 13 to 18 and then to 28 rpm for the collection of samples 5-7 respectively.

A cross section of these samples can be seen in Figure 2. The individual pellets can be seen in the cross section, showing that the pellets have been extruded without melting in the extruder. The pellets are held together within a matrix made up of the plasticized PVC powder layer, which melted during extrusion and fused the rigid PVC pellets together.

It was found that at 343F rod die temperature, 13 RPM screw speed with 1 pph K-flex plasticizer and 3pph plasticized PVC powder on the rigid pellets, samples were produced with a smooth skin layer and the pellets within the skin layer appeared to be strongly adhered together. Raising the die temperature to 365F and increasing the plasticized PVC powder to 4pph produced samples also with smooth skins and pellets with defined boundaries within. However, attempts to raise the rod die temperature higher than 365F during the production of sample 5 produced a rougher textured skin. As the rpm of the screw was raised during production of samples 6 and 7, the overall skin and interior pellet adhesion quality declined. *A density reduction of about 20% appears to be possible simply by solid state extrusion of rigid pellets, without any foaming process.*

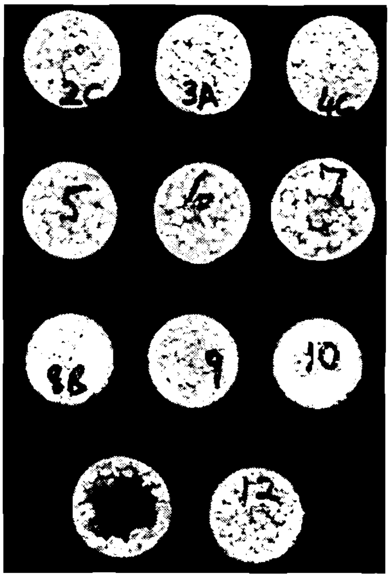

Figure 2 Solid state extruded PVC rod samples. Samples 2-7 are from plain PVC pellets, while samples 8-12 are from foamed PVC pellets. Sample 11 was obtained at a higher screw speed where the core crumbled due to poor adhesion of pellets

Foamed Pellet Extrusion

Microcellular PVC pellets were prepared as described earlier and extruded at the conditions described in Table 2. Samples 8 to 12 were collected at different processing conditions. The cross-sections of samples 8 to 12 can also be seen in Figure 2.

The morphology of the extruded rod from microcellular pellets was quite different from that seen earlier in rods made from rigid pellets. In sample 8 the pellets had less defined boundaries and the skin was rougher than sample 7. The rpm of the screw was increased to 28 rpm in sample 9 and the boundaries of the foamed pellets became more defined indicating a possible lower overall density. The PVC powder was increased to 6 pph in sample 10 and there was an observable difference in apparent pellet fusion compared to sample 9. The rpm of the screw was then increased further to 41 rpm. The pellet boundaries became still more defined in sample 11. The PVC powder was reduced to 4 pph in sample 12. Later, during sample preparation, the pellets in sample 11 lacked good adhesion and the core fell out (see Figure 2) while the pellets within sample 12 show better adhesion possibly because a higher thermal equilibrium had now been reached within the extruder through heat of shear. Sample 11 might be considered as a thermal transition sample in hindsight.

Both the extruder and rod die were shut down in clean condition by flushing with oil coated pellets and permitting the rod die to cool down during the flushing procedure and then finally removing all pellets from it. There was no evidence of polymer melting when the screw was pulled and examined after the run.

Solid-State Extrusion of Polystyrene

Trial 1:EMA/EMA/PS/EMA/EMA pellets

In this first trail hollow pellets of this 5 layered structure were prepared as described earlier. The EMA was expected to enhance the adhesion and fusion of pellets during the low-temperature extrusion. Foaming CO_2 saturated pellets during solid state extrusion was attempted to see if the separate step of pre-foaming the pellets could be eliminated. The extrusion conditions are given in Table 4. While the barrel was maintained at 200F or below to foam the saturated pellets in the extruder and cause them to sinter together, the die was gradually raised in temperature to reduce the back-pressure. Finally the screw speed was raised during condition 3.

The results from trial 1 were not satisfactory. The EMA outer layer was too 'tacky' to allow uniform feeding in the hopper, and steady-state conditions with CO_2 saturated pellets were not achieved.

Trial 2: PE/EMA/PS/PS/EMA/PE Pellets

For this trial, two changes were made to the pellet composition. First, an outer polyethylene layer was added to avoid the tacky pellets from the EMA surfaces that had created a feeding problem at the extruder. Second, significantly more polystyrene was added to the co-extruded pellets, so that low-density foamed pellets could be produced for solid-state extrusion. Details of the procedure used to produce these pellets have been presented earlier. These pellets were solid-state extruded, first plain and subsequently after foaming.

Extrusion of Co-extruded Hollow Pellets

Table 6 gives the extrusion conditions for the polyethylene coated pellets. At both 170F and 200F barrel temperatures, when the rod was cut, discrete pellets were seen inside the extruded rod and these were contained in a gel like matrix of PE and EMA. The hot die produced a smooth melted outer skin layer at all conditions. However, as the barrel temperature was increased to 250F, the discrete pellets became more fused and were completely melted at 300F.

As we see from the data in Table 6, density was lower at the lower barrel temperature conditions and at about 250F there was a transition to where the pellets began compacting and fusing to the true melt that occurred at 300F.

Extrusion of Co-extruded Foamed Hollow Pellets

Foamed pellets of 0.25g/cc bulk density were prepared as described in the experimental section and extruded at conditions given in Table 7. Using extrusion conditions that produced the lowest density rod from un-foamed pellets, the foamed hollow pellets were also extruded into 1.25 in diameter rod. Only the die temperature was varied to see what effect this would have on the rod density. As the data in Table 7 shows, the increase in die temperature did not seem to affect the density of the rod even when a skin was formed between samples 6A and 6B at the highest die temperature.

Figure 3 shows specimens from the foamed pellet solid-state extrusion. The lower specimen is at a die temperature of 220 F, and looks much like the familiar foamed polystyrene bead material commonly used in packaging. The difference of course is that our specimen was produced in a continuous process. This specimen clearly shows that the foamed pellets have retained their integrity after extrusion. By raising the die temperature we can melt the

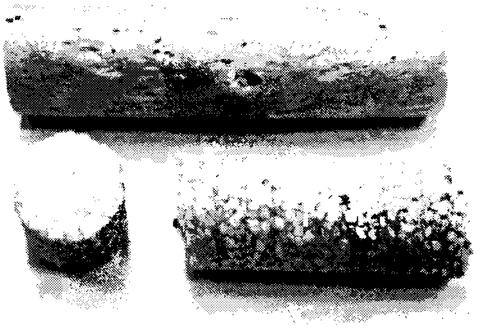

Figure 3 Photograph of the solid-state-extruded rods made from the hollow co-extruded PS pellets. The pellets were foamed by the batch microcellular process prior to extrusion. The foamed pellets are clearly intact in the lower specimen after the low-temperature extrusion process. The upper specimen has a skin that was created by melting the outer layer of the extruded rod. The gross density of the rods was 0.6 g/cc

outer layer of PE and create a skin (see the upper specimen in Figure 3) which adds considerable strength to the extruded rod. The skin in Figure 3 is not very smooth, however, as melting foamed pellets often leave a broken bubble on the surface.

DISCUSSION

We have described a novel low-temperature extrusion process in which solid particles of one polymer are carried and compacted in a matrix of a lower melting point second polymer, which governs the extrusion temperatures. Two different examples were presented that reduce this idea to practice. In both cases foamed pellets were successfully extruded into a rod in which the original pellet structure was kept intact.

Figure 4 shows schematically the differences between the PVC pellets of Example 1 and the hollow round co-extruded polystyrene pellets of Example 2. In Example 1, rigid PVC pellets were first enveloped with a liquid plasticiser and then dusted with a highly plasticized flexible PVC powder to create a polymer "mud" at low extrusion temperatures. The flexible PVC powder and

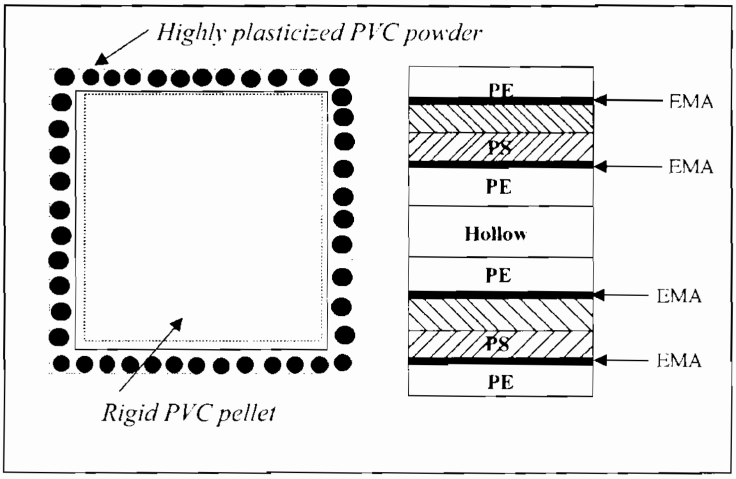

Figure 4 Schematic of a solid particle with a sheath of lower melting point material. PVC pellets were coated with highly plasticized PVC powder (left; example 1), while PS was co-extruded with PE outer layer, made hollow to gain additional weight reduction (right; example 2)

plasticizer encapsulation of each pellet provided the lubricity to cause the system to flow in an extruder without melting the rigid pellets. In example 2 we described a similar condition that was created by co-extruded EMA and polyethylene encapsulated hollow polystyrene pellets. In this case, the EMA provided adhesion to polystyrene and also to polyethylene and both polymers provided the lubricity to the solid polystyrene portion of the pellet during extrusion so that flow could take place at low extrusion temperature conditions. This example shows how the basic concept that reduces soil to mud was also recreated with co-extruded pellets. In both examples, we showed that pre-foamed pellets could be processed in this manner, creating novel compositions.

We believe that since the primary polymer to be extruded is not melted in this process, it will lead to many unique and unconventional processes and products. One possibility is cost-effective processing of recycled plastics, where mixed plastics could be ground and directly extruded into useful products without melting. The costly step of sorting and separating the stream of recycled plastics could potentially be avoided. Note that other solid phases may be added, such as wood particles for example, to make solid-state-extruded composite materials.

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