NEW HIGH OUTPUT VINYL COMPOUNDING SCREW

Keith Luker, Randcastle Extrusion Systems, Inc., Cedar Grove, NJ

Abstract

A new single screw mixing/venting element was tested for vinyl. This element combines multiple unique properties.

First, each mixing/venting element creates multiple elongational flow fields—the key to good compounding. Since the pressure is near zero, heat generated by mixing is very low.

Second, this mixing/venting element is also a melt separation screw somewhat similar to a barrier screw but without the need of high pressure (and consequent heat generation) or high compression (causing agglomeration before mixing). Rather than restraining material by means of a barrier, the mixing/venting/melting element forwards material and high output is achieved.

Third, the mixing/venting element makes a thin film over a large surface area at near zero pressure. Such thin films transported under barrel vent openings can efficiently extract volatiles, air or water.

Fourth, the entire mixing/venting element melts polymer in an axial length of only 3 or 4 L/Ds. Therefore, a 36/1 single screw extruder can then have 3 vents and the first mixing/venting element substantially melts the polymer.

A 1 inch, 36/1 L/D single screw extruder was built with three venting/mixing elements. Two screws, a Recirculator (hereafter mixer 1 and an Elongator (hereafter mixer 2) were tested. Five experiments were performed.

Using mixer 1, 0.5% red and 0.5% yellow were mixed in a Recirculator and made into heavy films.

Using mixer 1, a 72 and 95 durometer mixer were compounded and pelletized and then compared to a barrier screw.

Using mixer 1, rigid PVC was compounded with wood flour at 40% and made into tensile bars.

Using mixer 2, rigid PVC was compounded with 15 calcium carbonate powder and made into a strip.

Using mixer 2, clear rigid PVC was processed at a very high screw speed of 96 rpm without degradation.
This new element extends the utility of single screw extruders by allowing more vents in a shorter axial length than conventional screws; it allows for degassing even during the melting; it creates a large thin film for efficient degassing in each element; it is a high output melting mechanism and a melt separation element. Finally, it showed compounding of wood and calcium carbonate at up to 35%.

The element does not change the primary advantages of the single screw extruder: economy, high output, high stable pressures and low cost but extends its usefulness into the range of multi-screw extruders. Multi-screw extruders sometimes call this, “direct-extrusion”—meaning compounding while making a shape other than pellets but this requires a gear pump.

Since the precursor invention showed good mixing of immiscible blends in the submicron range (without a compatibilizer and the same size domains at multi-screw extruders) and with nano-particulates even at 50,000 to 100,000 times magnification (where pictures even from multi-screw machines are rare), the new screw elements should be of significant benefit.

Introduction

Historically, single screw extruders have been pumps first and compounders and degassers second.

Single screw mixers, or compounders, have lagged because they have lacked the multiple elongational flow fields of multi-screw extruders, simple upstream axial mixing, and the ability to degas during mixing.

As degassers, single screws have lagged because degassing did not occur during mixing and so lacked the superior surface renewal of multi-stage screws. Further, multi-screw twins commonly use multiple vents to sufficiently extract gases. Often one is a coarse vent and two are for fine degassing. But single screws have lagged because the second stage of a two stage screw uses about 12 L/D’s (~6 L/D pumping, 1 L/D compression, 4 L/D venting, 1 L/D decompression) of axial length—often practically limiting singles to one vent.

The UC mixer, Figure 1, is typical of a fluted mixer that after melting, pumps material through a shear plane. The design requires a relatively high input pressure to overcome the resistance of the entry flute (since it dead ends) and the resistance of the mixing land.

It is well known that elongational forces are more effective for dispersive mixing than shear [1]. Some attempts have been made to induce elongation in single screw extruders such as by a shaped pin [2].

Upstream axial mixing conveys material from a downstream to an upstream position along the screw such as by a screw within a screw [3] or a downstream flow passageway that leads upstream.

Various methods of venting in a single screw extruder are known [5] as are multiple flights in the extraction section for improved surface renewal [6].

Generally, the level of magnification measures the quality of mixing. Historically, mixing in single screws is judged by eye [7, 8] and optical microscope [9, 10, 11] but not with scanning electron microscope (SEM). The higher the magnification, the finer the mix. Most single mixing to date is done, at best, with optical microscopes at about 400 times magnification.

The goal of this paper is to describe a single screw mixing element that combines multiple elongational flows, upstream axial mixing and degassing during mixing. We then show some of the mixing results using SEM pictures from 3,000 to 50,000 times magnification and a degassing experiment.

Mixer Description/Operation

Figure 2 shows a section of a screw downstream of a flighted section and sectioned along A-A. Two channels, C1 and C2 separate P1 and P2. When rotated, P1 and P2 are drag flow pumps causing flow in the direction of the arrows. Greater drag flow—in the direction of the arrows—is enhanced when axial pressure flow is lessened towards zero in the C1 and C2 channels until all flow is cross axial at zero pressure.

Figure 3 and 3A show a more useful arrangement of channels and pumps in the "Recirculator" [12] (hereafter) mixer 1. One third of the mixer 1, circumferentially, is "laid flat" in Figure 3, show between flights and would be duplicated three times. This is useful in that, just as in multiple flights, melting, mixing and degassing benefit from processing in smaller amounts. Conceptually, this particular mixer 1 is shown after melting in the typical downstream position near the end of the screw though typically preceded by 1 to 3 other mixers as in Figure 3A. The flat section is bounded by a tight fitting boundary, B (similar in clearance to a typical flight).

Figure 3 shows an input flow from the flights on the right and flowing to the left as indicated by the arrows. In this case, the input flow is set substantially below the pumping rate of the P1 and P2 pumps either by a separate upstream starve feeder or by screw geometry (such as shallow input channels or narrow pitch) ahead of the mixer.

Flow in the input channel will be a combination of the pressure flow in the axial direction and drag flow in the cross axial direction. The combination continuously stretches the flow as the viscous material is pushed down the channel, where it will flow spirally, and pulled by the pumps. A cold screw pullout shows the angle of lines from a pigmented PP frozen on the screw in Figure 4. The stretching flow in most of the channel may be visualized continually unwrapping a spiral roll of "fluid paper."

As the flow in C1 approaches P1, it starts to resemble the flow preceding lobal kneading discs. Figure 5 shows lobal kneading discs superimposed over a cross sectional view of the mixer. In all mixing elements, the flow is divided into smaller masses for better processing. In all mixing elements, the material approaches a "lobe" in twin screw terms or a "pump" in this mixer's terms. In all mixing elements, the flow is a combination of pressure flow and drag flow.

Proceeding from the input channel entry flow, Figure 3, material sticks to the barrel as it is pumped over channel C1 as a film between P1 and P2 with a continually renewed surface and additional elongation.

Proceeding from P2, Figure 3, material enters C3. The material is constrained by the boundary, B, and flows to the left (pushed by the P2 pump).

Upon leaving the C3 channel, material can move in two axial directions. Material arriving on the downstream flight, to the left, will advance downstream. However, material may also enter the C2 and C1 channels flowing axially upstream, from right to left. In each case, the flow will again elongate and stretch (as previously described at the entry to C1 but now flowing upstream) for additional mixing and surface renewal.

Upstream axial flow may be increased, compared to the input flow. It is even possible that the upstream axial is greater in volume than the input flow, as in Figure 6, by additional starve feeding. This is particularly useful in cases where extreme distributive mixing is required and the polymer is not sensitive to degradation.

Alternatively, upstream axial flow can be reduced to zero if the polymer is sensitive to degradation by decreasing the starve feeding, or by flood feeding, as in Figure 7, or by reducing the length of the mixer.

As on multiple-screw extruders, kneading blocks can be placed far upstream. Likewise, one mixer was placed 7 L/D's from the water cooled feed section and the screw rotated to 250 rpm. There is little chance that the material will have completed melted before the mixer. Because the inlet channel is open downstream, it does not act as a barrier to flow. Whole pellets can enter the inlet channel and begin to melt. Since hard unmelted material cannot flow over P1, whatever melt exists is believed to drain over P1, leaving the solids in the C1 channel. We believe that this acts similarly to a melt separation screw. Once the solids soften sufficiently within C1, then they can pass over P1. If the pellets do not soften sufficiently, then the pellets exit C1, and enter C2 moving upstream for additional melting opportunities or move downstream.

Figure 8 shows a cold pullout of an upstream mixer 1. Natural PP pellets and yellow color concentrate were fed by a starve feeder (from right). Incoming pellets are clearly visible. Unfortunately, the cold pullouts within the mixer are fragile and tend to break during removal. The empty area was originally further downstream (to the left). Figure 9 (a larger view of Figure 8) shows partially melted pellets in C1 indicated by the arrows.

Since the mixers have empty regions, the pressure is near zero. This has three advantages. First, vents may be placed over the empty regions and a vacuum will communicate with the various flows within the mixers—especially the film between P1 and P2. Second, the lower the pressure consumed by a mixer, the less heat generated. Third, the empty regions dampen surges by acting as accumulators.

Results

Previous results have described the mixer 1 for distributive compounding of up to 40% wood flour and LDPE pellets; elastomer compounded with LDPE, and color mixing. [13].

Yu et al [9] studied various PS/LDPE 95/5 blends and achieved average domains of between 6 and 11 microns. Rauwendaal [14] studied a dry blend of high density polyethylene and polystyrene in 60:40 by weight ratio. Using an optical microscope, he found that one-third of the outer part of the extruded strand (approximately half the strand volume) was substantially coarser than the inner material and measured about 20 microns. The inner region reportedly measured about 4 microns. A somewhat similar dry blend, Figure 10, of high density and polystyrene, in a 80/20 by weight ratio, was processed using three of the mixers in a 5/8 inch, 50/1 L/D extruder. The outer boundary is negligible and the SEM shows PS domains of about 1 micron.

Ceramic particles in the 30 to 60 nanometer range were processed using the same 3 mixer extruder above. Figures 11, 12, and 13 show SEM at 5000 X, 10,000 X and 50,000 X where it is possible to distinguish individual and slightly agglomerated particles.

In a very brief experiment (25 grams of carbon nano tubes and 475 grams of PMMA) were processed in same extruder above but with 4 mixers (type 1) s and a low output screw. Figures 14, 15, and 16 show SEM at 1,000 X, 3000 X and 10,000 X where individual, apparently unentangled, carbon nano tubes are visible.

A 1 inch 36/1 extruder with up to three vents over a similar mixer, but with forwarding pitch (mixer 2), Fig. 16, proved very effective at transporting under a vent, and does not recirculate flow.[15] This is advantageous in limiting residence time for thermally sensitive materials. However, the elongational flow fields previously described and the thin film generation remain the same.

Figure 17 shows flexible PVC film, 15 mil thick processed on a UC mixing screw and Mixer 1. The difference is apparent.

Figure 18 and 19, shows two different durometers blended first on a barrier screw and then using Mixer 1 and made into pellets. The cross section of the pellets, Fig. 18, show a blended pellet using the mixer but not with the barrier screw. The serious degree of the problem is show, Fig. 19, where the more fluid vinyl (seen as white) has apparently coalesced around the higher viscosity material (seen as clear) and completely surrounded it. .

Figure 20, rigid PVC pellets mixed with 15% calcium carbonate on Mixer 2. There are no apparent agglomerates on the surface. The same sample shows a very smooth cross section, Fig. 21, also without apparent agglomerates. It is well known that single screw extruders typically show large agglomerates at much lower levels of calcium carbonate. Yet, Mixer 2 has shown that it can make a very smooth surface with even 35% fill levels [15].

A last test was performed on RPVC to determine how fast the screw could rotate with three Mixer 2 elements without degrading the material. Most commonly, RPVC on single screw is limited to about 30 rpm, sometimes as much as 45 rpm. In this case, 96 rpm produced a clear, apparently degradation free material at 18.4 pounds per hour without using screw cooling.

Discussion

Two broad mixing categories are polymer blends and particulate mixing. Of these, two difficult mixing areas include the immiscible polymer blends and nano particulate mixing.

The mixer is unique in its combination of properties within single screw technology. In addition to the specific properties described, this remains a single screw extruder and retains the ability to readily generate high, stable pressures without a gear pump.

Conclusions

This mixer shows a surprising degree of mixing. Prior magnification judged the quality of mixing from 0 to about 400 times magnification. This mixer can be judged by its 3,000 to 50,000 times magnification.

The color tests clearly demonstrate the much improved distribution of color using the Mixer when compared to the very popular UC mixer, Fig. 17.

Clearly, the mixture of two different viscosity vinyls, Fig. 18-19, favor the Mixer. This implies that very small domains were created which, at the macroscopic scale, prevented the coalescence.

The Mixer demonstrated that it can combine 40% wood flour with RPVC.

Filler levels as high as 15% with RPVC show an agglomerate free smooth surface, Fig. 21.

Output of the clear RPVC was very high using Mixer 2 elements. Usually, screw rpm on single screw extruders is limited to about 30 rpm. Sometimes, it is increased to as much as 45 rpm using screw cooling. However, we could find no reference to single screw extruders processing RPVC without degradation at more than double the highest screw speeds we could find.

Venting is often an important requirement of extrusion compounding as many fillers require degassing to remove air. This venting mechanism generates a thin film making removal of gases much more likely than in the traditional single screw methods. Initial tests are very promising.

Together with the earlier work cited, the mixer is a flexible processing tool for many different materials. The mixer can combine multiple elongational flows, upstream axial mixing, and venting in a unique single screw extruder that is still capable of high pressure development and stable pressures. The combination adds a powerful tool for the polymer processor. To use multi-screw terminology, it is a direct compounder.

Acknowledgements

To Tom Nosker and Jennifer Lynch of Rutgers for the SEMs of the nano ceramics, PE/PS blends and most agreeable help.

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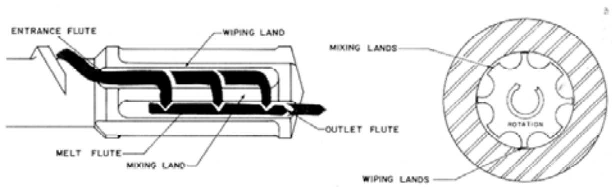
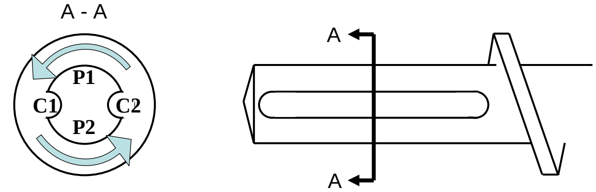
Figure 1: Union Carbide Mixer



The entrance flute dead ends at the wiping land. Pressure, generated upstream, forces material over the mixing flute where the material is sheared. The higher the pressure, the higher the heat generation.

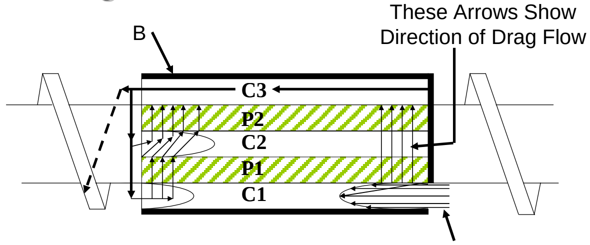
Figure 2: Pump and Drag Flow



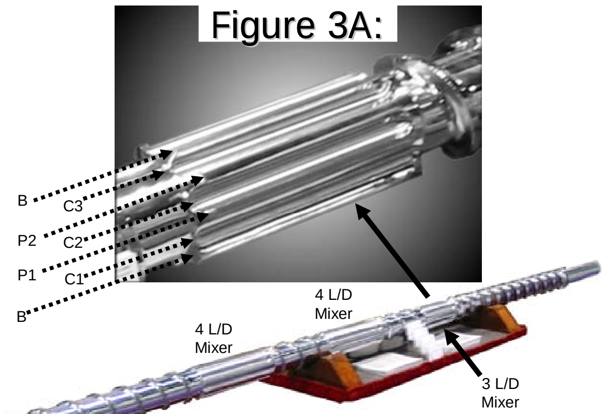
P = PUMPS C = CHANNEL

P1 and P2 will pump (rather than act as a barrier to pressure) when the pressure in the channels is low.

Figure 3: Flat View Of Mixer



Mixer Flow With Input Below Pumping Capacity of P1 and P2



Three Mixer Screw

Figure 4: Stretching Flow In Cold Screw Pullouts

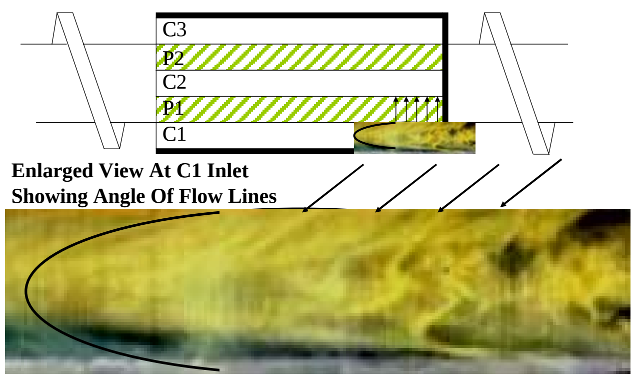


Figure 5: Comparison Lobal Mixers

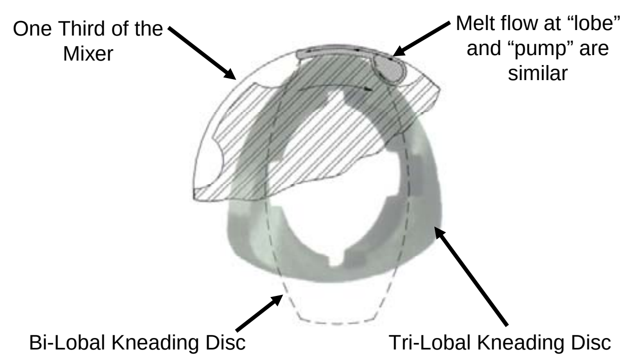
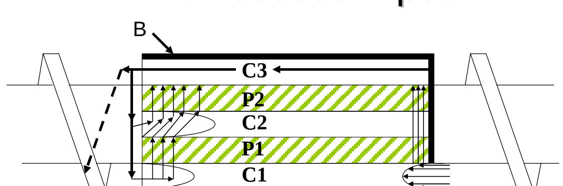


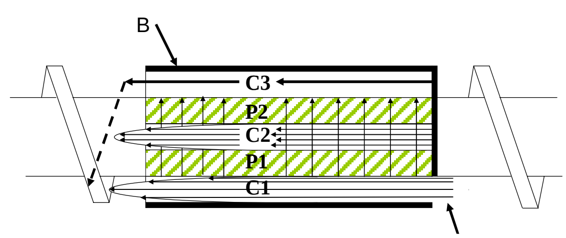
Figure 6: Flat View Of Mixer At Reduced Input



Entry Fill Length Reduced From Figure 2

C1 Recirculatory Flow, Left, Greater Than C1 Entry Flow, Right

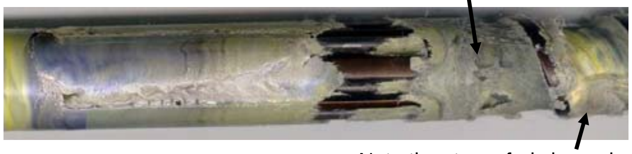
Figure 7: Flat View of Mixer Flood Fed Input



Upstream flow eliminated by increasing the input flow.

Figure 8: Melting In Mixer Cold Pullout

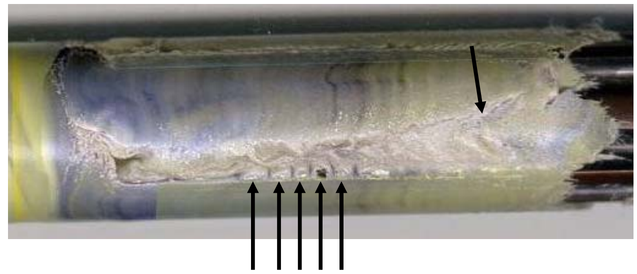
Pellets about to enter C1.



Note the starve fed channel

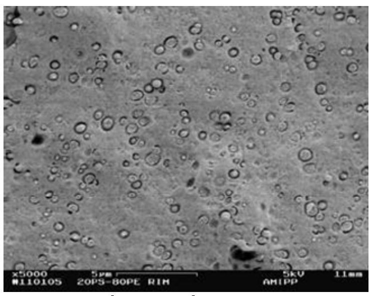
These clear PP pellets were mixed with yellow color concentrate. The fragile sample was damaged during removal. The empty volume in the mixer was further downstream (left).

Figure 9: Melting In Mixer Cold Pullout



These appear to be partially melted pellets

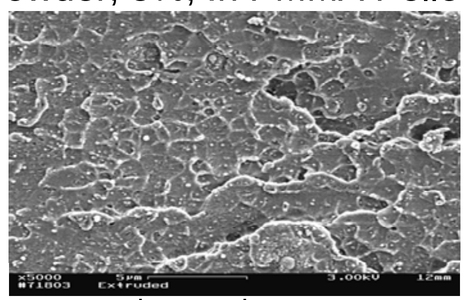
Figure 10: 20PS/80PE



5 microns

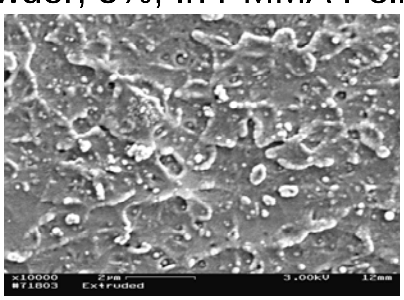
X5000 magnification, shows PS domains ~1 micron and smaller

Figure 11: 30 to 60 nm Ceramic Powder, 5%, In PMMA Pellets



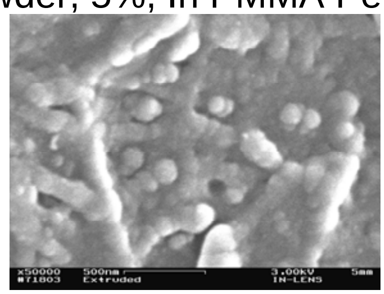
5,000 X 5 microns

Figure 12: 30 to 60 nm Ceramic Powder, 5%, In PMMA Pellets



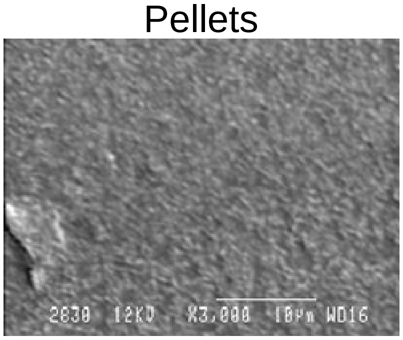
10,000 X 2 microns

Figure 13: 30 to 60 nm Ceramic Powder, 5%, In PMMA Pellets



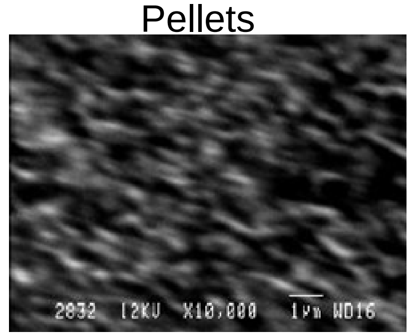
50,000 X 500 nm

Figure 14: 5% CNT and PMMA Pellets



3,000 X 10 microns

Figure 15: 5% CNT and PMMA Pellets



10,000 X 1 micron

Fig. 16: Mixer For Venting

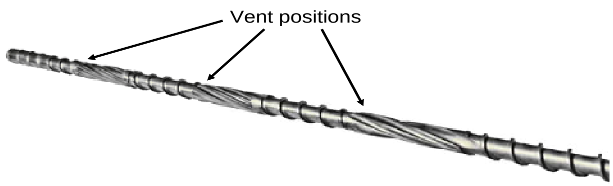
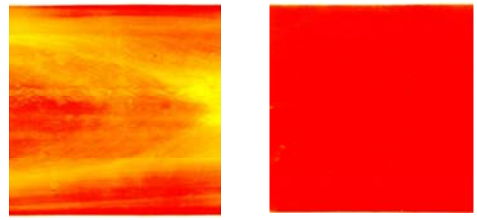


Fig. 17
Coloring Vinyl Film

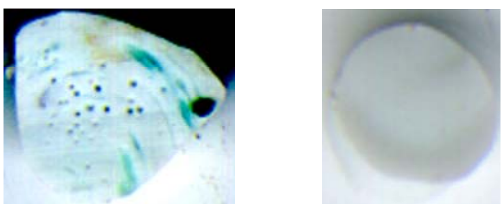
Flexible PVC pellets/0.5% red/0.5% yellow concentrate



UC Mixer **Mixer 1**

Fig. 18

PVC 95/72 Durometer



Barrier Screw Mixer 1

Fig. 19

PVC 95/72 Durometer

Fig. 20

40% Wood Flour in RPVC

Fig. 21

RPVC & 15% Calcium Carbonate