

Processability, Rheology, and Thermal, Mechanical, and Morphological Properties of Postconsumer Poly(vinyl chloride) Bottles and Cables

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ABSTRACT: The processability, rheology, and thermal, mechanical, and morphological properties of three different commercial poly(vinyl chloride) (PVC) compounds blended with postconsumer PVC bottles and PVC cables were examined with respect to the recycled PVC content. The addition of PVC bottle recyclates [recycled bottles (RBs)] into virgin PVC bottle (VB) and virgin PVC pipe (VP) compounds caused a progressive reduction in the average torque. No thermal degradation or color change in the RB-blended PVC compounds used was detected through carbonyl and polyene indices from IR analysis. The rheological properties for VP compounds were more sensitive to RB addition than those of VB compounds. The extrudate swell ratio did not change with the RB content. The decomposition temperature for the VB and VP compounds increased at 60–80% RB, whereas the glass-transition temperature was unaffected by the RB loading. The 20 and 80 wt % RB loadings were recommended for the VB and VP compounds, respectively, for the optimum impact strength, the blends showing ductile fracture with a continuous phase. At the optimum impact and tensile properties, introducing RB recyclates into

the VB compounds gave better results than the VP compounds. The hardness and density of the VB and VP compounds did not change with the RB content. The RB property change was comparatively faster than that of recycled PVC pipes. Adding the PVC cable recyclate [recycled cable (RC)] to virgin PVC cable (VC) had no obvious effect on the torque value of the RC/VC blends. The decomposition temperatures of the RC/VC blends stabilized at 20–60% RC and tended to decrease at 80% RC. The ultimate tensile stress was improved by the addition of the RC compounds, whereas the hardness and density of the VC compounds were unaffected by the RC content. It was concluded that the optimum concentrations of PVC recyclates to be added to virgin PVC compounds were different from one property to another and also depended on the type of virgin PVC grade used. © 2003 Wiley Periodicals, Inc. *J Appl Polym Sci* 89: 2738–2748, 2003

Key words: recycling; poly(vinyl chloride) (PVC); rheology; renewable resources

INTRODUCTION

In the breakdown of poly(vinyl chloride) (PVC) applications by field, civil engineering or construction is the largest, including domestic and industrial pipes and cable conduit tubes. The second field encompasses packaging and consumer goods applications, such as bottles and caps, films, toys, and footwear. PVC is also regarded as second behind polyethylene with respect to worldwide polymer consumption, but the recycling of postconsumer PVC is not as widespread as the recycling of polyethylene because of PVC's long-term applications. Recently, recycling PVC products has increasingly been required. For example, according to

data from the Association for the Promotion of Plastic Reprocessing,¹ the annual yield of waste plastics in Japan in 1996 was 9,090,000 tons, of which 3,580,000 tons was effectively used. Of this, 1,030,000 tons went to recycling. PVC products accounted for the greatest share (250,000 tons).

A number of attempts have been made to recycle PVC materials. Summers et al.² reviewed some examples to assess the feasibility of recycling PVC products. They suggested that vinyl products could be recycled into a variety of applications, including bottles, drainage pipes, and drainage pipe fittings, with good appearances and properties. Thomas and Quirk³ showed that recycled PVC bottles (RBs) could be used successfully in stabilized PVC foam formulations to produce profiles. It was also found that the profile properties were unaffected when virgin PVC was replaced with PVC bottle recyclates. Wenguang and Mantia⁴ studied the mechanical and processing properties of recycled PVC (collected from bottles and pipes) blended with pipe-grade virgin PVC. They found that the particle size and restabilization of the recycled PVC during

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processing were the two important factors controlling the properties of the PVC blends. The impact strength and processing behavior of the virgin PVC were improved with the addition of the recycled PVC because of the presence of modifier agents in the recycled PVC pipes (RPs), whereas the thermal resistance was slightly lowered. Ulutan⁵ conducted spectroscopic studies (e.g., IR and ultraviolet) and differential scanning calorimetry (DSC) for RBs heated at 160–180°C. The recycled PVC was considerably affected by a 180°C heat treatment, this being indicated by color changes, the loss of volatile components, and the formation of decomposition products. The study suggested that the reclaimed PVC bottles were recyclable at real processing times. Arnold and Maund⁶ studied the multiple recycling of PVC bottles through molecular weight determination and IR analysis. The results indicated that the degradation of PVC could be detected by the formation of polyene sequences, dehydrochlorination, and crosslinking, the degradation accelerating with small polyethylene (PE) contents and the depletion of the stabilizer contents. Recently, Sombatsompop and Thongsang⁷ investigated the possibility of recycling PVC pipes by the addition of recyclates of various concentrations into different PVC virgin grades, the rheological, morphological, mechanical, and thermal properties of the blends then being reported. The results showed an increase in the melt viscosity and no change in the die swell ratio as the concentration of the RPs was increased. The die swell ratio increased with the temperature, which was associated with the presence of a gel phase occurring especially at higher temperatures (ca. 210°C). The optimum tensile and impact strengths were observed, and the impact results were explained by the morphological structures of the blended compounds. The hardness results corresponded well to the density of the compounds. The glass-transition temperature (T_g), decomposition temperature (T_d), and heat deflection temperature shifted with the recycled PVC loading.

Because of the number of PVC applications, the recycling of PVC products has become demanding, especially for used bottles and cables, for which information is still limited in the literature. This article is a continuation of a previous work⁷ reporting part of an ongoing investigation into PVC recycling. Our objective was to assess the optimum properties of RBs and recycled PVC cables (RCs) that were added, with a wide range of concentrations, to various grades of virgin PVC compounds, the virgin grades including pipe, bottle, and cable compounds. The properties of interest were the ability to reprocess, the rheology, the thermal changes, and the physical, mechanical, and morphological properties of the blends. Some of the experimental results [for blends of virgin PVC bottle (VB) and RB grades] produced in this work were

TABLE I
Materials and Sample Codes

PVC materials	Sample code
Virgin PVC bottle grade (B0504BLA)	VB
Virgin PVC piping and tubing grade (Y5911BLA)	VP
Virgin PVC cable grade (05NA)	VC
Recycled PVC bottles from building site	RB
Recycled PVC cables	RC

compared with those given in the previous work by Sombatsompop and Thongsang.⁷

EXPERIMENTAL

Raw materials

The five different PVC compounds are listed below and are designated in Table I:

1. A VB compound (grade B0504BLA), supplied in a granular form by Thai Unions Co., Ltd. (Bangkok, Thailand). The compound contained 1.6 pph liquid thiotin (stabilizer), 12 pph methyl methacrylate butadiene styrene (MBS) (impact modifier), 2 pph processing aid (acrylic-type), and 1.5 pph fatty acid.
2. A virgin PVC pipe (VP) compound (grade Y5911BLA), supplied in a granular form by Thai Plastics and Chemicals Co., Ltd. (Bangkok, Thailand). The compound contained 1.2 pph calcium stearate, 1.2 pph tetrabasic lead sulfate, 0.1 pph polyethylene wax, and 4 pph CaCO₃.
3. A virgin PVC cable (VC) compound (grade 05NA), supplied in a granular form by Bangkok Cables Co., Ltd. (Bangkok, Thailand). The compound contained 52.0 pph di-iso octyl phthalate (DIOP), 5.0 pph basic lead carbonate, 1.0 pph dibasic lead stearate, and 40 pph CaCO₃.
4. RB flakes, materials reclaimed from PVC bottles that had been used in and collected from post-consumer PVC bottles. The collected bottles were washed for the removal of any contaminants and then were granulated, yielding recycled PVC flakes. The original compound used to produce the bottles was the same as the VB compound.
5. RCs, materials reclaimed from PVC cables that had been used at and collected from building sites. The collected PVC cables were washed for the removal of any contaminants and then were granulated, yielding recycled PVC flakes.

Experimental design for the PVC blending systems

The materials used in this work, derived from the blending of recycled PVC flakes into each virgin PVC

TABLE II
Blending Composition (wt%)

Sample code	Composition (wt%)				
	VP	VB	RB	VC	RC
VP100	100	—	—	—	—
VB100	—	100	—	—	—
RB100	—	—	100	—	—
VC100	—	—	—	100	—
RC100	—	—	—	—	100
RB20:VP80	80	—	20	—	—
RB40:VP60	60	—	40	—	—
RB60:VP40	40	—	60	—	—
RB80:VP20	20	—	80	—	—
RB20:VB80	—	80	20	—	—
RB40:VB60	—	60	40	—	—
RB60:VB40	—	40	60	—	—
RB80:VB20	—	20	80	—	—
RC20:VC80	—	—	—	80	20
RC40:VC60	—	—	—	60	40
RC60:VC40	—	—	—	40	60
RC80:VC20	—	—	—	20	80

compound at recycled PVC concentrations ranging from 0 to 100 wt %, are illustrated in Table II. The work was conducted in three different systems: (1) the addition of RB to VB, (b) the addition of RB to VP, and (c) the addition of RC to VC. The blended compounds from all the systems were then used, in both granular and test-piece forms, to evaluate the properties of the recycled PVC products, which included the ability to reprocess, the melt-flow index (MFI) and flow properties, the extrudate swell behavior, T_g and T_d , IR analysis, the tensile and impact strengths, the hardness and density, and fracture surface analysis.

PVC compounding

The recycled PVC flakes were granulated in a model 2835 granulator (Bosgo Engineering Co., Ltd., Bangkok, Thailand) before being blended with virgin PVC in a twin-screw extruder manufactured by Hakke Co., Ltd. (Germany). The head of the extruder contained a three-strand die (each strand having a diameter of 3 mm); this produced three extrudates at the die exit. The extrudates were then passed through a water bath with a pull-off unit before they were pelletized to produce compounded granules. The screw rotating speed was 100 rpm, with the barrel temperature setting on zone one (near the hopper) at 140°C, on zone two at 150°C, and on the die at 160°C. The drive torque during mixing in the twin-screw extruder was recorded so that we could follow the mixing performance or processability of the PVC blends.

Characterization

Because this article is a continuation of a previous work,⁷ only a brief summary of the characterization

methods and test procedures for the PVC compounds is given.

Rheological properties

The MFI of the PVC compounds was assessed with a CEAST 6542 (Torino, Italy) series melt-flow indexer (model D7053). The test procedure followed was as specified in ASTM D 3364 (1990). The flow curves of the PVC compounds were determined with an Instron 4467 extrusion rheometer (MA) (barrel diameter = 9.5 mm) fitted with a die 1.25 mm in diameter and 44 mm long; the test procedure is discussed elsewhere.⁸ For the elastic property, the extrudate swell ratio of the compounds was directly determined during extrusion from an Instron 4467 capillary rheometer with a 190°C test temperature and a shear rate of 33 s⁻¹.

Density and thermal properties

A Rosand density column (Gloucestershire, UK), per ASTM D 1505 (1990), was used to determine the compound density, the solvents being toluene and CCl₄. A PerkinElmer DSC-7 instrument (CT) was used to evaluate T_g 's of the PVC compounds. The temperature was scanned from room temperature to 120°C at a heating rate of 5°C/min. T_d 's of the compounds were determined with a PerkinElmer TGA-7 with a temperature range of 50–600°C at a heating rate of 20°C/min.

Fourier transform infrared (FTIR) analysis

Carbonyl and polyene indices were determined with IR analysis to assess the extent of the degradation of the PVC compounds.⁶ The average thickness of the PVC films was 125 μm, the sample being prepared by compression molding at 190°C for 3 min, and the tests were performed with a Nicolet Nexus 470 FTIR spectrometer (WI) to produce spectra of the transmission against the wave number, a typical IR plot being shown in Figure 1. In this work, peaks at three different wave numbers were of interest: (1) 2916 cm⁻¹ for C—H stretching, (2) 1720 cm⁻¹ for carbonyl groups, and (3) 1579 cm⁻¹ for polyene sequences. Equations (1) and (2) were used to determine the carbonyl and polyene indices, the details being given elsewhere.⁶

$$\text{Carbonyl index} = \frac{T_B - T_{1720}}{T_B - T_{2916}} \quad (1)$$

$$\text{Polyene index} = \frac{T_B - T_{1579}}{T_B - T_{2916}} \quad (2)$$

Tensile, impact, and hardness tests

The tensile test was performed on a Hounsfield (QMAT 1.23) tensile testing machine (Surrey, UK) at a

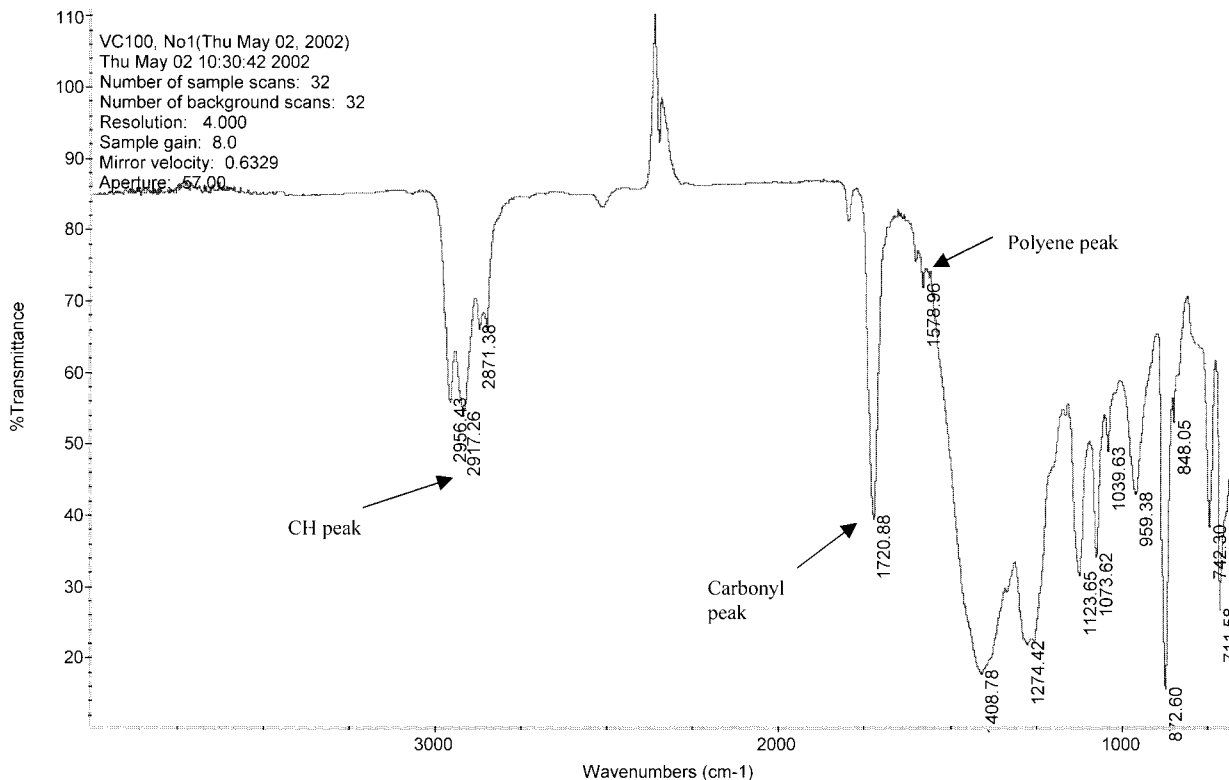


Figure 1 Typical IR spectrum of a PVC compound (VC-grade).

crosshead speed of 50 mm min⁻¹, the tensile test procedure following JIS K6732 (1987). The Izod impact tests were carried out according to ASTM D 256 (1990) on a Yasuda impact tester (Osaka, Japan), with the notched side facing the pendulum. The hardness was evaluated with a Shore D durometer (model 409) supplied by PTC Instruments Co., Ltd. (CA), the test procedure being specified by ASTM D 2240 (1990).

Morphological studies

The failure mechanisms were investigated with a JEOL JSM-6301F scanning electron microscopy (SEM) machine (MA) at a 15-kV accelerating voltage, the fracture surfaces from impact testing being examined. Details of the experimental procedure can be obtained elsewhere.⁷

RESULTS AND DISCUSSION

Blending PVC bottle recyclates (RB) into virgin PVC (VB and VP)

Processability test

In this work, the processability (ability to reprocess) of the PVC compounds was assessed by the measurement of the torque level and its stability during blending in the twin-screw extruder. Figure 2 shows the

torque curve measured as a function of the blending time for all the PVC compounds used (VB, VP, and RB). The average torque for all the compounds stabilized over the blending time, except for the RB recyclate, the torque stabilities indicating the homogeneity, consistency, and quality of the blends. The torque fluctuation for the RB recyclate was less than that for the other two virgin grades. This may be due to the fact that the RB had experienced a greater thermal

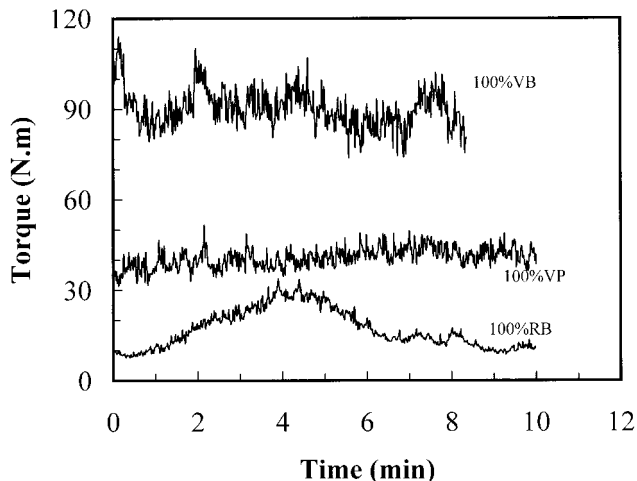


Figure 2 Torque curves of PVC compounds during blending in a twin-screw extruder.

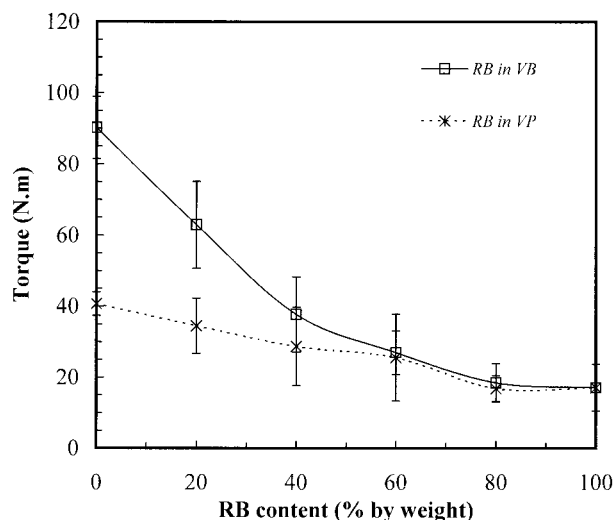


Figure 3 Average torque values as a function of the RB content in VB and VP compounds.

history and its structure became densified and compacted, the torque then being more consistent.⁸ However, the average torque values of these three compounds were different: 90.2 N m for the VB compound, 40.7 N m for the VP compound, and 17.1 N m for the RB recyclate.

The stability of the RB torque continuously changed over a period of time, whereas that of the VB and VP compounds did not. The fluctuations of the torque values for all the compounds were possibly caused by feed problems during blending. It is normally accepted that twin-screw torque is affected by many parameters, such as the material viscosity, temperature, and fullness of the screw (bulk density and feed rate). The torque value for the RB recyclate increased at the initial stage (0–4 min) and then decreased before approaching a steady state. Work by Arnold and Maund⁶ suggested that the increase in the torque of a PVC compound indicated some degradation (after three or four recycling passes) with the formation of polyene sequences. However, this was not the case in our work. Our FTIR results for all the RB/VB and RB/VP systems indicated very small polyene peaks (results not shown) that could be neglected if the experimental error was taken into account. Besides, no color changes in the compounds were seen during the experiment. Therefore, it could be said that no obvious degradation of the RB recyclate occurred in this experimental system. The decrease in the torque for the RB recyclate after 4 min of blending probably involved a reduction in the molar mass of the compound. The molar mass reduction did not cause the formation of polyene sequences. This was probably due to stabilizers in the PVC compound that prevented such degradation. This statement was confirmed by the measurement of the carbonyl groups, with the FTIR technique,

in the compounds. The carbonyl index decreased from 1.1 in the 100% VB compound to 0.7 in the 100% RB recyclate. Another cause of the reduced torque for the RB recyclate was non-PVC materials (e.g., polyolefin films, plastic labels, and adherent dirt) that were likely present in the RBs.

Figure 3 shows the changes in the average torque for VB and VP compounds loaded with different concentrations of RB. In both systems, the greater the RB content was, the lower the average torque was, the effect being more pronounced in the RB/VB system. The decrease in the torque value was due to the differences in the initial torque level, as suggested earlier, these results being in good agreement with those found in the previous work.⁷ Figure 4 shows a comparison of the changes in the torque level between the RB/VB system (in this work) and the VP/RP system (in ref. 7). Unlike for the RB/VB system, adding RPs to VPs did not change the torque and rheological nature of the compounds. This implied that the change in the rheological nature (and, therefore, processability) of the RBs was different from that of the RPs over a period of time during service. In addition, the dramatic torque reduction for RB/VB blends may be associated with the non-PVC materials that were more likely to be present in the RBs than in the RPs.

Rheological behavior

Figure 5 shows the changes in MFI for VB and VP compounds due to the addition of RB. In the RB/VB system, the MFI value slightly decreased with the RB contents at the initial stage before leveling off for higher loadings. In the RB/VP system, the MFI value progressively increased with the RB contents especially after 60% RB, because of the differences in the initial nature (grade) of the virgin compounds. The

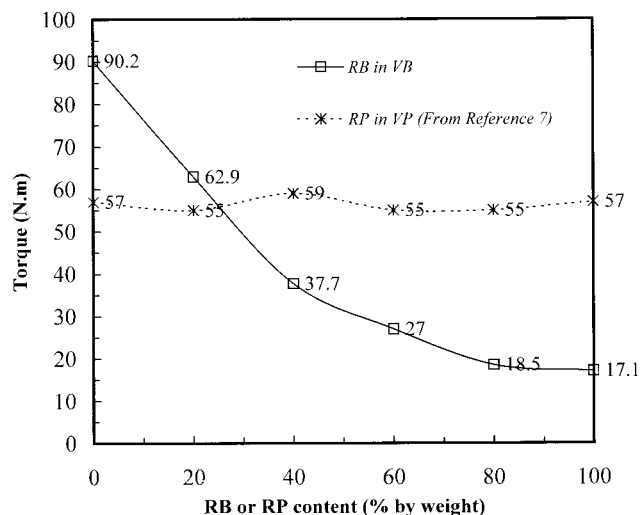


Figure 4 Comparison of average torque values as a function of the RB content for RB/VB and RP/VP systems.

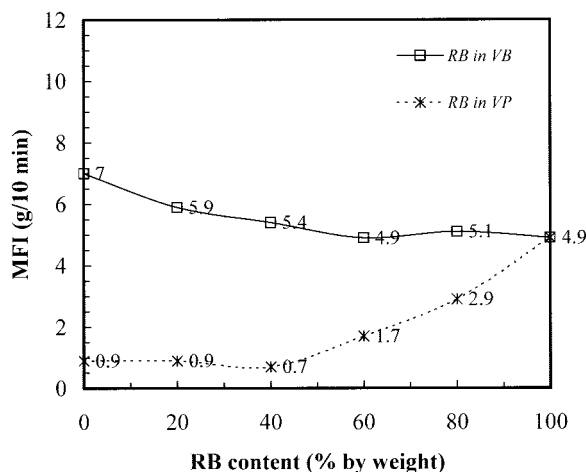
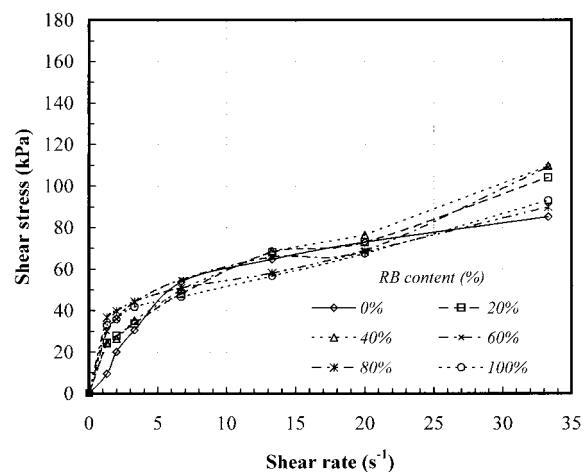


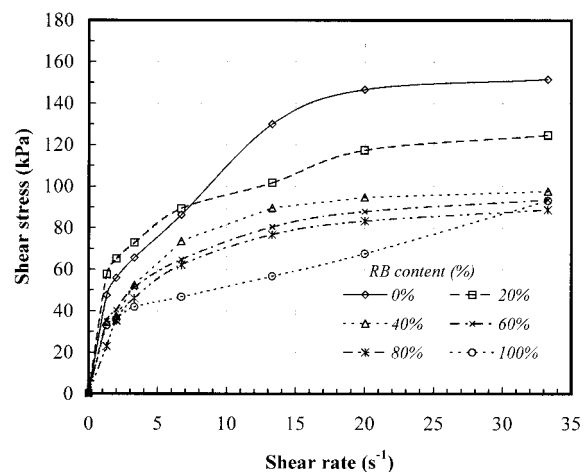
Figure 5 MFI values of and RB contents added to VB and VP compounds.

changes in the MFI values of VB and VP compounds due to the addition of RB recyclates also reflected the changes in the rheological nature of the blends. The relationships of the shear stress and shear rate for VB and VP compounds with added RB recyclates are shown in Figure 6(a,b), respectively. In all cases, the compounds exhibited a pseudoplastic non-Newtonian character, as one would expect. The original shear stress (also viscosity) of the VP compound was greater than that of the VB compound (also corresponding to the MFI results in Fig. 3). The rheological properties of the VP compound were more sensitive to the RB loading than those of the VB compound, being very marked at low RB contents (ca. 20–40 wt %). Generally, the shear stress of the VP compounds decreased with the RB contents. This was the opposite of the results from previous studies,⁷ which suggested that adding PVC pipe recyclates to virgin PVC compounds caused an increase in the shear stress and viscosity of the blends due to molecular compaction and gelation effects. It was postulated in this work that the gelation behavior did not occur in the compounds because the work was conducted at a relatively low temperature (190°C) and a low shear rate ($\sim 33 \text{ s}^{-1}$). The decrease in the shear stress and viscosity was mainly due to the differences in the original shear stress of the compounds and the lower molecular weight of the RB recyclates.

Table III shows the effects of the RB content on the extrudate swell ratio obtained from a capillary rheometer at a 190°C die temperature with a shear rate of 33 s^{-1} . Adding RB did not change the ratio of the extrudate swell within the experimental error ($\pm 2.5\%$). The swelling ratio ranged from 1.26 to 1.38. This range was less than that found in the previous work,⁷ which showed a swelling ratio of 1.40–1.60, the greater extrudate swell being caused by PVC gelation.^{9,10} The difference may be due to the fact that the



(a)



(b)

Figure 6 Shear stress and shear rate for (a) RB in VB compounds and (b) RP in VP compounds.

results in this work were obtained at lower temperatures and shear rates, whereas the previous work used temperatures of 190–210°C with a 280 s^{-1} shear rate. Therefore, the extrudate swell in Table III also sub-

TABLE III
Results of PVC Extrudate Swell Ratio Experiments from a Capillary Rheometer with a Shear Rate of 33 s^{-1} at a 190°C Test Temperature

RB content (wt%)	Extrudate swell ratio	
	PVC compound system	
	VB	VP
0	1.26	1.31
20	1.29	1.36
40	1.35	1.36
60	1.34	1.33
80	1.34	1.37
100	1.32	1.32

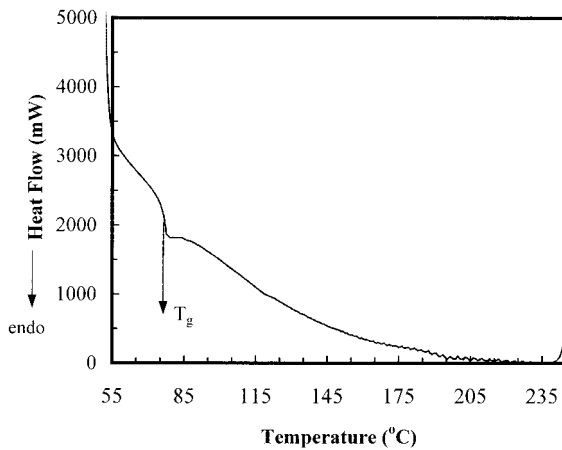


Figure 7 DSC curve of a 100% RB sample.

stantiated the absence of gelation, as discussed previously.

Thermal properties

In a DSC run, if any fusion or gelation of processed PVC samples occurs, one expects to observe two endothermic peaks, one being at a lower temperature (usually between 100 and 180°C) and the other being at a higher temperature (>180°C), after the onset of T_g . These two endothermic peaks (corresponding to the enthalpy changes) are associated with the primary and secondary crystallites of the PVC particles.¹¹ During the DSC experiment, we did not observe such peaks, even with the 100% RB sample (Fig. 7). This confirmed that there was no gelation or fusion occurring under the experimental conditions used in this work. Figure 8 shows the changes in T_g and T_d with various RB contents for VB and VP compounds. T_g of the VB compound suddenly dropped with 20% RB and then leveled off. Adding RB to the VP compound

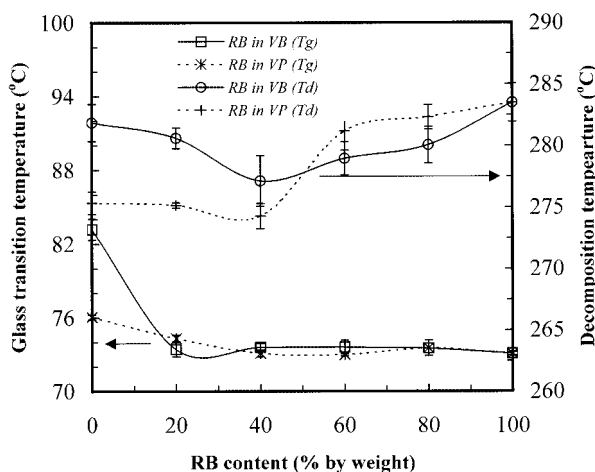


Figure 8 T_g 's and T_d 's for VB and VP compounds with various RB contents.

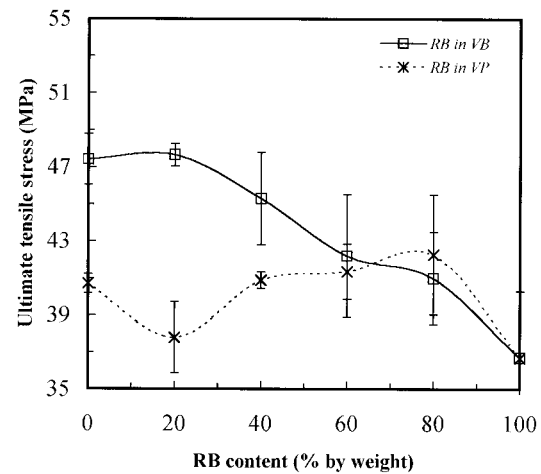


Figure 9 UTS for VB and VP compounds with various RB contents.

did not affect T_g , which had an average value of 73.5°C. Loading small amounts (20–40%) of RB did not affect the T_d value in VP but resulted in a slight drop in the T_d value in the VB compound. Above 40% RB, the T_d value progressively increased. The T_d values of VB and VP blended with RB recyclates ranged from 274 to 283°C.

Mechanical and morphological behavior

Figures 9 and 10 show the effects of the RB contents on the ultimate tensile stress (UTS) and impact strength of VB and VP compounds, respectively. Adding RB to the VB compound led to a reduction in the UTS for all recyclate contents, whereas the maximum UST was noted at 80% RB for the VP compound. For the impact strength, the maximum values were reached at 20 and 80% RB for the VB and VP compounds, respectively. The higher impact strength may also be due to the

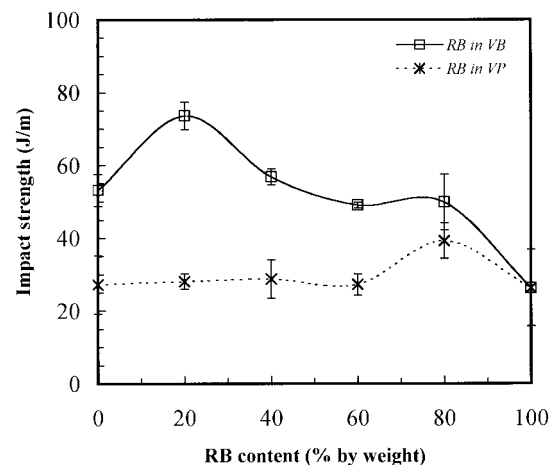


Figure 10 Impact strength for VB and VP compounds with various RB contents.

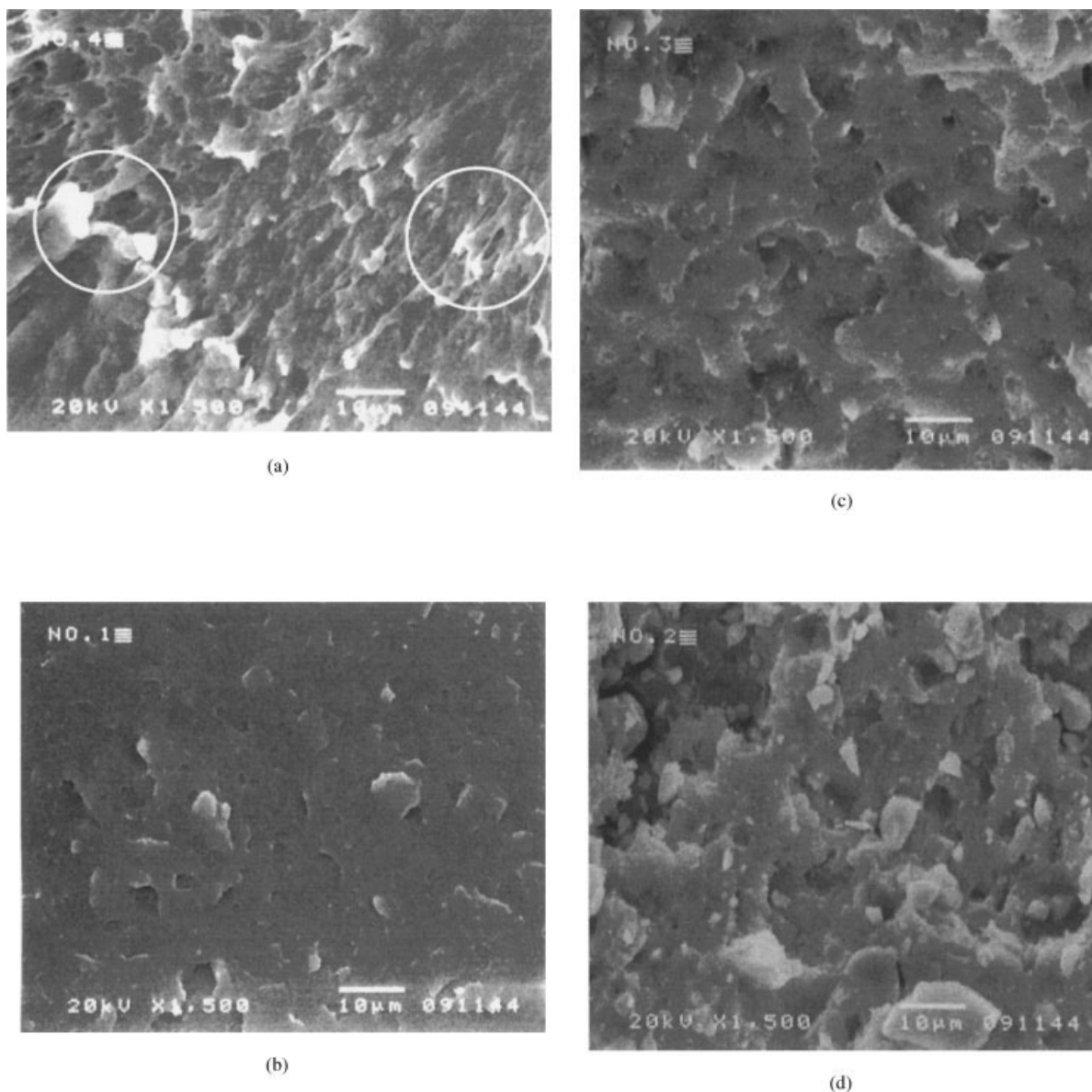


Figure 11 SEM micrographs of fractured surfaces of PVC samples: (a) RB20:VB80, (b) RB80:VB20, (c) RB80:VP20, and (d) RB20:VP80.

presence of impact modifiers in the bottle-grade PVC compounds (VB and RB in this case), this also being suggested in the work of Wenguang and Mantia.⁴ In relation to this work, a greater content of RB recyclates would then be required for the VP compound to obtain the maximum impact strength, with respect to the VB compound. The mechanical properties, therefore, were well defined, and this study was further supplemented by SEM studies of the selected fracture surfaces. Figure 11(a,b) shows the selected fracture surfaces of samples with the highest (20% RB) and lowest (80% RB) impact strengths, respectively, in the VB compound. The previous work⁷ indicated that samples with higher impact strengths exhibited ductile fracture, which was observed as the elongation of the polymer chains in the direction of the applied impact

force (circled), this also being the case for the fracture surface shown in Figure 11(a). Figure 11(c,d) shows the fracture surfaces of samples with the highest (80% RB) and lowest (20% RB) impact strengths, respectively, in the VP compound. The sample with 80% RB had a greater continuous phase than that with 20% RB. Moreover, RB20:VB80 had a much higher impact strength than RB80:VP20 because of the presence of impact modifiers in the VB and RB compounds.

Table IV shows a comparison of the tensile and impact strengths of two different systems: (1) blends of RB flakes with VB and VP and (2) blends of RP flakes with VB and VP. Increasing the bottle recyclates (RB) in the VB grade resulted in a progressive decrease in the tensile and impact strengths, whereas the opposite effect was found with the VP grade. Increasing

TABLE IV
Comparison of the Tensile and Impact Strength of RB and RP Blended in VB and VP Compounds

Maximum and minimum properties	Blending systems			
	Adding 20–80% RB (in this work)		Adding 20–80% RP (From ref. 6)	
	VB _(at %RB)	VP _(at %RB)	VB _(at %RP)	VP _(at %RP)
UTS				
Maximum (MPa)	43.2 _(20%)	42.3 _(80%)	75.2 _(40%)	65.3 _(20%)
Minimum (MPa)	41.0 _(80%)	37.8 _(20%)	60.4 _(20%)	57.1 _(60%)
Impact strength				
Maximum (J/m)	73.6 _(20%)	39.3 _(80%)	71.2 _(40%)	58.5 _(80%)
Minimum (J/m)	49.8 _(80%)	27.3 _(20%)	42.2 _(20%)	41.8 _(20%)

the pipe recyclates (RP) in the VB grade tended to increase the tensile and impact strengths up to an optimum point,⁷ whereas no definite trend could be observed for the VP grade. Moreover, under the optimum conditions, adding RB to the VB compound gave better tensile and impact properties than those of the VP compound.

Figure 12 illustrates the hardness properties of VB and VP compounds containing different RB contents. For a given RB content, the VP compound had greater hardness than the VB compound, the difference being associated with the presence of some compositions in the VP compound, such as calcium stearate and calcium carbonates (CaCO₃), that might have improved the dispersion of PVC particles during blending.¹² In this work, the average density was 1.28–1.38 g/cm³ in all cases. The previous work⁷ suggested that the changes in the hardness of the PVC blends was mainly caused by PVC gelation. As stated, there was no gelation seen in this work, and so only slight changes in the hardness and density for VB and VP compounds were observed when RB recyclates were added.

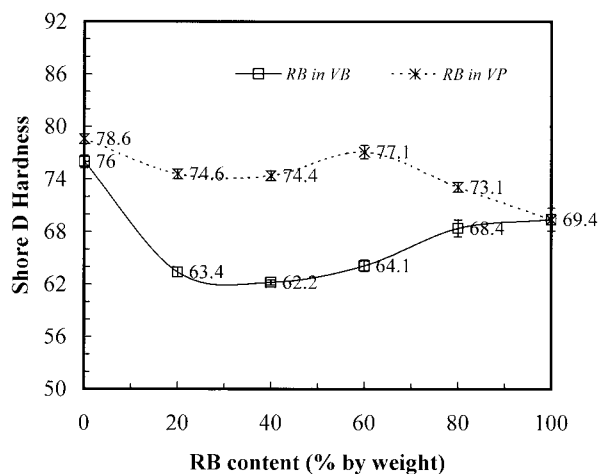


Figure 12 Shore D hardness as a function of the RB content in VB and VP compounds.

Blending PVC cable recyclates (RC) into virgin PVC (VC)

Figure 13 shows the average torque for VC compounds with various RC contents. The torque value in all cases was relatively low in comparison with values for RB/VB and RB/VP systems because of the effect of DIOP and chlorinated paraffin, which acted as plasticizers and plasticizer extender in the VC and RC compounds. Generally, the torque value did not change significantly; only a slight increase for the RC was noted. This marginal increase in the torque value probably happened for two reasons, one being a change in the bulk density of the blend, and the other being a depletion of the plasticizers as the RC recyclate was increased. As for the torque results, we did not observe any significant changes in the rheological properties (both the flow curves and extrudate swell) of the VC compound when the RC recyclate was introduced. Figure 14 shows T_d of the RC/VC blends, which stabilized for RC contents of 20–60% and then decreased at 80% RC. The reduction in the T_d value was probably caused by the stabilizer and/or plasticizer depletion. Table V shows the carbonyl and poly-

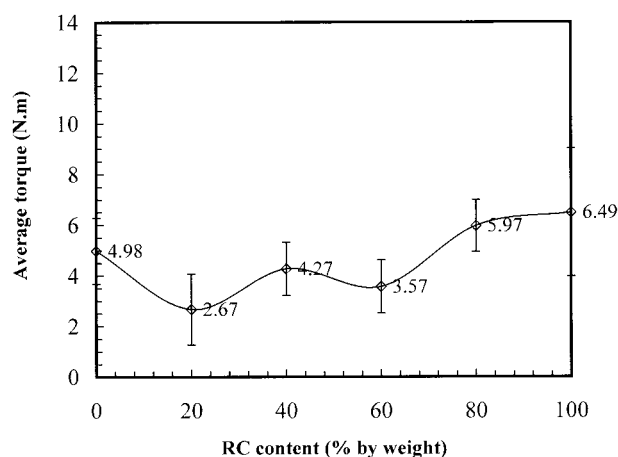


Figure 13 Average torque values for RC/VC compounds in a twin-screw extruder.

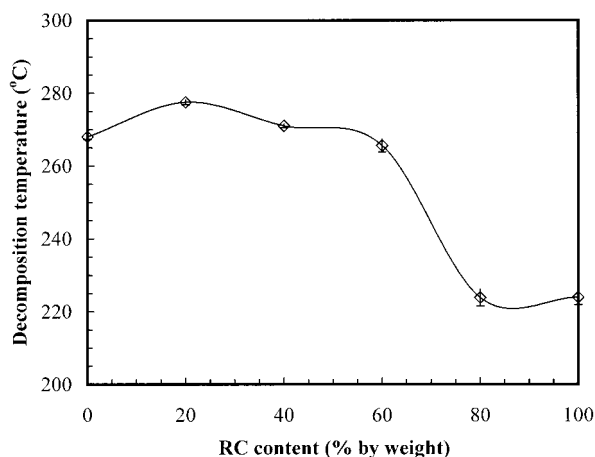


Figure 14 T_d 's of RC blended into VC compounds.

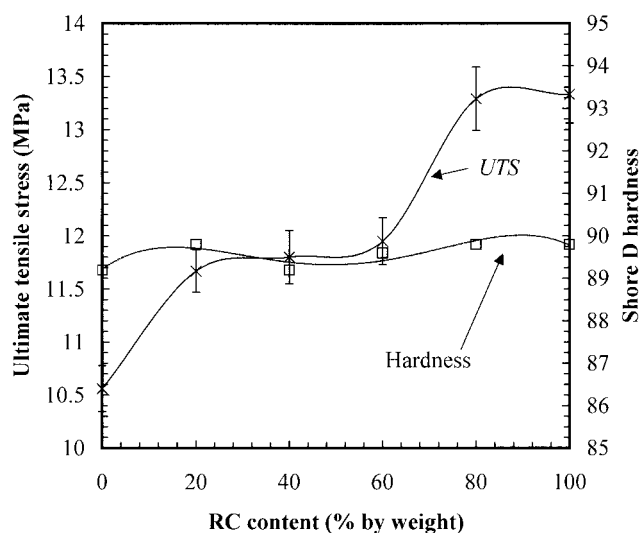


Figure 15 UTS and hardness of RC/VC blends.

ene indices for the RC/VC blends. Again, no increase in the polyene index was observed, which suggested no molecular degradation. The changing trend for the carbonyl index was virtually the same as that for T_d ; that is, the carbonyl index decreased at 80% RC. The UTS, shown in Figure 15, increased with the RC content. This was probably caused by the depletion of the plasticizers present in the RC recyclate. With increasing RC content, fewer plasticizers were left in the blend. The hardness property did not change with the RC content. This was also the case for changes in the compound density, which was unaffected by the RC recyclate (results not shown). The average density value of the RC/VC blends was 1.62 g cm^{-3} ; this surprisingly high density value probably resulted from the stabilizer (basic lead carbonate) in the blends, which had a specific gravity of $6.4\text{--}6.8 \text{ g cm}^{-3}$.¹²

CONCLUSIONS

Postconsumer PVC bottles and cables were introduced into different virgin PVC grades, and a number of properties were examined. It was recommended that the optimum concentrations of PVC recyclates to be loaded into virgin PVC compounds were different

TABLE V
Carbonyl and Polyene Indices from FTIR Curves for RC/VC Blends

RC content (%)	Indices	
	Carbonyl	Polyene
0	1.50 ± 0.01	0.43 ± 0.02
20	1.37 ± 0.02	0.43 ± 0.02
40	1.37 ± 0.03	0.38 ± 0.02
60	1.37 ± 0.03	0.40 ± 0.01
80	1.33 ± 0.02	0.38 ± 0.01
100	1.30 ± 0.02	0.38 ± 0.02

from one property to another, and this also depended on the properties of interest. The following points were noted:

- Loading PVC bottle recyclates (RB) into VB and VP compounds caused a reduction in the average torque level because of the relatively low initial torque of the RB recyclate. No thermal degradation of the RB recyclate was detected via IR analysis. The MFI and shear stress for the VP compound was more sensitive to the RB addition than those for the VB compound. The extrudate swell ratio did not change with the RB content because no gelation occurred under the experimental conditions used. The T_d values for the VB and VP compounds increased at 60–80% RB contents, whereas T_g was unaffected by the RB loading. It was recommended that the VB and VP compounds be added to 20 and 80 wt % RB recyclate, respectively, for the optimum impact strength to be obtained, the blends exhibiting a ductile fracture with a continuous phase. In addition, compared with that of RPs, the property change of RBs was faster, but adding RBs to the VB compound gave better impact and tensile properties than adding RBs to the VP compound. The hardness and density of the VB and VP compounds did not change very much with the RB content.
- Adding RC to VC compounds did not change the torque level very much, only a slight increase being observed due to the depletions of the plasticizers in the RC recyclate. The T_d values of the RC/VC blends stabilized at 20–60% RC and decreased at 80% RC because of the change in the carbonyl content of the blend. The UTS was im-

proved with 80% RC, whereas the hardness and density of VC did not change with the RC content.

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