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# BALLISTIC PERFORMANCE OF POLYCARBONATE/ POLYESTER AND POLYCARBONATE/STYRENE- ACRYLONITRILE MICROLAYER SHEETS

by

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## TABLE OF CONTENTS

	Page
LIST OF TABLES	iv
LIST OF FIGURES	iv
PREFACE	v
INTRODUCTION	1
MATERIALS	1
EXPERIMENTAL	1
Ballistic Testing.	1
Chemical Evaluation.	3
RESULTS AND DISCUSSION	3
Ballistic Testing.	3
Chemical Evaluation.	11
CONCLUSIONS	11
REFERENCES	12
APPENDIX A	13
DISTRIBUTION LIST	21

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## LIST OF TABLES

<b>Table</b>		<b>Page</b>
1.	Actual and Normalized $V_c$ and $V_{50}$ values with Sample Description for the Microlayer Materials	4
2.	Optical Appearance and Fraction of Brittle Failures for the Microlayer Materials	10

## LIST OF FIGURES

<b>Figure</b>		<b>Page</b>
1.	Diagram of Ballistic Test Setup.	2
2.	$V_c$ versus Areal Density for Microlayer Sheets.	6
3.	$V_{50}$ versus Areal Density for Microlayer Sheets.	6
4.	$V_c$ Normalized to $3 \text{ kg/m}^2$ versus Log of the Average Layer Thickness.	7
5.	$V_{50}$ Normalized to $3 \text{ kg/m}^2$ versus Log of the Average Layer Thickness.	7
6.	$V_c$ Normalized to $3 \text{ kg/m}^2$ versus Percent Composition of Polycarbonate.	8
7.	$V_{50}$ Normalized to $3 \text{ kg/m}^2$ versus Percent Composition of Polycarbonate.	8

## PREFACE

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The author would also like to thank Mr. Jeffrey N. Bremmer and the Dow Chemical Company for providing the microlayer composite samples.



# **BALLISTIC PERFORMANCE OF POLYCARBONATE/POLYESTER AND POLYCARBONATE/STYRENE-ACRYLONITRILE MICROLAYER SHEETS**

## **INTRODUCTION**

Currently, the material of choice for eye protection is polycarbonate. The impact resistant properties of polycarbonate are outstanding; however, the scratch and chemical resistance of the material are poor. There is a need for a material with good scratch and chemical resistance while improving upon the ballistic impact behavior of polycarbonate.

Recent studies with extruded microlayer sheets have shown that many of the microlayer materials possess mechanical properties superior to the sum of the components.<sup>1-4</sup> This work examines extruded microlayer sheets for ballistic performance and chemical resistance.

## **MATERIALS**

Extruded sheets of the polycarbonate/poly(cyclohexane-1,4-dimethylene terephthalate) (PC/PCTG) and the polycarbonate/poly(styrene-acrylonitrile) (PC/SAN) microlayer samples were provided by the Dow Chemical Company. The reported grades of polymers in the PC/PCTG sheets are Calibre<sup>®</sup> 200-22 and Kodar<sup>®</sup> 5445. The grades of polymers in the PC/SAN sheets are Calibre<sup>®</sup> 302-22 and Tyril<sup>®</sup> 1000B except for samples 41A and 39B, which also contain a different polycarbonate grade XU 73049.03 (11 MFR). Table 1 in the Results and Discussion section gives a listing of the samples with respect to polymer composition, numbers of layers, and thickness, as well as the ballistic testing results. Diethylene triamine (DETA) and xylene were used for chemical resistance evaluation.

## **EXPERIMENTAL**

**Ballistic Testing.** Ballistic performance was evaluated by testing the plaques according to MIL-STD-662E V<sub>50</sub> Ballistic Test for Armor<sup>5</sup> using a high-pressure helium gas gun. A 17-grain fragment simulator was used as the projectile. The test plaques were rigidly held in a sample holder made from two 13-inch square, 3/4-inch thick aluminum plates bolted together and placed in a mount. Four 1-inch diameter holes in the plates located in the center of each corner quadrant provided for the passage of the projectile through the plaques. After each shot, the sample holder was rotated in its mount to align the next sample. After a set of four shots, the holder was removed from the mount, opened, and the samples repositioned for the next shots. A schematic of the test setup is shown in Figure 1.



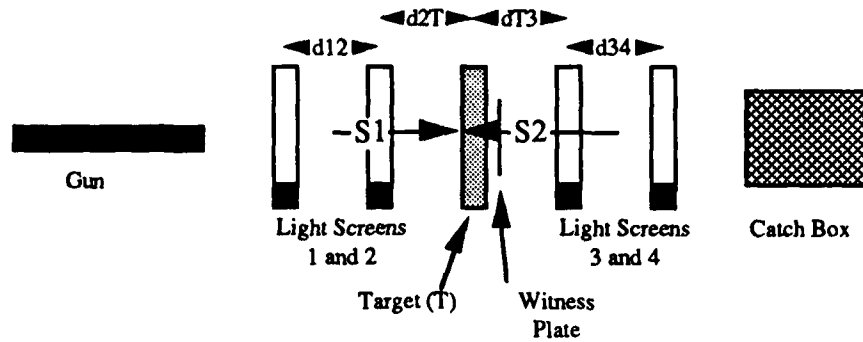


Figure 1. Diagram of Ballistic Test Setup.

Four light screens were used as triggers for timers to record the time-of-flight of the projectile to determine the velocity of the projectile before and after impact. The timers recorded the time-of-flight between screens 1 & 2, 2 & 3, 3 & 4 and 1 & 4 as a check. From measurements of the distance between each of the screens and target, and the time-of-flight between screens 1 & 2 and 3 & 4, the velocities at the midpoint between each set of screens can be determined. The distances from the midpoint of screens 1 & 2 and 3 & 4 to the target are referred to as S1 and S2, respectively. The striking and residual velocities were determined by taking air resistance into account over S1 and S2 as shown in equations 1 and 2<sup>6</sup>

$$V_s = V_{12} \left( 1 - \frac{S1}{C} \right) \quad (1)$$

$$V_r = V_{34} \left( 1 - \frac{S2}{C} \right) \quad (2)$$

- where  $V_s$  = the striking velocity of the projectile  
 $V_{12}$  = the velocity at the midpoint between screens 1 & 2  
 $S1$  = the distance from midpoint between screens 1 & 2 and the target  
 $C$  = correction constant, 52.4 m/s  
 $V_r$  = the residual velocity after penetration  
 $V_{34}$  = the velocity at the midpoint between screens 3 & 4  
 $S2$  = the distance from midpoint between screens 3 & 4 and the target.

A 0.05 mm thick aluminum witness plate was used to record complete penetrations. A complete penetration is defined as occurring "when the impacting projectile, or any fragment thereof, or any fragment of the test specimen perforates the witness plate, resulting in a crack or hole that permits the passage of light when a 60-watt, 110-volt bulb is placed proximate to the witness plate."<sup>5</sup> A catch box, layered with felt pads and Kevlar<sup>®</sup> fabric, was used to stop the projectile.

Two different characteristic velocities,  $V_{50}$  and  $V_c$ , were calculated.  $V_{50}$ , the velocity at which 50 percent of the impacts result in complete penetration, was calculated from the

arithmetic mean of the five highest partial and five lowest complete penetration impact velocities. A complete penetration is defined as an impact that causes a perforation of the witness plate. A partial penetration is defined as an impact that does not cause a perforation of the witness plate.  $V_c$ , the critical velocity for complete penetration, was calculated by fitting the following equations<sup>7, 8</sup>

$$V_r^2 = A V_s^2 - B \quad (3)$$

$$V_c^2 = \frac{B}{A} \quad (4)$$

$$V_r = (A(V_s^2 - V_c^2))^{1/2} \quad (5)$$

where  $V_s$  = the striking velocity of the projectile

$V_r$  = the residual velocity after penetration

$V_c$  = the critical velocity for complete penetration

A = the slope of the line

B = the intercept

to all striking and residual velocities where striking velocity was the greater than or equal to the lowest complete penetration velocity. A minimum of 20 shots was used for each set of samples, with at least eight shots spread over the range from  $V_{50}$  to approximately 120 m/s above the  $V_{50}$ .

**Chemical Evaluation.** The chemical evaluation by immersion was conducted at the U.S. Army Research Laboratory, Materials Directorate. Only the PC/PCTG samples were tested because diethylene triamine (DETA) and xylene are good solvents for SAN.<sup>9</sup> DETA is a major ingredient in DS2, a decontaminating solution. The PC/PCTG microlayer samples were immersed in DETA and xylene for one week.

All samples were also exposed to drops of DETA at room temperature. The drops were directly applied to the surface and left in place for 88 hours. The samples were rinsed with water and wiped with a paper towel to remove the DETA. The surfaces were examined for deterioration visible to the eye. The drop testing was conducted at the U.S. Army Natick Research, Development and Engineering Center.

## RESULTS AND DISCUSSION

**Ballistic Testing.** The ballistic testing results are summarized in Table 1. Graphs of the striking velocity versus the residual velocity are shown in Appendix A.

The ballistic testing results are not easily discernible. These materials have different compositions, number of layers, thicknesses, and areal densities. The failure mechanism is also important. It is unacceptable for the material to produce spall when impacted. Spall is

Table 1. Actual and Normalized  $V_c$  and  $V_{50}$  Values with Sample Description for the Microlayer Materials

Sample ID	% Composition Polycarbonate	Second Polymer	Number of Layers	Thickness (mm)	Areal Density (kg/m <sup>2</sup> )	$V_c \pm 0$ (m/s)	$V_{50} \pm 0$ (m/s)	$nV_c^*$ (m/s)	$nV_{50}^*$ (m/s)
55B	80	PCTG	Blend (1)	2.64	3.18	205 (3)	206 (3)	196	197
49C	80	PCTG	1857	2.57	2.99	191 (8)	195 (2)	192	196
49A	60	PCTG	1857	2.59	3.16	186 (10)	189 (4)	178	181
55A	80	PCTG	3713	1.98	2.70	163 (7)	157 (3)	178	172
53A	60	PCTG	3713	2.72	3.31	200 (7)	202 (9)	184	186
25C	100		1	2.90	3.40	221 (4)	218 (1)	200	198
25B	85	SAN	Blend (1)	2.84	3.36	198 (10)	201 (2)	179	183
25A	70	SAN	Blend (1)	2.95	3.33	125 (14)	146 (25)	108	129
15B	85	SAN	233	2.87	3.36	215 (6)	211 (5)	196	193
13B	70	SAN	233	2.77	3.20	117 (16)	118 (17)	107	108
19C	85	SAN	929	2.84	3.30	205 (4)	204 (6)	189	189
19B	70	SAN	929	2.87	3.31	180 (11)	170 (5)	164	155
41A	80	SAN	1857	1.35	1.53	117 (5)	117 (3)	193	191
39B	70	SAN	1857	1.40	1.59	94 (10)	101 (8)	167	172
Injection molded	100		1	3.20	3.99	221 (3)	218 (6)	170	168
Injection molded	100		1	1.60	2.01	136 (4)	130 (6)	187	180

\*  $V_c$  and  $V_{50}$  normalized to a 3 kg/m<sup>2</sup> areal density.

the detachment or delamination of a layer of material in the area surrounding the location of impact, which may occur on either the front or rear surfaces of the sample and is produced as a result of a brittle failure mechanism.

Ballistic testing results are usually compared with regard to the material's areal density. This is the mass of the material per unit area or the density of the material multiplied by the thickness. To compensate for the various areal densities of the samples, the  $V_c$  and  $V_{50}$  values have been normalized to a  $3 \text{ kg/m}^2$  areal density. This normalization is an acceptable treatment based on data in Figures 2 and 3 that demonstrate a relationship between  $V_c$  or  $V_{50}$  and areal density with the exception of two PC/SAN samples. Linear regressions for the  $V_c$  and  $V_{50}$  versus areal density yield an average correlation coefficient of 0.951. Values for the 70/30 PC/SAN blend and 233 layer samples were not included in the regression, as it is clear in Figures 2 and 3 that those points are outlying values; however, values for two injection-molded polycarbonate samples from a previous study were included,<sup>10</sup> demonstrating the general applicability of the relationship.  $V_c$  and  $V_{50}$  values were normalized to a  $3 \text{ kg/m}^2$  areal density by the following equation,

$$V_n = [ a (3 - D)] + V \quad (6)$$

where  $V_n$  = the normalized  $V_c$  or  $V_{50}$  for the sample

$V$  =  $V_c$  or  $V_{50}$  for the sample

$D$  = the areal density in  $\text{kg/m}^2$

$a$  = the slope of the regressed line (51.755 for  $V_c$ , 50.377 for  $V_{50}$ ).

A direct comparison between samples is now possible. The next variable to consider is the number of layers. Since the normalization effectively changes the dimensions of the sample, the number of layers is no longer a meaningful value; instead the average layer thickness is considered. A 3 mm thick sample with 3000 layers is not the same material as a 2 mm thick sample with 3000 layers but a 2 mm thick sample with an average layer thickness of 0.001 mm could be considered to be made of the same material. Figures 4 and 5 show plots of the normalized  $V_c$  and  $V_{50}$  versus the log of the average layer thickness. Most of the data fall between 155 and 200 m/s for both normalized  $V_c$  and  $V_{50}$ . The exception to this range are the 70/30 PC/SAN samples. No general trends can be seen in either Figures 4 or 5. There is a significant improvement in both the  $V_c$  and  $V_{50}$  in the 70/30 PC/SAN samples that occurs between the 233 and 929 layer samples. This improvement continues into the 1857 layer sample.

Figures 6 and 7 show plots of the normalized  $V_c$  and  $V_{50}$  versus the percent composition of polycarbonate. For the PC/PCTG microlayer samples, the results were

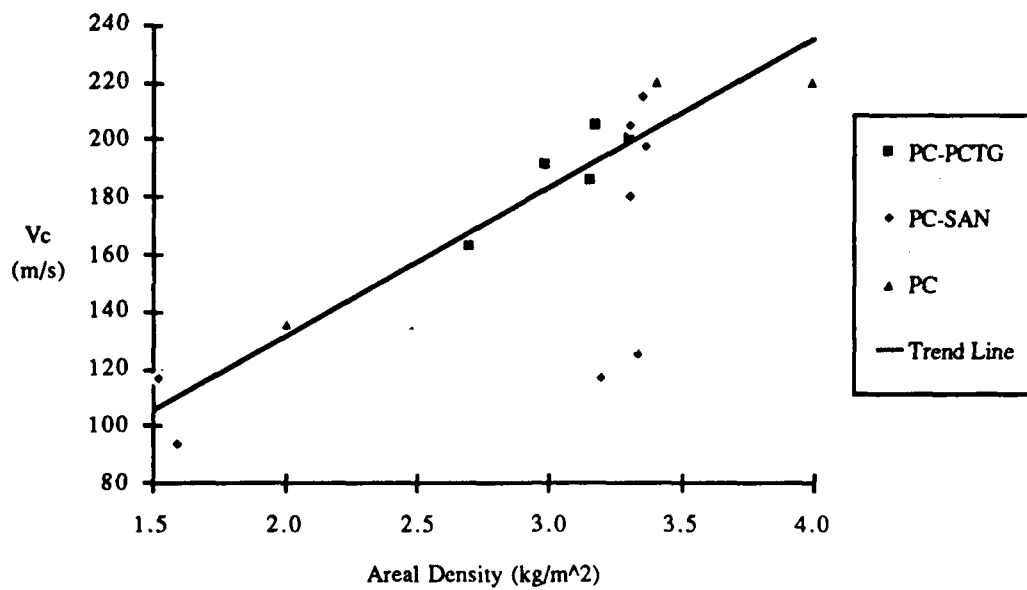


Figure 2.  $V_c$  versus Areal Density for Microlayer Sheets.

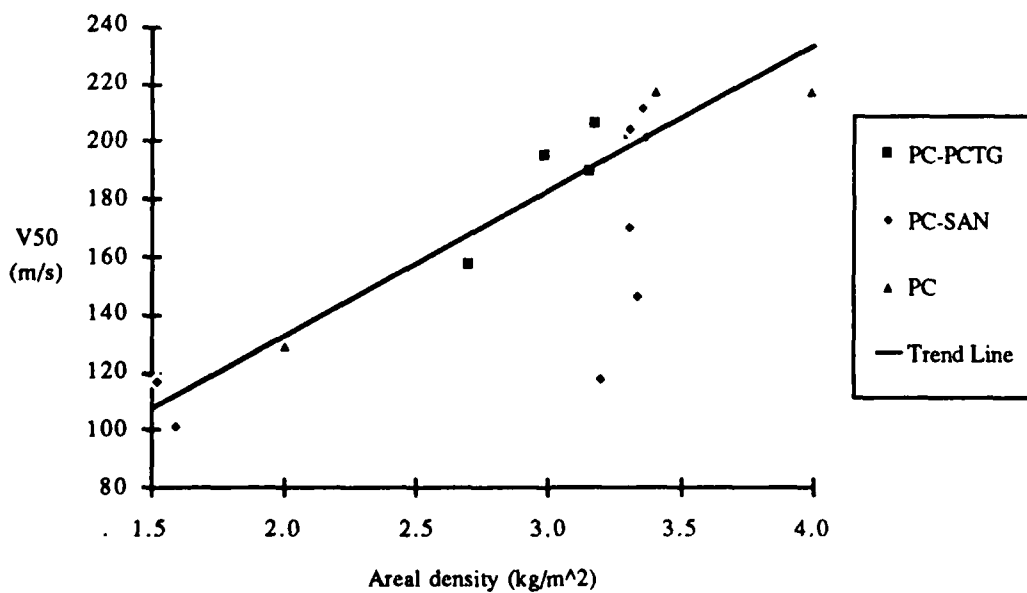


Figure 3.  $V_{50}$  versus Areal Density for Microlayer Sheets.

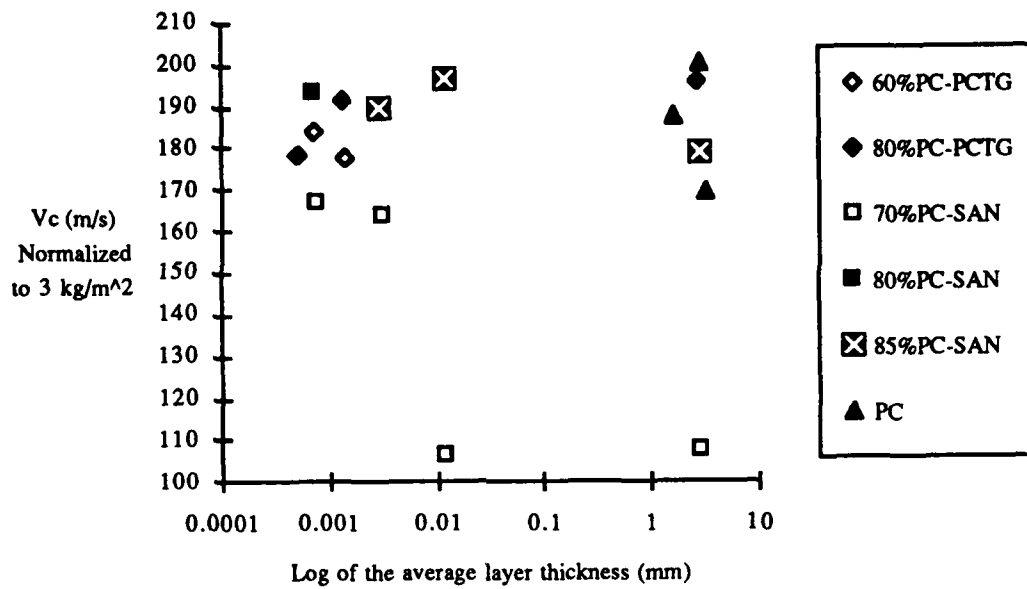


Figure 4.  $V_c$  Normalized to  $3 \text{ kg/m}^2$  versus Log of the Average Layer Thickness.

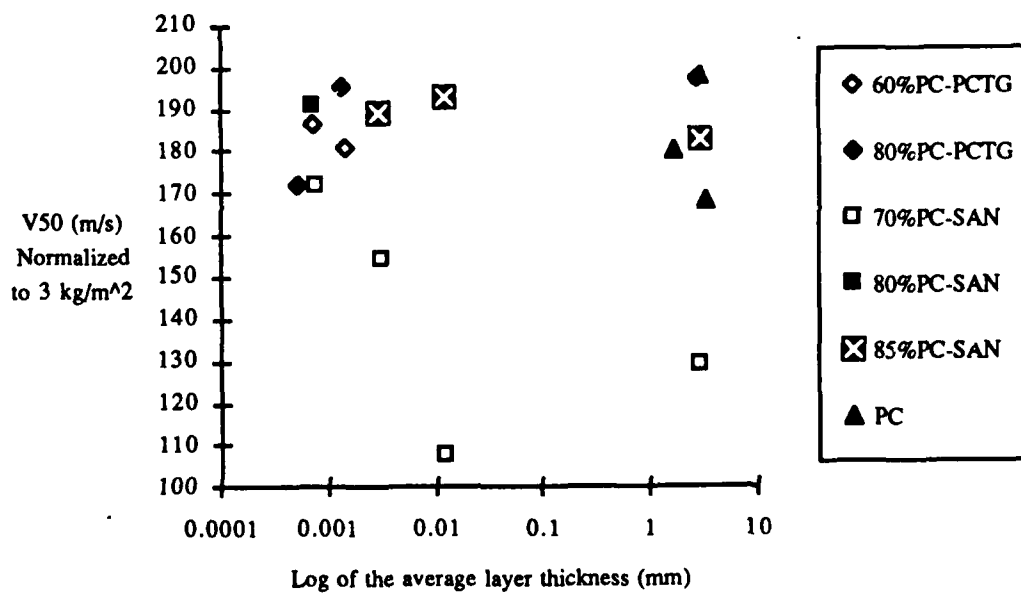


Figure 5.  $V_{50}$  Normalized to  $3 \text{ kg/m}^2$  versus Log of the Average Layer Thickness.

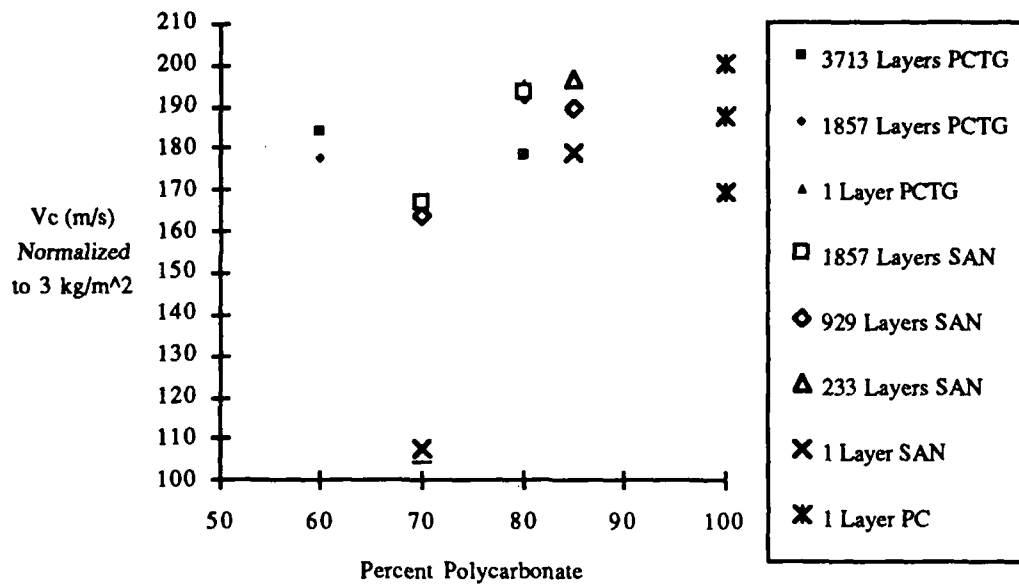


Figure 6.  $V_c$  Normalized to  $3 \text{ kg/m}^2$  versus Percent Composition of Polycarbonate.

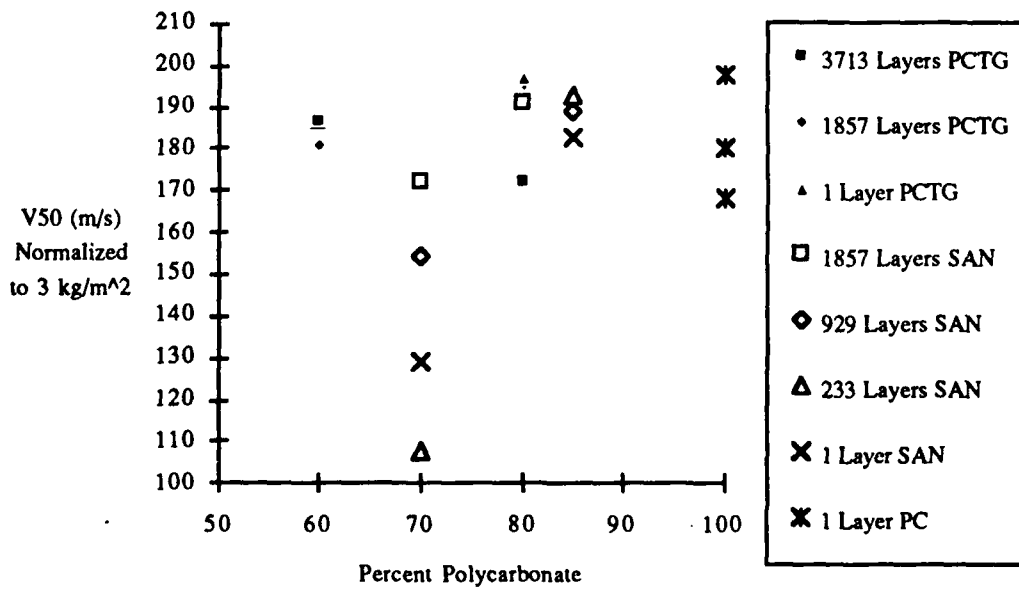


Figure 7.  $V_{50}$  Normalized to  $3 \text{ kg/m}^2$  versus Percent Composition of Polycarbonate.

rather uniform. For the precision of the test method, the differences in the results may be statistically insignificant. The precision in the  $V_c$  is determined by the x-intercepts of a confidence band for the regression of each ballistic data set.<sup>11</sup> A 95 percent confidence interval for the  $V_c$  is given as the  $\pm$  associated with each  $V_c$  in Table 1. This spread in the data can also be observed by inspecting the  $V_s$  versus  $V_r$  graphs in Appendix A. The precision in the  $V_{50}$  can be estimated by the range in each data set used for the calculation of  $V_{50}$ . This range is represented as the  $\pm$  associated with each  $V_{50}$  in Table 1. The range is not a true  $\pm$  since the calculated  $V_{50}$  need not be centrally located within the range.

The results for the PC/SAN microlayer samples are very different. The 70/30 PC/SAN has a range of results from 108 to 172 m/s normalized  $V_{50}$  with a general trend of increasing normalized  $V_{50}$  with increasing numbers of layers. The 80/20 and 85/15 PC/SAN are less scattered. It appears that the  $V_c$  and  $V_{50}$  drop off with less than 80 percent polycarbonate in the PC/SAN composite. The highest normalized  $V_c$  and  $V_{50}$  values are 200 and 198 m/s for sample 25C, the extruded polycarbonate control sample.

The material behavior on impact and optical appearance are as important as the material performance. Table 2 lists the optical appearance and fraction of brittle failures for the microlayer materials. The PC/SAN blends have 100 percent brittle failures, while the PC/PCTG blend and the polycarbonate sheet have no brittle failures. In both the PC/SAN and the PC/PCTG microlayer materials, the fraction of brittle failures decreases with both increasing polycarbonate composition and increasing number of layers.

The ballistic performance of the PC/SAN microlayer sheets conforms to the impact results of Im et al.<sup>3</sup> for PC/SAN microlayer sheets at 3.4 m/s impact velocity. Im found that impact strength increases with polycarbonate content and also with the number of layers for a given polycarbonate content. The PC/SAN microlayer sheets showed a brittle to ductile transition corresponding to a sharp rise in the impact strength. This transition shifted to a lower polycarbonate content with increasing numbers of layers. Im also reported that a 55/45 PC/SAN with 391 layers has 95 percent of the impact strength of the polycarbonate control.

The PC/SAN samples in this study, for the most part, contain a greater number of layers than the materials used in Im's standard impact study and this study's composition is predominately polycarbonate. Materials tested in this study would be within 95 percent of the impact strength of the polycarbonate control used in Im's impact study, except for the 233 layer PC/SAN sample. Thus, few clear trends for the normalized  $V_c$  and  $V_{50}$  ballistic impact results are noticeable. The precision of the ballistic test for  $V_c$  and  $V_{50}$  is not great enough to discern the slight differences in the impact strength of the materials. The ballistic performance of the PC/PCTG microlayer materials should also be able to be explained in a



Table 2. Optical Appearance and Fraction of Brittle Failures for the Microlayer Materials

Sample ID	% Composition Polycarbonate	Second Polymer	Number of Layers	Optical Appearance	Fraction of Brittle Failures
25B	85	SAN	Blend (1)	opaque	24 / 24 (100%)
25A	70	SAN	Blend (1)	opaque	39 / 39 (100%)
15B	85	SAN	233	clear	5 / 20 (25%)
13B	70	SAN	233	clear	29 / 32 (91%)
19C	85	SAN	929	clear	7 / 24 (29%)
19B	70	SAN	929	clear	18 / 28 (64%)
41A	80	SAN	1857	clear	0 / 24 (0%)
39B	70	SAN	1857	clear	2 / 28 (7%)
55B	80	PCTG	Blend (1)	clear, lt. yellow	0 / 20 (0%)
49C	80	PCTG	1857	clear, lt. yellow	1 / 28 (4%)
49A	60	PCTG	1857	clear, lt. yellow	3 / 23 (13%)
55A	80	PCTG	3713	clear, lt. yellow	0 / 23 (0%)
53A	60	PCTG	3713	clear, lt. yellow	2 / 32 (6%)
25C	100		1	clear	0 / 24 (0%)

similar manner especially since PCTG, rather than SAN, is more like polycarbonate.

**Chemical Evaluation.** Both polycarbonate and PCTG are attacked by diethylene triamine (DETA). Polycarbonate dissolves in DETA within 24 hours. PCTG dissolves slightly in DETA. When the microlayer PC/PCTG samples were immersed in DETA for one week, the top polycarbonate layer dissolved and the PCTG layer flaked off to expose the next polycarbonate layer. A top-down process was apparent.

Both polycarbonate and PCTG crystallize when immersed in xylene. The polycarbonate turns opaque; the PCTG crystallizes slightly and turns translucent. When the microlayer PC/PCTG samples were immersed in xylene for one week, the samples fractured in the middle of the thickness due to stress cracking. The samples turned white.

All samples from the drop testing showed a remaining drop beading on the surface of the sample. When rinsed with water, these drops were found to be swollen polymer. The PC/PCTG samples all show the same results. Where the drop was placed, a hazy patch that is slightly rough to the touch when compared to the rest of the surface formed. The polycarbonate sample shows the same results as the PC/PCTG samples and there is also a dimple or crater where the drop was placed that can be seen and felt.

The two blended PC/SAN samples show the same results as the 100 percent polycarbonate sample. The surface appears hazy by reflected light since the sample is opaque. All the microlayer PC/SAN show only a slight effect from the drop of DETA. One can tell where the drop was by an outline on the surface of the sample. The surface where the drop was placed appears normal for all but sample 41A. On sample 41A, the surface where the drop was placed is slightly hazy. The PC/SAN samples do show a depression where the drop of DETA was placed but it is different from the depressions in the polycarbonate and the PC/SAN blended samples. Those showed a concave surface in the material where the drop was placed. In the microlayer PC/SAN, the depression appears flat to the eye as if the DETA uniformly dissolved the material as it sank into the surface.

## CONCLUSIONS

$V_c$  and  $V_{50}$  follows a linear relationship with areal density that allows the results to be normalized. Two trends can be seen for the normalized velocities. For the PC/SAN microlayer composite, the  $V_c$  and  $V_{50}$  decrease with less than 80 percent polycarbonate. In both the PC/PCTG and PC/SAN, the fraction of brittle failures decreases with both polycarbonate composition and increasing number of layers.

The microlayer composites do show some promise as a ballistic armor material since some samples performed as well as and better than injection-molded polycarbonate.

However, the extrusion and subsequent thermoforming would add cost to an item that is currently injection molded. The increase in performance may be offset by the increase cost, so switching materials may not be cost effective. Also, the chemical resistance for these materials, while an apparent improvement over neat polycarbonate, is still poor.

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APPENDIX A

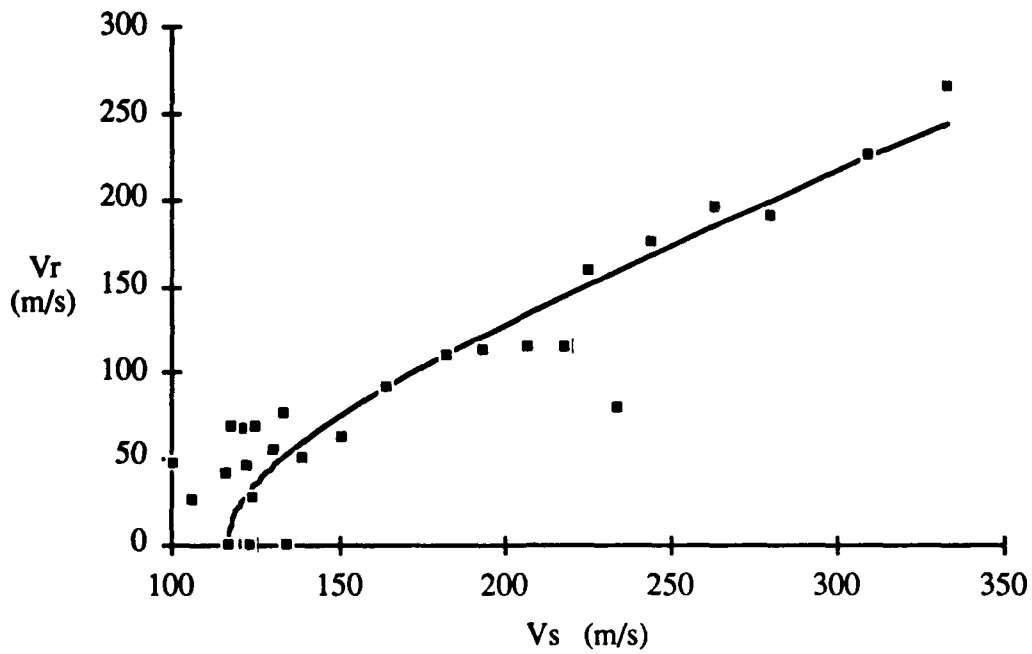


Figure A-1. Residual Velocity Versus Striking Velocity for Sample 13B.

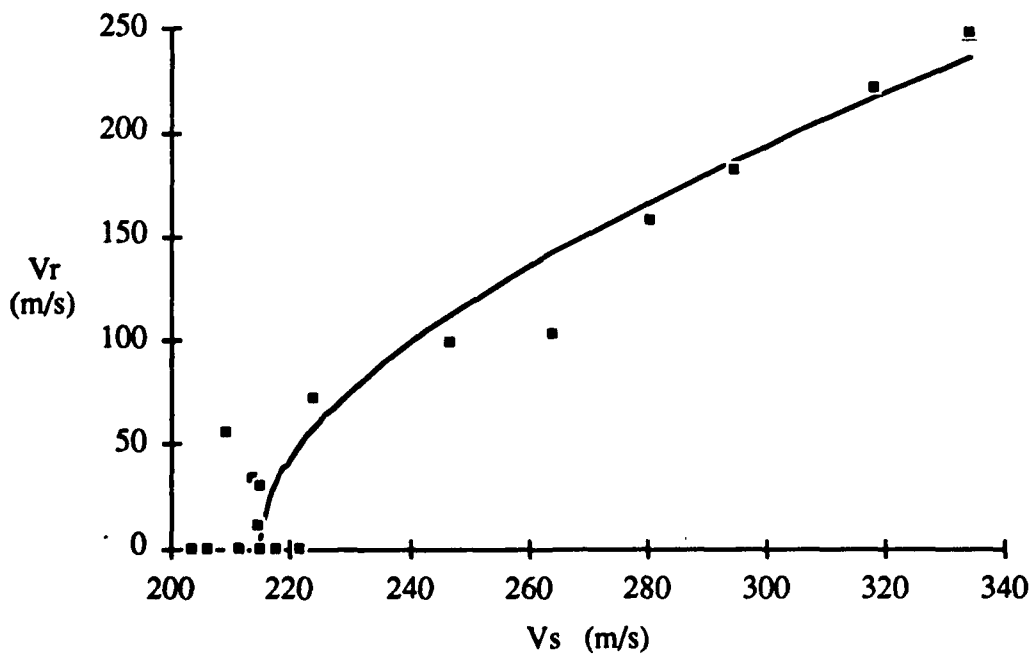


Figure A-2. Residual Velocity Versus Striking Velocity for Sample 15B.

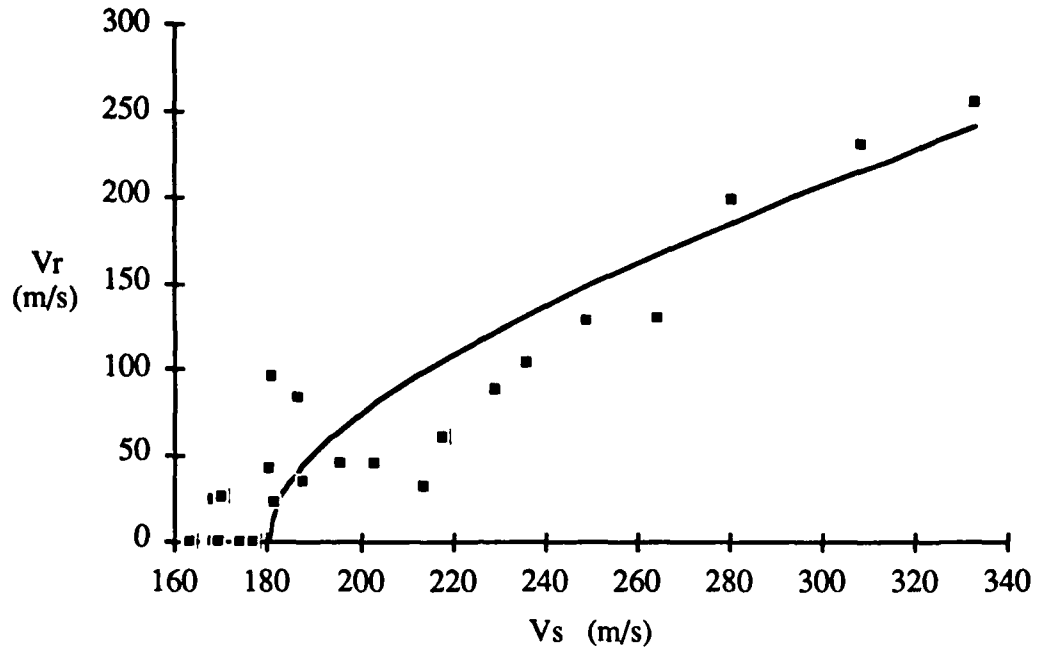


Figure A-3. Residual Velocity Versus Striking Velocity for Sample 19B.

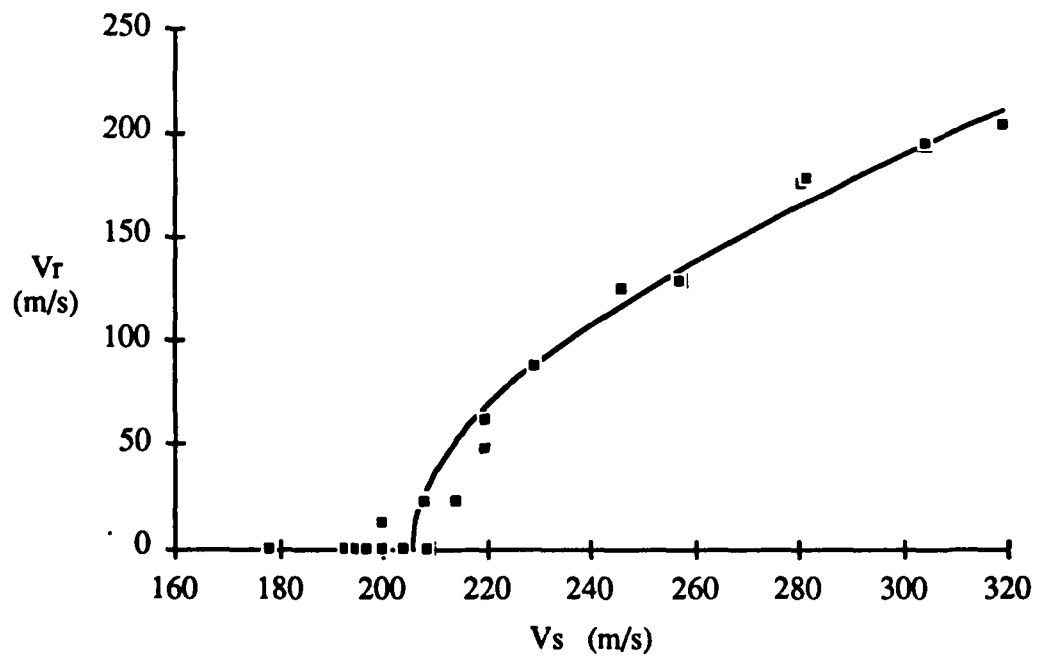


Figure A-4. Residual Velocity Versus Striking Velocity for Sample 19C.

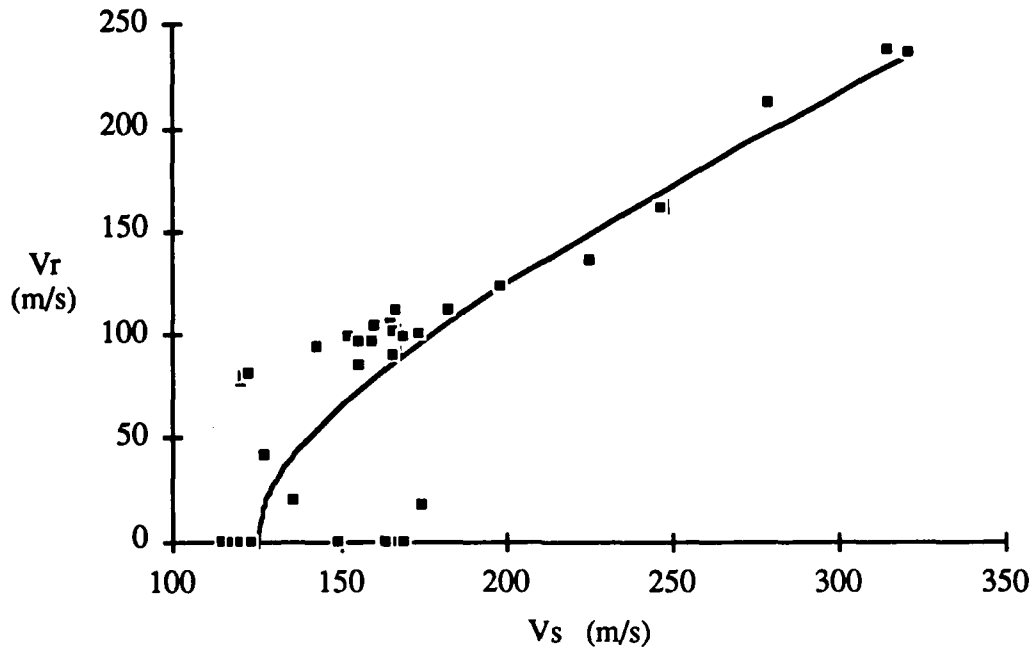


Figure A-5. Residual Velocity Versus Striking Velocity for Sample 25A.

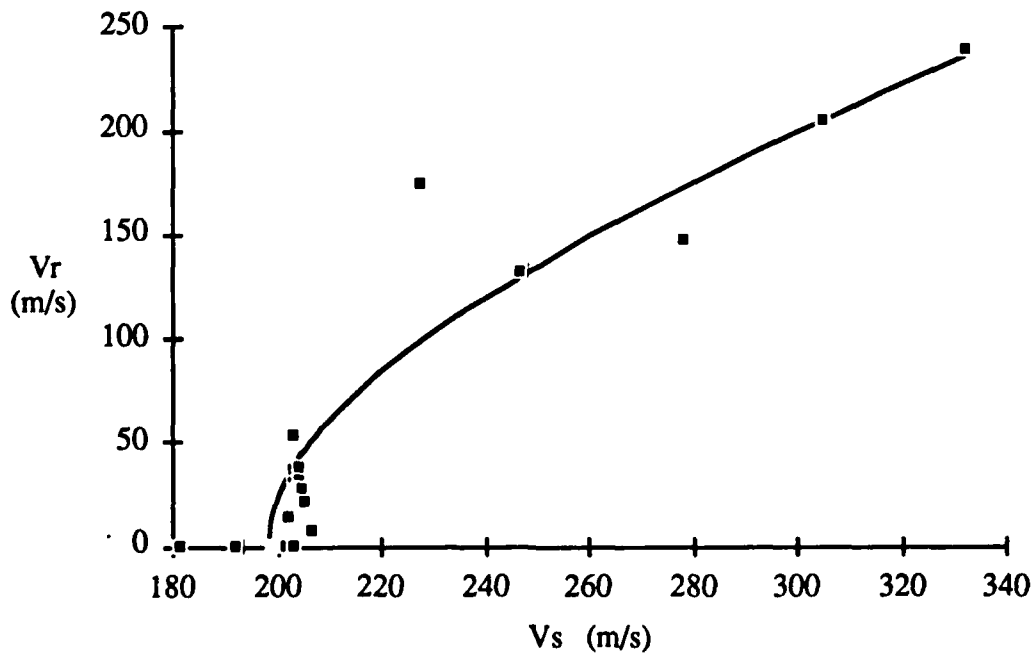


Figure A-6. Residual Velocity Versus Striking Velocity for Sample 25B.

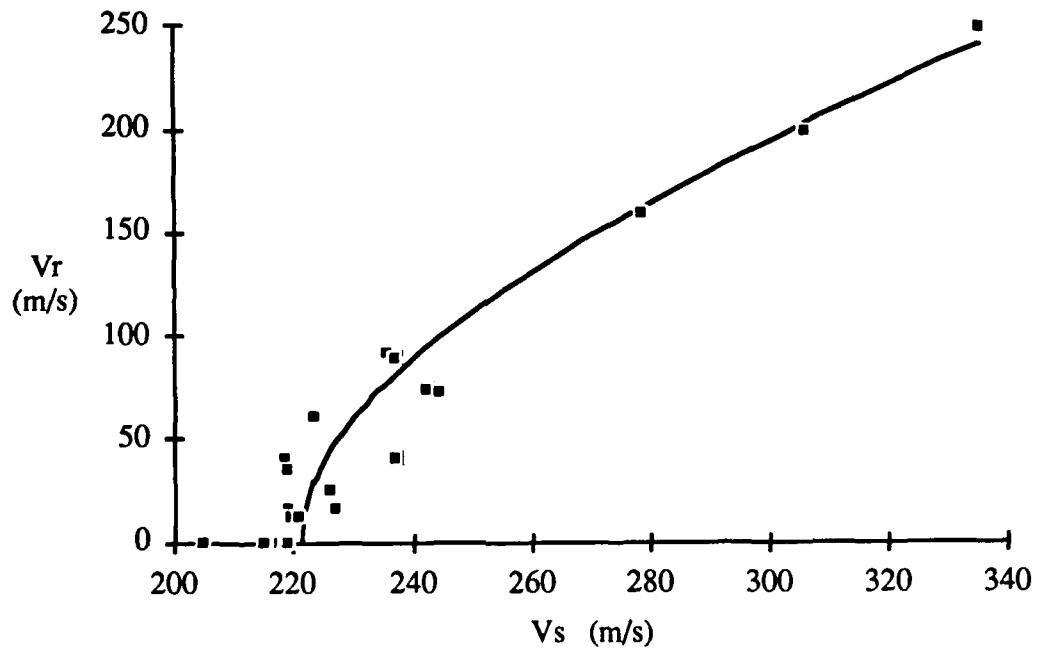


Figure A-7. Residual Velocity Versus Striking Velocity for Sample 25C.

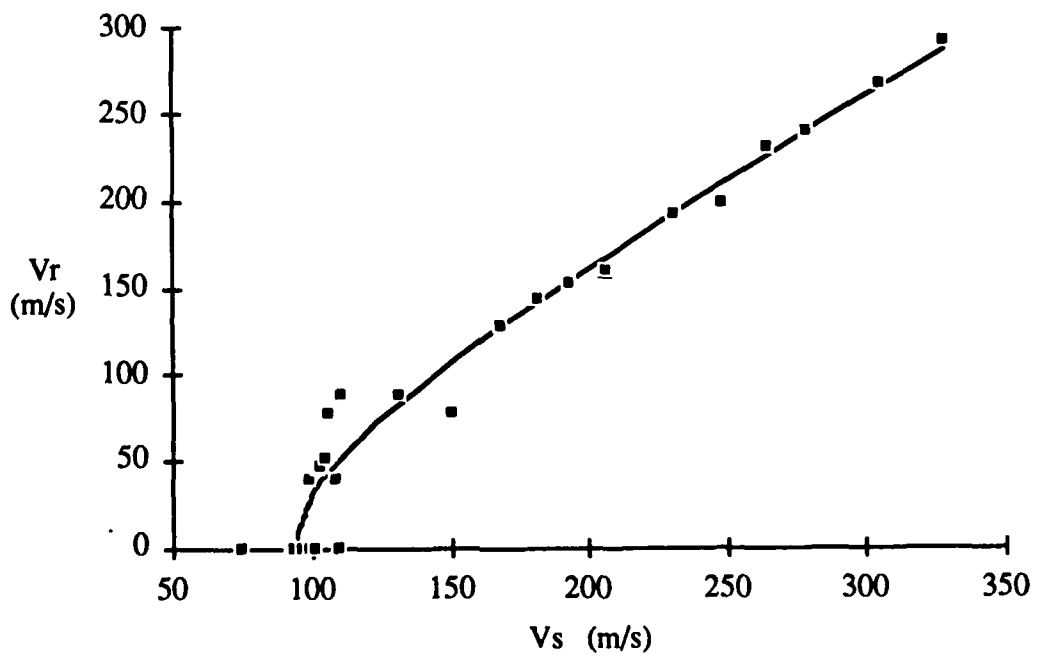


Figure A-8. Residual Velocity Versus Striking Velocity for Sample 39B.



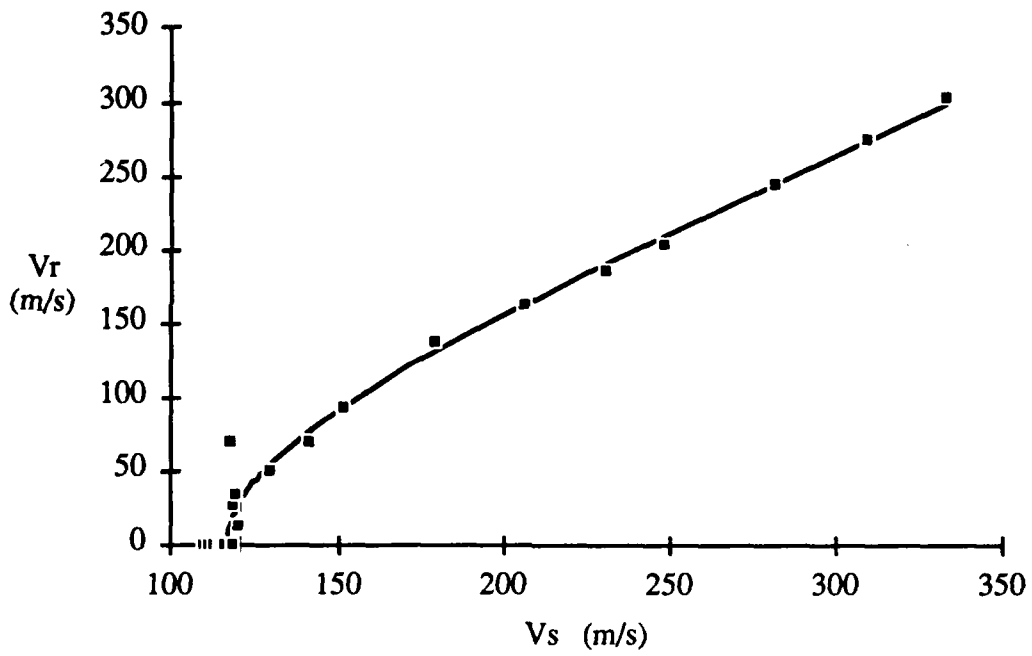


Figure A-9. Residual Velocity Versus Striking Velocity for Sample 41A.

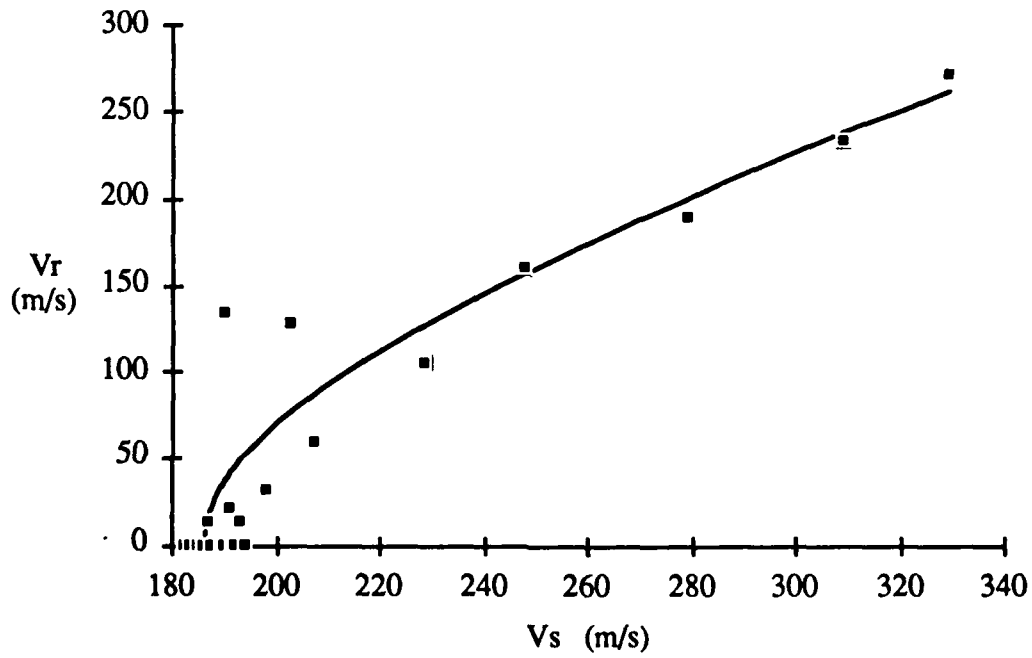


Figure A-10. Residual Velocity Versus Striking Velocity for Sample 49A.

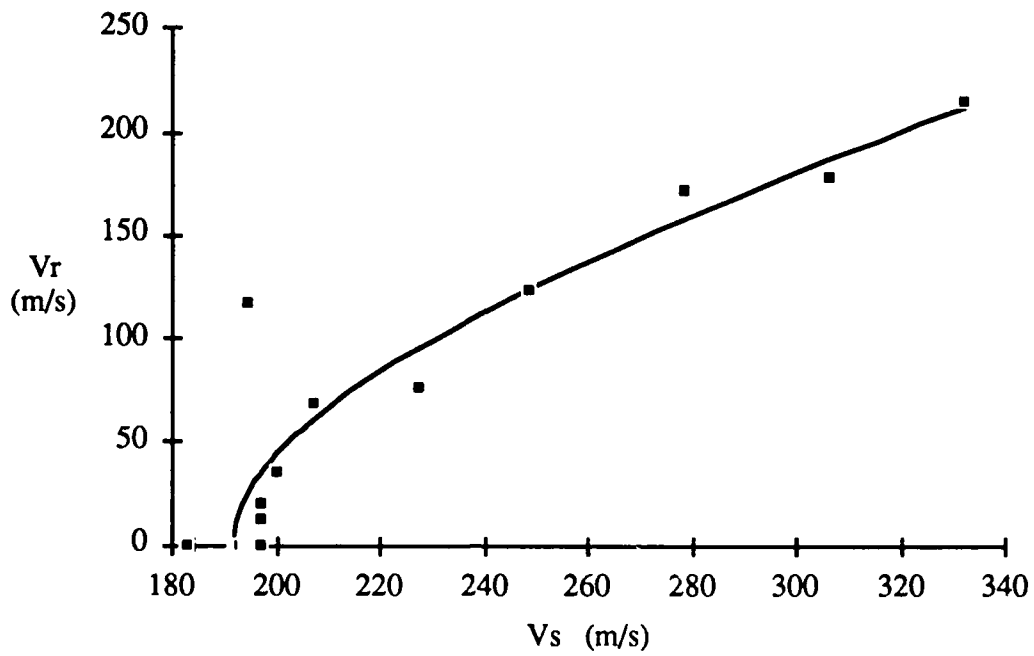


Figure A-11. Residual Velocity Versus Striking Velocity for Sample 49C.

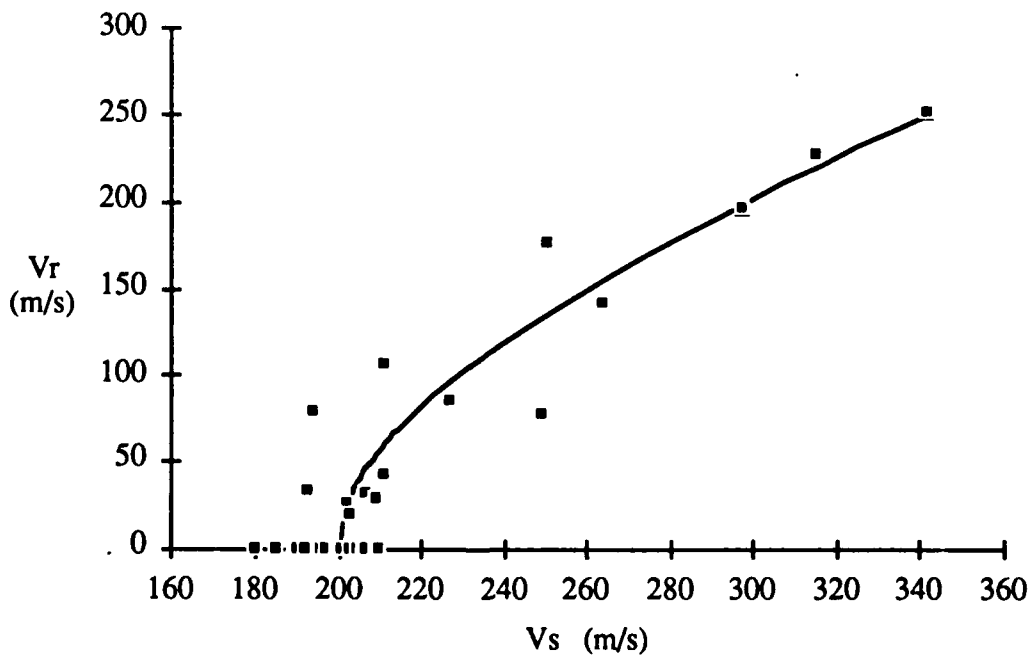


Figure A-12. Residual Velocity Versus Striking Velocity for Sample 53A.

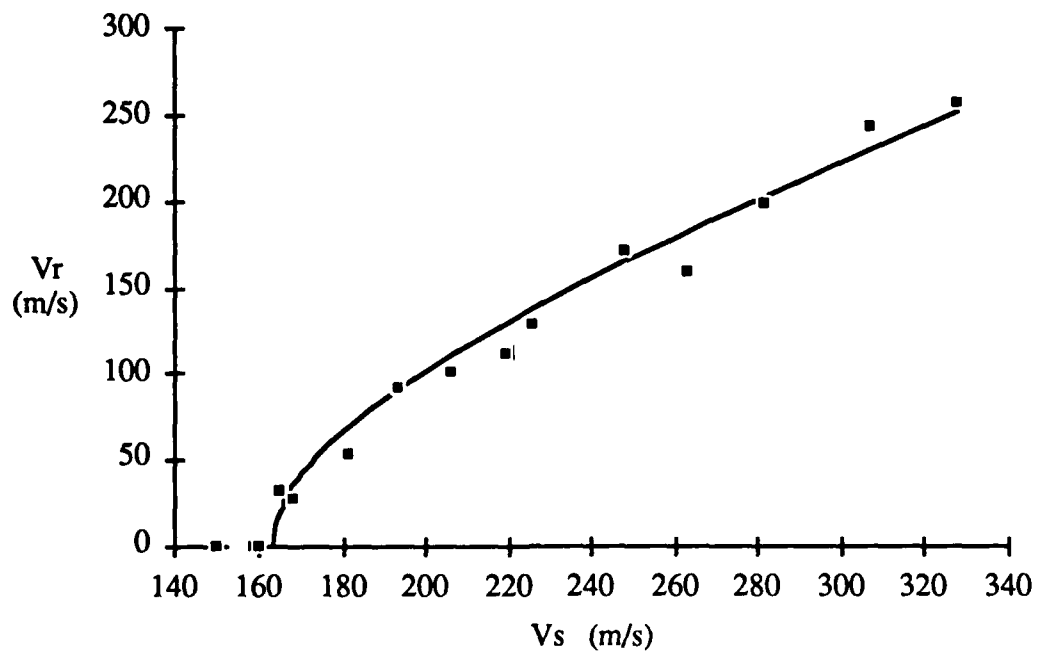


Figure A-13. Residual Velocity Versus Striking Velocity for Sample 55A.

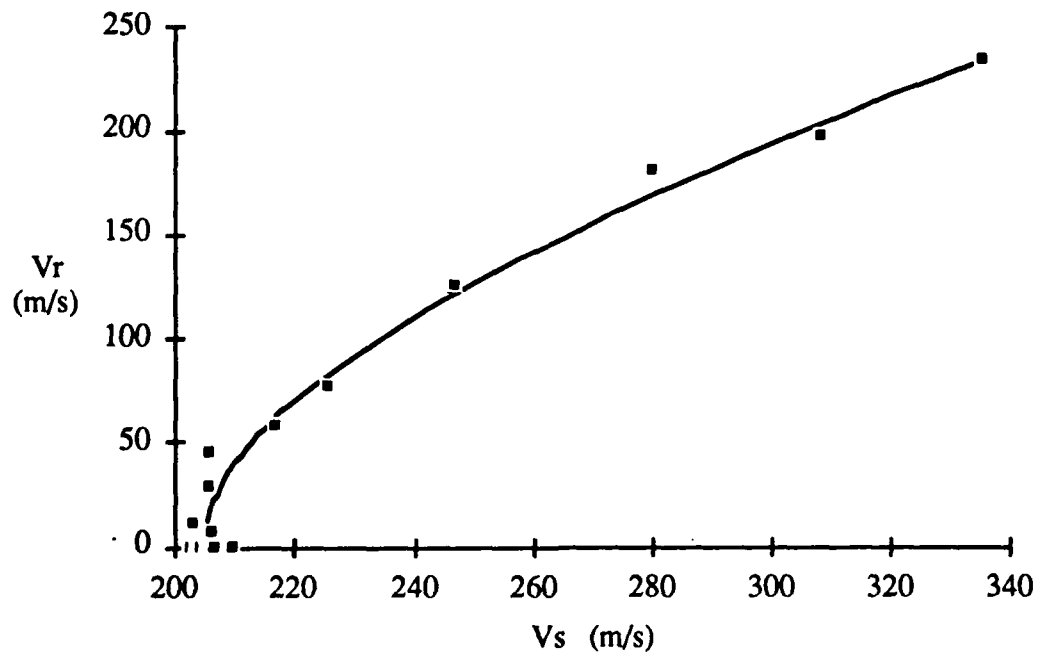


Figure A-14. Residual Velocity Versus Striking Velocity for Sample 55B.

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