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PROCESSING-MORPHOLOGY-PROPERTY RELATIONSHIPS
FOR COMPOUNDING WOOD FIBERS
WITH
RECYCLED HDPE USING TWIN-SCREW EXTRUDER

presented by

Binoj Kumar Gogoi

has been accepted towards fulfillment
of the requirements for

M.S. degree in PACKAGING

Major professor
Susan E. Selke

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**PROCESSING-MORPHOLOGY-PROPERTY RELATIONSHIPS
FOR COMPOUNDING WOOD FIBERS
WITH
RECYCLED HDPE USING A TWIN-SCREW EXTRUDER**

**By
Binoy Kumar Gogoi**

A THESIS

**submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

School of Packaging

1989

ABSTRACT

PROCESSING-MORPHOLOGY-PROPERTY RELATIONSHIPS FOR COMPOUNDING WOOD FIBERS WITH RECYCLED HDPE USING A TWIN-SCREW EXTRUDER.

By

Binoy Kumar Gogoi

The development of composites consisting of wood fibers and recycled plastics offers not only an opportunity to utilize an abundant natural resource but also a means to alleviate the serious problem of plastics waste disposal. In this study, aspen fibers are incorporated into recycled high density polyethylene using a co-rotating intermeshing twin-screw extruder. Mixing conditions are varied to study the effects of fiber pre-treatment, screw configuration and compounding temperature on the mechanical properties of the composite. Tensile, impact and flexural strength are measured as a function of fiber concentration while the fracture surfaces of tensile specimens are studied using the SEM. Theoretical predictions for tensile strength and tensile modulus are compared with experimental data.

To my father and mother, Jogneshwar and Bijoya Gogoi.

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B.K.Gogoi

5.10.1989

TABLE OF CONTENTS

page	
LIST OF TABLES	viii
LIST OF FIGURES	ix
I. INTRODUCTION	1
II. SHORT FIBER REINFORCED PLASTICS	6
III. COMPOUNDING TECHNIQUES	
A. GENERAL INFORMATION ON COMPOUNDING	11
1. Continuous versus batch process	11
2. Equipment available :	12
a). Banbury Mixer	12
b). Continuous Mixer	12
c). Two Roll Mill	14
d). Kneader	14
B. MELTING MECHANISM	14
C. EXTRUSION FOR FIBER REINFORCENENT	17
1. Single Screw versus Twin-Screw Extruder	18
2. Twin screw extruder.	19
D. FEATURES OF EXTRUSION COMPOUNDING	23

IV. MATERIALS AND METHODS	
A. MATERIALS	24
1. Polymer matrix	24
2. Filler	24
B. METHODS	24
1. Processing	24
2. Properties	26
a). Tensile properties	27
b). Impact strength	28
c). Flexural properties	28
d). Fiber length distribution	29
e). Fracture surface	29
V. RESULTS AND DISCUSSIONS	
A. EFFECT OF FIBER TREATMENT	30
1. Tensile strength, tensile modulus, and elongation	30
2. Impact strength	36
3. Flexural properties	36
4. Selection of fiber from pre-treatments	39
B. EFFECT OF SCREW CONFIGURATION	39
C. FIBER LENGTH IN TERMS OF MOMENTS OF DISTRIBUTION	49
D. EFFECT OF COMPOUNDING TEMPERATURE	49
1. Tensile strength and tensile modulus	49
2. Flexural strength and flexural modulus	51
E. SCANNING ELECTRON MICROSCOPY	51

F. THEORETICAL PREDICTIONS VS. EXPERIMENTAL DATA	60
1. Tensile Strength	60
2. Tensile Modulus	67
VI. SUMMARY	
A. SUMMARY AND CONCLUSIONS	75
B. SUGGESTIONS FOR FURTHER WORK	76
VII. APPENDIX	
A. GLOSSARY	78
VIII. BIBLIOGRAPHY	80

LIST OF TABLES

Table	Item	Page
I	I	I
1.	Details of screw configuration . . .	31
2.	Average fiber length and polydispersity	50
3.	Coeff. of correlation for heat treated aspen fibers(Tensile strength) . . .	63
4.	Coeff. for heat treated aspen fibers (Tensile strength)	64
5.	Coeff. for heat treated aspen fibers (Tensile modulus)	72
6.	Coeff. for acetylated aspen fibers (Tensile modulus)	73
7.	Coeff. for untreated aspen fibers (Tensile modulus)	74
I	I	I

LIST OF FIGURES

Figure I_____I	Item	Page I_____I
1.	Schematic view of an extruder	13
2.	Melting mechanism of a polymer in a single-screw extruder	15
3.	Co-rotating twin-screw operation	20
4.	Counter-rotating twin-screw operation	20
5.	Flow profile for twin-screw extruder	21
6.	Rotary Grinder :: setting arrangement of blades	25
7.	Tensile strength vs fiber content(SC 1, 150 °C)	32
8.	Tensile modulus vs fiber content(SC 1, 150 °C)	33
9.	Elongation at break vs fiber content(SC 1, 150 °C)	34
10.	Izod impact strength vs fiber content(SC 1, 150 °C)	37
11.	Flexural yield strength vs fiber content(SC 1, 150 °C)	38
12.	Flexural modulus vs fiber content(SC 1, 150 °C)	40
13.	Agitator design worksheet	41
14.	Probability density curves for fiber length	43
15.	Effect of SC on tensile strength(untreated fiber, 150°C)	45
16.	Effect of SC on tensile modulus(untreated fiber, 150°C)	46
17.	Effect of SC on flexural yield strength (untreated fiber,150°C)	47

18.	Effect of SC on flexural modulus (untreated fiber, 150 °C)	48
19.	Effect of compounding temp. on tensile strength (untreated fiber, SC 1)	52
20.	Effect of compounding temp. on tensile modulus (untreated fiber, SC 1)	53
21.	Effect of compounding temp. on flexural yield strength (untreated fiber, SC 3)	54
22.	Effect of compounding temp. on flexural modulus (untreated fiber, SC 3)	55
23.	SEM :: 32 % untreated fibers,150 °C, SC 4	57
24.	SEM :: 30 % untreated fibers,150 °C, SC 1	57
25.	SEM :: 25 % untreated fibers,150 °C, SC 1	58
26.	SEM :: 25 % untreated fibers, 210 °C, SC 1	58
27.	SEM :: 38.5 % heat treated fibers,150 °C, SC 1	59
28.	SEM :: 28 % acetylated fibers,150 °C, SC 1	59
29.	Correlation of theory with tensile strength data (Heat treated aspen fibers in HDPE matrix)	62
30.	Correlation of theory with tensile strength data (Untreated aspen fibers in HDPE matrix)	65
31.	Correlation of theory with tensile strength data (Acetylated aspen fibers in HDPE matrix)	66
32.	Correlation of theory with tensile modulus data (Heat treated aspen fibers in HDPE matrix)	69
33.	Correlation of theory with tensile modulus data (Acetylated aspen fibers in HDPE matrix)	70
34.	Correlation of theory with tensile modulus data (Untreated aspen fibers in HDPE matrix)	71

I. INTRODUCTION

INTRODUCTION

In recent years, polymer composites containing wood fibers have received considerable attention both in the literature and from industry (Belmaris et al., 1981; Pal et al, 1985; Semsarzadeh, 1985, 1986; Ramirez and Solis, 1984; Rowlands et al., 1986). This is because wood fibers are strong, light weight, non-abrasive, non-hazardous, inexpensive (Majali et al., 1979) and can serve as an excellent reinforcer or extender for plastics (Cruz - Ramos, 1986). Wood fibers are also plentiful and renewable; in the United States, one third of the land is covered by forest (Youngquist, 1983). Wood fibers, as fillers or reinforcing agents, can alleviate the rising cost and possible shortage of plastics (Modern Plastics, 1986) and can help to satisfy the increasing demand for inexpensive high-performance building materials (Sheldon, 1982; Semsarzadeh, 1985). Wood fiber composites can be prepared by extrusion and compression/injection molding to produce a variety of products which may be used in packaging, paper products, building materials, automobile parts, etc. (Soule and Hendrikson, 1966; Kokta et.al., 1986). The use of wood fibers is relatively limited (Pal et. al., 1984) although talc, mica, clay, starch, rice husks and wood flour are commonly used as fillers for plastics (Dahl, 1948; Shepherd et al., 1974; Westhoff, 1974; Otey, 1976; Lightsey, 1981; Theberger, 1981; Willis and King, 1981). Combined with plastics, the short hardwood fibers have the potential for developing a new type of composite _ one

that could offer good strength and mechanical properties, and ease of moldability.

Increased emphasis has also been placed on the recycling of plastic wastes because of the highly publicized problems associated with waste disposal. The availability of landfill space has decreased rapidly and the cost of land-filling plastic wastes has increased enormously while the "NIMBY" (Not In My Back Yard) phobia rises in all its severity to reject any potential site for waste disposal (Selke, 1987). Environmentalists, journalists, industrialists, researchers and others are showing concern over the threat of water and air pollution as US citizens continue to generate more than 410,000 tons of solid waste every day. Plastic packaging, which constitutes 4 % to 7 % (6 million tons per year) of this consumer generated waste, has become a major target of public attack because of its high visibility (Packaging Technology, 1988). Most of this six million plastic packaging waste consists of items like HDPE milk bottles, PET bottles and polystyrene packages which have short use cycles. Generally post-consumer HDPE has properties similar to those of virgin but is sold for less than half the price (Yam, 1987). In terms of economic value, considering the average value of recycled plastics as \$0.20 per pound, the amount of waste is \$2.4 billion _ a staggering amount which calls for proper investigation and exploitation. The National Academy of Sciences estimates that 52 million pounds of packaging materials are being dumped into the ocean each year and these together with other plastic solid wastes are responsible for the

yearly death of one to two million sea birds, 100,000 sea mammals and countless fish (Packaging Technology, 1988).

The increasing concerns for the disposal of plastic waste have led to recycling as a priority in most waste management programs. Large quantities of recycled plastics may be available as feedstock in the future and HDPE milk bottles show considerable promise in this regard. In 1987, 740 million pounds of blow-molded HDPE milk bottles along with another 1.357 billion pounds of other HDPE blow-molded bottles were produced in the United States (Modern Plastics, 1988). The disadvantage of recycled plastics is that they are of lower grade due to contamination and degradation, and thus they are not suitable for applications related to food products. Nevertheless recycled plastics can be used as an effective matrix for polymer composites, such as those containing wood fibers. Woodhams et al. (1984) has shown that high density polyethylene (HDPE) reinforced by thermomechanical pulp (TMP) has a stiffness/weight ratio equal to or exceeding those of steel, aluminum and fiberglass composites. We also find that composites containing wood fibers are already finding applications as pipes, channels and housing. Short hardwood fibers are preferred because they are thicker walled and less likely to break during compounding.

The objective of this research is, therefore, to investigate the processing - morphology - property relationships for compounding wood fibers with recycled HDPE using a twin-screw extruder. It is necessary to study the effects of

processing conditions on the mechanical properties of wood fiber-recycled HDPE composites so that it may be possible to identify the optimum processing conditions which will give an end product with the best properties.

The present understanding of fabrication techniques, bonding mechanisms, mechanical properties, effect of moisture and weathering resistance etc., for wood fiber reinforced plastics is incomplete and scattered (Landel, 1981; Youngquist, 1983; Marra, 1984). Particularly, very little has been studied on the effects of processing history on recycled plastics. A twin-screw extruder with two stages can be used to effectively incorporate the wood fibers into polymers : the polymer is melted in the first stage and the fibers gently blended in the second stage to minimize fiber breakage. Good mechanical properties of short-fiber-reinforced thermoplastic composites depend on the extent of mixing of the fibers and the polymer matrix. While preparing fiber reinforced composites using extrusion techniques, it is necessary to optimize the amount of compounding : inadequate compounding causes poor dispersion and poor wetting of the fibers while excessive compounding causes severe fiber damage _ both leading to reduced mechanical strength.

This thesis has been organised in ten main sections. The introduction is followed by a brief review of the theoretical concepts governing short fiber reinforced plastics. The third chapter outlines the prevalent techniques of compounding and brings out the essential features of a twin-screw extruder

which makes it specifically suitable for compounding shear sensitive fibers. Materials & Methods are discussed in chapter IV. The experimental results presented in Chapter V first compare the mechanical properties of aspen fibers with three different types of treatment _ untreated, heat treated and acetylated _ and then evaluate the fiber with the best properties and least cost. Theoretical predictions are correlated with experimental results in this chapter. Conclusions and suggestions for further work are on pages 75, 76 and 77. A glossary of important terms is included as an appendix.

II. SHORT FIBER REINFORCED PLASTICS

At the critical aspect ratio, both the fiber and the matrix will fracture at the same plane. Additional increase in the fiber length will not increase the strength of the composite as failure will take place at the critical aspect ratio. If the fibers are shorter than the critical aspect ratio, full load transfer will not be achieved and there will be fiber pull out during tensile stress. The polymer will slide past these short fibers instead of breaking them until all the ductility is lost and the polymer fractures. Inadequate wetting of the fibers by the polymer matrix creates weak sites at the polymer ends, causing reduction in fiber-matrix reinforcements. To achieve maximum reinforcing efficiency, the fibers must be at least 10 times longer than the critical length (Cloud, 1975; Wall, 1987). Bonding the filler to the resin by means of a coupling agent helps to prevent phase separation and results in a stronger material (Beshay et. al., 1985). Studies on the effect of wood fibers incorporated into cement using coupling agents are reported by Gautts and Campbell (1979). The results of the investigation confirm that the mechanical performance of wood fiber reinforced cement composites can be altered by the use of coupling agents. Promising mechanical properties have also been cited for composites of grafted olefin polymers and cellulose fibers (Coran and Patel, 1982; Goettler, 1983; Kokta et al., 1983).

The critical aspect ratio is related to the fiber tensile strength σ and the fiber matrix interfacial bond strength τ as follows (Bigg, 1985) :

$$(L/D)_c = \frac{\sigma}{2\tau} \quad \dots (1)$$

where, L = fiber length

D = diameter of fiber

and c = subscript for critical

Since extensive fiber damage occurs during compounding and molding, it is desirable to increase the interfacial bond in order to reduce the critical aspect ratio as much as possible. Fibers between the critical aspect ratio and ten times the critical aspect ratio provide fractional reinforcement.

The shear stresses at the interface govern the slip process (Piggott, 1982). The shear stresses are also strongly influenced by processing conditions and adhesion between the fibers and the polymer matrix. Fiber breakage during compounding and the moulding process, fiber degradation due to processing conditions, moisture content of the fibres, inter-fiber cling, environmental factors, orientation of the fibers and compatibility of the fiber and the polymer matrix are some of the factors which seem to affect interfacial shear stresses.

A model representing an elastic matrix with uniaxially oriented short fiber composites is given by the expression (Piggott, 1981) :

$$\sigma = (\phi_f E_f + \phi_m E_m) \epsilon_c - \frac{\phi_f E_f^2}{4\tau q} \quad \dots (2)$$

where σ = strength

ϕ = volume fraction

E = modulus

ϕ = volume fraction

E = modulus

ϵ = unit elongation

τ = interfacial fiber matrix
shear stress

q = fiber aspect ratio

f, m = subscripts for fiber &
matrix, respectively

The values of τ and q are major contributing factors in determining reinforcement.

The tensile strength of short fiber-filled composites is commonly represented as (Bigg, 1987) :

$$\sigma_c = \sigma_m \phi_m + \sigma_f \phi_f \epsilon_0 \epsilon_1 \quad \dots(3)$$

where, σ_c = tensile strength of composite

σ_m = tensile strength of matrix

σ_f = tensile strength of fibers

ϕ_m = volume fraction of matrix

ϕ_f = volume fraction of fibers

ϵ_0 = efficiency factor : fiber

orientation : ($\epsilon_0 \leq 1$)

ϵ_1 = efficiency factor : fiber

reinforcement : ($0 < \epsilon < 0.95$)

Random in-plane oriented fibers are most frequently encountered in injection moulded and compression moulded composites.

Theoretical predictions versus experimental data are treated separately as sub-chapter 'F' under 'RESULTS AND DISCUSSIONS'.

III. COMPOUNDING TECHNIQUES

COMPOUNDING TECHNIQUES

A. GENERAL INFORMATION ON COMPOUNDING

To enhance the properties of resins, they are usually compounded with other materials and tailored to end uses. The process of intimately mixing the components into a homogeneous mass is known as "compounding" (Plastics Engineering Handbook, 1987). Compounding involves fusion of different materials into a homogeneous mass, uniform in composition and structure. When thermoplastics are compounded, they are subjected to laminar shear deformations so that the initial non-random distribution approaches some degree of randomness. However, due to interparticulate forces leading to particle agglomeration, adequate stress must be exerted on such agglomerates to ensure proper compounding. Compounding results in substantial breakage of the reinforcing fibers. Bigg (1985), concluded that the damage done to fibers is related to the type of compounder used.

Techniques used for compounding are governed by the nature of the resin and compound to be incorporated.

1. Continuous versus batch process

Continuous compounding provides the advantages of economies of scale. But when the feedstock is not meterable, batch system like the Banbury mixer would be the choice. Both processes are widely used, however, batch processes have certain limitations such as :

- a). Potential batch to batch variation.

- b). Greater manpower requirement.
- c). Poor economies of scale.
- d). Lesser output per unit time.
- e). Tend to occupy more floor space.
- f). Equipment generally more bulky.
- g). Set-up time high.
- h). More handling equipment required.

2. Equipment available :

a). **Banbury Mixer** It is a batch mixer consisting of totally enclosed mixing chambers _ two spiral shaped rotors providing the kneading action. Batch temperature is controlled by steam or cooling water fed to the cored rotor. The rotors revolve in opposite directions and at slightly different speeds. Material is fed through a hopper and an air operated ram confines the batch within the mixing chamber. The ridge between the two cylindrical chamber sections assists in the mixing; and the convergence of the rotors and the chamber walls imparts shear.

b). **Continuous Mixer** The rotors and mixing action are similar to Banbury and material is interchanged between the two bores of the mixing section. A short feed zone leads to the mixing zone where intensive shear occurs between the rotor and the chamber wall. Temperature can be adjusted over a wide range and then set constant for the production run. The mixer is not completely self purging. The single screw and multiple screw extruders can also be grouped under continuous mixers. A schematic view of an extruder is shown in Figure 1.

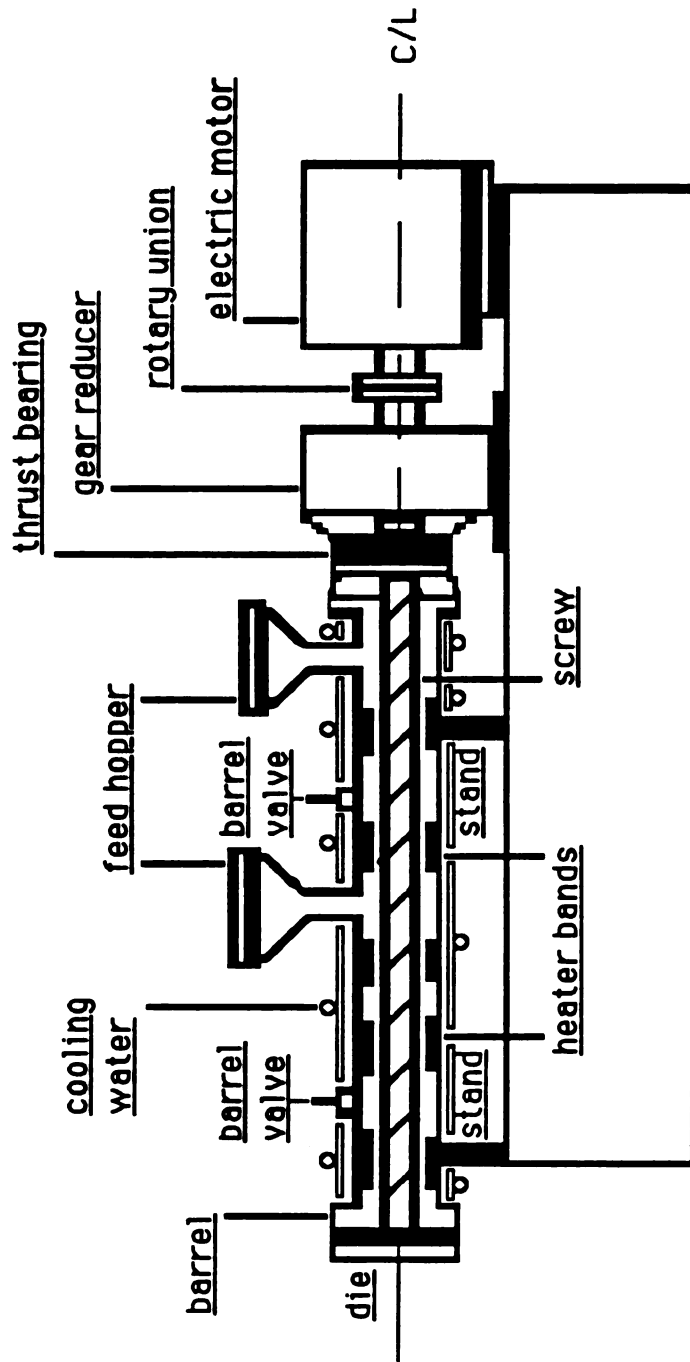


Figure 1. Schematic view of an extruder

c).Two Roll Mills They consist of two counter-rotating parallel rollers placed close to one another with the roll axes lying on the horizontal plane so that a relatively small space or nip between the cylindrical surfaces exist. The rollers rotate at different speeds to facilitate formation of sheets and the gap between them determines the severity of mixing and the thickness of the formed sheets. Material is deformed by friction forces between itself and the rollers. To ensure a highly homogeneous mix, a series of rollers are sometimes used for continuous compounding. The rollers are heated by steam or cooled by water to maintain the desired compounding temperature.

d).Kneaders They work on the principle of both drag flow and positive pumping action. The rotating screws also oscillate between the stationary teeth in the barrel and interrupted flights on the screw. Material movement is in an axial direction. Due to the machines unique melting and mixing characteristics, processing of materials can be achieved in a much shorter length as compared to counterparts of the single or twin screw extruder. High shear is produced in the material.

B. MELTING MECHANISM

The general melting mechanism of a polymer in a screw of an extruder is shown in Figure 2. The melting in the screw of an extruder starts typically in the feed section and continues through the transition and the metering sections. The start and end of the melting and the mechanism of melting depend upon many factors such as type of resin used, the feed

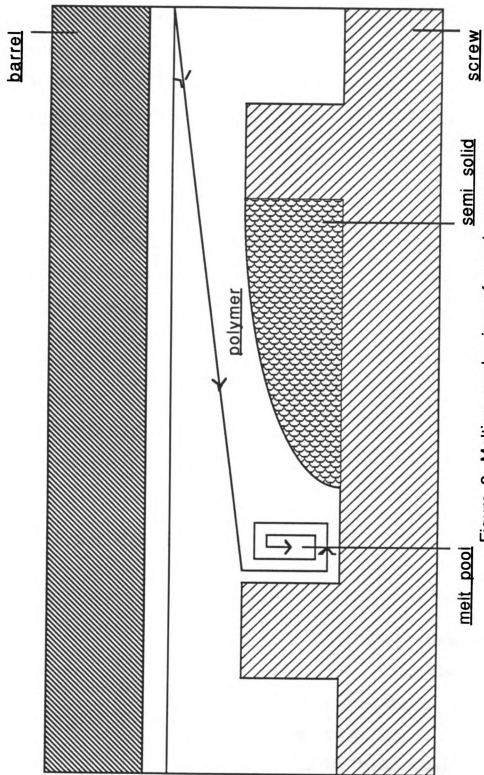


Figure 2. Melting mechanism of a polymer in a

single screw extruder

stock (pellets, granules, powder, etc.), the screw design, the barrel profile, and the output rate. The mechanical energy created by shear due to rotation of the screw is converted to heat and this along with the heat provided by the external heating system melts the material. A typical heat balance of a corotating twin-screw extruder shows that approximately 55% of the energy reaching the material comes from the screws and 45% from the heater bands. The shear rate " γ " and the related power " Z ", which is transferred to the material when the flights are full is (Martelli, 1983) :

$$\text{Shear Rate, } \gamma = \frac{\pi D_e n}{h} \text{ (Sec}^{-1}\text{)} \quad \dots (4)$$

where D_e = equivalent screw dia. for
the twin-screws.

n = screw speed

h = channel depth

Power transferred (Martelli, 1983),

$$Z = \mu \gamma^2 V \cdot 10^{-10} \text{ (Kw)} \quad \dots (5)$$

where, μ = coefficient of viscosity

V = volume of material involved

= area of channel x

equivalent elix x

no. of flights filled

This is the power which is dissipated into the material as heat, and contributes to the melting because of shear. Various mechanisms like reverse flights, zero flights and forward flights are incorporated in the screw design by proper orientation of the mixing paddles to create shear at a particular section of the screw where we want to melt the material.

C. EXTRUSION FOR FIBER REINFORCEMENT

Fibrous reinforcement of a polymer matrix demands sophisticated mixing equipment which must provide extensive intake and conveying capabilities, polymer wetting, and dispersion of the reinforcement. The resin and the constituents must be blended to yield a product that combines the properties of each of the components. Some of the basic requirements in compounding fiber reinforced thermoplastic (FRTP) materials are (Stade, 1977) :

- a). Low, controllable thermal degradation of base polymer.
- b). Optimum fiber length in the finished product.
- c). Good dispersion of additional additives, eg. inorganic fillers or flame retardent additives.
- d). An economic production.

The process should provide for controlled shear, temperature and residence time. This is to minimise material exposure to heat, prevent degradation, and to meet product requirements.

The extrusion process is a proven economical method for fiber reinforcement of polymers and co-rotating intermeshing twin-screw extruders are particularly suited for these tasks

(Eise et.al, 1985). Positive conveying, self wiping, and shear sensitive mixing characteristics provided by the screw mechanism satisfy requirements of reinforcement compounding. This mechanism results in interruption of streamline flow, which is needed to disperse both high and low aspect ratio reinforcing agents into a suitable polymer matrix.

1. Single-Screw versus Twin-Screw Extruder

The aim of the extrusion process is to mix the matrix and the filler so that samples taken from any portion of the extrudate show uniform properties. Twin-screw extruders are superior to single-screw extruders in terms of mixing capability and pumping. It is sometimes difficult to get stable operation in a single-screw extruder at high throughput rates because the extent of shear, the material temperature, and the mixing are highly interdependent and cannot be separately controlled (Levy, 1981; Gibbons et. al., 1987). In a twin-screw extruder, the functions of pressure buildup and shear mixing are basically independent and it is possible to vary each of them by appropriate screw design and machine control. The ability to control shear therefore makes it specifically suitable for compounding shear sensitive materials. Further, two stage twin-screw extruders enable a more gentle treatment to the fibers, which are fed to the second port to minimize machine wear and fiber breakage (Jakopin, 1982; "Operating Manual, Baker Perkins MPC/V, " 1987).

2. Twin Screw Extruder

The operation of a co-rotating and counter-rotating twin-screw extruder are shown in Figures 3 & 4. In twin-screw extruders, the depth of the flights, their intermeshing and their fit within the channels are of significant importance. Non-intermeshing screws function in the same manner as a single-screw extruder and friction is the basic factor which causes flow of the material. When one screw penetrates into the channel of the other, there is interaction between the screw and the material contained in the channel. The flights of the screw limit the rotational movement of the material round each screw and as they continue to rotate, the materials slide within the channels, assuming an almost linear motion towards the end of the barrel – thus resulting in positive pumping action. The more the flights of one screw match with the channels of the other screw, the more prominent is the pumping.

The drag or pressure flow does not have any significant effect on the output or pressure at the head of the extruder. Unlike the single-screw extruder, the maximum shear occurs at the root of the screw and not at the barrel. The drag, pressure, and net-velocity profiles for a twin-screw extruder are shown in Figure 5 (Wyman,1975). The drag and pressure flows are additive and equal to the flow of the progressing cavity to produce a dynamic equilibrium condition. Shear on the material is unaffected by the delivery rate (Levy, 1981) and much less shear is produced under normal operating

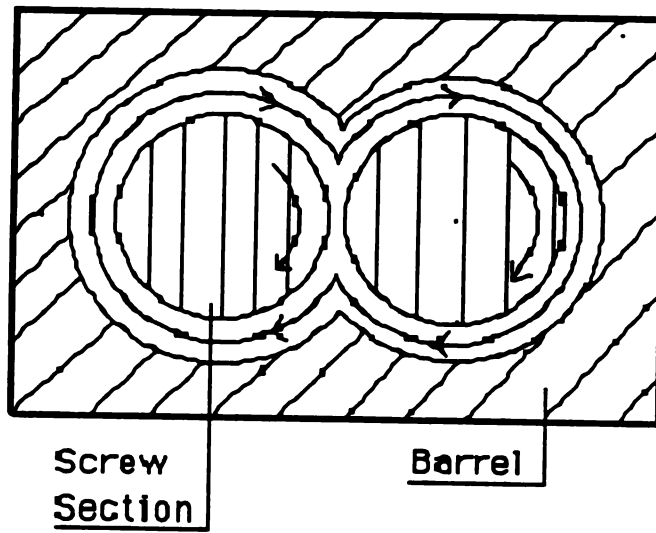
CO-ROTATING

Figure 3. Co-rotating twin-screw operation

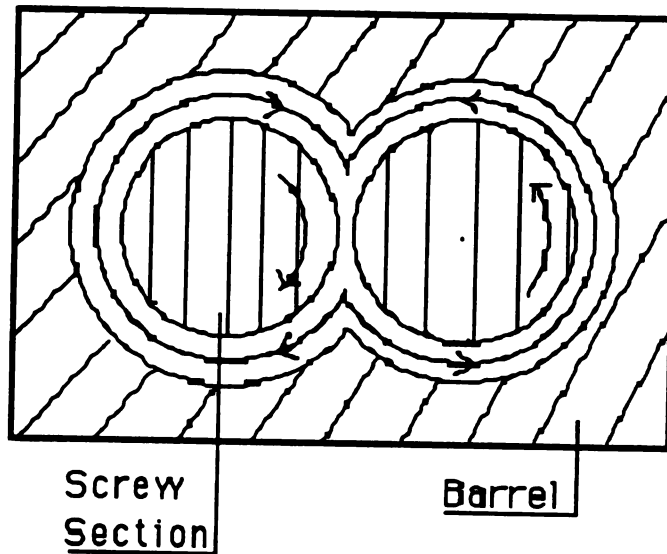
COUNTER-ROTATING

Figure 4. Counter-rotating twin-screw operation

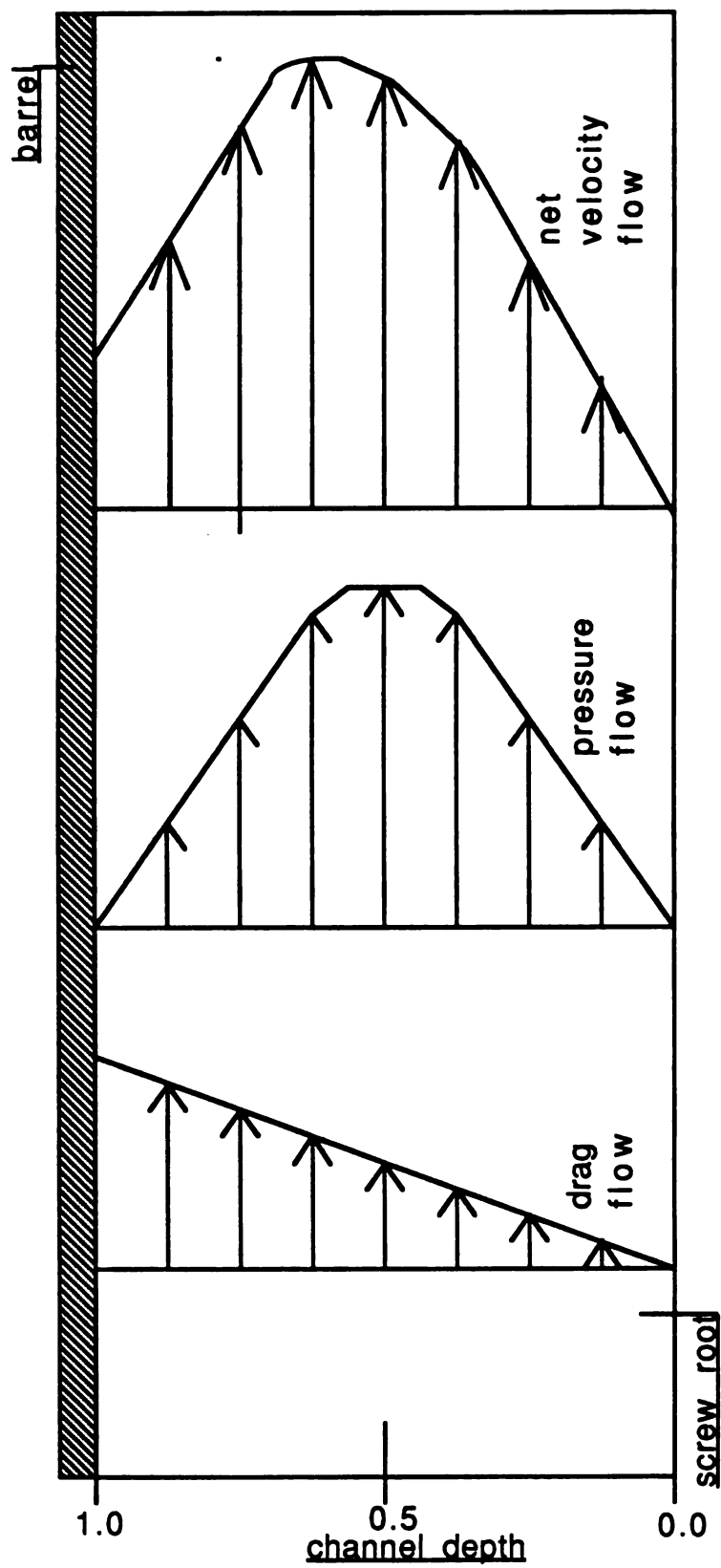


Figure 5. Flow profile for twin-screw extruder

conditions. The mixing mechanism ensures that all the materials go through the same shear history.

In counter-rotating screws, the material is more or less sealed in C-shaped chambers formed by the intermeshing conjugated threads. The drag effect makes the material flow in opposite directions. Leakage flow around the screw and leakage within the intermeshing region due to non-conjugation (for less shear) reduces the pumping efficiency as the factor "q" in the equation below increases .

$$\text{ie. } Q_{\max} = Q_c - q, \quad \dots(6)$$

where, $Q_{\max}$ = maximum output

Q_c = output without leakage

q = leakage flow

For counter-rotating screws the value of "q" is between $0.65Q_c$ to $0.5Q_c$ and mixing is determined mainly by the size of the gaps.

The situation is quite different for a co-rotating screw where the material is not enclosed but there are passages at the flight tips and material is transported to the second screw in a figure '8' path. The material coming from a single channel of one screw is divided into two streams, each of which joins with another coming from a different channel. This mixture is further divided at the next and subsequent intermeshing points. The output of the screws however does not diminish appreciably as the drag flow acts in the same direction as the pressure flow.

D. FEATUERES OF EXTRUSION COMPOUNDING

Extrusion compounding enables processing of a broad range of products without hardware modification. Some of its attractive features are uniformity of stress distribution, ease of maintenance, self cleaning, segmental screw design, and reproducibility of product quality even with worn parts. When all the ingredients are meltable with similar melt temperatures, a single stage compounding would be the choice. However, for alloying polymers having widely different melt temperatures or viscosity, reinforcing soft and fragile fibers or for incorporating abrasive fillers, a two stage operation increases the versatility of extrusion compounding.

IV. MATERIALS AND METHODS

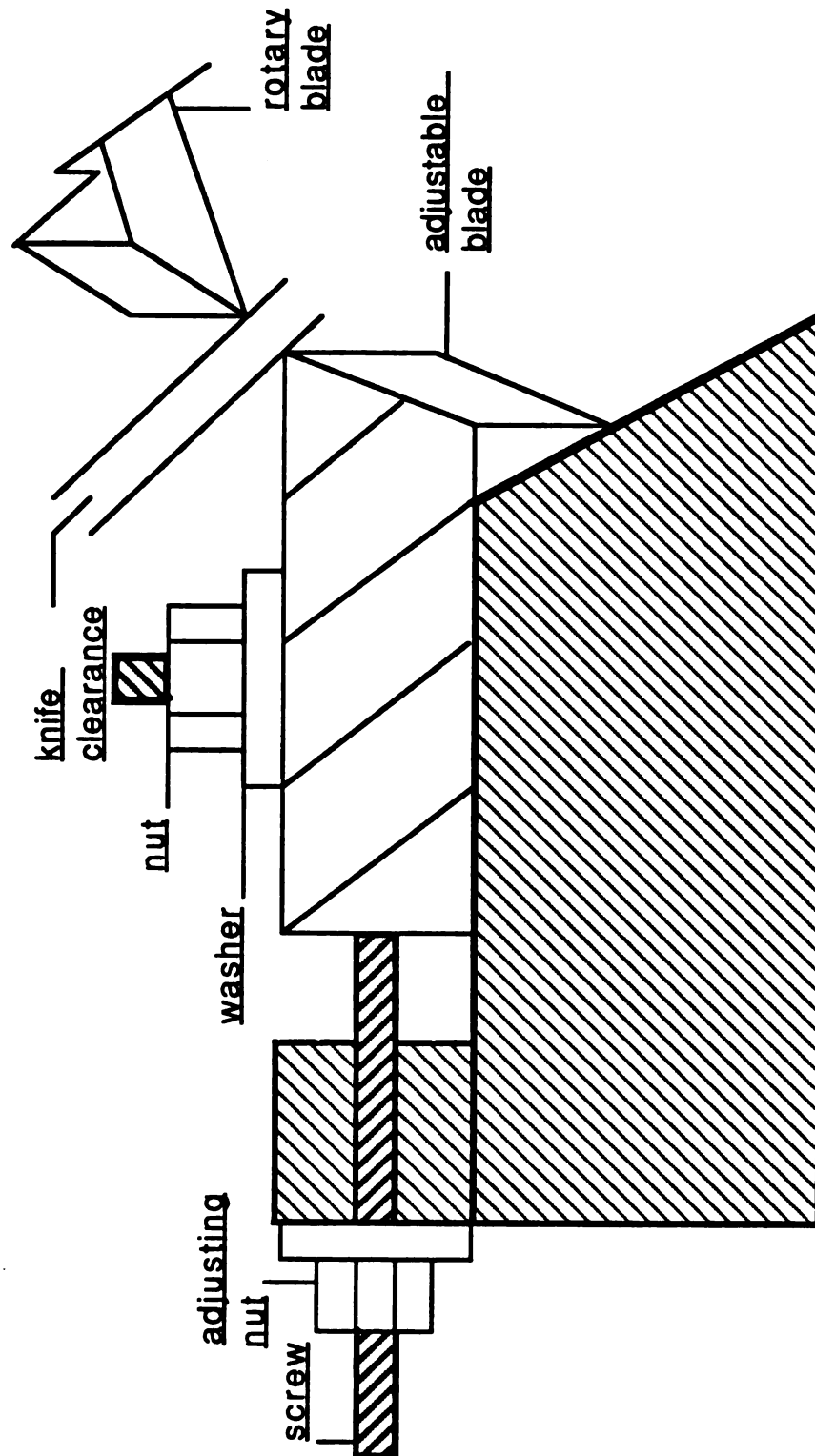


Figure 6. Rotary Grinder :: setting arrangement of blades

temperature, a wide land orifice plug was selected so as to ensure complete melting of the polymer matrix.

Paddles are the primary working component of the agitator shaft. The motion of the paddles relative to each other and the barrel causes the melting of the polymer, dispersion of the agglomerates, and distribution of the ingredients. Segmental screw design enables ease of set-up for both forwarding (downstream) and reversing (upstream) conveying. The conveying ability of the extruder was varied by manipulating the relative orientation of the paddles. The general rule followed while designing paddle orientation was

- a). Conveying ability greatest for 45° paddles.
- b). No conveying tendency for 90° paddles.
- c). Some conveying tendency for 60° paddles.

Mixing stage 1 and mixing stage 2 are also shown in Table 1 along with their relative conveying abilities. Compounding temperatures were 150°C , 170°C , 190°C , and 210°C . The screw speed was 100 rpm. The processing parameters were set through a computer connected to the extruder.

2. Properties

The extrudate from the MPC/ V-30DE was compression molded in a Carver Laboratory Press (Model M, 25 Ton). The internal dimensions of the mold were 6" x 6" x 1/8". Mylar slip sheets were placed on both sides of the mold. A pressure of 3 Ton was maintained in the mold for 10 minutes at 150°C . Cold water was circulated through the press to cool the molded

sheet for another 15 minutes. The sheet was finally conditioned at room temperature for at least 48 hours before cutting into standard sizes for tensile, impact, and flexural tests.

i). Tensile Properties

ASTM D638-86, "Standard Test Method for TENSILE PROPERTIES OF PLASTICS," was followed. Test specimens were cut from the molded sheets to sizes of 6" x 3/4" x 1/8" by a band saw. These were further cut to dumbbell shape type I according to ASTM 638 in a Tensilkut Machine (Model 10-13). An Instron Tensile Machine (Model 1114) was used to measure tensile properties. Prior to the tests it was observed that in order to obtain a good output in the chart recorder it was necessary to maintain a cross-head speed of 2 in/min for HDPE test samples and 0.5 in/min for wood fiber composites _ there being no significant differences of tensile strength, tensile modulus and elongations at these two strain rates. Test conditions were as follows :

- a). Load cell range : 500 lbs.
- b). Cross-head speed
 - i). HDPE : 2 in/min.
 - ii). wood-fiber composite : 0.5 in/min.
- c). Chart-speed : 5 in/min.
- d). Grip separation : 2 in.

Abrasive paper was used between the grips to prevent slippage. The chart recordings were analysed for calculating tensile modulus and elongation at break.

The samples consisted of different weight percentages of untreated, heat-treated and acetylated wood-fibers with HDPE as the polymer matrix. Maximum fiber loading was 60% (weight percent).

ii). Impact Strength

ASTM D-256-84, "Standard Test Methods for IMPACT RESISTANCE OF PLASTICS AND ELECTRICAL INSULATING MATERIALS," was followed. Test specimens were cut to sizes of 2 1/2" x 1/2" x 1/8" and notched to a depth of 0.1 in. in a TMI Notching Machine (Model 22-05). Izod impact strength was measured in a TMI Impact Testing Machine (Model 43-02-00) using a 5 (five) pound pendulum. The machine is programmed to give digital readout for the average impact strength & the standard deviation. Printed results were obtained from an on-line printer. The samples consisted of different weight percentages of untreated, heat-treated and acetylated wood-fibers with HDPE as the polymer matrix. Maximum fiber loading achieved in the extruder was 60% (weight percent).

iii). Flexural Properties

Procedure ASTM D790-86, "Standard Test Methods for FLEXURAL PROPERTIES OF UNREINFORCED AND REINFORCED PLASTICS AND ELECTRICAL INSULATION MATERIALS," was followed. A 22 KPS MTS Testing Machine was used for the flexural tests. Test specimens were cut to sizes of 5" x 1/2" x 1/8". Flexural properties were measured based on a three-point loading system. The support span was 4" and support span to depth ratio was 32 : 1. An on-line printer attached to the MTS Testing

Machine recorded the load deflection plots. The flexural yield strength and the energy at yield were calculated at a cross-head speed of 0.04 in/min.

The samples consisted of different weight percentages of untreated, heat-treated and acetylated wood fibers with HDPE as the polymer matrix. Maximum fiber loading was 60% (weight percent).

iv). Fiber Length Distribution

Samples were cut from the molded plates representing different fiber weight percentages. These were boiled in xylene to dissolve the HDPE. Slides containing the wood fibers were then prepared to project the images on a large screen with a magnification of about 15 (fifteen). Fiber length was determined by measuring the length of each fiber. Each datum was a measure of the average of approximately 300 fibers.

v). Fracture surface

A JEOL T-300 scanning electron microscope (SEM) was used to study the fracture surface of tensile test specimens. The test specimens of size 1/4" x 1/4" x 1/2", with the fracture surface facing upwards, were glued to a circular pedestal using aluminum paint. They were coated with gold to a thickness of approximately 200 Angstroms in a Polaron Plasma Coater to facilitate electron scanning. The study of the fracture surfaces was conducted in magnification ranges from 100 to 5000.

V. RESULTS AND DISCUSSIONS

100
101
102

RESULTS AND DISCUSSIONS

A maximum fiber loading of 60% by weight can be achieved in a HDPE matrix while compounding in a twin-screw extruder. The density of the wood fiber composite increases with fiber content and is approximately 1.20 g/cc for 60% weight of fiber content. Each datum reported here is the mean of at least three measurements and the error bars represent one standard deviation from the mean.

A. EFFECT OF FIBER TREATMENT

The effect of fiber treatment on the mechanical properties of wood fiber composites was first evaluated. The fibers studied were untreated, acetylated and heat treated. These fibers were compounded with HDPE regrind in a Baker Perkins twin screw extruder (Model MPC/V-30DE). The processing conditions were as follows :

- a). Screw Configuration : SC 1(see Table 1)
- b). Processing Temperature : 150 °C.
- c). Screw Speed : 100 rpm.

1. Tensile strength, tensile modulus, and elongation at break

Figures 7, 8, and 9 show the tensile strength, tensile modulus, and elongation at break of the composite as a function of fiber content. The tensile strength decreases gradually with increase in fiber content. The data for acetylated and untreated fibers showed an upper bound trend, indicating adhesion, while heat treated fibers showed a lower bound response, indicating low adhesion. Bataille (1987), found

Table 1. Details of screw configuration

<u>SC</u>	<u>Mixing Stage 1</u>	<u>Mixing Stage 2</u>	<u>Conveying ability</u>
1	0DF 60DF 60DF 90DA 90DA	0DF 60DF 60DF 90DA 90DA	starting configuration, SC
2	60DF 60DF 90DA 90DA 90DA	60DF 90DA 90DA 90DA 90DA	less than SC
3	60DF 60DF 60DF 90DA 90DA	60DF 60DF 60DF 90DA 90DA	more than SC
4	0DF 60DF 60DF 90DA 90DA	45 DF 45DF 45DF 45DF 45DF	much more than SC

Note:

SC = starting configuration

DF = degree forward

DA = degree alternating ..

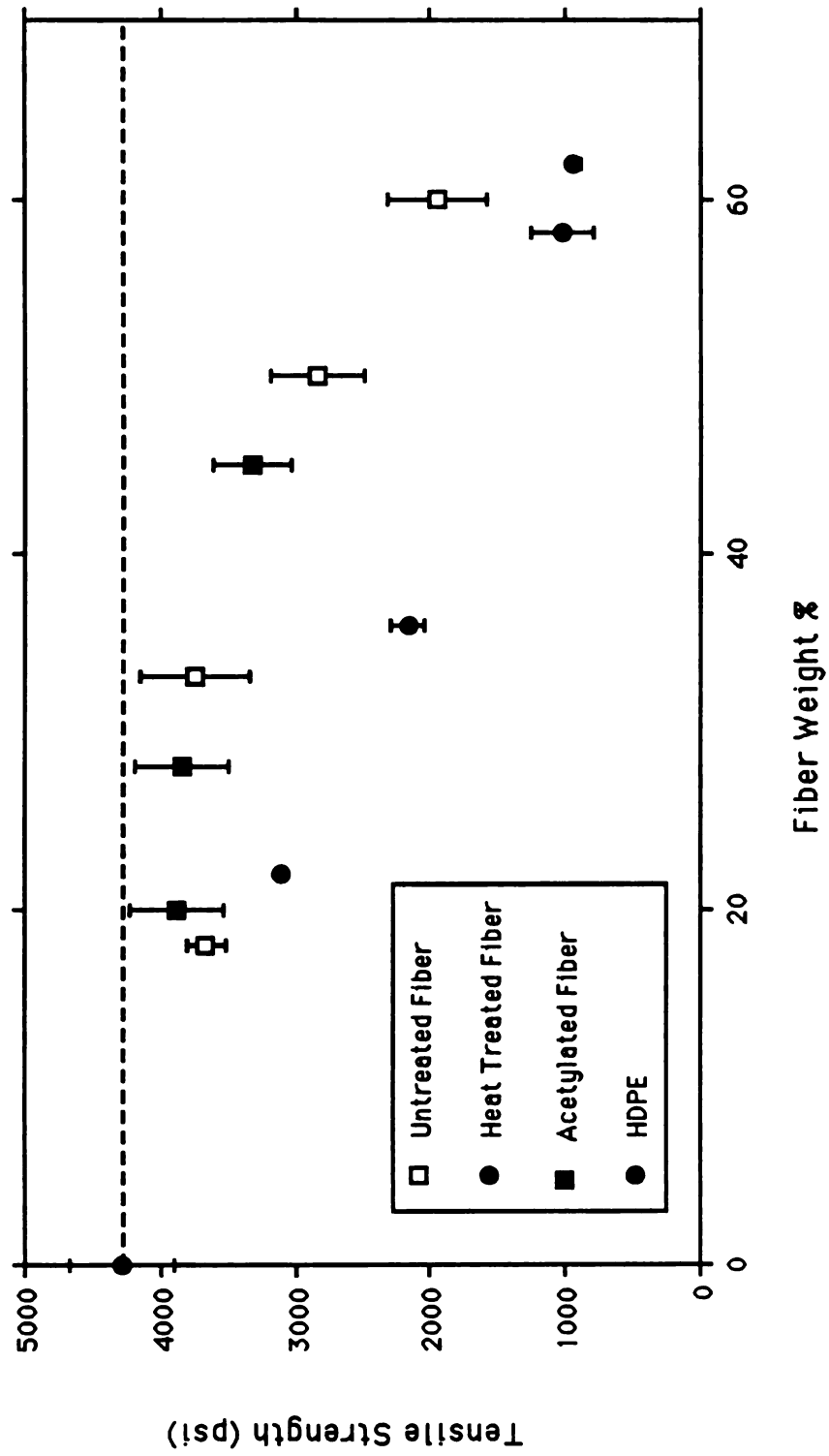


Figure 7. Tensile strength vs fiber content (SC L 150 C)

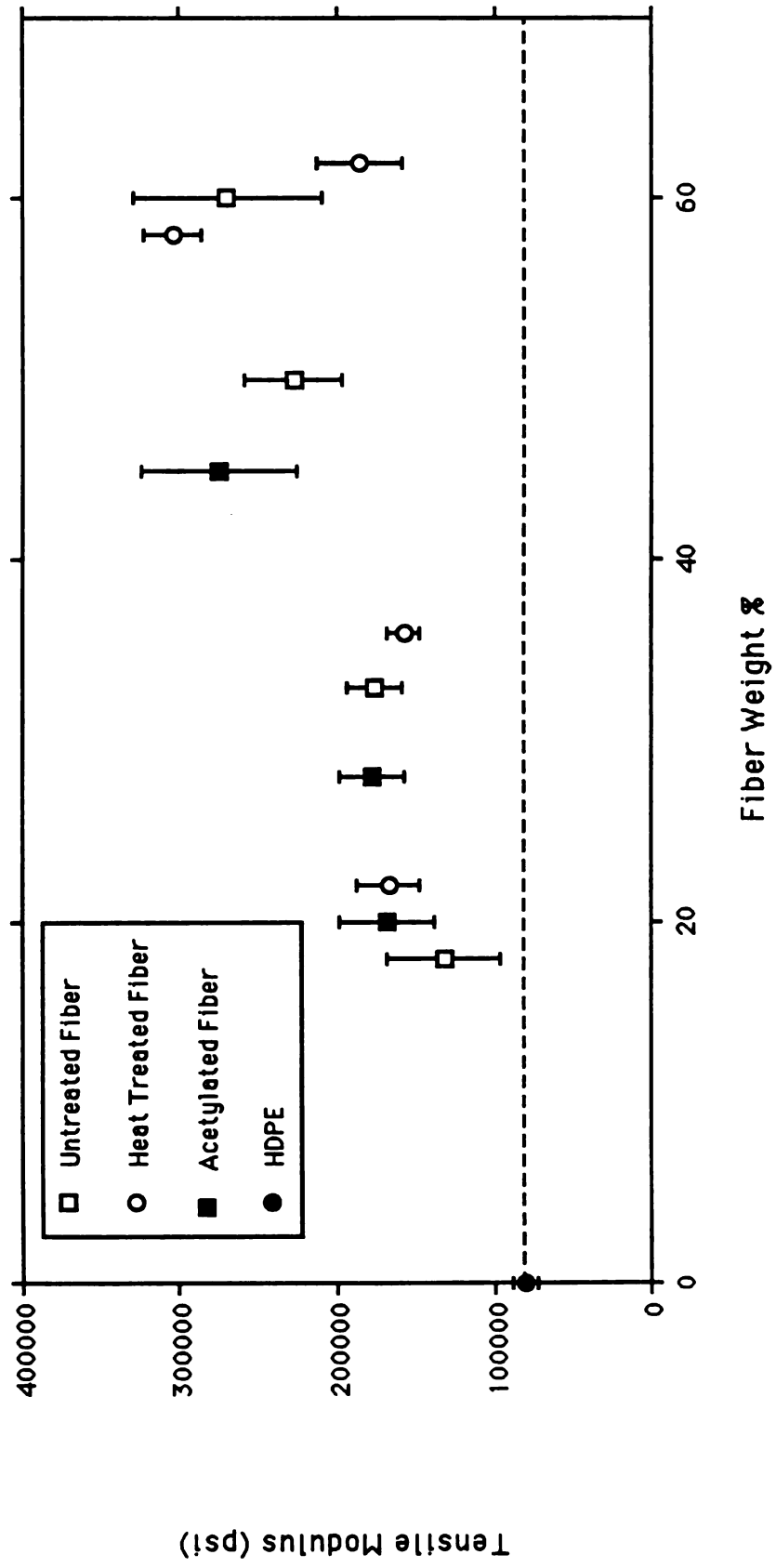


Figure 8. Tensile modulus vs fiber content (SC 1, 150 C)

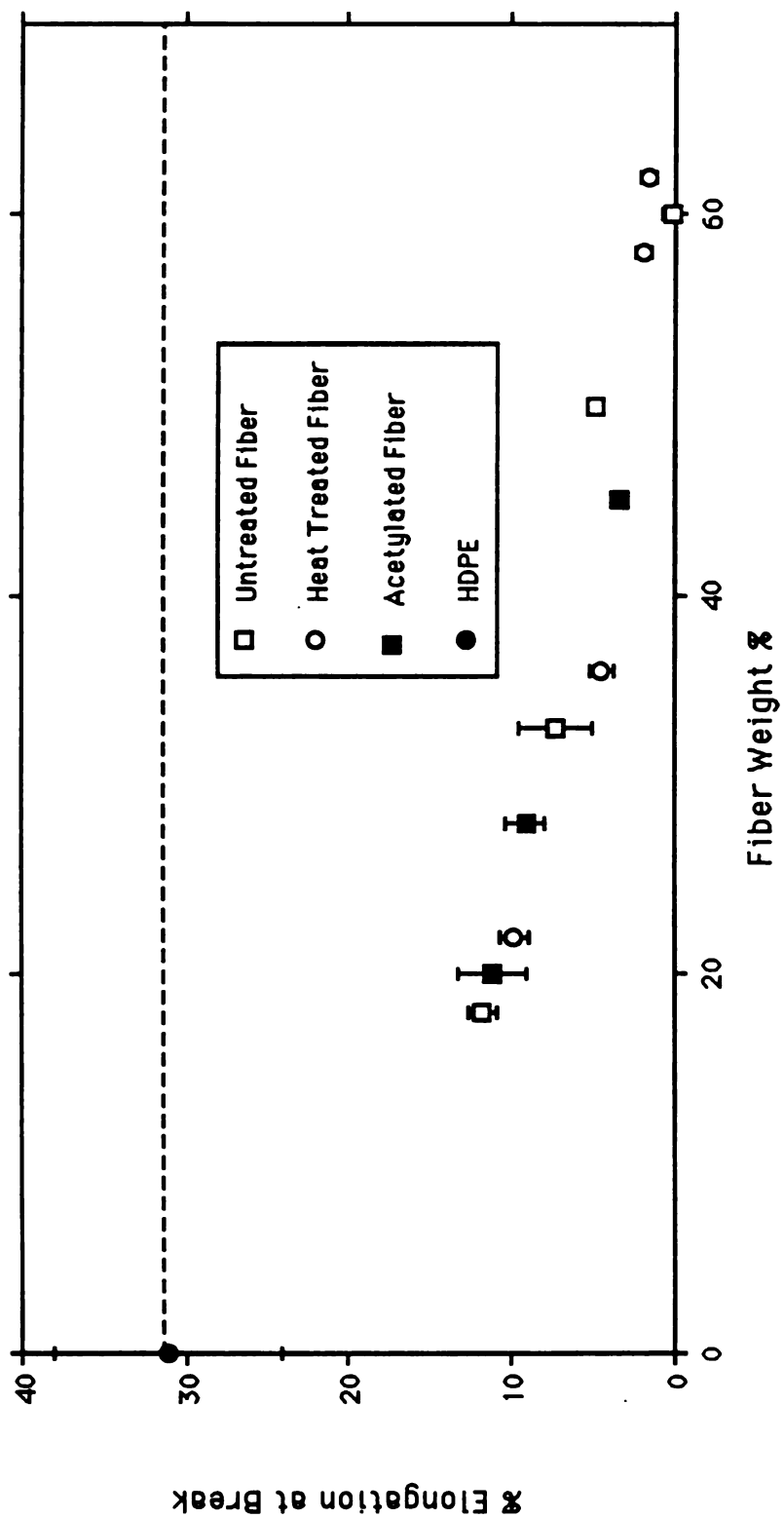


Figure 9. Elongation at break vs fiber content (SC 1, 150°C)

a lower bound response for tensile strength versus untreated cellulose in a polypropylene matrix indicating no adhesion between the two components. The data of other researchers (Klason et.al., 1984; Woodhams et. al., 1984) show an upper bound response, perhaps due to difference in fiber species, treatment or processing technique. Composites of untreated and acetylated fibers seem to have the same strength which is higher than that of heat treated fibers. The higher tensile strength of the untreated fibers is possibly due to retention of most of their lignin and natural waxes _ materials which can aid fiber dispersion in non-polar hydrocarbon polymers (Woodhams, 1984). The tensile modulus increases with fiber content. It seems that there is adhesion between the wood fibers and the polymer matrix. The fibers are able to resist the stresses and strains set up in the polymer matrix resulting in an increase in elastic energy and consequent stiffening of the composite. The increase in tensile modulus is about 250% at 60% fiber weight. There is a precipitous drop in tensile modulus at 62% for heat treated fiber _ perhaps due to excessive fiber interaction at high fiber content. Woodhams et.al., 1984, Beshay et.al, 1985, and Kokta et.al., 1986 did not find such a drop at high fiber levels although it may be noted that maximum fiber loading in their case was 40%, 50%, and 40% by weight respectively, with fiber treatments differing from this study. Fiber treatment does not seem to have any effect on tensile modulus so that the choice of material will depend upon price. There is also a sharp drop in elongation

(Figure 9) at low filler levels. Elongation properties do not change with fiber treatment and tend to drop to zero values beyond 50% fiber content. It seems that there is very little effect on elongation beyond 35% fiber content.

2. Impact strength

Figure 10 represents the investigations for Izod impact strength. A sharp drop is seen at low fiber contents, perhaps because of voids in the sample due to volatiles generated by oils, waxes, moisture, and by degradation of the lignin and hemicellulose at high temperatures. The recycled HDPE matrix has an Izod impact strength of 2.5 ft-lb/in and the average impact strength for the fibers with different treatments levels out to 0.7 ft-lb/in for fiber loadings beyond 20% by weight. It seems that voids between the hydrophobic matrix and the hydrophilic wood fibers result in propagation of fracture even at low fiber contents.

3. Flexural properties

The flexural yield strength of the composite seems to be better than the polymer matrix (Figure 11). The untreated and acetylated fibers also perform better than heat treated fibers. The strength first decreases to a minimum and then after reaching a maximum, again drops with increase in fiber loading. There is some reinforcement of flexural strength for fiber contents between 20% and 50%. This would seem to agree with the findings of Woodhams (1984) that a critical fiber content is required for attaining reinforcement. The maximum value for flexural modulus is 75,000 psi. at 60% fiber weight

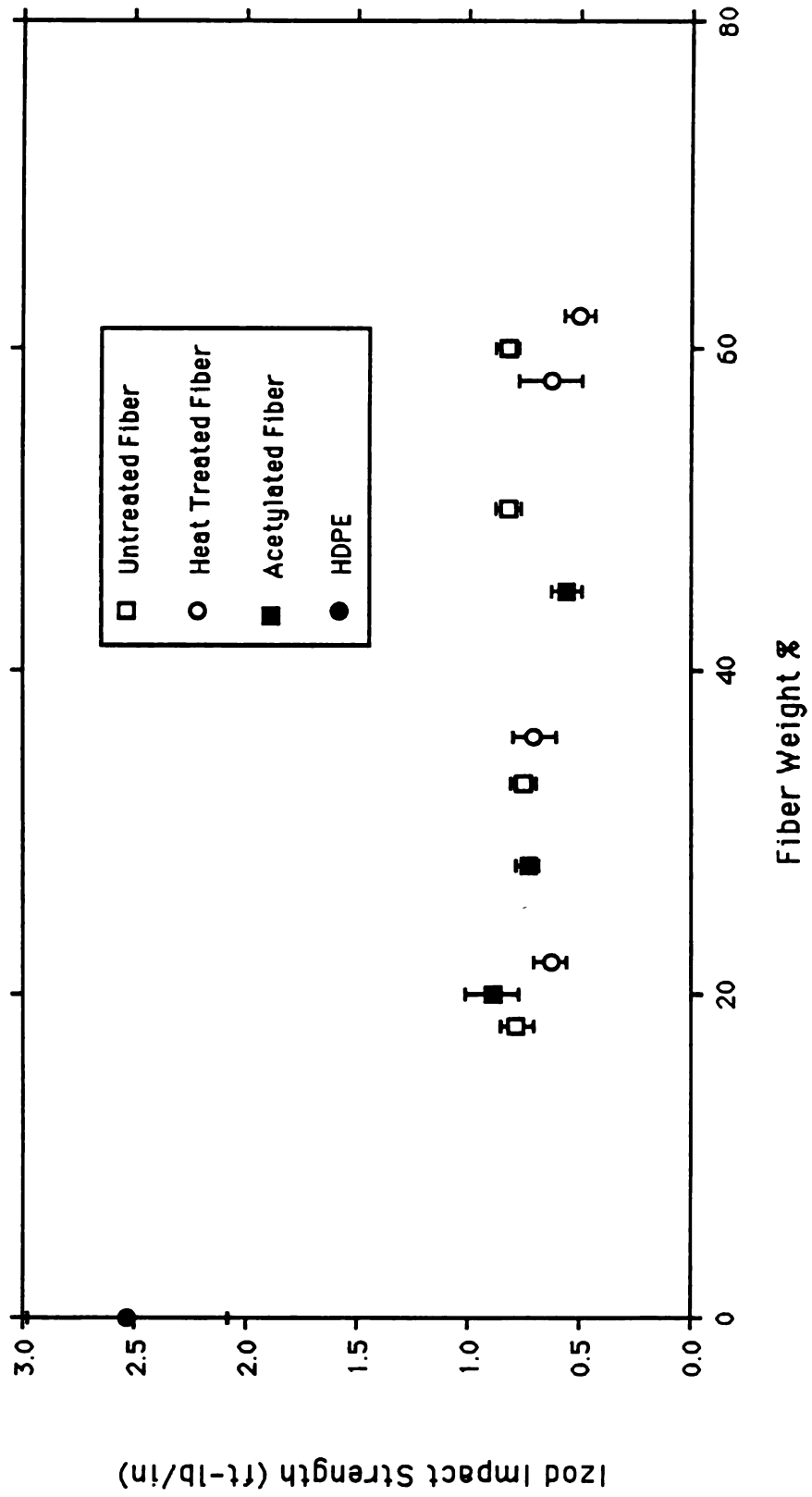


Figure 10. Izod impact strength vs fiber content (SC 1, 150 °C)

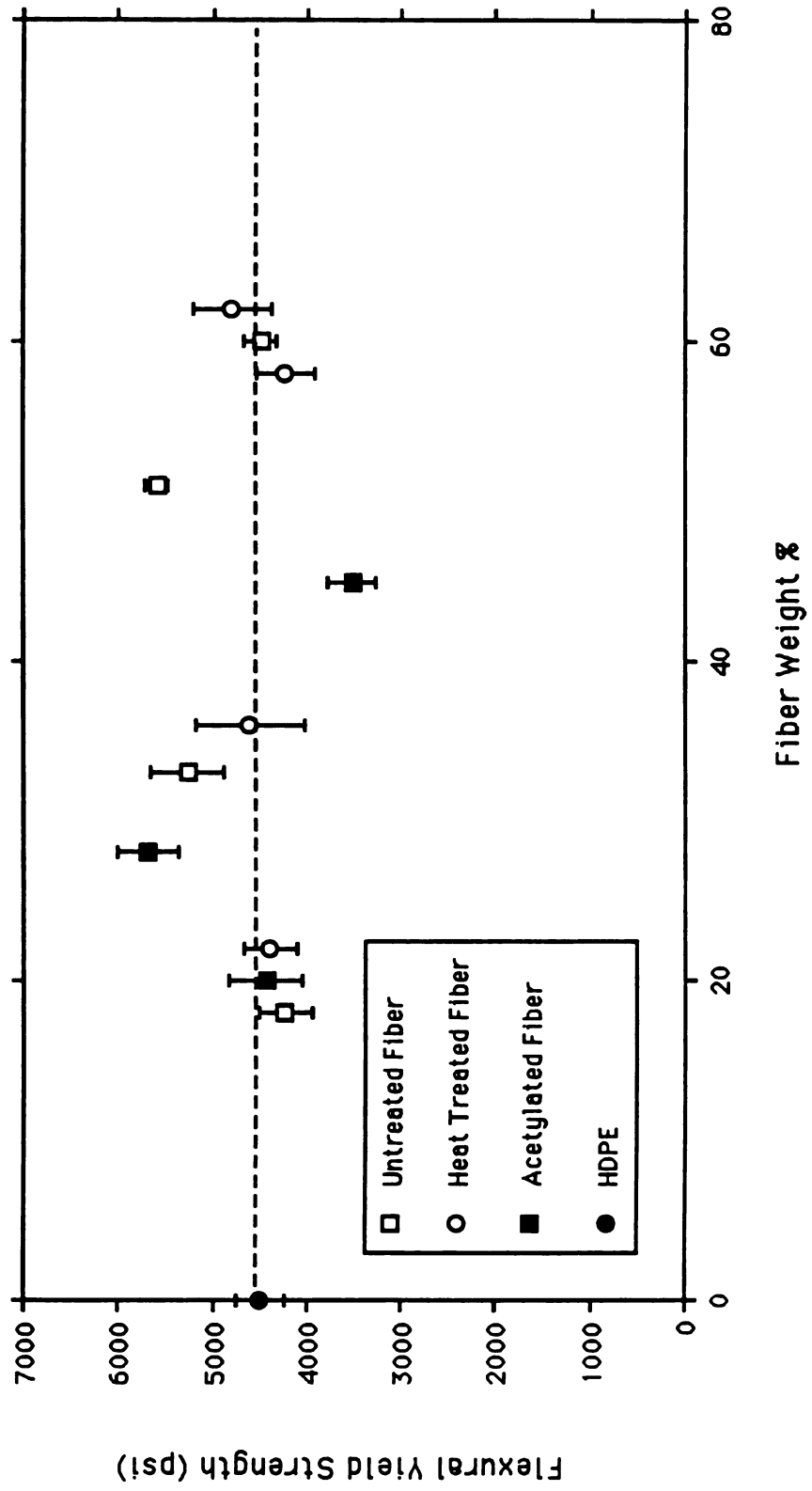


Figure 11. Flexural yield strength vs fiber content (SC 1, 150 °C)

(Figure 12). Compared to the polymer matrix, there is a 340% increase in the modulus. Excessive fiber interaction at high fiber contents has perhaps resulted in a precipitous drop at 62%. Fiber treatment does not seem to have any effect on the flexural modulus. Woodhams, 1984 also found "minor differences" in flexural modulus for different pulp samples including softwood pulps, hardwood pulps, or newsprint reclaim. However, it may be noted that he added a small percentage of stearic acid (2% by weight of pulp) to HDPE and used a Brabender Mixer with slightly different mixing conditions.

4. Selection of fiber from pre-treatments

From the above results, we find that acetylated and untreated fibers perform better than heat treated fibers for tensile and flexural yield strength. Fiber treatment also does not have any effect on tensile modulus, flexural modulus, impact, and elongation properties of the wood fiber composite.

Since untreated fibers are least expensive, they would be most suitable for commercial applications. These fibers have therefore been used for further evaluation.

B. EFFECT OF SCREW CONFIGURATION

Four screw configurations (Table 1) were examined. The starting configuration was chosen by considering a balanced conveying ability. The various sections of the screw and the orientations of the paddles in the mixing section were marked on an "Agitator design worksheet" (Figure 13). This design

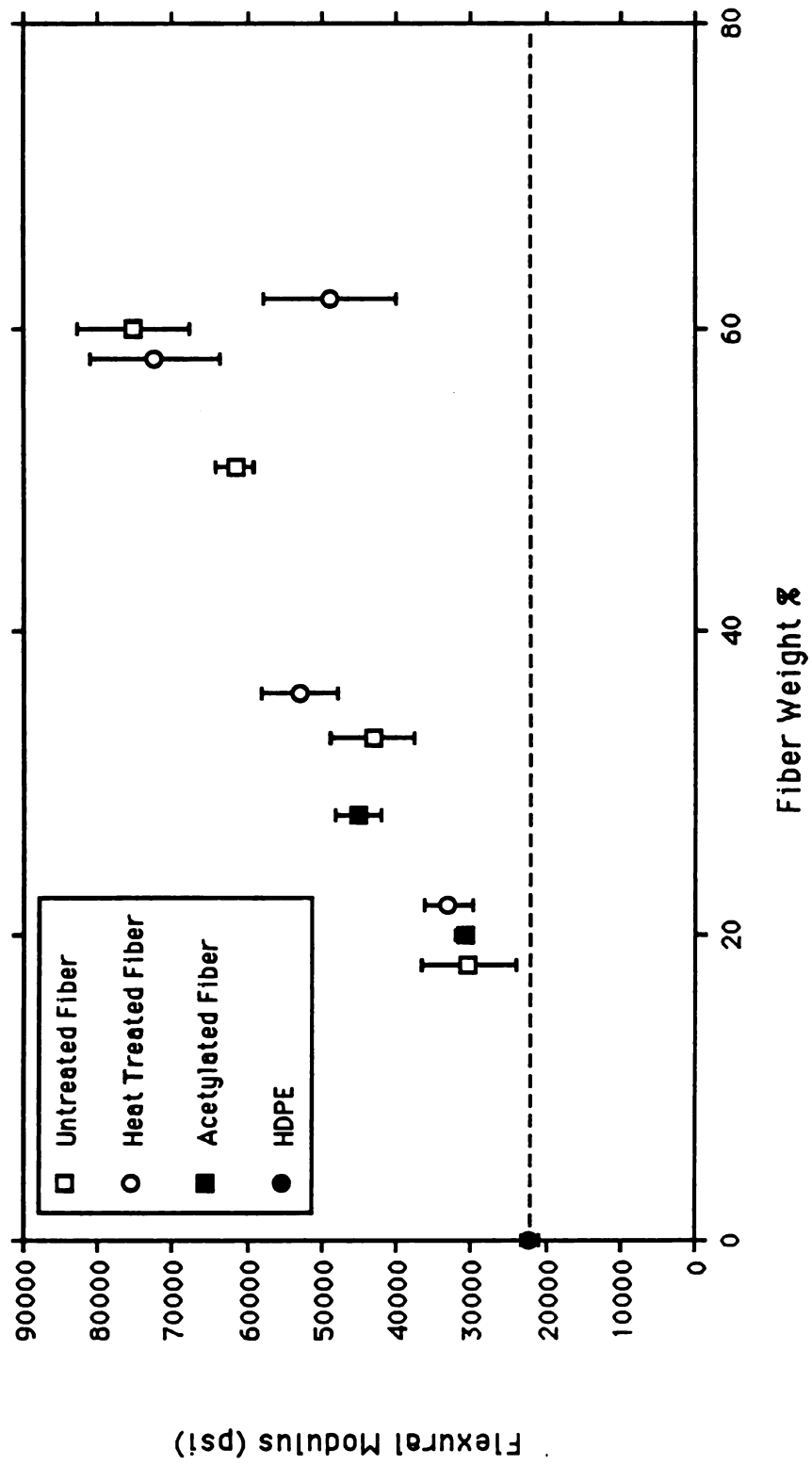
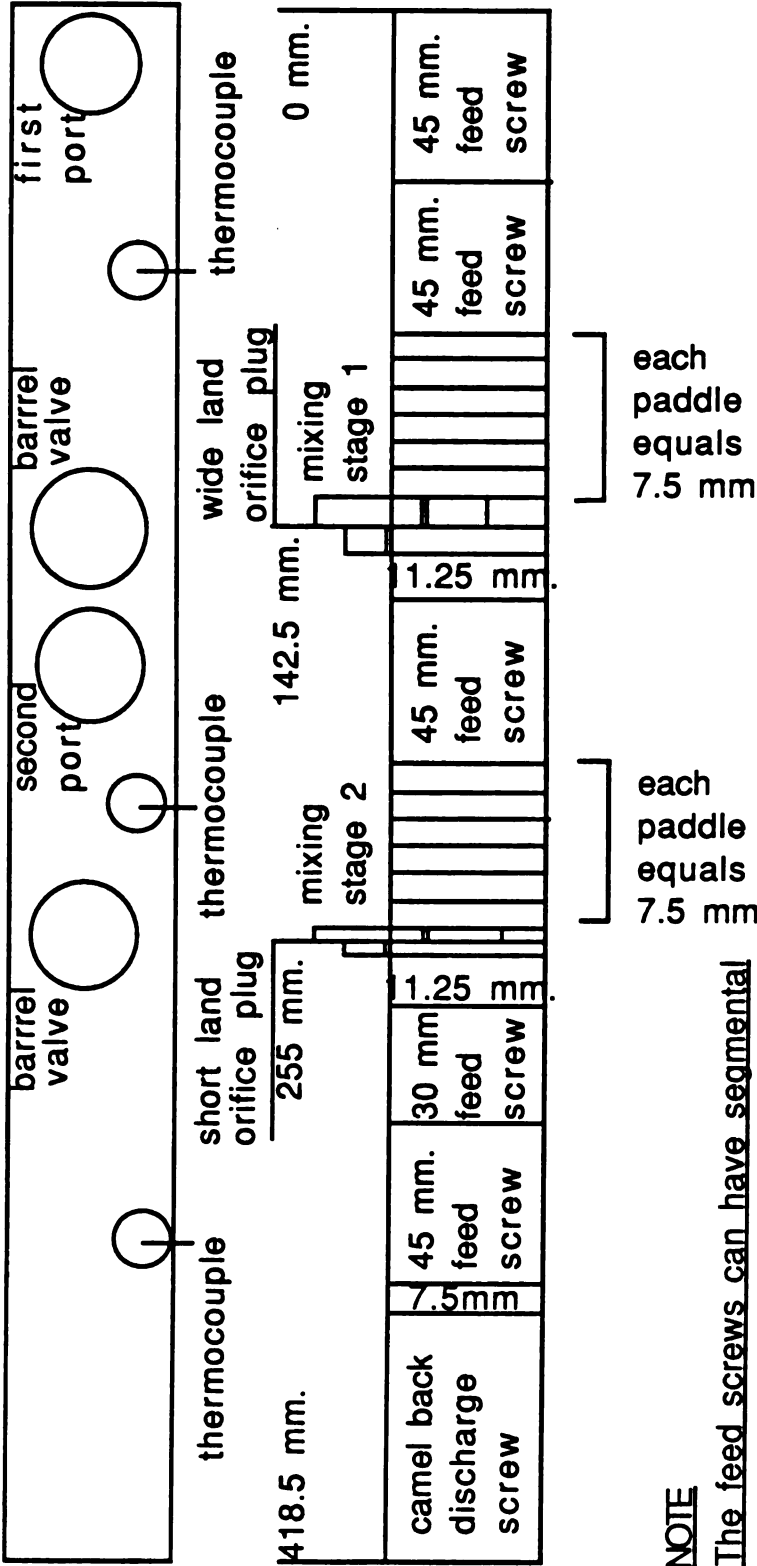


Figure 12. Flexural modulus vs fiber content (SC 1, 150 °C)



NOTE

The feed screws can have segmental design to match the total dimension

Figure 13. Agitator design worksheet

sheet is used for the assembly of the twin screws of the extruder and serves as a reference for comparing different screw designs. Variations were introduced in the orientations of the paddles in both mixing stage 1 and mixing stage 2 in order to make changes in the conveying ability and mixing. Screw configuration 2 (Table 1) was eliminated because of its poor conveying ability.

The mixing stage 1 has to ensure that the polymer, which is introduced in the first port, completely melts before it reaches mixing stage 2. A wide land orifice plug placed immediately after the mixing stage 1 assisted in the melting by maintaining the filled length. The barrel of the extruder was opened quickly after the extrusion to observe the melt in mixing stage 1. It was seen that there was proper melting of the polymer in all the three paddle configurations of mixing stage 1.

The variations in the paddles of mixing stage 2 had different effects on fiber breakage and mechanical properties of the composite. The effects of screw configurations 1, 3 and 4 on the fiber length distribution are shown in Figure 14. The processing conditions were as follows :

- a). Screw configuration : 1, 3 and 4
- a). Processing Temperature : 150 °C.
- b). Screw Speed : 100 rpm.

The better mixing (low conveying ability) of configuration 1 caused maximum fiber damage and resulted in shorter fibers for a fiber content of 50 % by weight. The fiber length

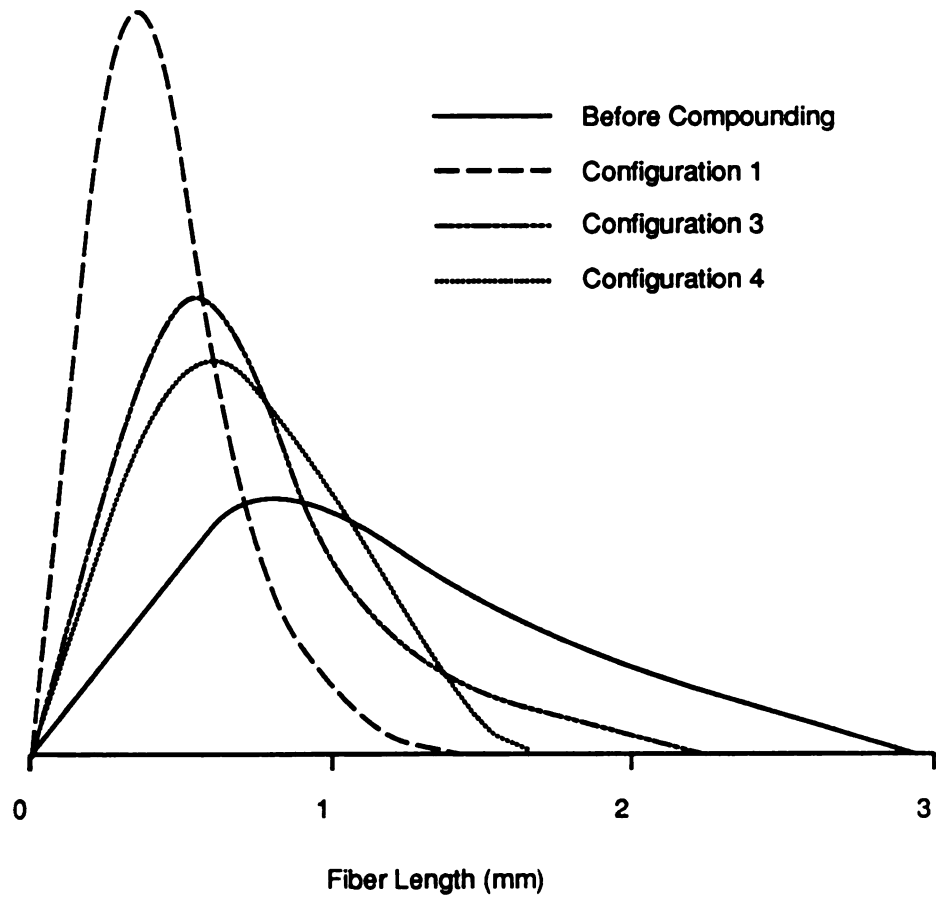


Figure 14. Probability density curves for fiber length.

distributions for configurations 3 and 4 are almost identical. The mean fiber length had reduced from 0.8 mm to 0.4 mm — bringing down the aspect ratio by 50%.

The results of tensile strength (Figure 15) and tensile modulus (Figure 16) show that configuration 1 is better than configuration 3 and 4. Flexural yield strength (Figure 17) and flexural modulus (Figure 18) show the same trend. We may again note that in the case of flexural yield strength, the trend is first a decrease to a minimum, then increase to a maximum and finally decrease with increasing fiber content.

The data under this processing condition seem to indicate that shorter fiber lengths impart higher strength to the composite, which is generally contrary to expectations. We may however note that Configuration 1 provides better dispersion and tends to enhance fiber matrix interaction with resultant shorter fiber length. Recalling equation ... 2 (Piggott, 1981), it was expected that the strength of uniaxially oriented short fiber composites would increase with fiber length and fiber-matrix adhesion. However, from the above analysis fiber adhesion seems to be a more dominating factor than fiber length for imparting strength to the composite. McNally et.al., 1978, found that better dispersion results in a stronger interface, which might lead to a stronger composite even though the fiber length is degraded. This may be due to better wetting of the fibers and the absence of microvoids. Bitaille, 1987, also found an increase of elastic modulus with mixing time using a Brabender Mixer to mix 20 % cellulose with

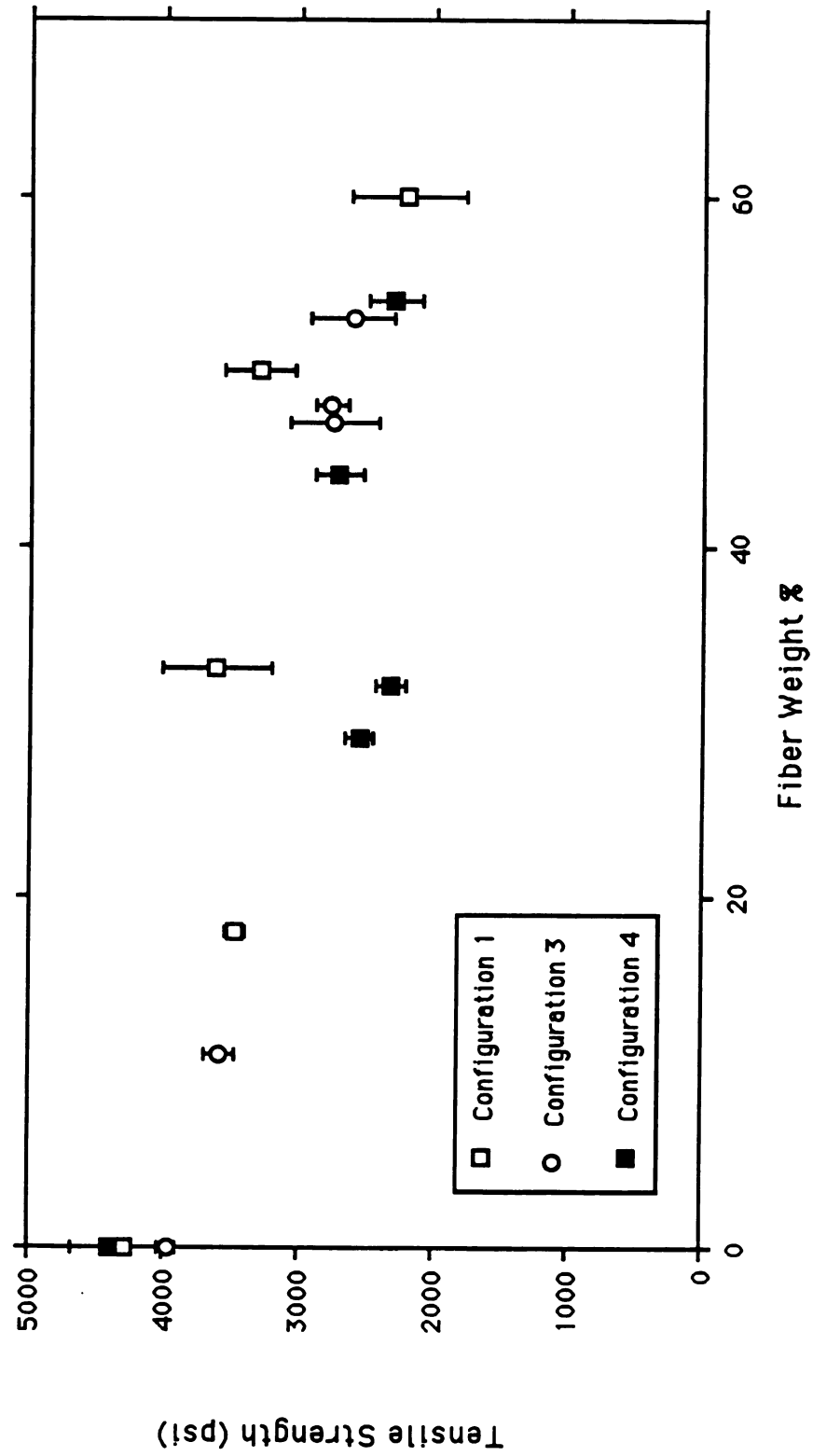


Figure 15. Effect of SC on tensile strength (untreated fiber, 150 °C)

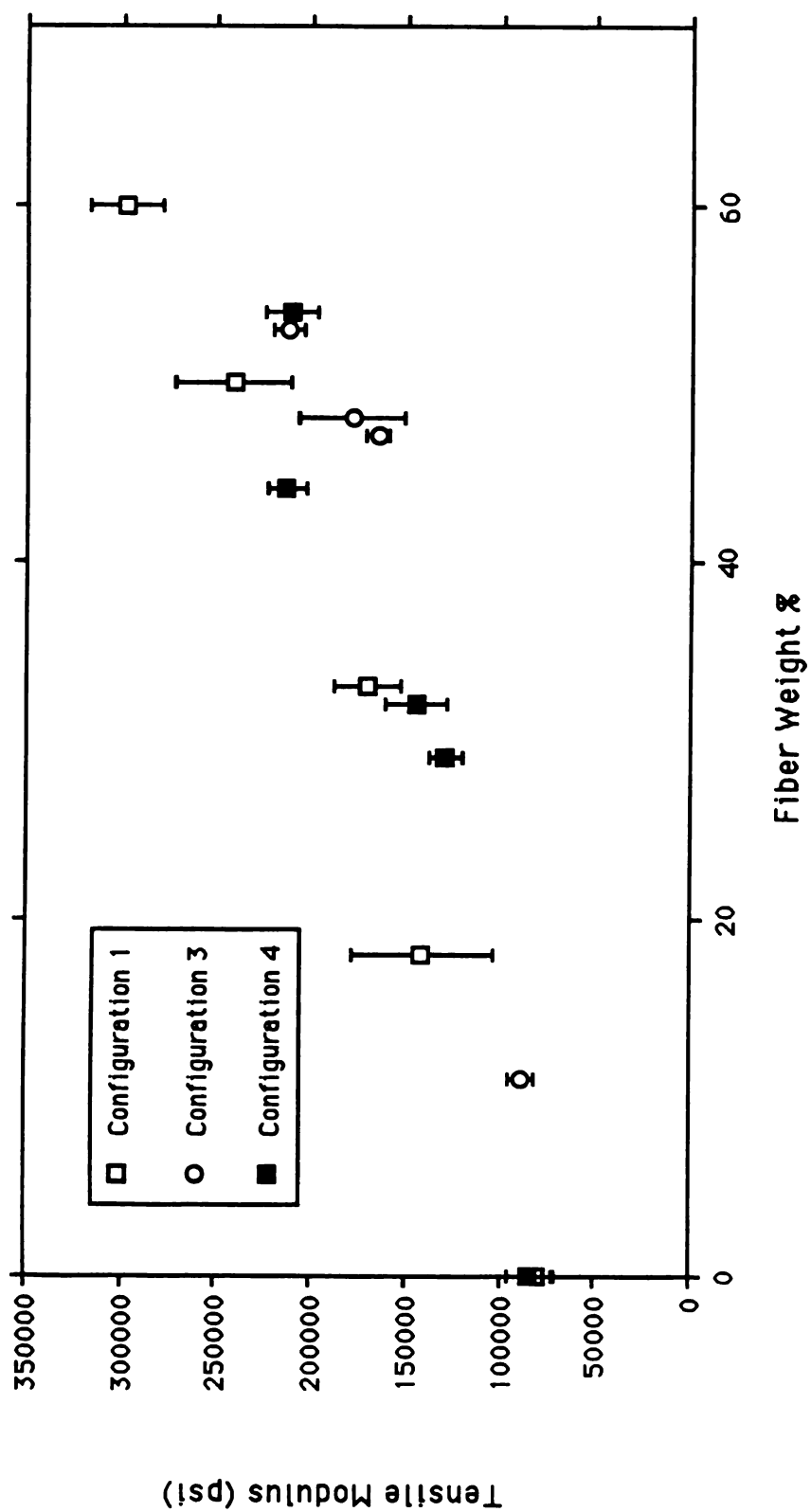


Figure 16. Effect of SC on tensile modulus (untreated fiber, 150 °C)

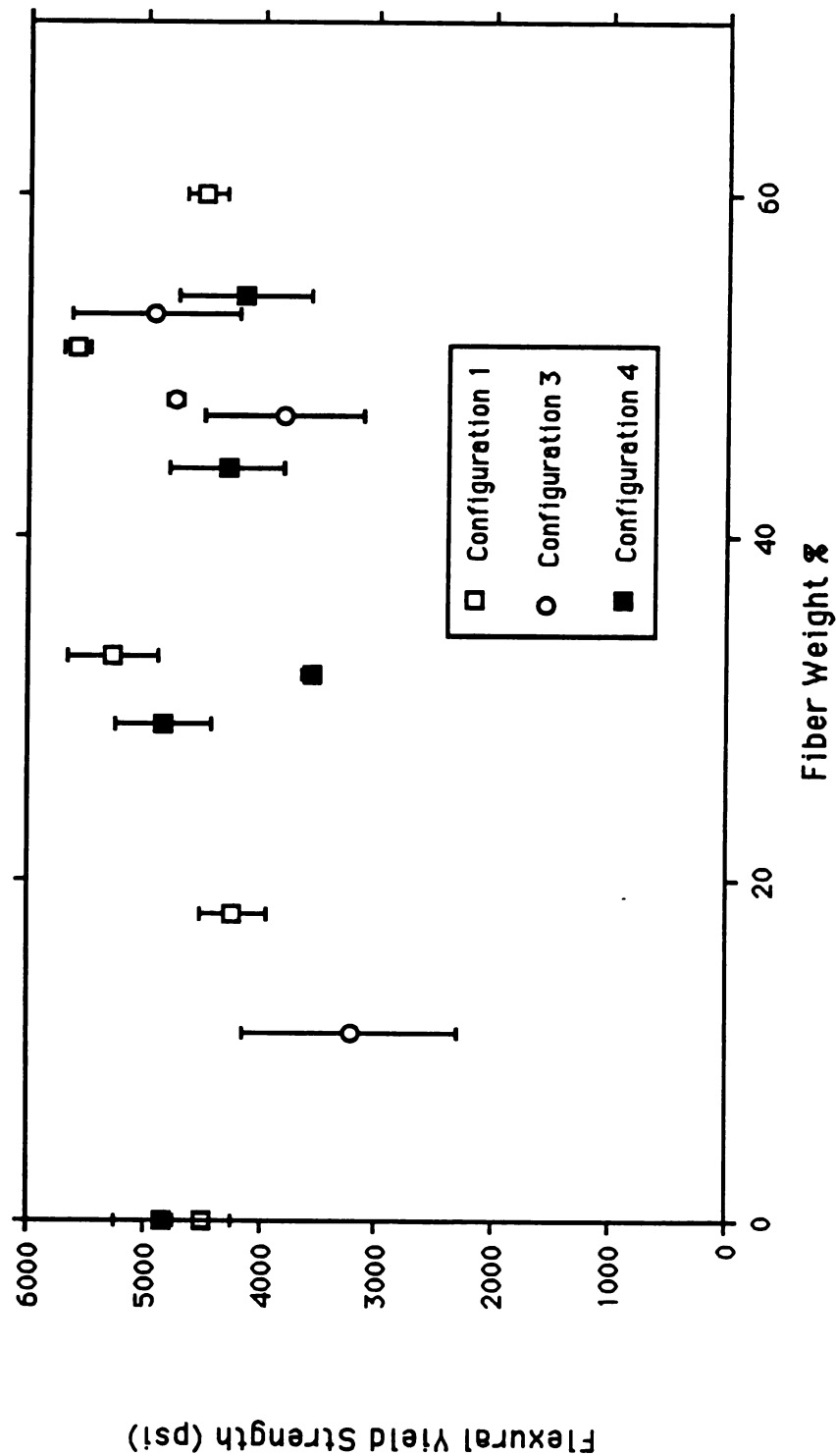


Figure 17. Effect of SC on flexural yield strength (untreated fiber, 150 °C)

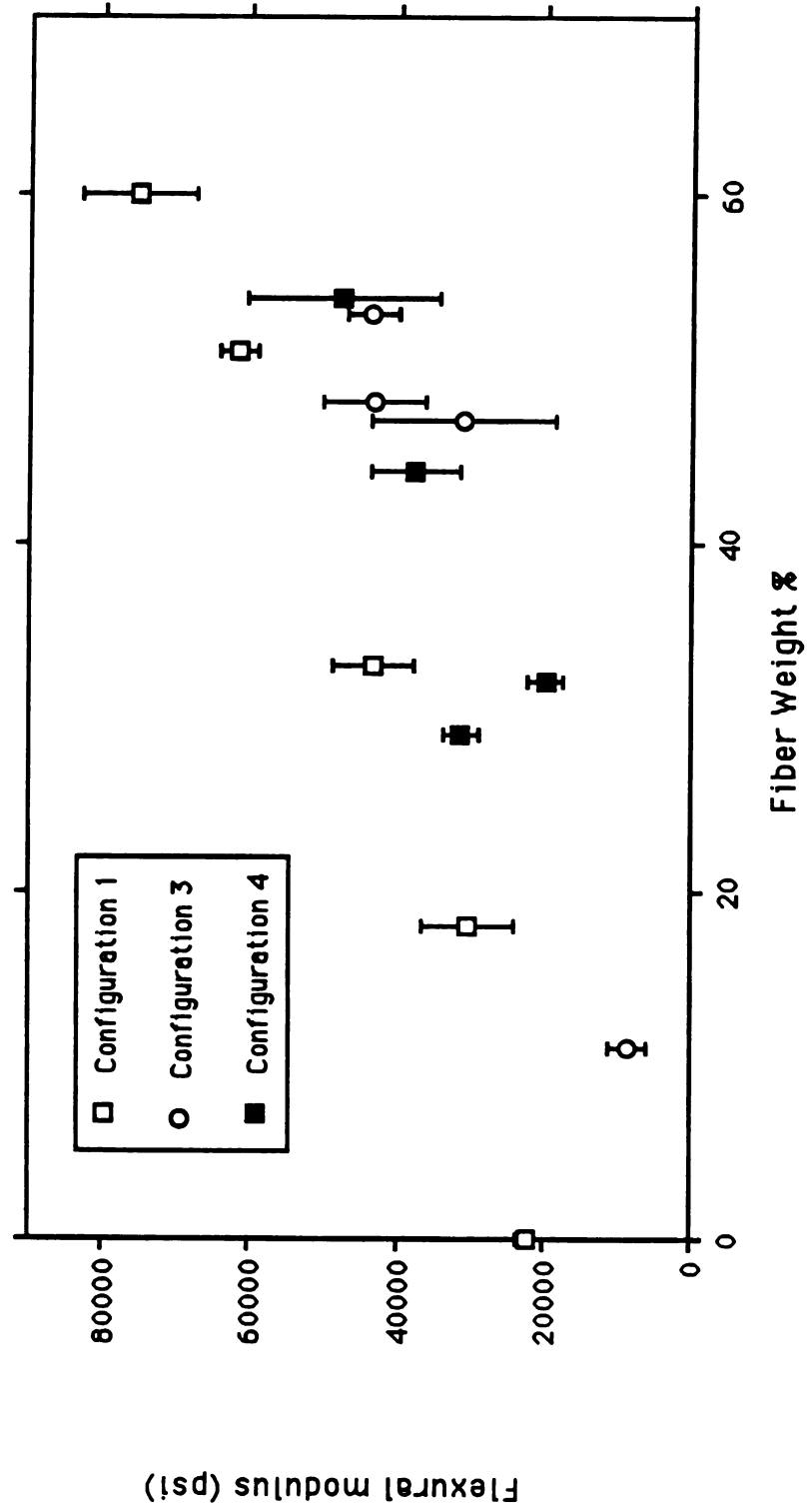


Figure 18. Effect of SC on flexural modulus (untreated fiber, 150 °C)

polypropylene at 190 °C. It seems that this complex behaviour needs more indepth study so as to characterise the same.

C. FIBER LENGTH IN TERMS OF MOMENTS OF DISTRIBUTION

We may express the fiber length in terms of moments of distribution similar to the manner a polymer chemist describes molecular weight distribution.

$$L_n = \frac{\sum N_i L_i}{\sum N_i} \quad \dots (7)$$

$$\text{and } L_w = \frac{\sum N_i L_i^2}{\sum N_i L_i} \quad \dots (8)$$

The result is shown in Table-2, where L_w/L_n is the polydispersity. The average width of the fibers was 0.03 mm.

D. EFFECT OF COMPOUNDING TEMPERATURE

Compounding temperature is an important design factor for processing. Thermal degradation of the fiber sets limits to the processing temperature. Lignin starts to degrade at 200 °C. and most natural fibers begin to lose their strength at 160 °C. (Cruz-Ramos, 1986). The effect of compounding temperature was therefore studied in the range of 150 °C. to 210 °C..

1. Tensile strength and tensile modulus

Processing conditions were as follows :

- a). Screw Configuration : SC 1
- b). Screw Speed : 100 rpm.
- c). Compounding temperature: 150 °C., 170 °C., 190 °C.,
and 210 °C.
- d). Fiber Type : Untreated Aspen

Table 2. Average fiber length and polydispersity

<u>Sl.No.</u>	<u>item</u>	<u>Ln (mm)</u>	<u>Lw (mm)</u>	<u>Lw/Ln</u>
1	Before Compounding	1.26	1.58	1.26
2	Configuration 1	0.49	0.61	1.24
3	Configuration 3	0.78	0.96	1.24
4	Configuration 4	0.72	0.91	1.25

Tensile strength and tensile modulus are both highest for a processing temperature of 150 °C. (Figure 19 and Figure 20).

2. Flexural strength and flexural modulus

Processing conditions were as follows :

- a). Screw Configuration : SC 3
- b). Screw Speed : 100 rpm.
- c). Compounding temperature: 150 °C., 170 °C., 190 °C.,
and 210 °C.
- c). Fiber Type : Untreated Aspen

Flexural strength and flexural modulus seems to be highest for a processing temperature of 170 °C. (Figure 21 and Figure 22).

The results seem to indicate that tensile and flexural properties are sensitive to compounding temperature. It is further observed that for better tensile properties, a longer mixing time (screw configuration 1) requires a lower compounding temperature. A shorter mixing time (screw configuration 3) requires a higher compounding temperature for better flexural properties. The composite also tends to darken as function of time and there seems to be thermodegradation. Two competing mechanisms may be present _ cellulose degradation and increase of adhesion.

E SCANNING ELECTRON MICROSCOPY

The fracture surfaces for tensile specimens compounded with screw configuration 1 were examined. Figure 23 shows a clean surface at 3500 magnification (untreated fibers, 150 °C., 32% fiber). Scanning electron micrographs at 1500 magnification show adhesion for untreated fiber at 170 °C.

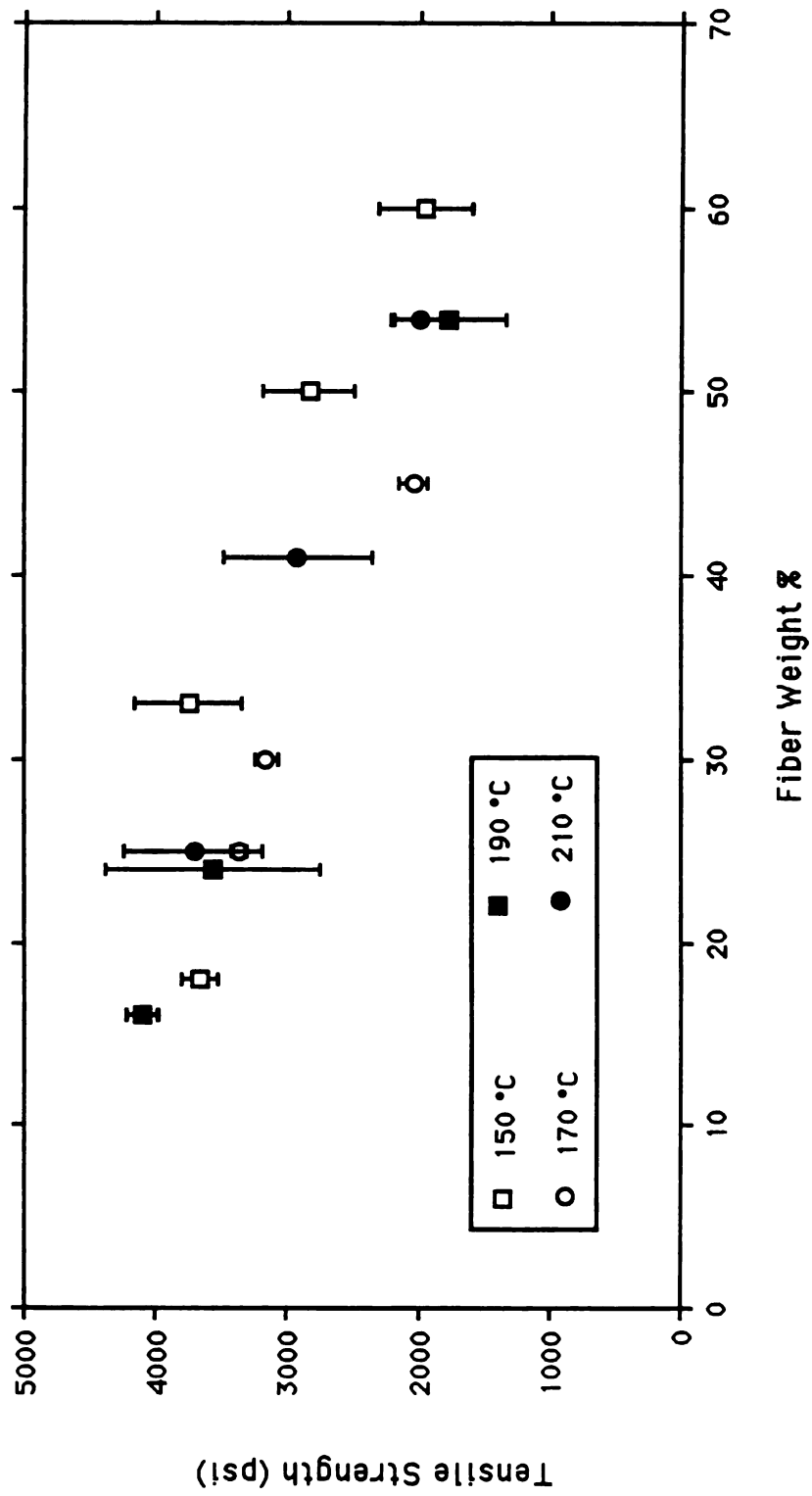


Figure 19. Effect of compounding temp. on tensile strength (untreated fiber, SC 1)

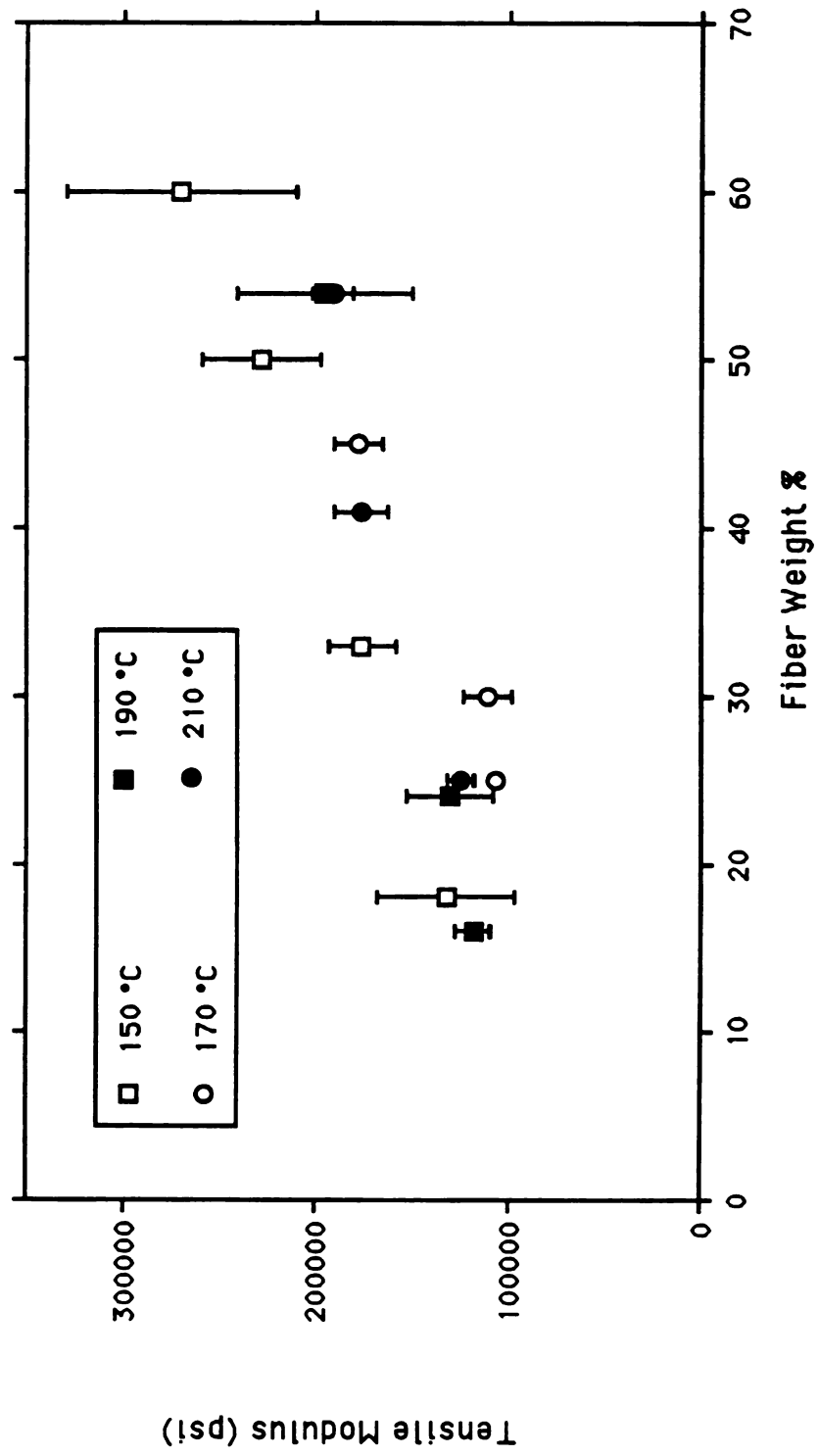


Figure 20. Effect of compounding temp. on tensile modulus (untreated fiber, SC 1)

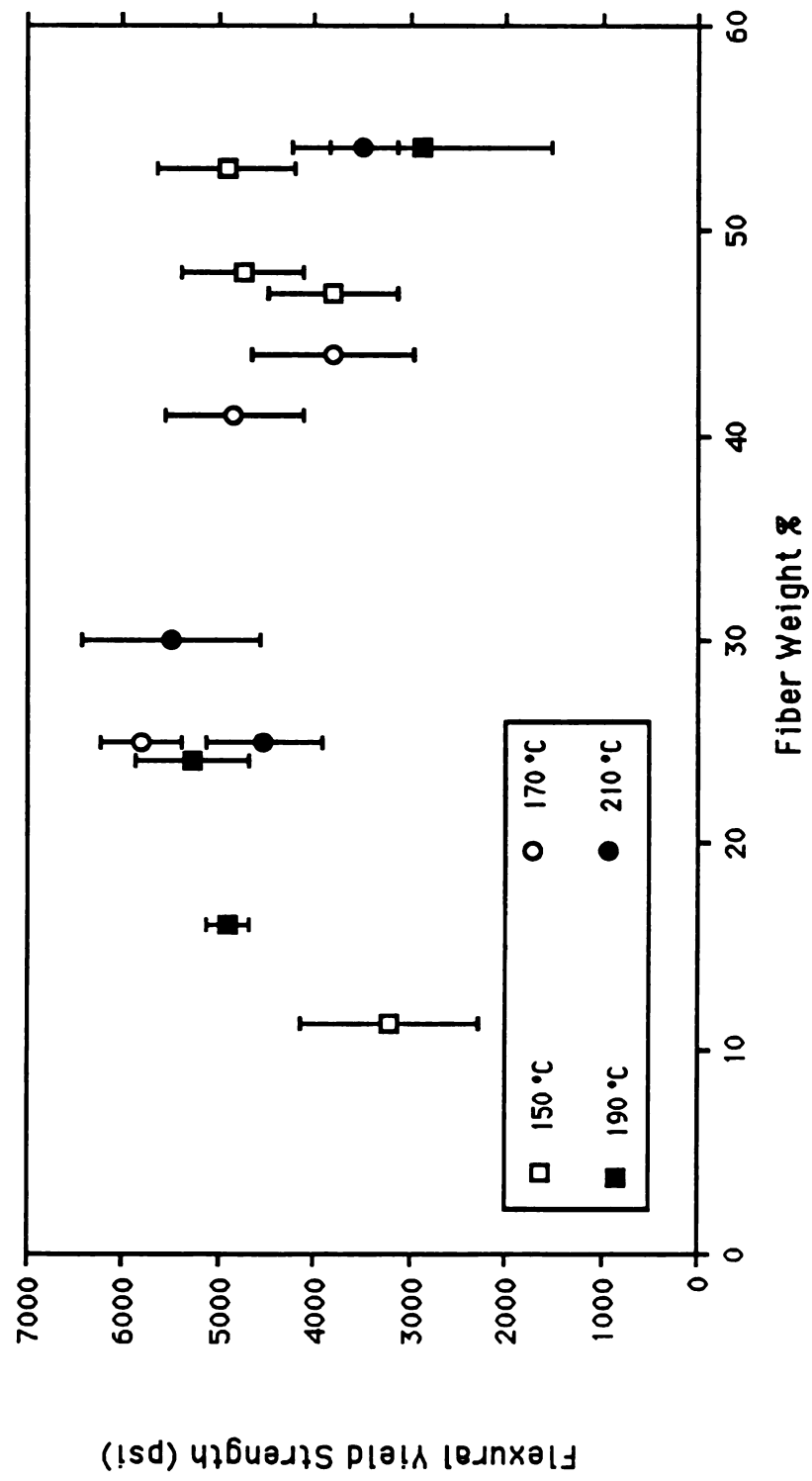


Figure 2.1. Effect of compounding temp. on flexural yield strength (untreated fiber, SC 3)

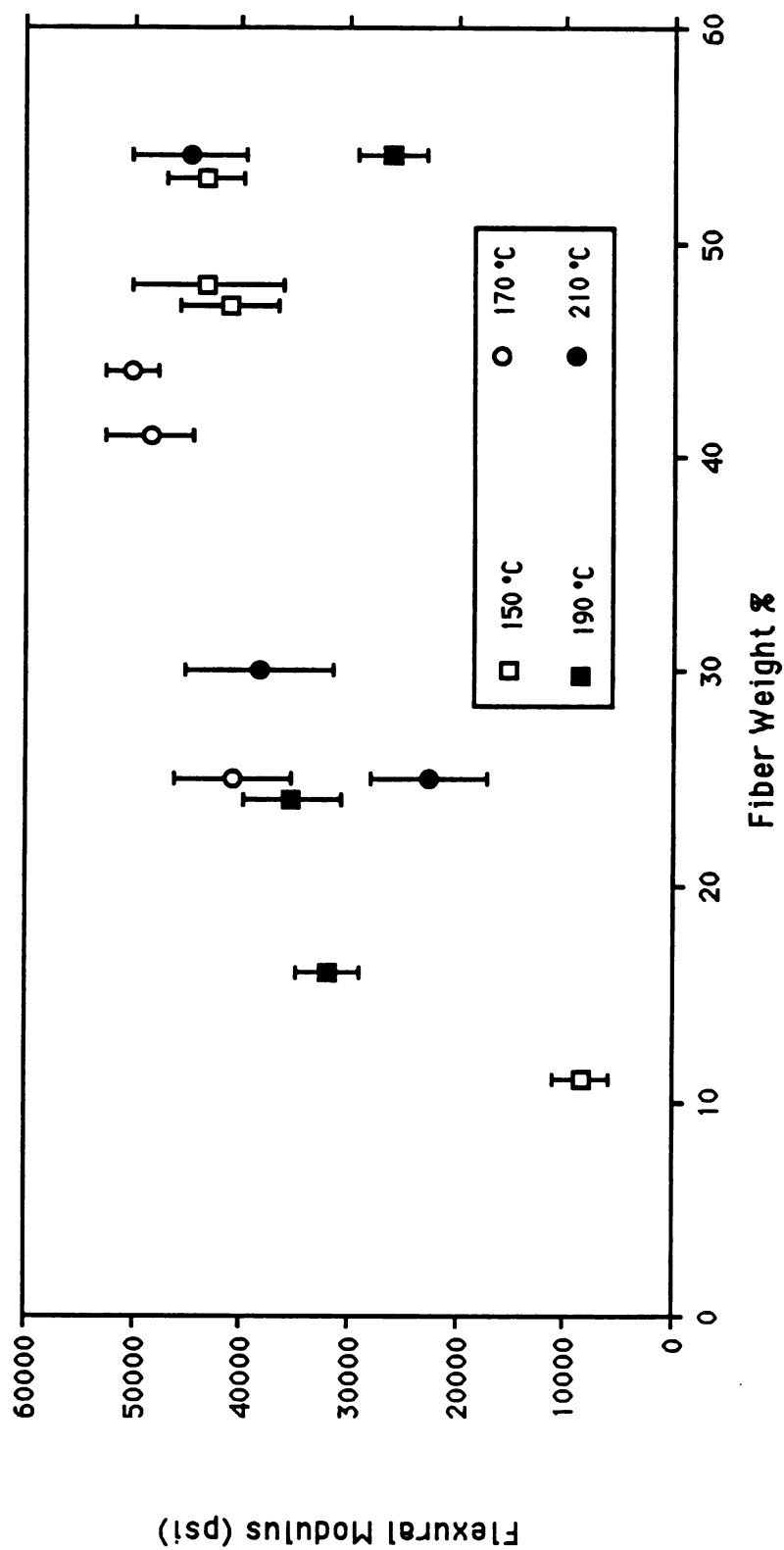


Figure 22. Effect of compounding temp. on flexural modulus (untreated fiber, SC 3)

(Figure 24) and lack of adhesion at 190 °C.(Figure 25) and 210°C.(Figure 26). The fiber content was approximately 30% by weight. Heat treated fibers at 1500 magnification (Figure 27) also showed lack of adhesion at 150 °C.. The fiber concentration was 35.8% by weight. Acetylated fibers at 28% by weight show some adhesion at 2000 magnification (Figure 28). Other micrographs at magnifications of 350 and 200 indicate a high degree of fiber pull-outs with consequent low degree of adhesion for fibers processed at 150 °C.

A comparison of the micrographs for 30% acetylated, 30% untreated, and 33% heat treated fibers, which were processed with screw configuration 1 (Table 1) do reveal that there is considerable adhesion of HDPE on acetylated fibers and very little adhesion on heat treated fibers. The fracture surface of the composite with untreated fibers however indicate a large degree of fiber pull outs. Their corresponding tensile strengths of 3900 psi., 3700 psi., and 2150 psi. would perhaps correlate with the micrographs. In order to make a conclusive statement regarding this complex phenomenon of adhesion, a more indepth study of the fracture surface using SEM would be necessary. However, the large degree of fiber pull outs and their clean surfaces seem to indicate the presence of voids as one the contributing factors in crack propagation. The above studies also seem to indicate the potentiality for increasing the strength of the wood fiber composite by better bonding between the hydrophobic HDPE

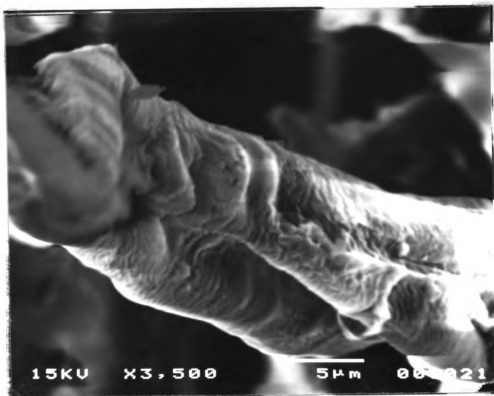


Figure 23. SEM :: 32 % untreated fibers, 150 °C, SC 4

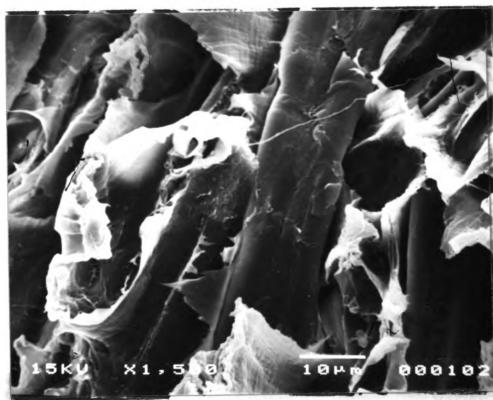


Figure 24. SEM :: 30 % untreated fibers, 150 °C, SC 1

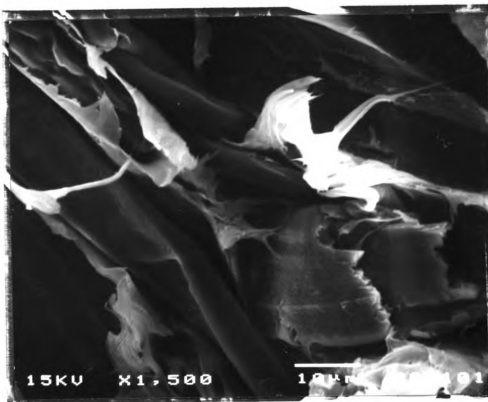


Figure 25. SEM :: 25 % untreated fibers , 150 °C. SC 1

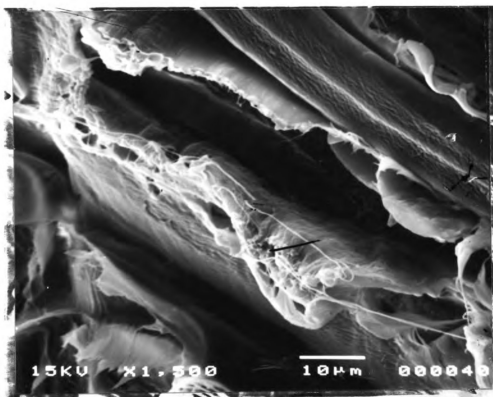


Figure 26. SEM :: 25 % untreated fibers. 150 °C. SC 1

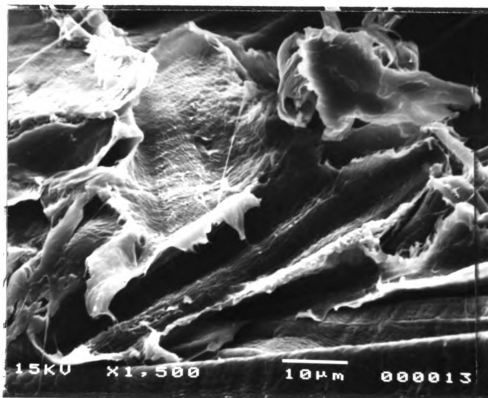


Figure 27. SEM :: 38.5 % heat treated fibers, 150 °C, SC 1

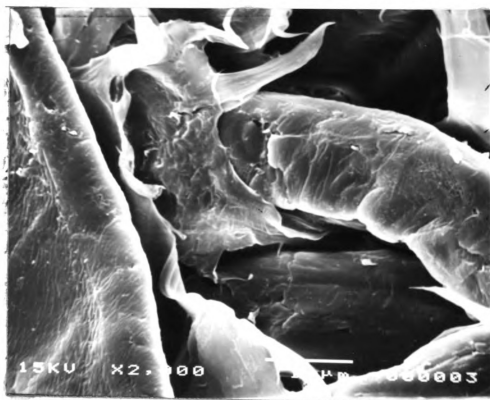


Figure 28. SEM :: 28 % acetylated fibers, 150 °C, SC 1

and the hydrophilic aspen fibers and reduction of voids.

F. THEORETICAL PREDICTIONS VERSUS EXPERIMENTAL DATA

There are several theories in the literature that can predict tensile strength and tensile modulus of filled polymers but there seems to be none that can predict impact strength of filled polymers.

1. Tensile strength

Landon (1977) and Bigg (1979, 1987) showed upper bound and lower bound relationships between the tensile strength and the volume fraction of the filler. The upper bound curve indicates adhesion while the lower bound curve indicates little or no adhesion. The lower bound response can be expressed by the mathematical model (Nicholais et.al.,1973) :

$$\sigma_c = \sigma_p (1 - a \phi^b) \quad \dots(9)$$

where, σ_c = tensile strength of composite

σ_p = tensile strength of polymer

a = constant related to stress conc.

b = constant related to geometry of
filler

ϕ = volume fraction of filler

$$\text{or,} \quad \frac{\sigma_c}{\sigma_p} = 1 - a \phi^b \quad \dots(10)$$

$$\text{or, } \ln \left(1 - \frac{\sigma_c}{\sigma_p} \right) = \ln a + b \ln \phi \quad \dots(11)$$

Bigg (1987) has reported that for spherical particles having no adhesion to the polymer matrix, 'a' has been found to be equal to 1.21 and when there is some adhesion 'a' is smaller than 1.21. The value of 'b' is 2/3 for random fracture of a composite and 1 when failure is by planar fracture. The experimental data for heat treated fibers fitted quite well (Figure 29) to equation (11) although the values of 'a' (1.68) and 'b' (1.032) obtained from the plot seemed to deviate slightly from the limits reported by Bigg. The coefficient of correlation is 0.996 (Table 3). Thus the model for heat treated fibers (Table 4) is :

$$\sigma_c = \sigma_p (1 - 1.68 \phi^{1.032}) \quad \dots(12)$$

Data for untreated and acetylated fibers deviate from this model (Figures 30,31), indicating some adhesion between the fibers and the polymer matrix.

Thus it can be concluded that the model at equation (9), which assumes no adhesion between the filler and the polymer matrix, fits well to the tensile strength curve for the heat treated fibers. Our assumption that there is lack of adhesion for heat treated fibers agrees well with this model. For acetylated and untreated fibers, the model indicates better adhesion and therefore higher tensile properties.

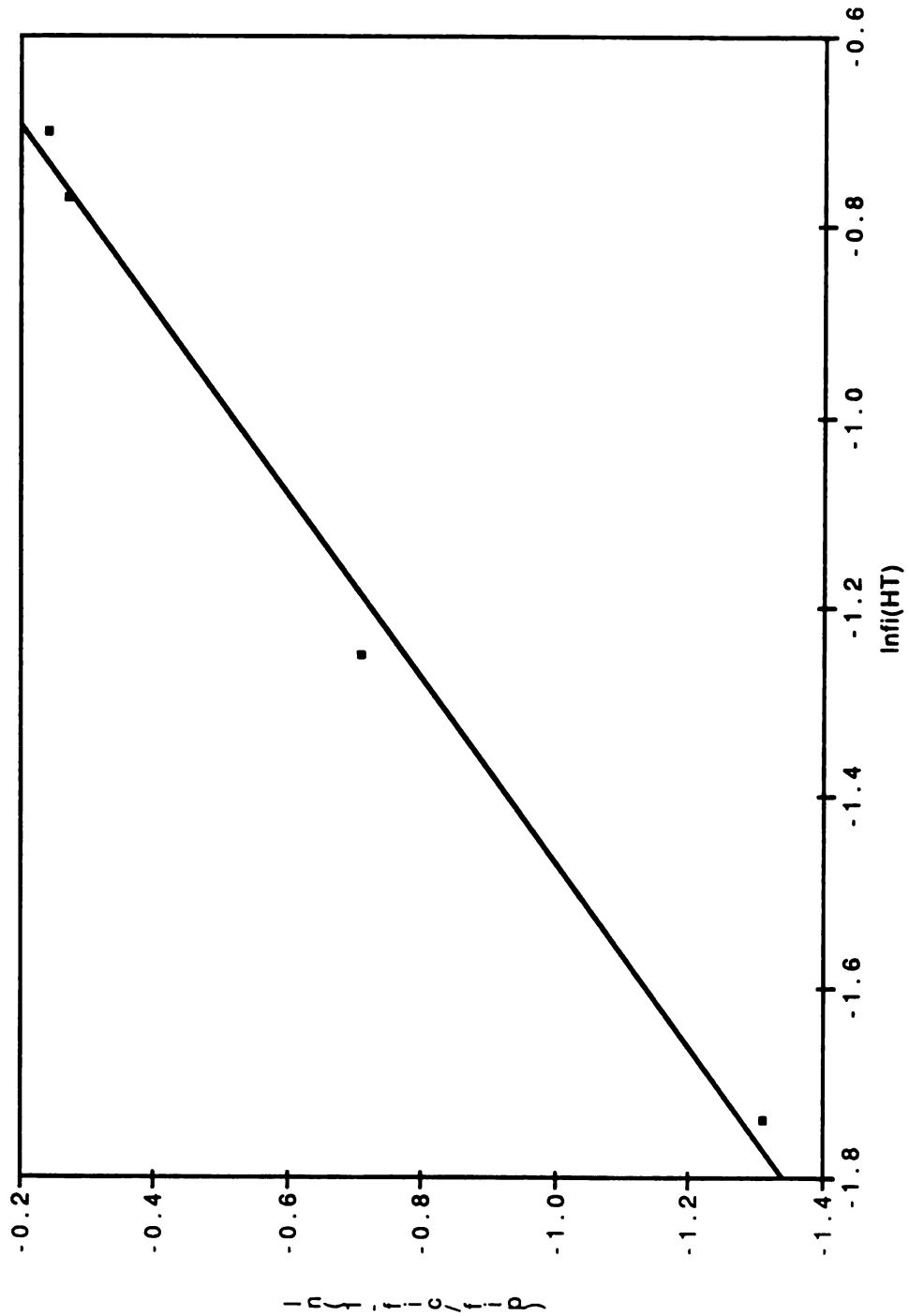


Figure 29. Correlation of theory with tensile strength data (Heat treated aspen fibers in HDPE matrix)

**Table 3. Coeff. of correlation for heat treated aspen fibers
(Tensile strength)**

StatWorks™ Data ANOVA Table

Data File: TheoryData(T)

Source	Sum of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Prob>F
Model	0.744	1	0.744	240.116	0.003
Error	0.006	2	0.003		
Total	0.750	3			

Coefficient of Determination 0.992
 Coefficient of Correlation 0.996
 Standard Error of Estimate 0.056
 Durbin-Watson Statistic 2.699

Table 4. Coeff. for heat treated aspen fibers
(Tensile strength)

StatWorks™ Data Coefficients

Data File: TheoryData(T)

Variable Name	Coefficient	Std. Err. Estimate	t Statistic	Prob > t
Constant	0.517	0.079	6.526	0.019
Infi(HT)	1.031	0.067	15.496	0.003

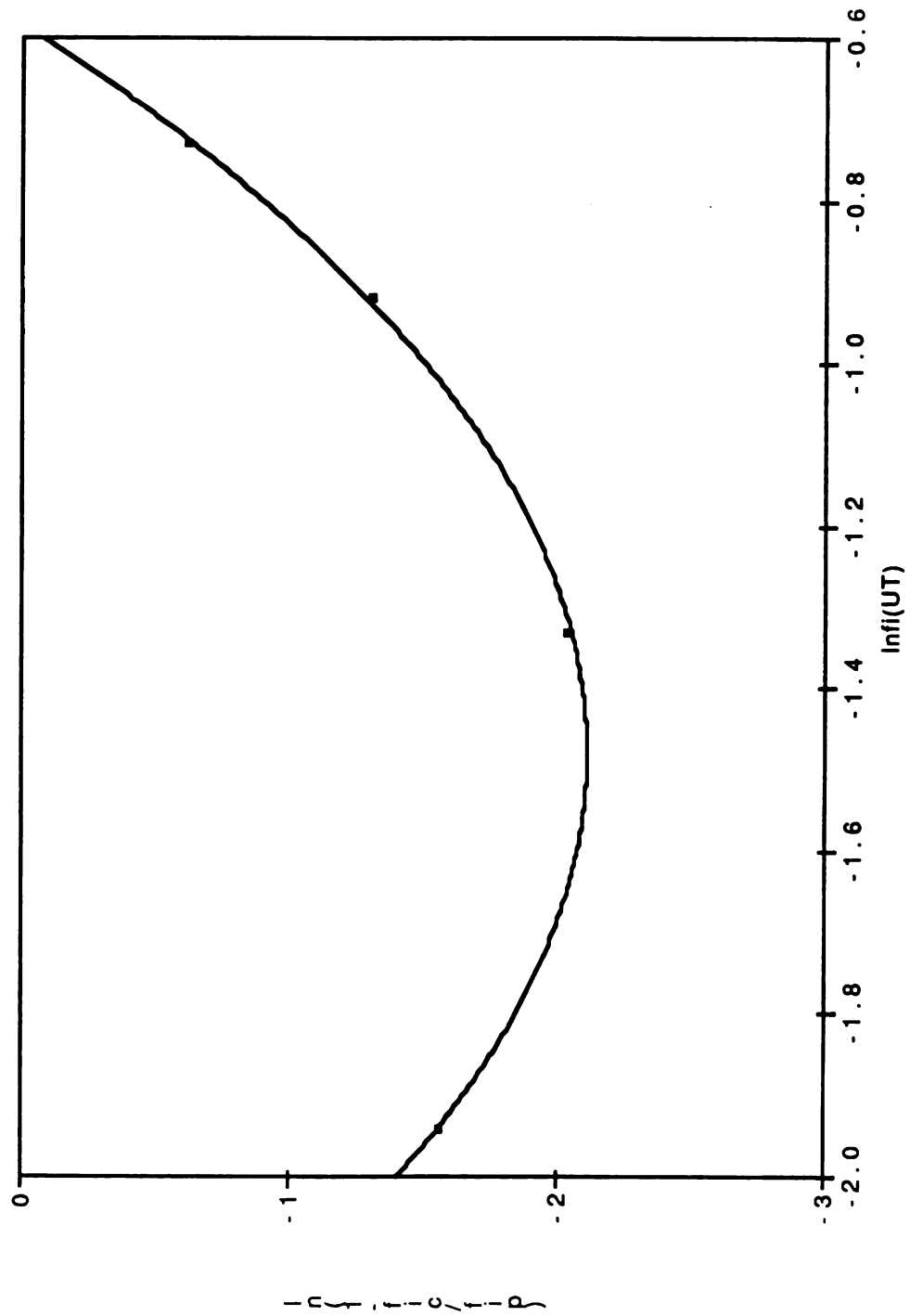


Figure 30. Correlation of theory with tensile strength data
(Untreated aspen fibers in HDPE matrix)

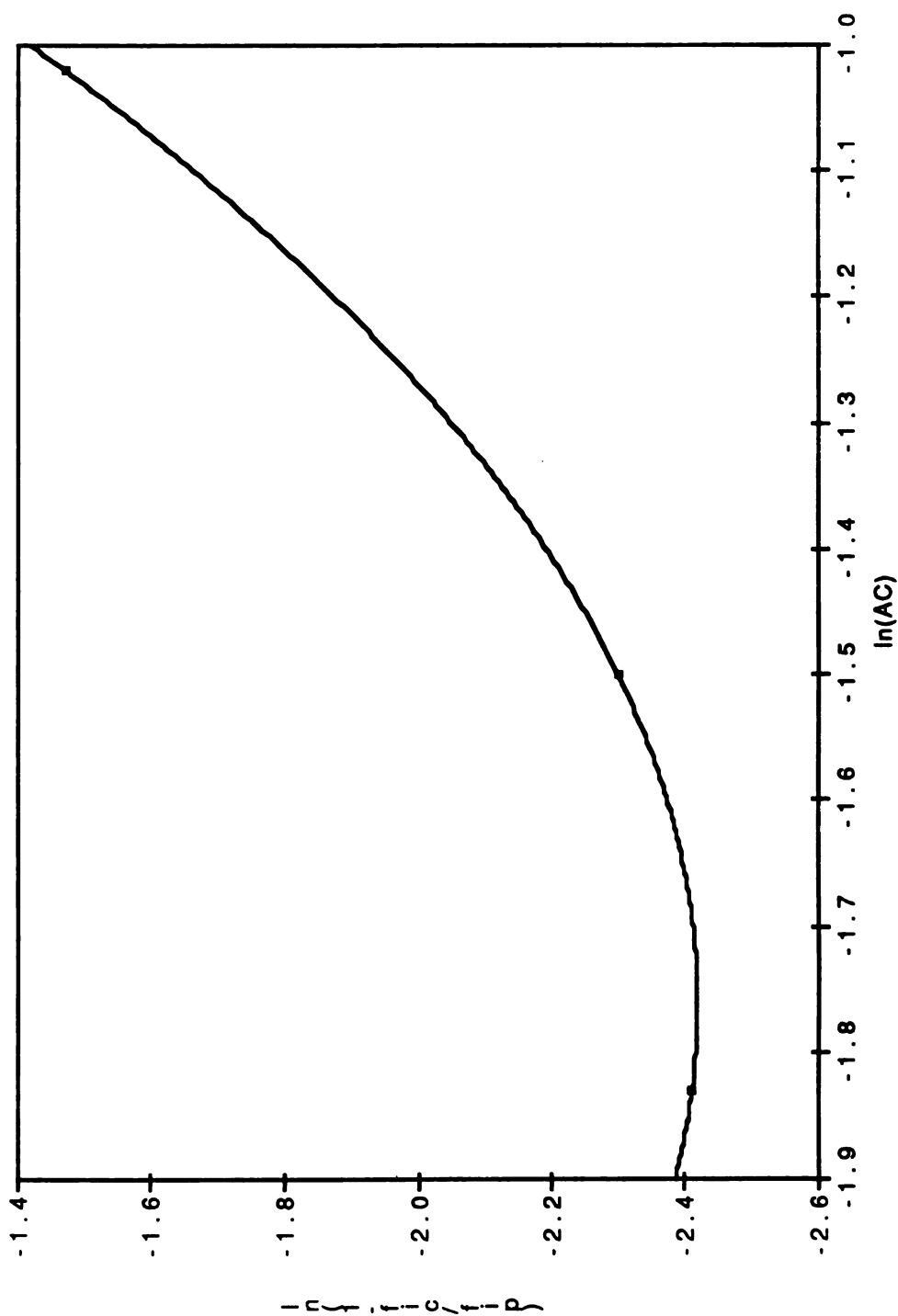


Figure 31. Correlation of theory with tensile strength data (Acetylated aspen fibers in HDPE matrix)

2. Tensile modulus

The frequently used models to predict modulus are applicable only at low filler concentrations (Einstein, 1906; Mooney, 1951, Frankle - Acrivos, 1967). Nielson, 1970, introduced the concept of geometry of the filler particle while Guth's model (1944) is an extension of Einstein's model ie.

$$\eta^* = \eta [1 + 2.5 c] \quad (13),$$

to take into account interparticle attractions at higher filler concentrations. In Einstein's model ' η^* ' and ' η ' are the viscosity of the emulsion and solvent and ' c ' is the volume fraction. Replacing the viscosity ' η ' by the tensile modulus ' E ', we obtain Einstein's model for computing modulus for materials filled with low concentrations of non-interactive spheres. Although the above theories give some insight into the behaviour of the elastic modulus of polymer filled systems, a satisfactory treatment of the strength behaviour of composites reinforced with rigid fillers has not yet been developed (Leidner et. al., 1974).

Besides the independent action of the filler particles, Guth considered the mutual interaction of pairs of spheres and generalised Einstein's viscosity law as follows :

$$\eta^* = \eta [1 + 2.5c + 14.1c^2] \quad \dots (14)$$

$$\text{or, } E^* = E [1 + 2.5c + 14.1c^2] \quad \dots (15)$$

It is proposed to modify Guth's model for wood fibers as follows :

$$E_c = E_p [1 + a\phi + b\phi^2] \quad \dots(16)$$

$$\text{or, } E_r = 1 + a\phi + b\phi^2 \quad \dots(17)$$

$$\text{where, } E_r = \frac{E_c}{E_p} = \text{relative modulus}$$

The coefficient 'a' is a geometric correction factor and is equal to 2.5 for non-interactive spheres (Einstein, 1906). The coefficient 'b' is a correction for higher filler concentration.

Using the experimental values in the above equation, we get the curve fits for relative modulus versus fiber content for heat treated, acetylated, and untreated fibers as shown in figures 32, 33 and 34. The corresponding coefficient of correlation are 0.962, 0.994 and 1.000, respectively. This shows a very close fit for the second degree polynomials. A "Statworks" program was used to evaluate the above. The values of 'a' and 'b' obtained from Tables 5, 6, and 7, give the following mathematical model :

$$1. \text{ Heat-treated : } E_r = 1 + 1.121 \phi + 7.694 \phi^2 \quad \dots(18)$$

$$2. \text{ Acetylated : } E_r = 1 + 3.201 \phi + 6.253 \phi^2 \quad \dots(19)$$

$$3. \text{ Untreated : } E_r = 1 + 2.712 \phi + 2.775 \phi^2 \quad \dots(20)$$

More data may be required to perfect the above models in view of the high standard error.

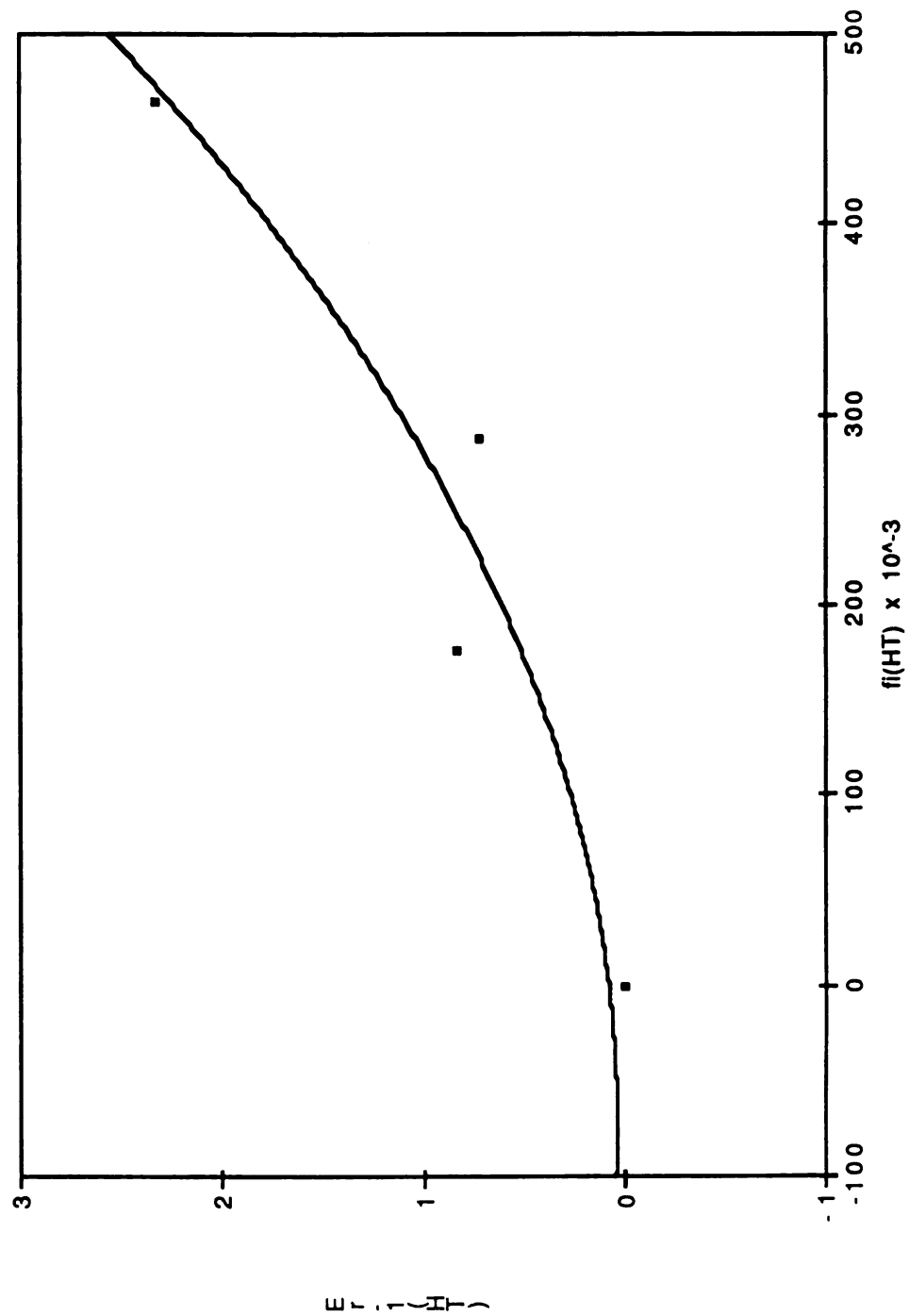


Figure 32. Correlation of theory with tensile modulus data
(Heat treated aspen fibers in HDPE matrix)

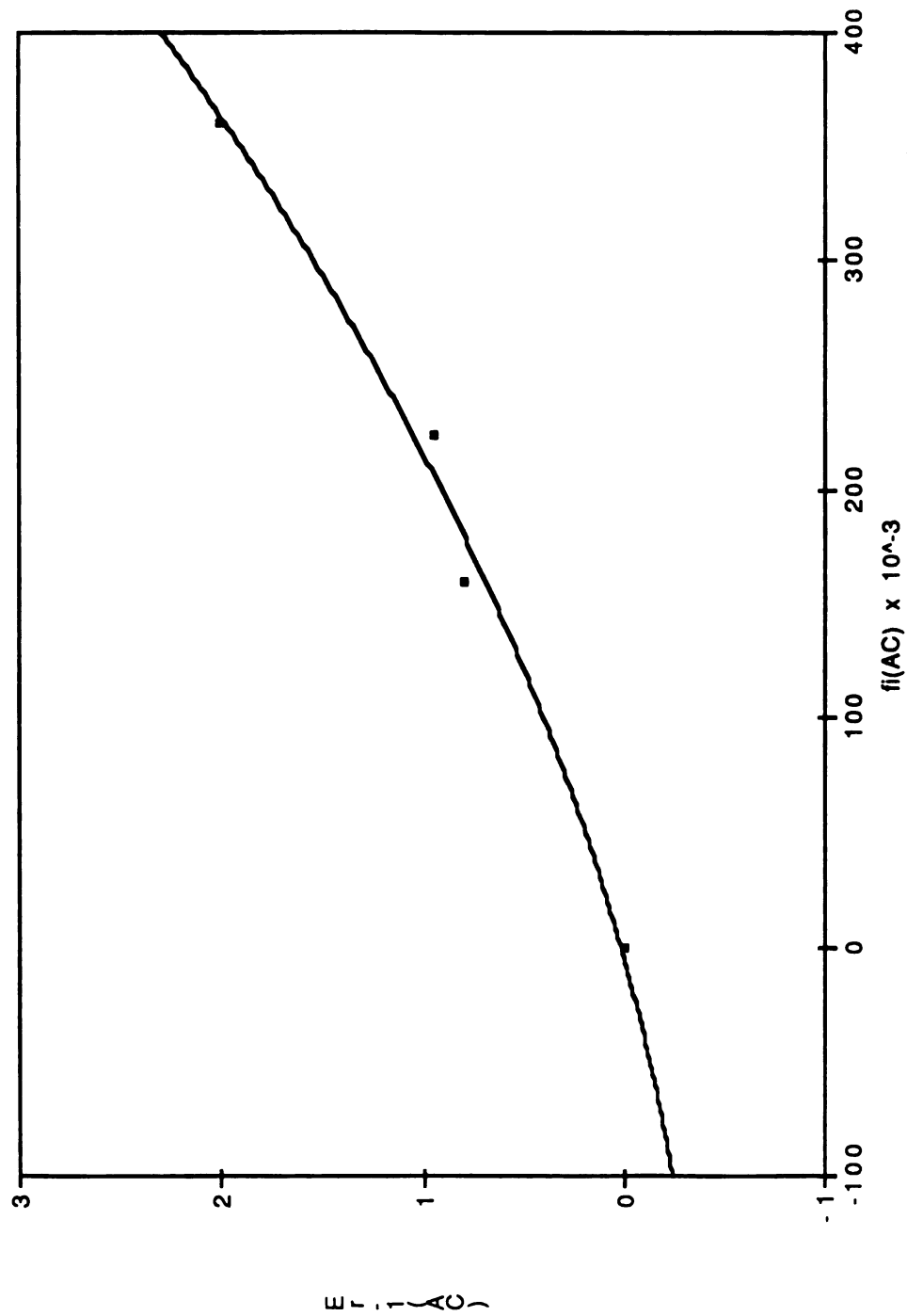


Figure 33. Correlation of theory with tensile modulus data (Acetylated aspen fibers in HDPE matrix)

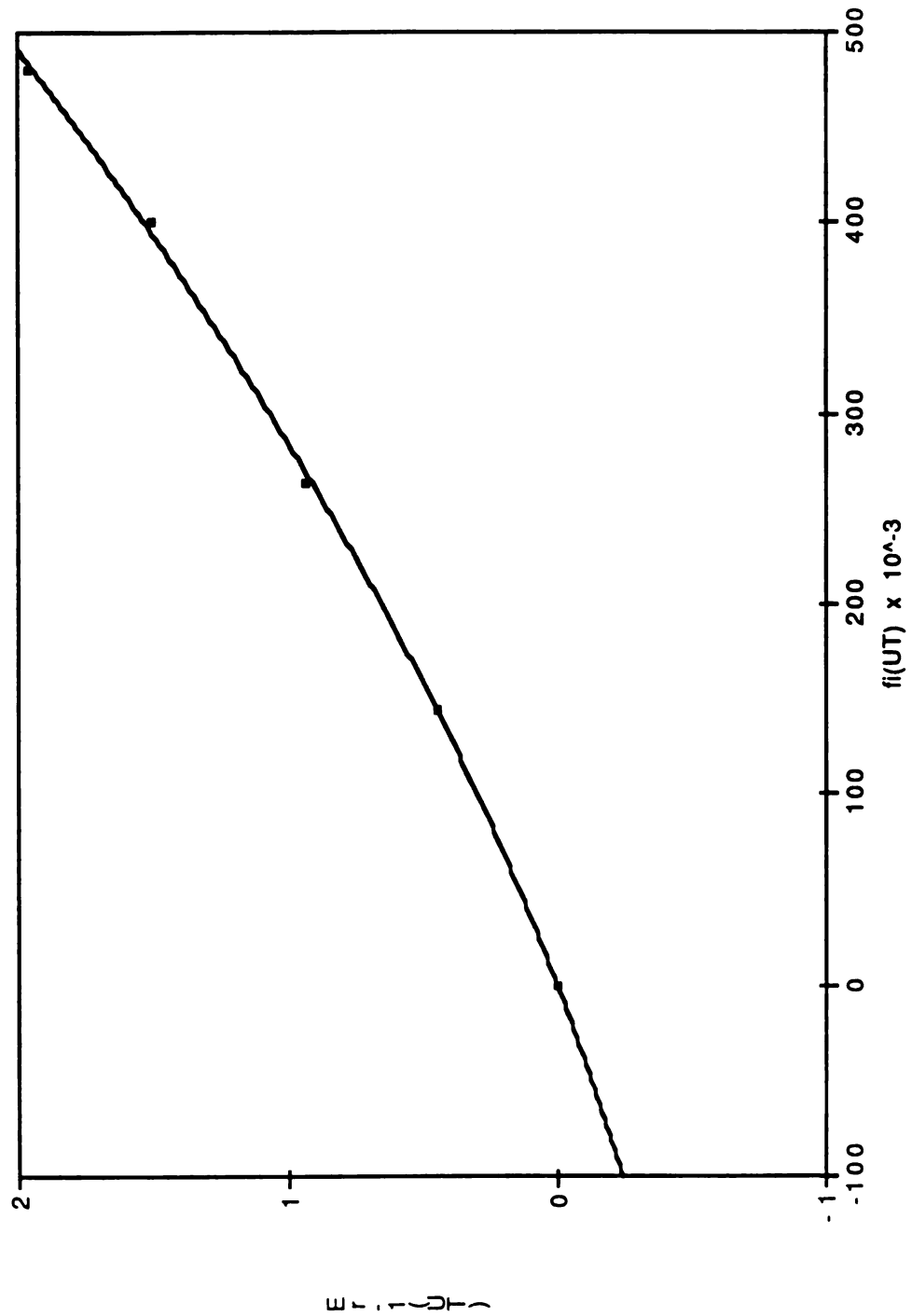


Figure 34. Correlation of theory with tensile modulus data (Untreated aspen fibers in HDPE matrix)

Table 5. Coeff. for heat treated aspen fibers
(Tensile modulus)

StatWorks™ Data Coefficients

Data File: Modulus

Variable Name	Coefficient	Std. Err. Estimate	t Statistic	Prob > t
Constant	0.077	0.456	0.168	0.875
fi(HT)	1.121	4.447	0.252	0.816
fi(HT) ^2	7.694	9.118	0.844	0.511

Table 6. Coeff. for acetylated aspen fibers
(Tensile modulus)

StatWorks™ Data Coefficients

Data File: Modulus

Variable Name	Coefficient	Std. Err. Estimate	t Statistic	Prob > t
Constant	0.016	0.149	0.108	0.921
fi(AC)	3.201	1.800	1.778	0.218
fi(AC) ^2	6.253	4.800	1.303	0.323

Table 7. Coeff. for untreated aspen fibers
(Tensile modulus)

StatWorks™ Data Coefficients

Data File: Modulus

Variable Name	Coefficient	Std. Err. Estimate	t Statistic	Prob > t
Constant	0.003	0.027	0.092	0.930
fi(UT)	2.712	0.266	10.207	0.002
fi(UT) ^2	2.775	0.528	5.254	0.012

VI. SUMMARY

SUMMARY

A. SUMMARY AND CONCLUSIONS

Composites with recycled HDPE as the polymer matrix and acetylated and untreated aspen fibers as fillers are superior to heat treated fibers in terms of tensile and flexural yield strength. Untreated fibers may therefore be the choice for a composite with recycled HDPE because of their lower cost. Fiber treatment does not seem to have any effect on tensile modulus and elongation properties. Data for impact strength may be indicative of voids between the wood fibers and the HDPE matrix. A critical fiber content of 20% by weight is required before reinforcement occurs for flexural yield strength. The mechanical properties of the composite are sensitive to screw configuration and temperature. Screw configuration 1 (Table-1) with a processing temperature of 150 °C. imparts the best overall strength to the composite although it has a longer mixing time and produces maximum damage to the fibers. Dispersion of fibers seem to be a dominating factor in these experiments. Scanning electron micrographs seem to indicate that recycled HDPE has better adhesion to acetylated and untreated fibers than to heat-treated aspen fibers at 30% fiber contents. However, more research is required in this area to make any conclusive statement. Theoretical predictions for tensile strength seem to agree with experimental data. Mathematical model for predicting tensile strength and tensile

5. The composite has to be finally evaluated in terms of commercial applicability.

VII. APPENDIX

APPENDIX

A GLOSSARY

1. *Composite material* : Two or more materials combined for suitable structural applications are known as "composite material".

2. *Co-extrusion* : The extrusion process where two melt streams or a polymer melt and fiber are combined in the die to make an extrusion of two materials.

3. *Co-rotating screws* : Two screws rotating in the same direction . either both clockwise or both counter-clockwise.

4. *Counter-rotating screws* : Two screws rotating in the opposite direction _ either both clockwise or both counter-clockwise.

5. *Die* : An orifice used to shape a plastic melt stream in the extrusion process.

6. *Drag flow* : Mechanism by which material is caused to flow in single screw extruder and build pressure. The polymer must wet both the screw and barrel to produce drag flow effects.

7. *Extruder* : A machine which accepts solid particles or liquid feed and conveys it through a surrounding barrel by means of a rotating screw and pumps it under pressure through an orifice.

8. *Extruder Length to Diameter Ratio* : L/D = The distance from the forward edge of the feed opening to the forward end of the barrel bore divided by the bore diameter and expressed as a ratio where the diameter is reduced to 1 (one).

9. *Extruder size* : The nominal inside diameter of extruder barrel.

10. *Extrusion* : Process of making a product by forcing material through a die orifice.

11. *Helix angle* : It is the angle the flight of the screw makes with a plane perpendicular to the screws axis while it winds around the roots of the screw. The elix angle determines the pitch of the screw.

12. *Flight Pitch* : Distance in an axial direction from the center of a flight at its periphery to the center of the next flight.

13. *Shear rate* : The rate at which a material is undergoing deformation in response to a shear stress.

14. *Shear Stress* : The force per unit area applied to a planar element inducing shear movement of a material.

15. *Single -screw extruder* : Extruder using a single conveying screw to pump plastics.

16. *Twin- screw extruder* : Extruder using two intermeshing screws to convey plastics.

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