

## CHAPTER IV

### RESULTS AND DISCUSSION

The effect of wood flour content, coupling agent and the nature of the filler on mechanical properties of polypropylene were studied. The samples of polypropylene filled with wood flour (WF) were prepared by a two roll mill and then were compression moulded. The filled polypropylene composites were tested for the following properties, tensile strength, tensile modulus, elongation at rupture, Izod impact strength, and hardness. The microstructures of tensile fractures were observed by means of a scanning electron microscope. The changes of some physical properties of the composites were investigated.

#### 4.1 Characteristic of Wood Flour

Wood flour is the natural filler that is composed of complex structure. The individual properties of wood flour play a significant role on the properties of composites, such as composition, particle size and surface characteristic. The composition of wood flour is summarized in Table 4.1. The particle size distribution of wood flour is illustrated in Table 4.2 and Figure 4.1. Figure 4.2 is the scanning electron micrograph (SEM) of the wood flour.

Table 4.1 Some Properties of Wood Flour

Detail	Value(% by wt)
Hot-water solubility	6.90
1% NaOH solubility	23.60
Alcohol-benzene solubility	13.80
Lignin (ash corrected)	29.80
holocellulose	61.50
Alpha-cellulose	37.20
Moisture content	5.0-8.0

Table 4.2 Particle Size Distribution of Wood Flour

Particle size	Cumulative mass fraction
Finer than 104 $\mu\text{m}$	13.52
" " 147 $\mu\text{m}$	51.32
" " 175 $\mu\text{m}$	78.76
" " 250 $\mu\text{m}$	100.00

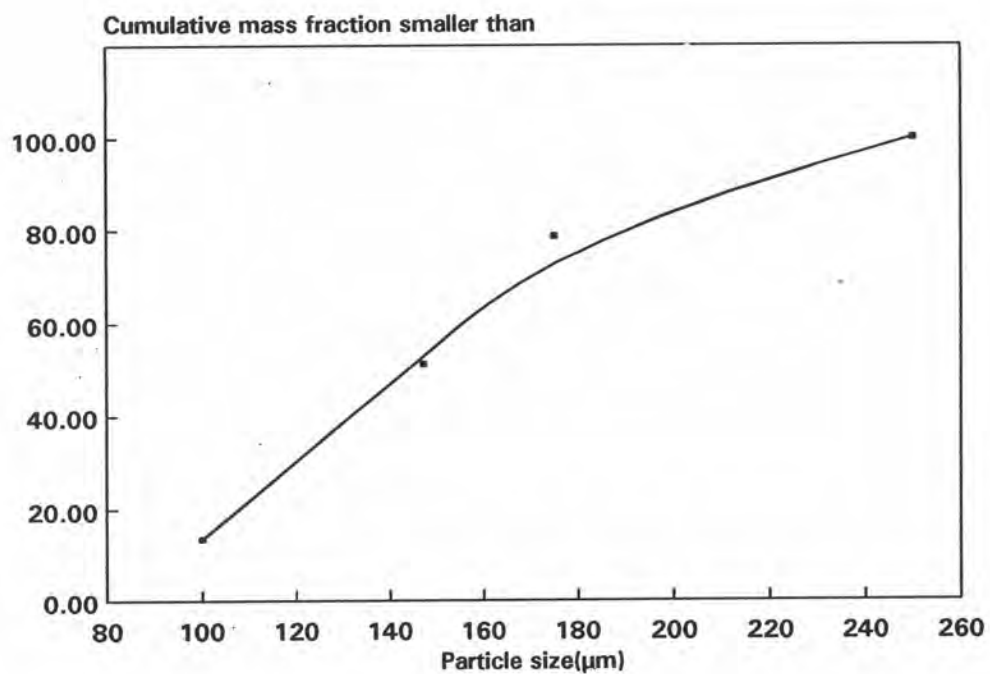


Figure 4.1 Particle size distribution curve of wood flour.

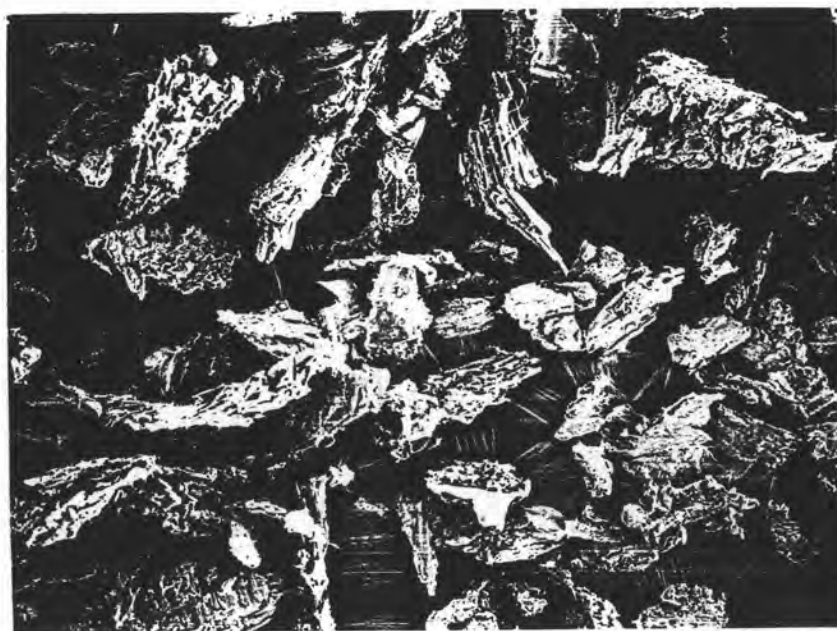


Figure 4.2 SEM micrograph of wood flour surface.

Original magnification 75x. ( — : 100 μm)

#### 4.2 Effect of Epolene E-43P Concentration on Mechanical Properties of Composite

Table 4.3 and Figures 4.3 - 4.4 illustrate the influence of Epolene E-43P concentration on mechanical properties. Tensile strength and tensile modulus were moderately increased with Epolene E-43P concentration ranging from 0-2% while elongation at break of composite was decreased. Further increase in Epolene E-43P concentration did not produce any substantial gain in tensile properties. Impact resistance was moderately decreased with increasing Epolene E-43P concentration but hardness property was increased in the narrow scale.

In this part, the chosen Epolene E-43P concentration used in the following experiments was 2% because Epolene E-43P concentration more than 2% gave little increase in mechanical properties. Moreover, the higher Epolene E-43P concentration, the greater the loss in impact energy. Discoloration of the composites with higher concentrations of Epolene E-43P occurred. As noted previously[17], loss in impact energy with the addition of Epolene E-43 may be compensated by the greater strength and stiffness of the composites. Additionally, the lower impact strength probably results from the increase in wood filler brittleness caused by wood decomposition at high temperatures, and catalyzed by the acidic nature of Epolene E-43P.

Table 4.3 Properties of Wood Flour-Filled Polypropylene (20% filler) at Various Epolene E-43P Concentrations

Mechanical Properties	Epolene E-43P Concentration(%)					
	0	1	2	3	4	5
Tensile strength, MPa	18.60 (0.74)	23.62 (1.12)	25.79 (0.61)	25.93 (0.74)	26.10 (0.40)	24.46 (0.48)
Modulus of elasticity, GPa	1.39 (0.03)	1.41 (0.08)	1.63 (0.05)	1.60 (0.10)	1.56 (0.10)	1.63 (0.09)
Elongation at break, %	5.67 (0.62)	4.35 (1.04)	4.05 (1.20)	3.96 (0.72)	3.89 (0.30)	3.40 (0.58)
Izod impact energy, J/m	32.02 (3.38)	30.83 (3.33)	31.08 (3.67)	29.44 (2.51)	29.06 (3.03)	28.57 (0.00)
Hardness, Scale D	56.20 (1.30)	56.90 (0.22)	57.20 (0.76)	57.10 (2.88)	57.30 (1.72)	57.20 (2.17)

Values in parentheses are standard deviations.

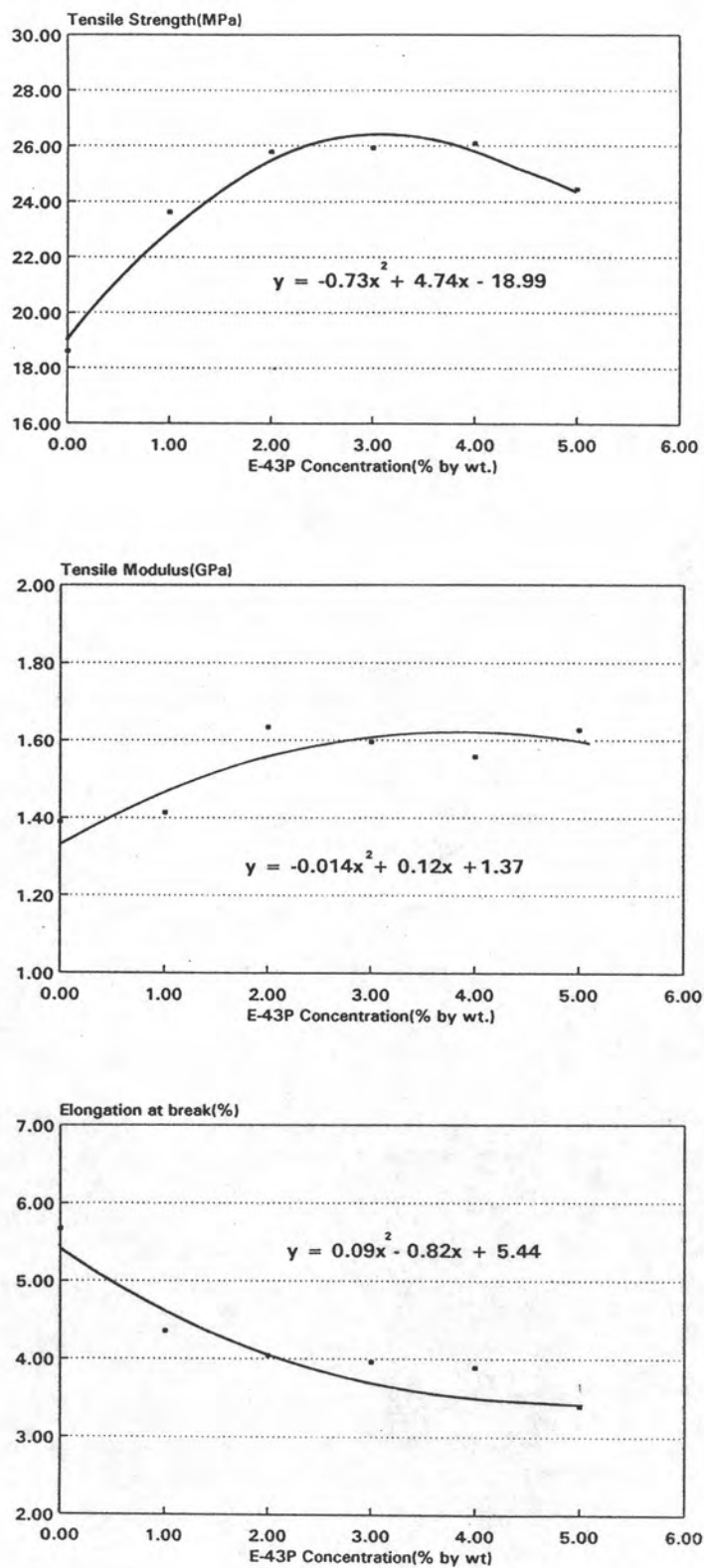


Figure 4.3 Effect of Epolene E-43P concentration on tensile properties of the composite.

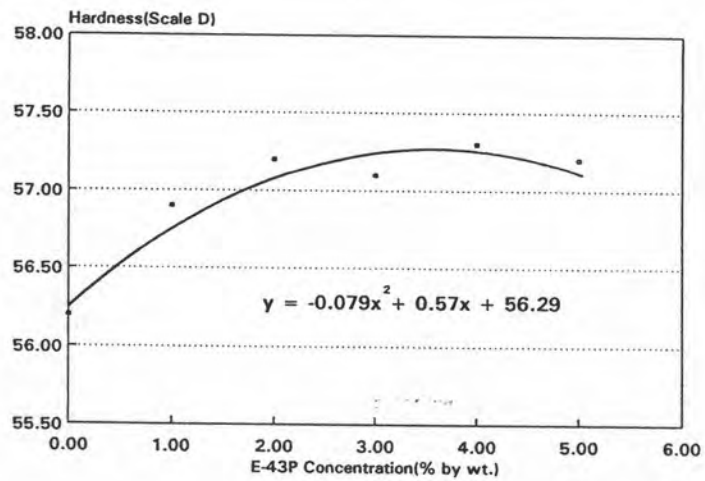
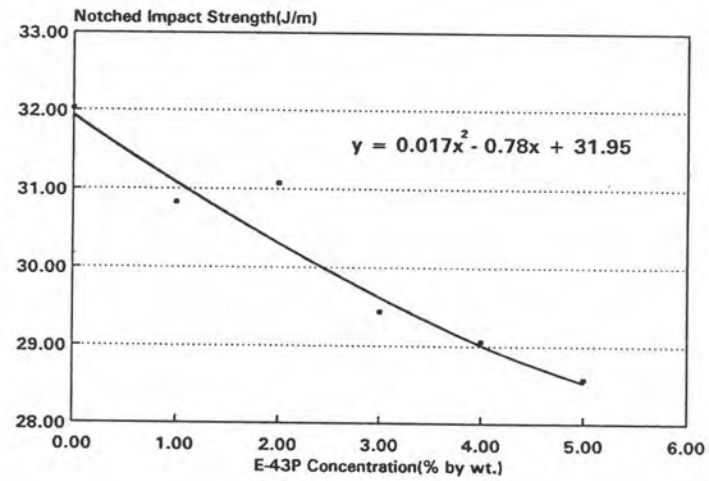


Figure 4.4 Effect of Epolene E-43P concentration on impact and hardness properties of the composite.

### 4.3 Stress-Strain Curve of the PP-WF Composite with Different Coupling Agents

Figures 4.5 - 4.7 depict the stress-strain curves of PP-WF composites. Each figure shows the influence of wood flour content and its surface treatment on the tensile behavior.

The stress-strain curves of unfilled-PP compared with the filled-PP system are presented. The maximum strength (yield strength) of PP was obtained in the range of 9-11% elongation and the elongation at break was approximately of 160%. For the filled-PP system, the patterns of stress-strain curve with different coupling agents at various percent fillers were similar. In contrast with the unfilled-PP, tensile strength and elongation at rupture of the filled-PP were decreased, while the slope at the initial linear portion of stress-strain curves was increased with increasing filler content.

At all proportions of the untreated WF and the 10-20% treated WF content, the composites were still of the hard-ductile polymer. At 20-50% treated WF content, the composites were of the hard brittle material. Tensile properties of the treated WF-filled PP composite were higher than of that of the untreated WF composite possibly attributed by the improved interfacial adhesion of the PP-WF system. Stress-strain curves of the composite indicated that the composite possesses the plastic behavior which depends on the type of filler and interfacial adhesion of the system. The order of the plastic behavior is shown as follows:



Polypropylene > 10% > 20% > 30% > 40% > 50% WF and

Polypropylene > Untreated > A-1100 > A-174 > Epolene E-43P

The plastic behavior decreased with the increasing filler loading and interfacial adhesion.

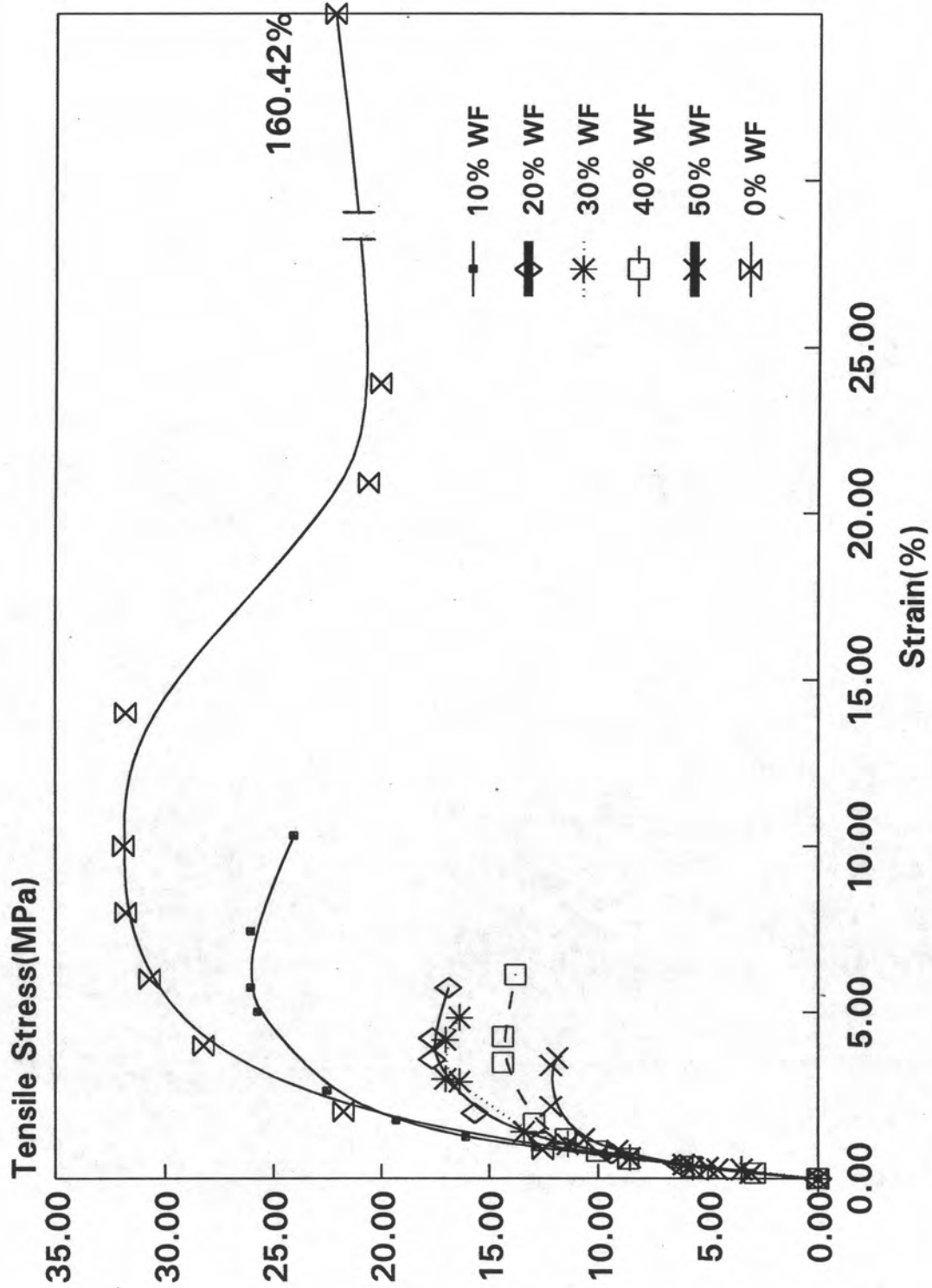


Figure 4.5 Stress-Strain curve of the PP-untreated WF composite at various percents of WF.

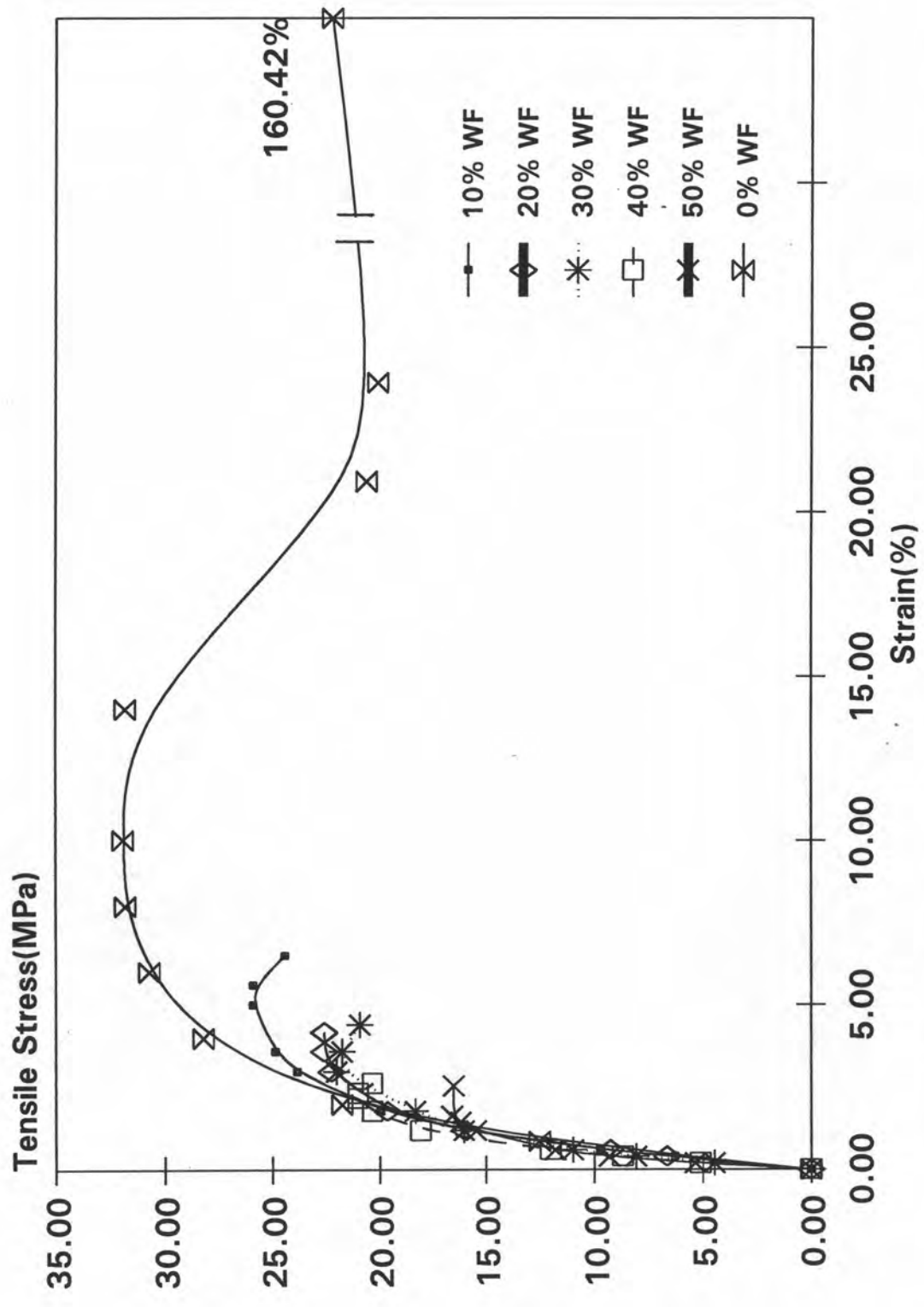


Figure 4.6 Stress-Strain curve of the PP-silane A-174 treated WF composite at various percents of WF.

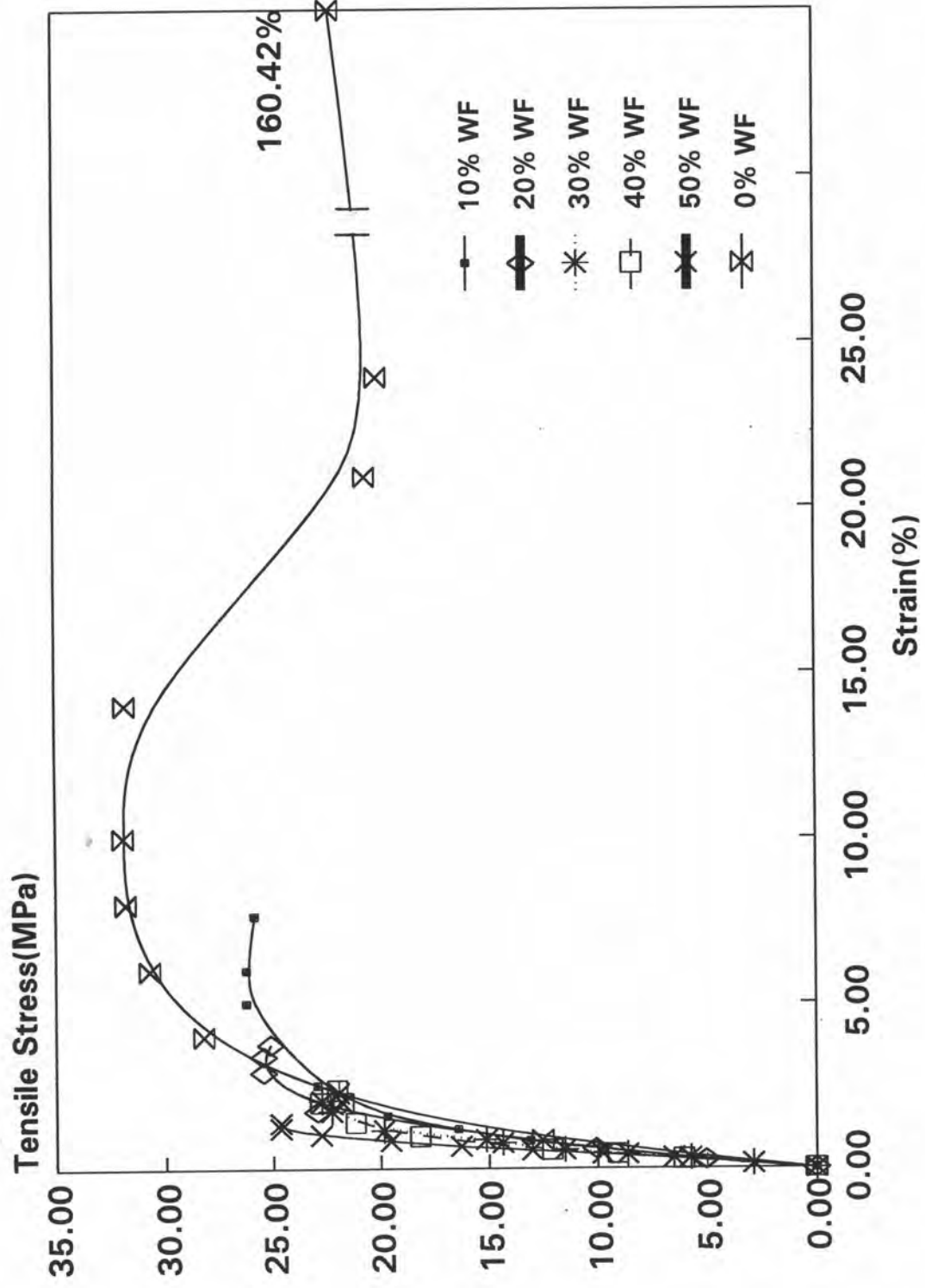


Figure 4.7 Stress-Strain curve of the PP-Epoxy E-43P treated WF composite at various percents of WF.

#### 4.4 Effect of Filler Content on Mechanical Properties of the PP-WF Composites

The effect of filler content and coupling agent on mechanical properties of the WF-filled PP composites is shown in Figure 4.8-4.11. The variation of properties with addition of wood flour filler to PP shall be discussed as follows.

Figure 4.8 illustrates the effect of the untreated WF content on mechanical properties. Tensile strength, elongation at break and impact energy decreased while tensile modulus and hardness increased with increasing filler loading. This effect may be attributed to dewetting of the wood flour particle and the matrix that has opposite polarity. Dewetting behavior is clearly dependent on the wood flour and its surface characteristics which can be shown in the following section of the SEM and polarity studies. Because the wood flour does not adhere to PP, the wood flour cannot carry any load [34]. The more extender content, the higher non-compatibility that exhibit a higher loss in impact resistance.

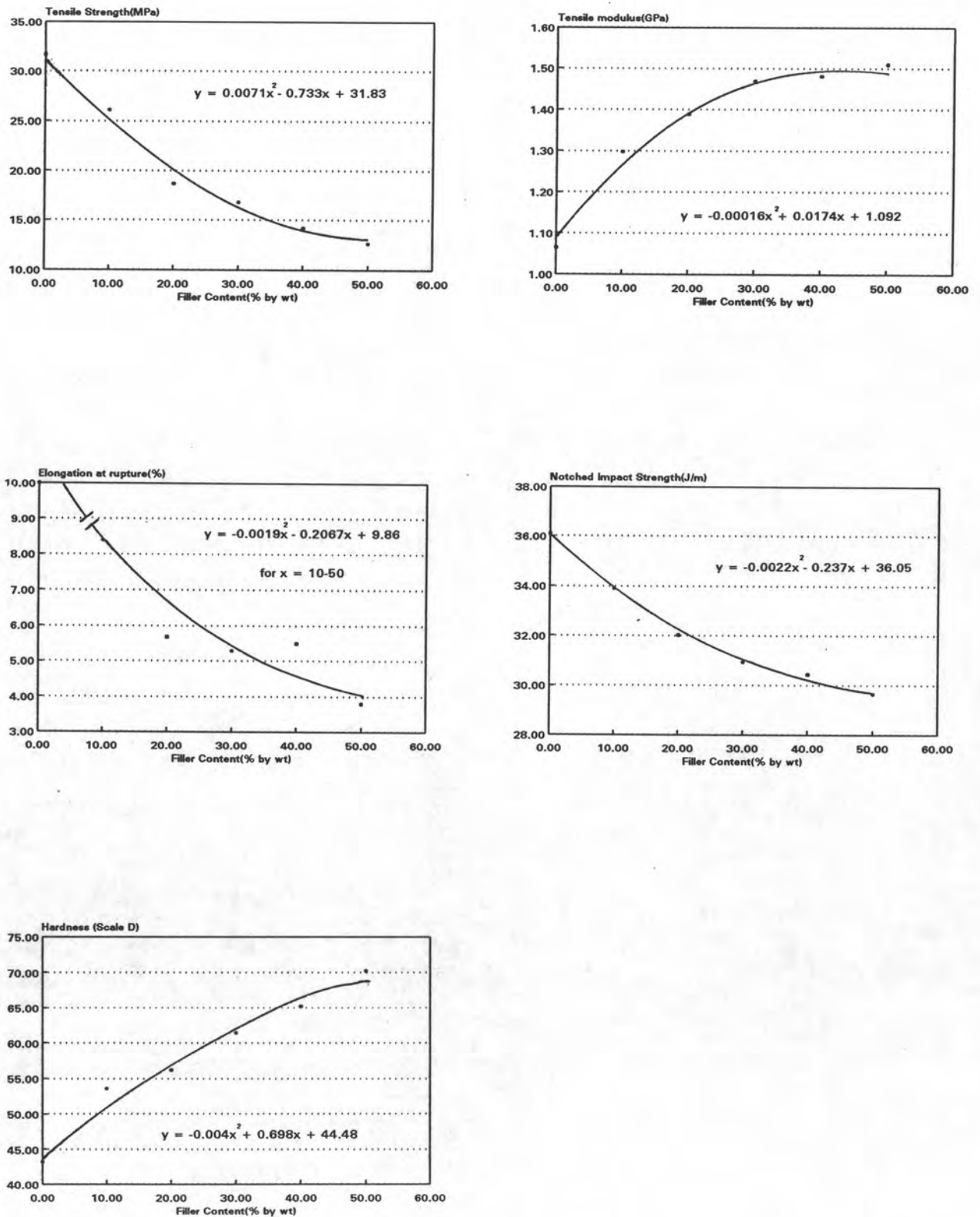


Figure 4.8 Effect of the untreated WF content on mechanical properties.

Nevertheless, the considerable reasons for the variation in properties are the individual properties of wood flour, which depend on the lignin content and the pores in the structure. In this work, the lignin content in the wood flour is approximately of 30%. It was observed in the earlier study by Kubat et al.[32] that the presence of lignin in the filler influences its adhesion to the matrix polymer. Furthermore, lignin content had a strong effect on the modulus, elongation at break and impact resistance as reported in Figure 2.12. As expected, the addition of lignin in polypropylene markedly reduced the ductility of the specimen, as reflected by a sharp drop of the elongation at break and impact strength.

The change of properties may also be explained by the pores in the wood flour structure. In general, typical wood flour contains voids which are interconnected in a very tortuous manner so that permeation of the polymer is difficult [34]. This reason may be led to the poor packing and wetting characteristics.

The mechanical properties of PP-WF composites with different coupling agents are presented in Figures 4.9-4.11. The change at the wood flour surface due to the coupling agent plays an important role in determining the properties of the composites. This is evidenced by an improvement in mechanical properties of the PP-WF composites which contain silane A-1100, silane A-174 or Epolene E-43P. However, effects of the treated WF and the untreated WF contents on mechanical properties were similar.

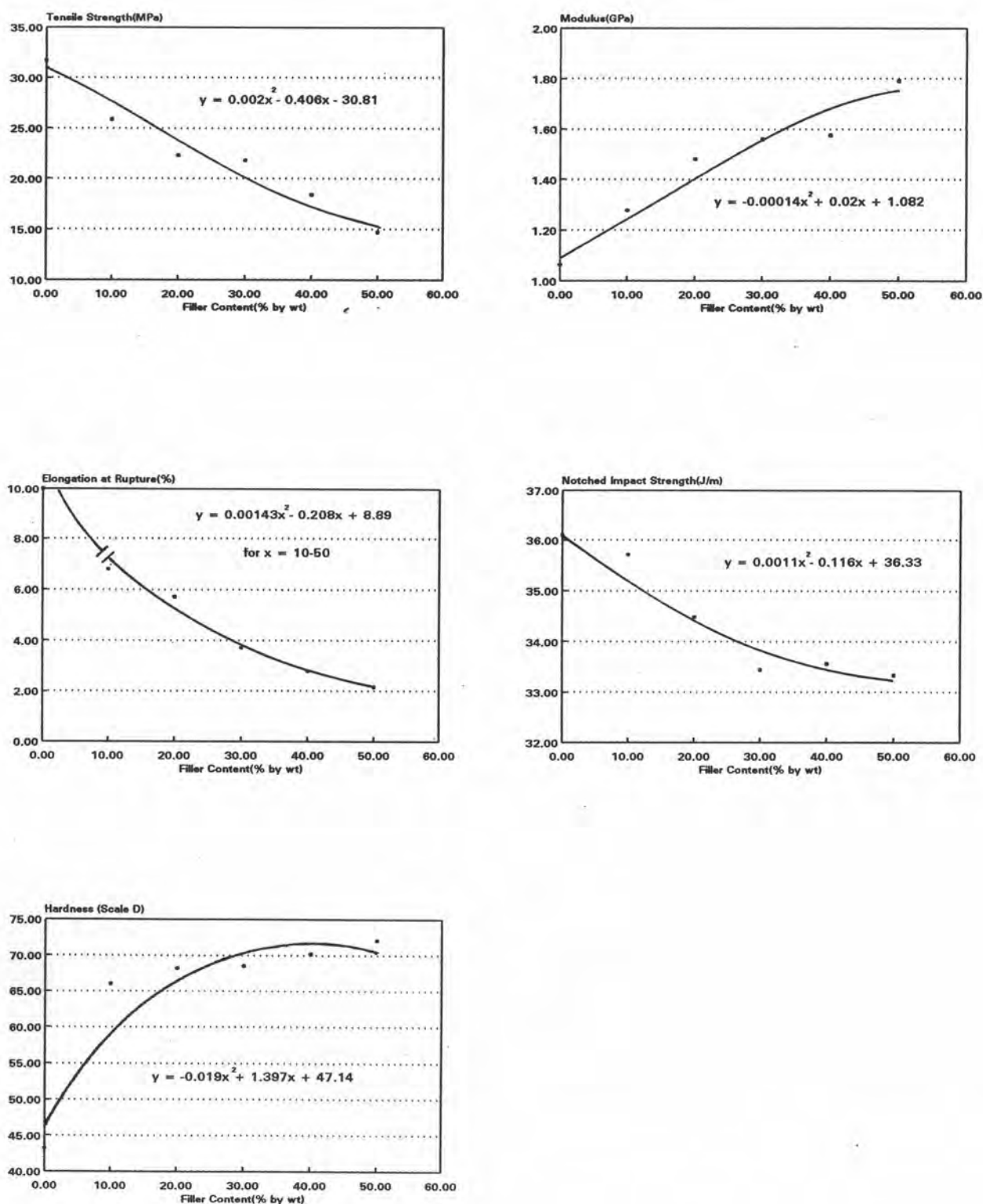


Figure 4.9 Effect of the silane A-1100 treated WF content on mechanical properties.



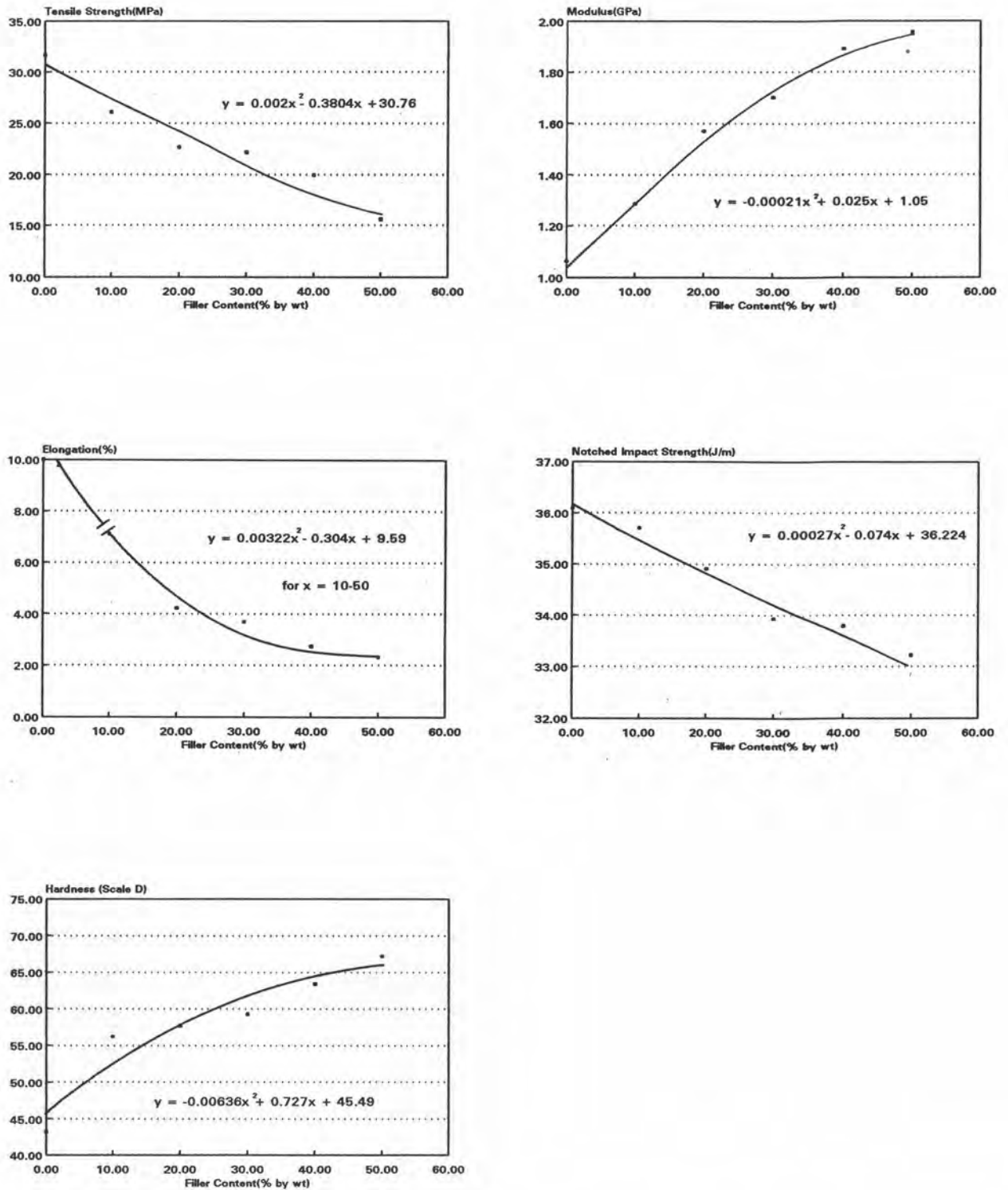


Figure 4.10 Effect of the silane A-174 treated WF content on mechanical properties.

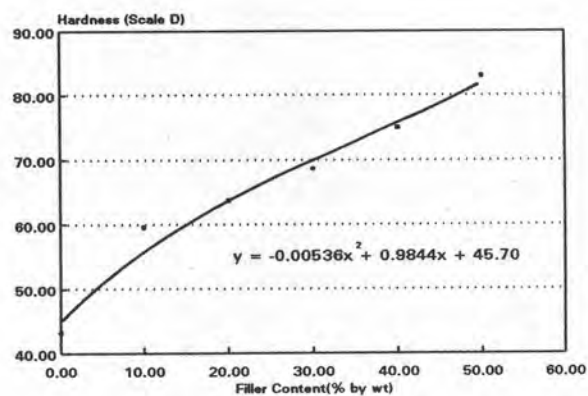
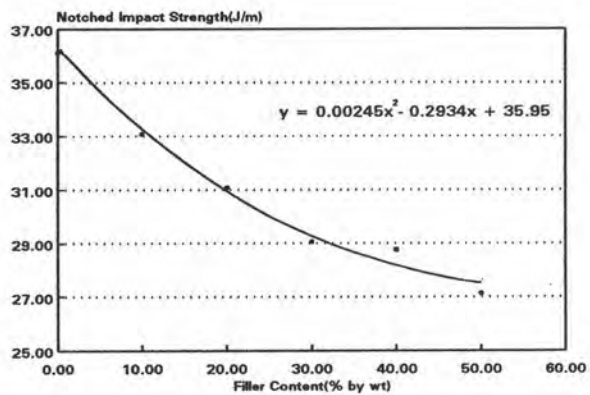
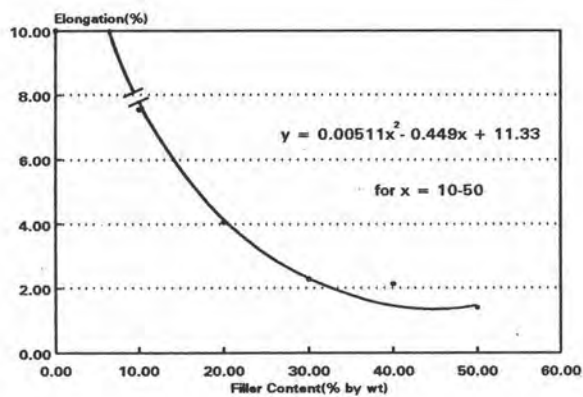
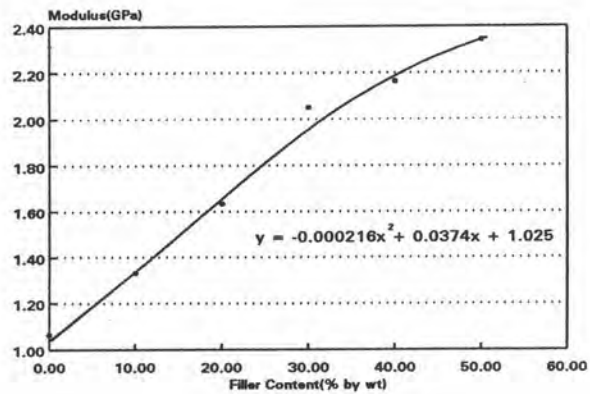
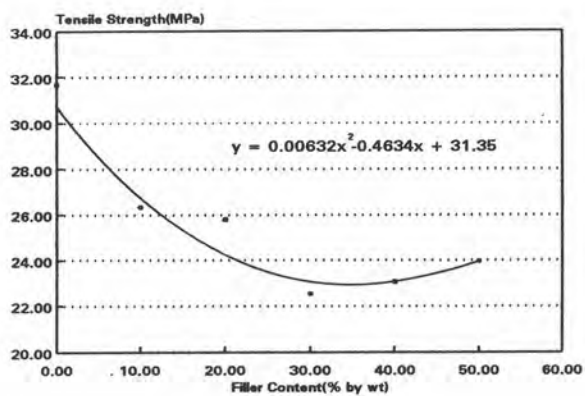


Figure 4.11 Effect of the Epolene E-43P treated WF content on mechanical properties.

#### 4.5 Comparison of Mechanical Properties of the PP-WF Composite with Different Coupling Agents

The comparison of mechanical properties of the PP filled with untreated WF, silane treated WF and Epolene E-43P treated WF are summarized in Table 4.4 and Figures 4.12-4.16. Figure 4.12 shows the comparison of tensile strength of different composites. Tensile strength of PP was decreased from 31.66 to 12.63 MPa with increments of untreated WF content from 0 to 50%. Tensile strength of the WF-filled PP composites containing silane A-1100, silane A-174 or Epolene E-43P was improved. PP-Epolene E43-P treated WF composites gave the highest tensile strength. At 50% WF content, tensile strengths of the PP-untreated WF and PP-Epolene E-43P treated WF composites were 12.63 and 23.96 MPa, respectively, therefore, the increase in tensile strength was 89.7%. The composite containing silane A-174 provided the higher tensile strength than did silane A-1100.

The comparison of tensile modulus is shown in Figure 4.13. Modulus of elasticity of all composites increased with filler content. The order of increasing tensile modulus by using different coupling agents is as follows;

Epolene E-43P > A-174 > A-1100 > Untreated

Tensile modulus reached a maximum value of 2.34 GPa in the PP containing 50% Epolene treated WF compared to 1.61 GPa in the untreated WF composite. The increase in tensile modulus was 45.34%. At the same filler content (50%), the increase in modulus of composites containing silane A-1100 or silane A-174 was approximately 20% and 30%, respectively, compared to the untreated WF composite.

Table 4.4 Effect of Different Coupling Agents on Mechanical Properties of the Composites at Various Percents of the Filler

Types	Filler Content (%)	Properties				
		Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation at Rupture (%)	Izod Impact Energy (J/m)	Hardness (Scale D)
Polypropylene	-	31.66 (1.34)	1.06 (0.02)	160.42 (48.67)	36.10 (0.36)	43.20 (0.45)
Untreated	10	26.09 (0.78)	1.30 (0.03)	8.39 (1.50)	33.91 (3.03)	53.60 (1.52)
	20	18.86 (0.74)	1.39 (0.03)	5.67 (0.62)	32.02 (3.38)	56.20 (1.30)
	30	16.78 (0.41)	1.47 (0.09)	5.29 (1.17)	30.93 (3.24)	61.40 (1.52)
	40	14.17 (0.23)	1.48 (0.14)	5.49 (0.75)	30.44 (3.69)	65.20 (0.45)
	50	12.63 (0.20)	1.61 (0.09)	3.80 (0.70)	29.65 (3.88)	70.20 (1.79)
A-1100	10	25.86 (0.19)	1.28 (0.04)	6.80 (0.79)	35.71 (0.00)	66.00 (1.27)
	20	22.32 (0.31)	1.48 (0.04)	5.71 (0.58)	34.48 (0.00)	68.20(1.40)
	30	21.82 (0.24)	1.56 (0.04)	3.71 (1.05)	33.44 (3.02)	68.50 (1.12)
	40	18.37 (0.54)	1.58 (0.08)	2.79 (0.39)	33.56 (0.31)	70.00 (0.00)
	50	14.71 (0.32)	1.79 (0.06)	2.16 (0.21)	33.33 (0.00)	72.10 (0.89)
A-174	10	26.08 (0.98)	1.29 (0.07)	7.11 (1.09)	35.71 (0.00)	56.20 (1.64)
	20	22.68 (0.52)	1.57 (0.08)	4.23 (0.62)	34.97 (0.51)	57.70 (0.67)
	30	22.18 (0.54)	1.70 (0.09)	3.69 (0.39)	33.93 (3.29)	59.30 (0.67)
	40	19.93 (1.40)	1.89 (0.05)	2.74 (0.21)	33.79 (0.25)	63.40 (1.14)
	50	15.60 (0.60)	1.96 (0.08)	2.32 (0.37)	33.22 0.24)	67.20 (0.84)
Epolene E-43P	10	26.33 (0.38)	1.33 (0.03)	7.55 (1.19)	33.06 (3.63)	59.60 (0.55)
	20	25.79 (0.61)	1.63 (0.05)	4.05 (1.20)	31.08(3.67)	63.00 (0.71)
	30	22.54 (0.35)	2.05 (0.09)	2.28 (0.34)	29.06 (3.03)	68.60 (1.52)
	40	23.05 (1.07)	2.16 (0.11)	2.13 (0.30)	28.76 (2.88)	75.00 (2.12)
	50	23.96 (1.14)	2.34 (0.12)	1.40 (0.11)	27.12 (0.00)	83.00 (3.16)

Values in parentheses are standard deviations.

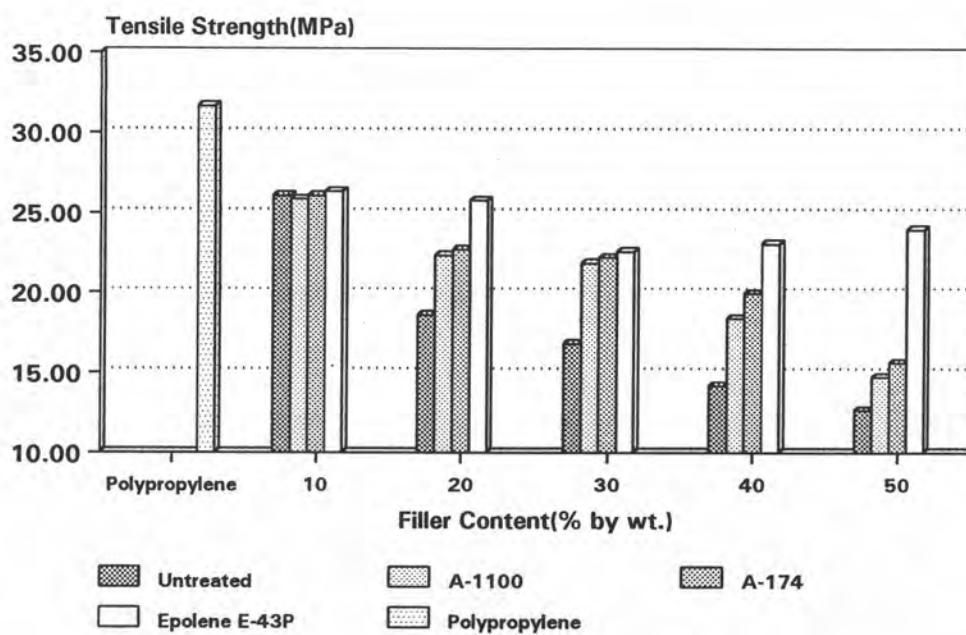


Figure 4.12 Tensile strength vs. WF content treated with different coupling agents.

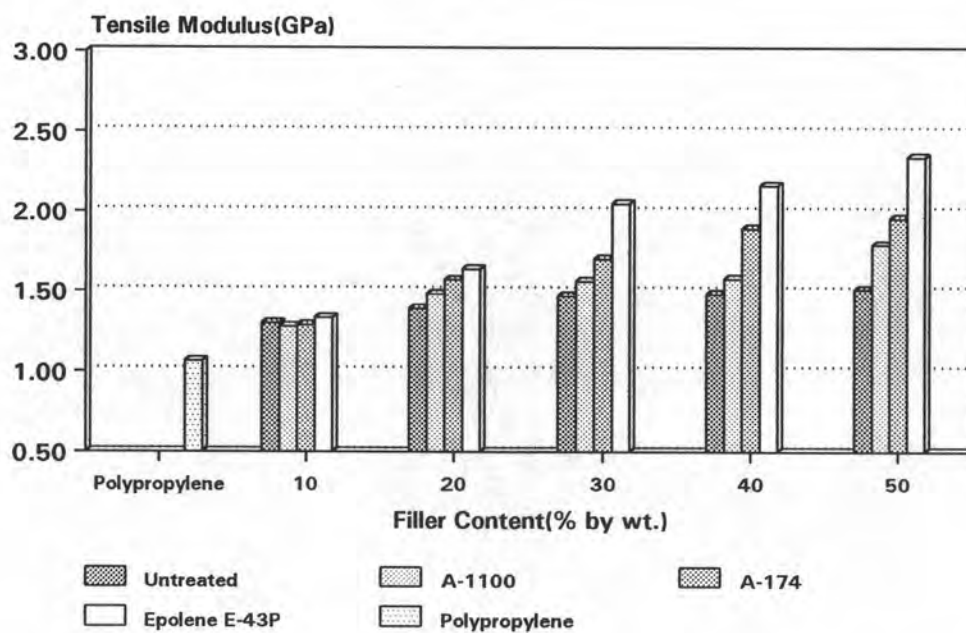


Figure 4.13 Tensile modulus vs. WF content treated with different coupling agents.

Figure 4.14 illustrates the comparison of the elongation at rupture of different composites. The elongation at break of PP was drastically decreased from 160.42% to lower than 10% with increase in WF content from 0 to 50%. The PP-untreated WF composite gave the lowest rate in decreasing elongation, while those of the PP-treated WF were sharply dropped. At 10% filler, the elongation at break of the composites appeared to be no significant difference between the treated and untreated WF. At 50% filler content, the PP-Epolene E-43P treated WF composite gave the lowest elongation at break because of the syneristic effect of the highest filler level and the improved adhesion in the composite.

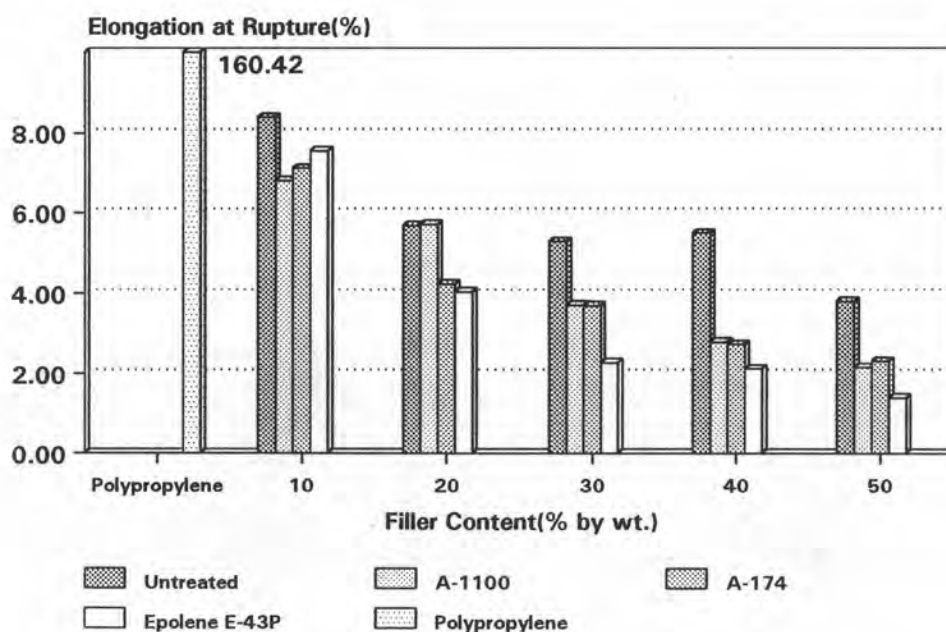


Figure 4.14 Elongation at rupture vs. WF content treated with different coupling agents.

Impact resistance of the composite was decreased with the rise in filler content as presented in Figure 4.15. At the 10% WF-silane treated composites, the impact value (35.71 J/m) was closed to the value of the pure polypropylene (36.10 J/m). For the PP-Epolene E-43P treated WF composites, impact strength fell sharply, while impact strength of the composites containing silane treated WF and the untreated WF dropped gradually. At 50% WF, impact resistance of the PP-Epolene E-43P treated WF and PP-untreated WF composites were 27.12 and 29.65 J/m, respectively, the decrease in impact resistance was 5.53%.

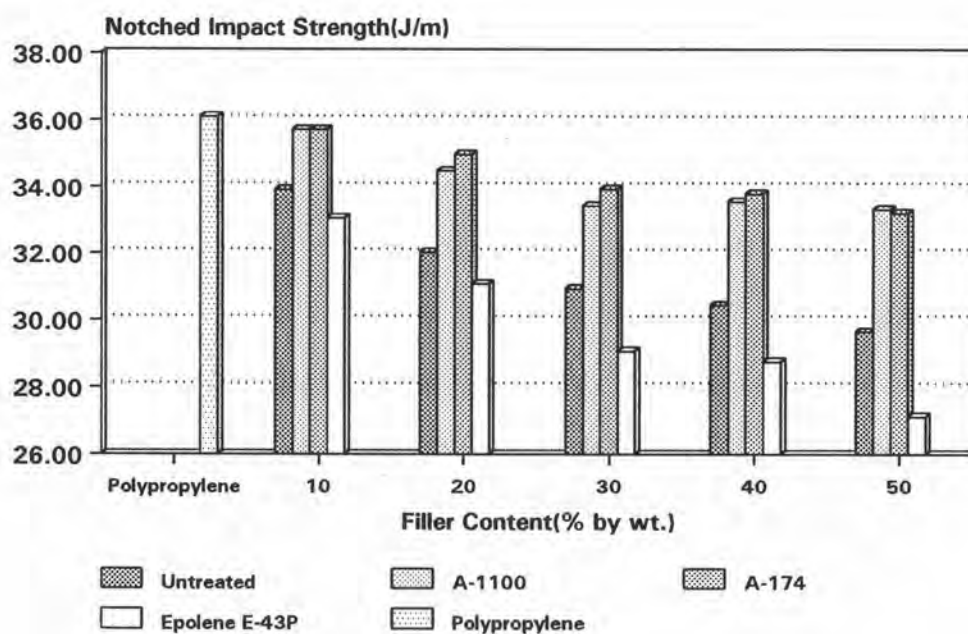


Figure 4.15 Notched impact resistance vs. WF content treated with different coupling agents.

Hardness property of the untreated WF composite was greater than that of polypropylene, while other treated WF composites provided the similar results (Figure 4.16). The hardness increased with the filler content. The order of hardness values is as follows:

Epolene E-43P > A-1100 > A-174 ~ Untreated > Polypropylene.

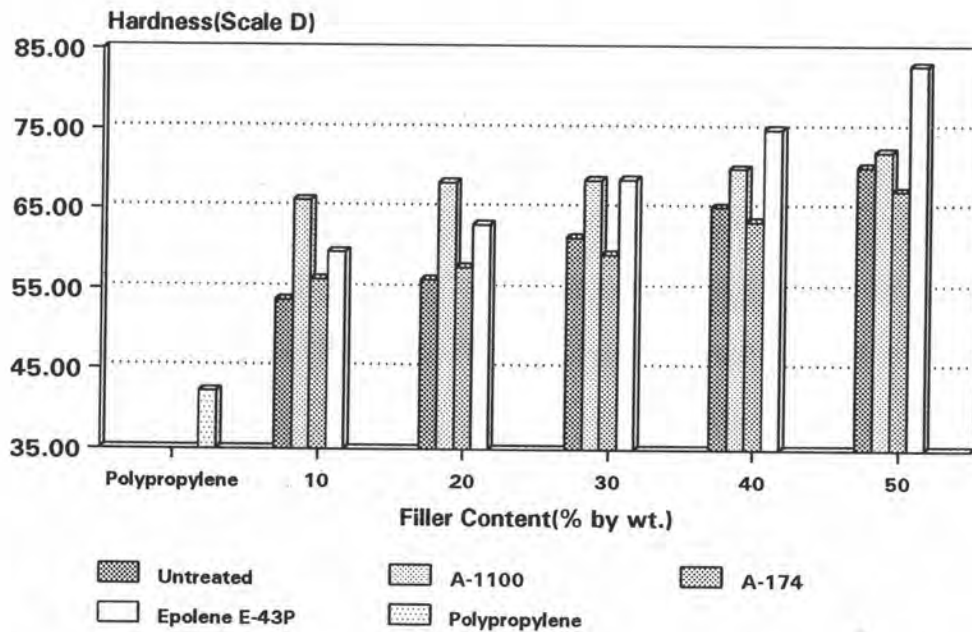


Figure 4.16 Hardness vs. WF content treated with different coupling agents

For the enhancement of the mechanical properties of the composite using such coupling agents, possible explanations on the functions of the coupling agent can be made based on the previous work. [15-17,24-28]



In case of Epolene E-43P, it contains anhydride groups, which are located within the polypropylene chain or at the chain ends.[22-23] With wood filler, the anhydride groups are presumably attracted by (possibly reacted with) the wood. This may be related to its ability to penetrate the wood and form a strongly held hydrophobic layer that is attractive to the polypropylene. The reasons of the similarity of isotactic structure and the molecular weight of the Epolene E-43P, the compatibility of its polypropylene segment with polypropylene matrix occurred, thereby, increasing both the effective bonding area and mechanical interlocking. The interpretations of the decrease in notched impact energy with the addition of the Epolene E-43P are less obvious. However, the strong interaction between the filler and matrix could also inhibit polymer mobility and therefore lower the ability of the system to absorb energy during fracture propagation. It may embrittle the wood through degradation. The observed decrease in notched impact energy with the addition of Epolene E-43P is comparable to that reported by Myers et al.[28,17]

The use of two different silane coupling agents with different functional organic groups were for surface treatment of the wood flour. A possible coupling mechanism of polymer-coupling agent-wood fiber was demonstrated in Figure 2.10 by Raj et al.[15] This mechanism suggests that, during wood fiber treatment, the silane might be prehydrolyzed to form silanetriols,  $-\text{Si}(\text{OH})_3$ , which could develop either covalent (siloxane bond) or hydrogen bonds with OH groups of cellulose. Subsequently, the radicals from organic peroxide could extract hydrogen atoms from polyethylene which one added to the functional

group of the coupling agent to form covalent bonds. So, the improved interfacial bonding could possibly be achieved. As for different organofunctional groups, an increase in mechanical properties indicated that silane A-174 (containing the methacryl functional group) performed better as a coupling agent in this system than did the silane A-1100. Vinyl groups in silane A-174 may react with the matrix through a radical reaction whereas this should not be the case with aminopropyl groups in silane A-1100.

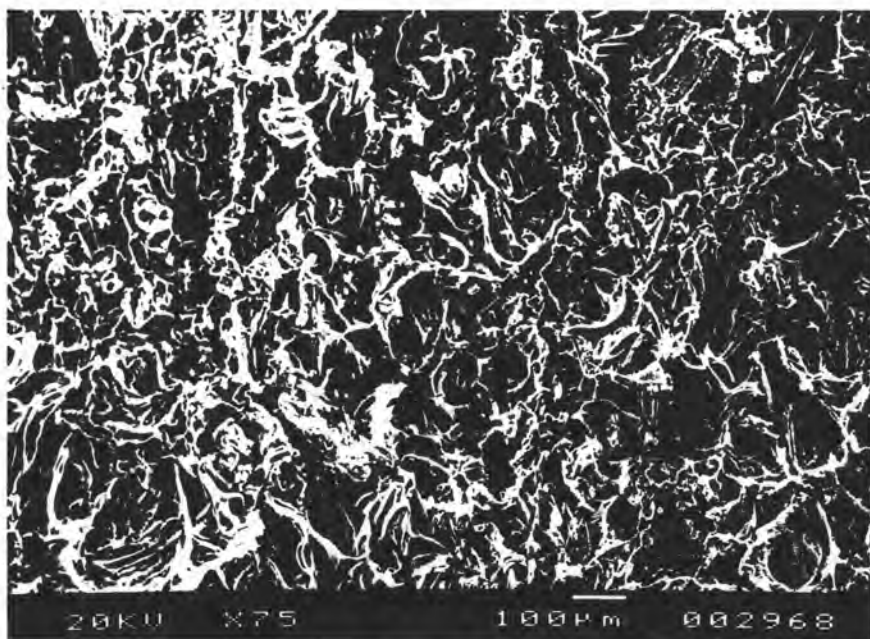
In addition, the other function of the coupling agent is to assist processing. During the compounding period, Epolene E-43P acted as processing and dispersing aids [21], at the moment the mixture of the PP-silane treated WF was on the two roll mill. Moreover, it was difficult to remove the sheet of PP-silane treated WF composite from the mould. The more the filler level, the greater the difficulty. All three coupling agents also acted as dispersing agent, this is confirmed by SEM micrographs of fracture surface of the PP-WF composites (section 4.7).

#### 4.6 Scanning Electron Microscope (SEM) of Composites

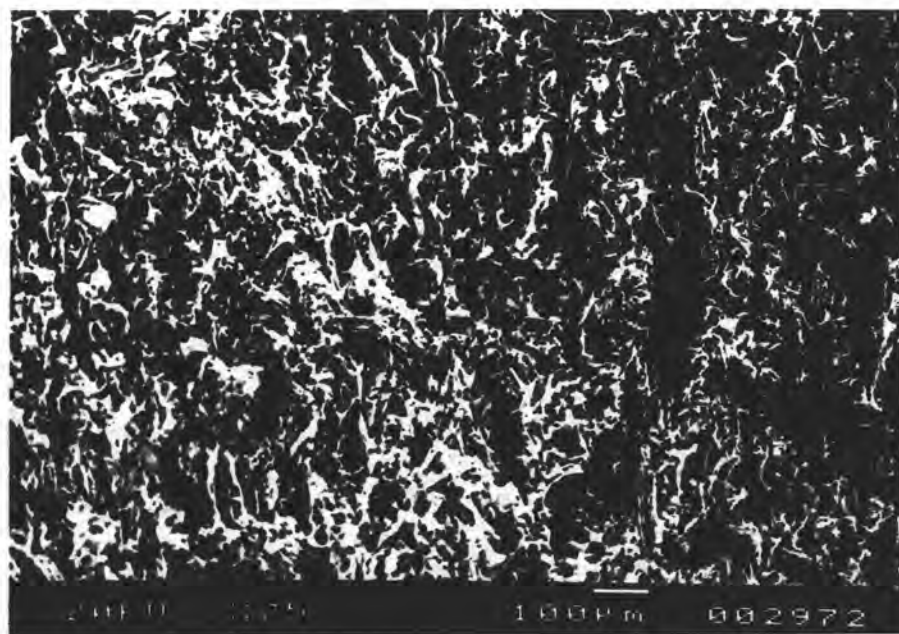
The scanning electron microscope was employed to investigate the fracture surface of the samples from the uniaxial tensile tests. The SEM micrographs (Figures 4.17-4.22) show the fracture surface of the PP-WF composites at various percents of wood flour.

At low magnification, the SEM micrograph of the PP-untreated WF composite (Figure 4.17) shows poor interfacial adhesion or dewetting behavior. At the high percent filler content (50%), this dewetting behavior appeared to be reduced at high ratio of WF/PP as shown in Figure 4.17b. At the same magnification, Figure 4.18b reveals the better compatibility and dispersibility of WF treated with Epolene in PP matrix compared to the untreated WF composite (4.18a).

At 200x magnification, Figure 4.19a shows the holes which have been occupied by the fillers and represent the ease in losing the particles out of polymer matrix. As can be seen from the fracture surface of the PP-Epolene E-43P treated WF composite (Figure 4.19b), the wood flour was covered by the polymer matrix. Figure 4.20 shows the fracture surface of the PP-silane treated WF composite. Silane A-174 caused the higher dispersibility than did silane A-1100. At higher magnification (Figures 4.21-4.22), surfaces of WF treated with coupling agents exhibited the improved interfacial adhesion which leading to the enhancement of the mechanical properties.



(a)

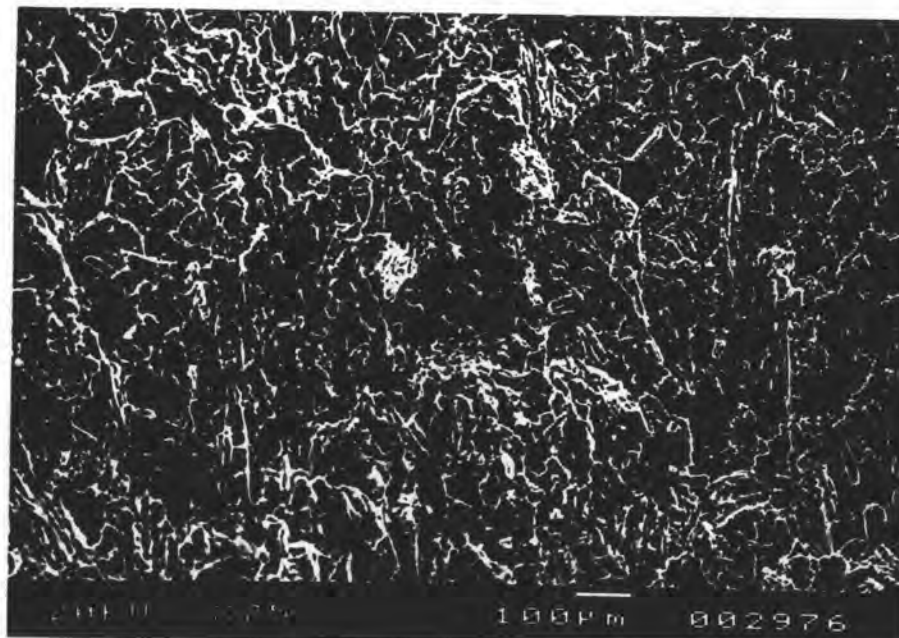


(b)

Figure 4.17 SEM micrographs of fracture surface of the PP filled with 10% (a) and 50% untreated WF (b). Original magnification 75x.



(a)



(b)

Figure 4.18 SEM micrographs of fracture surface of the PP filled with 30% untreated WF (a) and 30% WF treated with Epolene E-43P (b). Original magnification 75x.

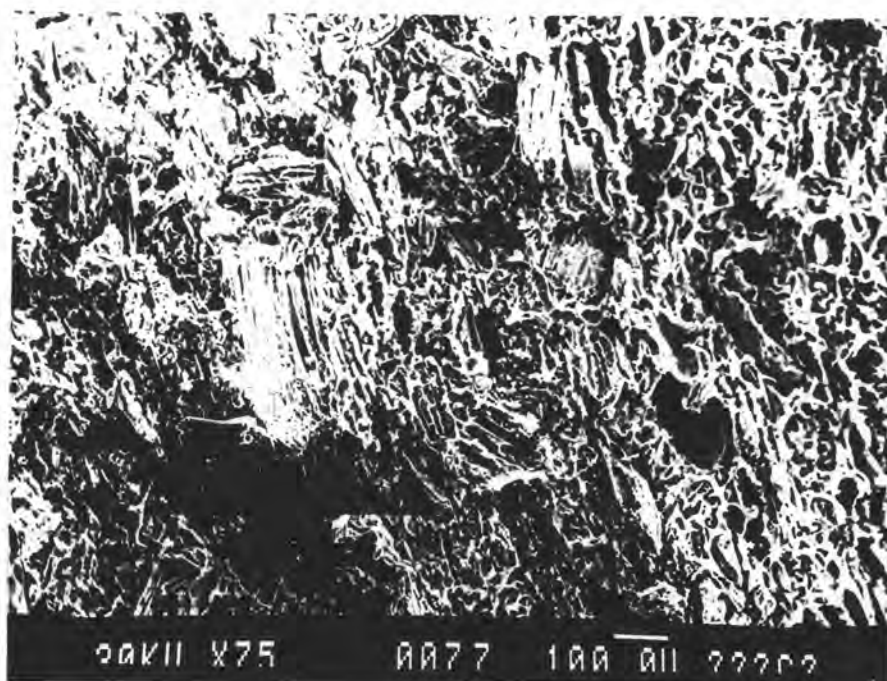


(a)

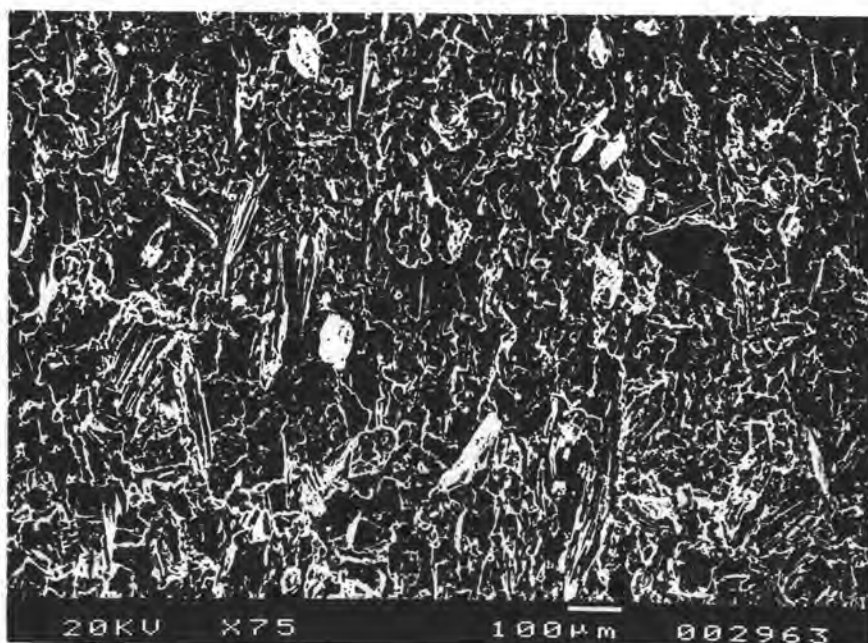


(b)

Figure 4.19 SEM micrographs of fracture surface of the PP filled with 10% untreated WF (a) and 10% WF treated with Epolene E-43P (b). Original magnification 200x.



(a)

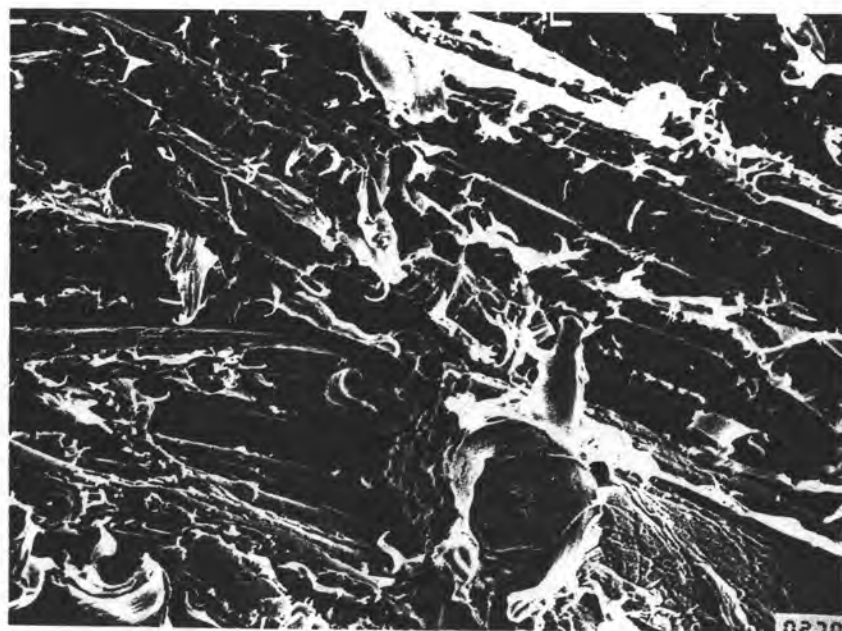


(b)

Figure 4.20 SEM micrographs of fracture surface of the PP filled with 30% WF treated with silane A-1100 (a) and treated with silane A-174 (b). Original magnification 75x.



(a)



(b)

Figure 4.21 SEM micrographs of fracture surface of the PP filled with 50% WF treated with silane A-174 (a) and treated with Epolene E-43P (b). Original magnification 750x. ( — :10 um)



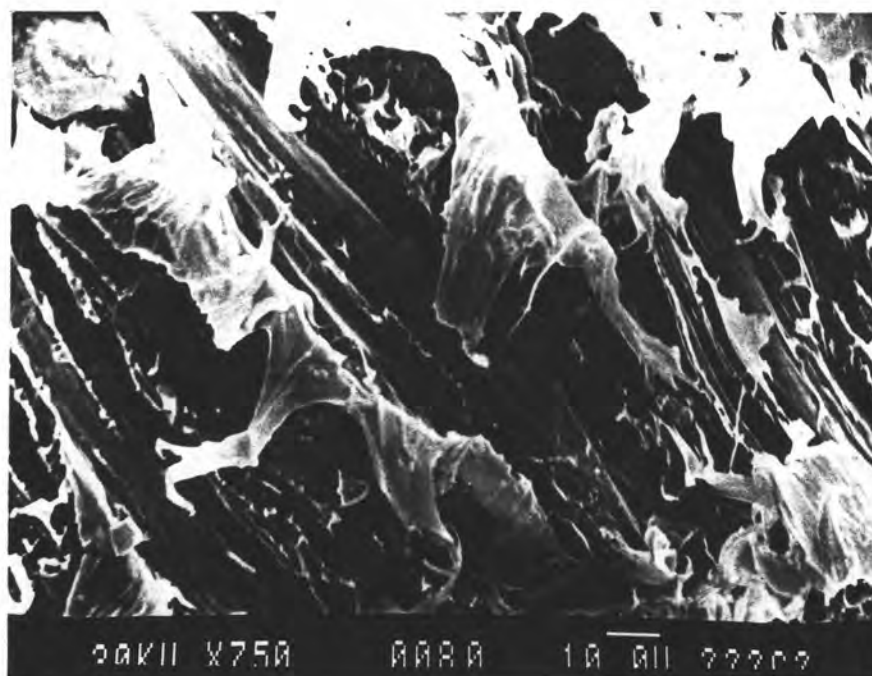


Figure 4.22 SEM micrograph of fracture surface of the PP filled with 50% WF treated with silane A-1100. Original magnification 750x.

The result of SEM studies can also be described by Nielsen's model.[34] This model is divided into two cases, perfect adhesion between polymer and filler and no adhesion between polymer and filler. Nielsen's model and theoretical curve of elongation at break of both cases can be illustrated in Figures 4.23 and 4.24 respectively.

a) Perfect adhesion between polymer and filler, the elongation at break of composite is expected to decrease with increasing filler content because the matrix is modified by filler in carrying load as shown in Figure 4.23a.

b) No adhesion between polymer and filler, the elongation at break is expected to decrease in the lower proportion than the former case. According to a poor adhesion, the transfer of load from matrix to filler through the interfacial bond cannot occur (Figure 4.23b).

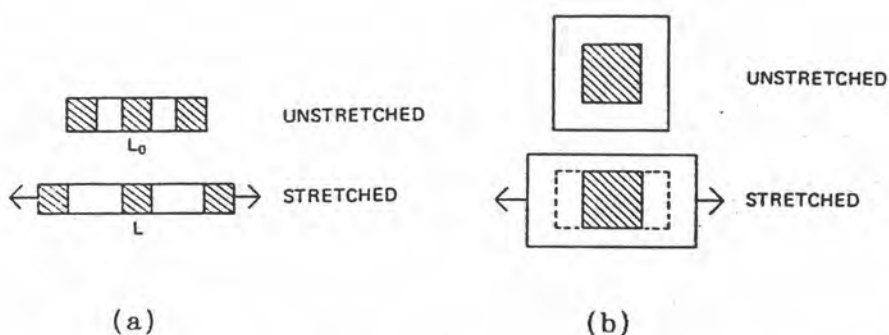


Figure 4.23 Models for the filled polymers (Nielsen, 1966)

a) Perfect adhesion b) No adhesion

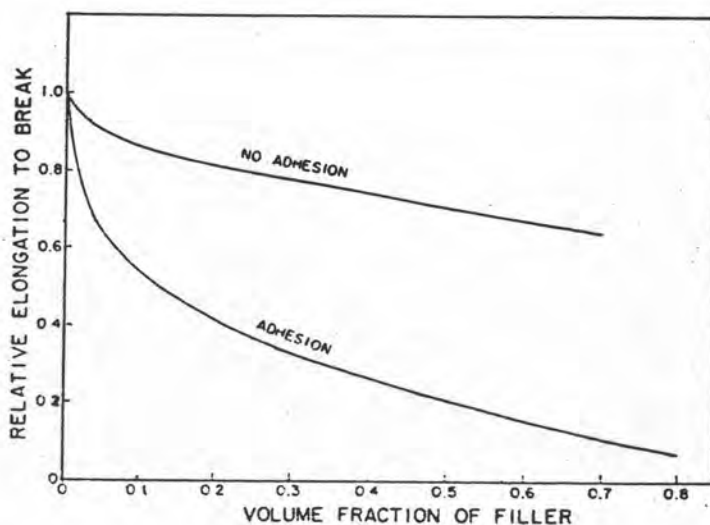


Figure 4.24 Theoretical curves for the elongation to break for the case of perfect adhesive and no adhesive between the filler and polymer phases.

#### 4.7 Effect of the Coupling Agent on the Polarity of Wood Flour

In this experiment, the difference in the nature of interaction between the polypropylene matrix and wood flour as filler was examined for the PP-untreated WF, PP-silane A-1100 treated WF, PP-silane A-174 treated WF and PP-Epolene E-43P treated WF composites. These four composites were extracted with hot xylene in a Soxhlet extractor for 8 hours, and the unextracted WF residues were dried and shaken in an excess ethyl ether-water mixture, and then allowed to stand at room temperature overnight. Figure 4.25 shows the results of this experiment, the WF residue from the PP-untreated WF composite was precipitated at the bottom of the water layer, but the WF residue from the PP-treated WF composites was partially precipitated. For the PP-silane A-1100 treated WF and PP-silane A-174 treated WF composites, the WF residue was found both at the bottom and at the interface between the water and ethyl ether. However, the amount of the WF residue of the composites containing silane A-174 was less than the composite containing silane A-1100. The WF residue from the PP-Epolene E-43P treated WF composite coalesced around the water-ether interface. These findings implied that the residue from the PP-untreated WF composite is hydrophilic, while the residue from the PP-Epolene E-43P treated WF composite is hydrophobic. The residue from the PP-silane treated WF composites approaches to hydrophobic property. Such hydrophilic nature suggests that a complete removal of the polymer remained in the outer and inner surfaces has been carried out, whereas hydrophobic properties are due presumably to the PP remaining at the surface of the WF. The amount of the residue remained at the

water-ether interface shows the strong interfacial adhesion between PP and WF.[26]



Figure 4.25 Existence of solvent extracted WF residue within the ethyl ether-water two layer system

#### 4.8 Differential Thermal Analysis (DTA) of Wood Flour-Filled Polypropylene Composites

DTA thermographs of the PP, untreated WF and treated WF filled PP composites were shown in Figure 4.26. The melting temperature,  $T_m$ , of PP is 164 °C, while that of the PP-untreated WF composite is 158 °C. In the presence of coupling agents, the observed melting point temperatures of both silane composites and Epolene E-43P composite were found at 161 and 162 °C, respectively. The elevation of  $T_m$  of the treated WF composite may be due to the existence of the coupling agent.

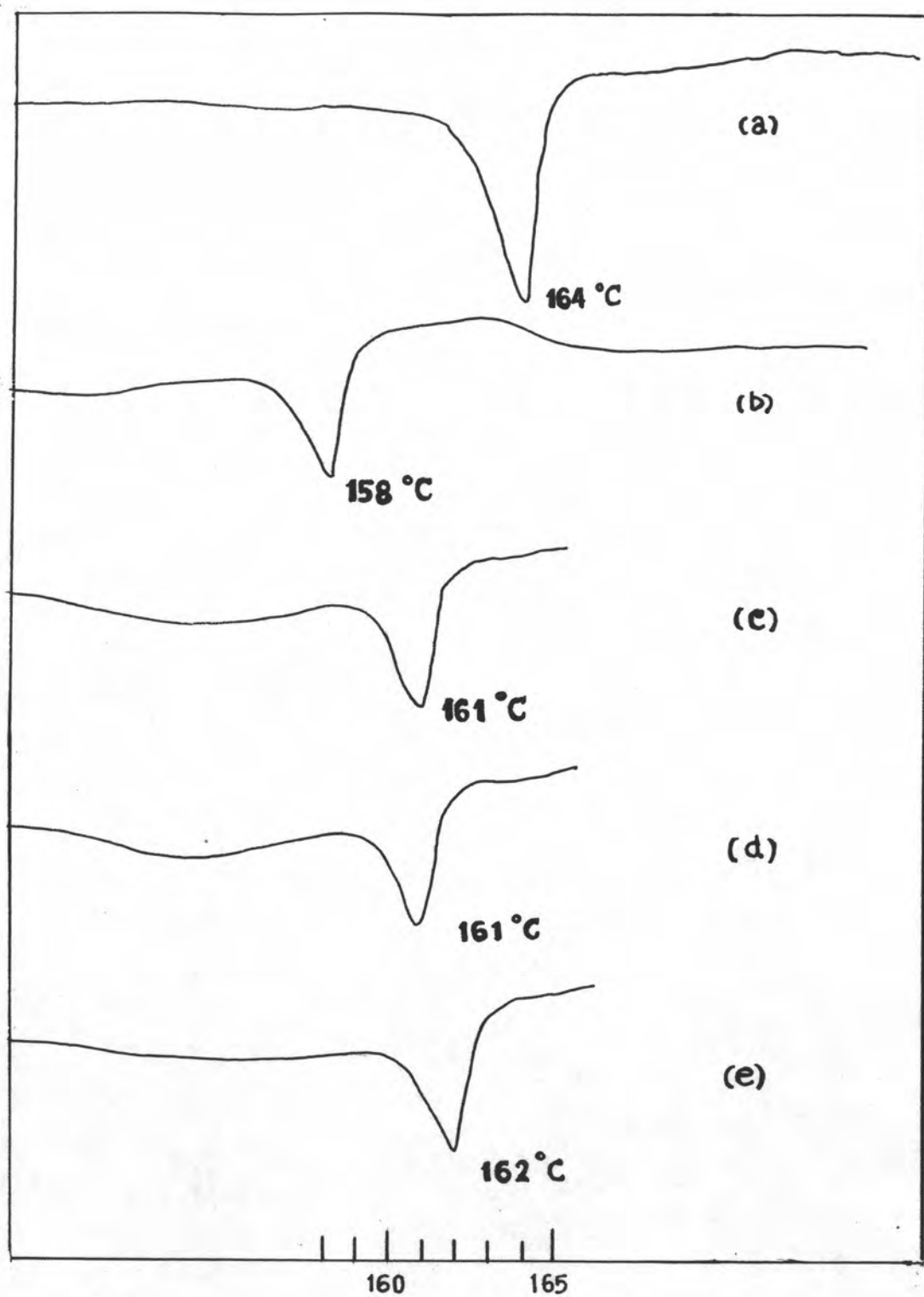


Figure 4.27 DTA thermographs of unfilled-PP and filled-PP (50% filler). Pure PP (a), PP-untreated WF (b), PP-silane A-1100 treated WF (c), PP-silane A-174 treated WF (d), and PP-Epolene E-43P treated WF (e).

#### 4.9 Economic Consideration

From the results of this research, the best coupling agent for this system should be Epolene E-43P due the high mechanical properties of composites at various WF contents. The advantage of WF/PP products is the cost reduction. In this work, the cost of WF obtained from sawdust was negligible. So, the cost of this composite is mainly based on the costs of PP and coupling agent. The costs of Epolene E-43P and PP were 180 Baht/kg and 25 Baht/kg, respectively. However, the high cost of Epolene E-43P can be compensated by the negligible cost of WF and rather less costly of PP. Table 4.5 indicates the cost of the filled-PP composite with different WF contents. The more WF content, the higher the cost reduction of the composites. The maximum cost reduction was 42.80% at 50% WF content.

Table 4.5 Cost Analysis of PP-Epolene E-43P treated WF Composites.

Filler Content (%)	Starting Materials (Baht/kg)			Cost of Composite <sup>b</sup> (Baht/kg)	Cost Reduction <sup>c</sup> (%)
	PP	WF	Epolene E-43P <sup>a</sup>		
0	25.00	0	0	25.00	0
10	22.50	0	0.36	22.86	8.56
20	20.00	0	0.72	20.72	17.12
30	17.50	0	1.08	18.58	25.68
40	15.00	0	1.44	16.44	34.24
50	12.50	0	1.80	14.30	42.80

$$a = (2\% \text{ by weight of WF content}) \times (180 \text{ Baht/kg})$$

$$b = [((25 \text{ Baht/kg}) \times (\text{fraction of PP})) + (a)]$$

$$c = [(25 \text{ Baht/kg} - (b))/(25 \text{ Baht/kg})]$$