Chapter 3

Mechanical Properties of PALF/LDPE Composites

Part of the results presented in this chapter has been (i) published in Journal of Applied Polymer Science, 57, 843 (1995); and (ii) communicated for publication to Journal of Thermoplastic Composites.

3.1 Introduction

The incorporation of stiff fibres into soft matrices can lead to new materials with outstanding mechanical properties encompassing the advantages of both the fibre and the matrix. These composites are generally characterised and evaluated by means of various standard tensile, flexural and fatigue tests performed on composite specimens. Fibrous fillers are widely employed in thermoplastics for reinforcement and the stiffness and strength of fibre reinforced plastics are functions of fibre properties and the quality of fibre incorporated.

Owing to the high price of composites, the user industries demand a lower price for production of fibre components and at the same time an improvement in quality. It was found that these can be achieved by the use of natural fibres. Compared to inorganic fillers, the main advantages of these fibres are their low cost, low density, high specific strength and modulus,
renewable nature and comparatively easy processability. For better processability, these composite materials often incorporate short discontinuous fibres oriented in the direction of applied load in order to take full advantage of the reinforcing property of fibre. Properties of fibre reinforced composites depend on many factors like fibre-matrix adhesion, volume fraction of fibre, fibre aspect ratio, fibre orientation as well as stress transfer efficiency of interface. Extensive research studies have been carried out over the last few years in the field of natural fibre reinforced thermoplastics. These include the interesting works of Kokta and co-workers. Felix et al. reported the effect of compatibilising agent and the nature of adhesion in composites of cellulose fibres and polypropylene (PP). Recently, Thomas and co-workers reported the use of different natural fibres (sisal, banana, coir, PALF) as potential reinforcing agents in thermoplastics (polyethylene, polystyrene) thermosets (epoxy resin, phenol formaldehyde, polyester) and elastomers (natural rubber, styrene butadiene rubber).

In structural test procedures, it is necessary to make allowances for the degradation that can occur in some of the mechanical properties of materials due to exposure to environmental conditions. Degradation is usually confined to a reduction in the matrix dependent properties, although some fibre property degradation can also occur. Therefore the study of the mechanical behaviour of composites at higher temperature is important. In some of the applications, a temperature variation is quite common. This temperature variation influences the properties of the composites. The effect of elevated temperatures on tear resistance of different rubber vulcanisates and threshold energy value for fracture have been reported by many researchers. Setua reported on the influence of increasing temperature on the tear resistance of short silk fibre reinforced elastomers and the effect of fibre orientation on the retention of tear strength. Mechanical properties and fracture surface morphology of clay filled thermoplastics-1,2 polybutadiene rubber at elevated temperatures were reported by Bhagawan et al. Schultz and
Friedrich studied the effect of temperature and strain rate on the strength of PET/glass fibre composites. The effects of temperature and strain rate on strength and toughness of fibre reinforced plastics were reported by many researchers. But studies on the temperature dependence of cellulose fibre reinforced plastics have not been studied yet, even though influence of elevated temperature on sisal fibre was reported by Chand and Hashmi.

In this chapter, results of investigations on the effects of short pineapple leaf fibre reinforcement on the mechanical properties of low density polyethylene have been presented. The influence of processing conditions, fibre loading, fibre orientation and fibre length on the physico-mechanical properties of the composites are analysed. Also, the results of the effect of test temperature and strain rate on the failure properties of PALF/LDPE composites are reported. The tensile failure surfaces are examined by SEM in order to gain an insight into the fibre orientation, fibre damage and fibre-matrix adhesion. Finally, the properties of pineapple leaf fibre composites are compared with those of other two cellulose fibres (sisal and jute) reinforced LDPE composites.

3.2 Results and discussion

3.2.1 Melt mixed composites

(a) Mixing characteristics

The mixing characteristics of LDPE-PALF composites have been studied using the Brabender plastographs which are plots of torque versus mixing time. As shown in Figure 3.1 the mixing torque initially increases rapidly when LDPE granules are charged into the mixer chamber. This is associated with the unmolten nature of LDPE granules. As the mixing proceeds, LDPE undergoes melting resulting in a decrease of torque which levels off at longer times. The fibre is incorporated into molten PE after two minutes. Addition of fibres results in an increase of torque because of the increased viscosity of the system.
torque reaches constant value at longer times when incorporation of PALF fibres in the LDPE matrix is complete. In melt mixed composites, the properties of the system are dependent on mixing conditions such as mixing time, rotor speed and temperature of mixing. In order to optimise these parameters, a series of PALF/LDPE composites are made by varying rotor speed, mixing time, and temperature.

Figure 3.1 Plastographs for PALF/LDPE composites at different fibre loading. (Rotor speed 60 rpm, mixing time 6 min, temperature 120°C).

(b) Mechanical properties

The effect of mixing time on strength and Young’s modulus of both oriented and random PALF/LDPE composites is depicted in Figure 3.2. These mixes were carried out at a temperature of 120°C and at a rotor speed of 60 rpm.
When the mixing time is less, tensile strength and Young's modulus are low because of the ineffective mixing and poor dispersion of the fibre in LDPE matrix. However, as the mixing time increases, both the tensile strength and modulus increase and attain maximum value which levels off after 6 min. As expected, oriented composites show higher strength compared to randomly oriented composites, i.e., orientation provides better reinforcement to the matrix.

![Graph showing variation of tensile strength and modulus with mixing time.](image)

**Figure 3.2.** Variation of tensile strength and modulus with mixing time of melt mixed composites. Fibre content 30%.

Figure 3.3 shows the effect of Brabender rotor speed on tensile strength and modulus of oriented and random composites mixed at 120°C for 6 min. Composites prepared by the mixing of fibre and LDPE at lower rotor speed show low tensile strength due to the poor dispersion of fibre. But as the rotor speed is
increased from 20 to 60 rpm, there is an increase of strength by 60% in the case of oriented composite. However, as the rotor speed is increased to 80 rpm, reduction in strength occurs due to the fibre breakage at higher rotor speed. A similar trend is observed in the case of Young’s modulus also. Evidence for fibre breakage at higher rotor speed is provided in terms of fibre distribution curves given in Figure 3.4. It has been noticed that about 70% of fibres extracted from the composite prepared by mixing fibre and LDPE at 60 rpm are of 2.5 to 4 mm length. On the other hand, about 65% of fibres from composite mixed at 80 rpm are in the range of 0.5 to 3 mm. This indicates that fibre breakage is extensive and severe at 80 rpm. Since the fibre length is extremely short, much shorter than the critical length, the stressed fibre debonds from the matrix and therefore the composite exhibits low strength.

![Figure 3.3](image)

Figure 3.3 Tensile strength versus rotor speed of melt mixed composites (Fibre content 30%).
Effect of processing temperature on the composite at a rotor speed of 60 rpm and a mixing time of 6 min on tensile properties is given in Table 3.1. It can be seen that the tensile strength and Young's modulus of both oriented and random composites increase with temperature and reach maximum at 130°C. However, above 130°C there is a reduction in strength and modulus. This may be due to the degradation of fibre at higher temperature. Moreover, the dispersion of fibre in LDPE matrix will be poor due to the decrease in matrix viscosity at high temperature.
Table 3.1. Effect of processing temperature on the tensile properties of melt mixed PALF/LDPE composites (Fibre length 6 mm, fibre content 30 wt %).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>33.7 (7)</td>
<td>1020 (500)</td>
<td>4.0 (6.0)</td>
</tr>
<tr>
<td>130</td>
<td>25.3 (14)</td>
<td>1200 (670)</td>
<td>6.8 (7.3)</td>
</tr>
<tr>
<td>140</td>
<td>22.8 (11.5)</td>
<td>1030 (500)</td>
<td>7.1 (7.4)</td>
</tr>
</tbody>
</table>

Figures in the parentheses are the properties of random composites.

The optimisation of melt mixing parameters indicates that for the best balance of properties, PALF/LDPE composites should be melt mixed in an internal mixer for a period of 6 min at a temperature of 130°C using a rotor speed of 60 rpm.

3.2.2 Melt mixed/solution mixed composites

Table 3.2 shows the effect of fibre loading and mixing techniques on the tensile properties of randomly oriented PALF/LDPE composites. In the case of solution mixed composite due to the addition of 10% fibre, the tensile strength and modulus are increased by 20 and 68% respectively. However, with further addition of fibres, the increase is gradual. This is associated with the fibre to fibre interactions at high fibre loading. The elongation at break of the composite undergoes a sharp fall upon the introduction of fibres in the mixes. As loading is increased the decrease is not very sharp but gradual. On the introduction of fibres into LDPE matrix, the fibres inhibit the orientation of molecular chains and hence the elongation at break decreases substantially.

Compared to the solution mixed composites, the melt mixed composites show lower mechanical properties at low fibre loading. For example at 10% fibre loading, Young’s modulus and tensile strength of melt mixed composites are
lower than that of solution mixed composites by 58% and 18%, respectively. The differences are less pronounced at high fibre loading. During melt mixing in a Brabender plasticorder the fibres undergo considerable damage like splitting and peeling due to the high shear forces. This can be seen from SEM photographs given in Figures 3.5a to 3.5c. The extent of fibre breakage in melt mixed composites is also evident from the optical photographs shown in Figures 3.6a and 3.6b. Here fibres were extracted from the melt mixed and solution mixed composites using toluene as solvent. The extracted fibres were examined under a microscope. It is seen that fibre breakage is severe in the melt mixed composites than in solution mixed composites. In solution mixed composites, the fibres retain their original length. This can be further understood from Figure 3.7 which shows the fibre length distribution in melt mixed and solution mixed composites. It is interesting to note that in melt mixed composites, only 5% of the fibres retains the 6 mm length. More than 70% of fibres are distributed in the range of 2 to 4 mm. But in solution mixed composites maximum distribution occurs at 6 mm. Therefore, the reduction in tensile properties in melt mixed composites is due to severe fibre breakage and damage.

**Table 3.2.** Variation of tensile properties of randomly oriented melt mixed and solution mixed composites (Fibre length 6 mm).

<table>
<thead>
<tr>
<th>Fibre content (wt %)</th>
<th>Melt mixed composites</th>
<th>Solution mixed composites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tensile strength (MPa)</td>
<td>Young’s modulus (MPa)</td>
</tr>
<tr>
<td>0</td>
<td>8.5</td>
<td>130</td>
</tr>
<tr>
<td>10</td>
<td>8.6</td>
<td>138</td>
</tr>
<tr>
<td>20</td>
<td>10.6</td>
<td>310</td>
</tr>
<tr>
<td>30</td>
<td>13.7</td>
<td>503</td>
</tr>
</tbody>
</table>
Figure 3.5. Tensile fracture surfaces of melt mixed composites showing fibre damage: (a) and (c) splitting, (b) peeling.

Figure 3.6. Optical photographs of fibres extracted from (a) solution mixed composite (b) melt mixed composite showing extent of fibre breakage.
3.2.3 Solution mixed composites

(a) Effect of fibre length

The strength of fibre reinforced composites depends on the degree to which an applied load is transferred to fibres. The extent of load transmittance is a function of fibre length and magnitude of fibre-matrix interfacial bond. In short fibre reinforced composites there exists a critical fibre length that is required for the fibre to develop its fully stressed condition in the matrix. If the fibre is shorter than this critical length, the stressed fibre will debond from the matrix and the composite will fail at a low load. When the length is greater than the critical length the stressed composites result in fibre breakage and a composite of high strength.

Mechanical properties of longitudinally oriented solution mixed composites at 30% loading as a function of fibre length are shown in Table 3.3.
When the fibre length is increased from 2 to 6 mm there is an enhancement in strength by about 13%. Similarly there is an increase in modulus by 15% due to the effective stress transfer between the matrix and fibre. When the fibre length is increased further to 10 mm, there is only a 4% increase in tensile strength and modulus is unaffected. This clearly indicates that the mechanical properties level off beyond 6 mm fibre length. The plateau effect is associated with poor dispersion of fibre in the matrix and fibre to fibre entanglements at higher fibre length. The study was limited to 10 mm fibre length since the extrusion of composite was extremely difficult at higher fibre length. Even the extrusion of composite containing 10 mm fibre length was not easy. Therefore from the overall mechanical properties and processability, fibre length of 6 mm was found to be the optimum value for effective reinforcement in LDPE.

Table 3.3. Variation of mechanical properties of longitudinally oriented solution mixed PALF/LDPE composites with fibre length (Fibre content 30 wt%).

<table>
<thead>
<tr>
<th>Fibre length (mm)</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.5</td>
<td>130</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>19.7</td>
<td>930</td>
<td>4.4</td>
</tr>
<tr>
<td>6</td>
<td>22.5</td>
<td>1100</td>
<td>4.0</td>
</tr>
<tr>
<td>10</td>
<td>23.4</td>
<td>1100</td>
<td>7.2</td>
</tr>
</tbody>
</table>

(b) **Effect of fibre loading**

Figure 3.8 shows the stress-strain curve of longitudinally oriented solution mixed PALF/LDPE composites at different fibre loading. Stress-strain behaviour of the composite is controlled by the characteristics of the fibre and the matrix. In the case of pure LDPE, elongation is quite high, i.e. the material shows low initial elastic modulus followed by yielding at larger strains and the failure is
essentially ductile. Addition of 10% fibre results in an increase in the initial elastic modulus and reduction in elongation at break by about 90%. Further addition of fibres rapidly increases the modulus of the composite and the system becomes more and more brittle.

![Stress-strain curve of PALF/LDPE composites at different fibre loading.](image)

**Figure 3.8.** Stress-strain curve of PALF/LDPE composites at different fibre loading.

Effects of fibre loading on the mechanical properties of longitudinally oriented composites are shown in Table 3.4. It is observed that by adding 10% fibres there is an increase of 90% in tensile strength and by the further addition there is only an increase of 20%. The modulus also increases with fibre loading. Addition of 10% fibre, increases the modulus by 300%. It can be noticed that above 10% fibre loading, the increase in tensile strength and modulus is less pronounced. This is possibly due to high fibre to fibre interactions. The elongation at break of the composite exhibits a sharp fall by the introduction of fibres in these mixes. At higher fibre loading the decrease is gradual.
Tension set after failure was found to be lowered with fibre content as shown in Table 3.4. A tension set of 24% was found for LDPE, but it was only 1 to 2% for the composite. This is due to the fact that the addition of fibres to LDPE makes the system highly brittle and the ductility of LDPE is completely lost.

Table 3.4. Mechanical properties of longitudinally oriented solution mixed PALF/LDPE composites (Fibre length 6 mm).

<table>
<thead>
<tr>
<th>Fibre content (wt %)</th>
<th>Tensile strength (MPa)</th>
<th>Young's modulus (MPa)</th>
<th>Elongation at break (%)</th>
<th>Tear strength (kN/m)</th>
<th>Hardness (Shore D)</th>
<th>Tension set (%)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.5</td>
<td>130</td>
<td>110</td>
<td>63</td>
<td>45</td>
<td>24</td>
<td>0.90</td>
</tr>
<tr>
<td>10</td>
<td>16.3</td>
<td>610</td>
<td>11</td>
<td>72</td>
<td>55</td>
<td>2.4</td>
<td>0.95</td>
</tr>
<tr>
<td>20</td>
<td>19.8</td>
<td>900</td>
<td>9.0</td>
<td>81</td>
<td>60</td>
<td>2.0</td>
<td>0.99</td>
</tr>
<tr>
<td>30</td>
<td>22.5</td>
<td>1100</td>
<td>4.0</td>
<td>97</td>
<td>65</td>
<td>1.1</td>
<td>1.03</td>
</tr>
</tbody>
</table>

It can be seen from the table that tear strength increases with fibre content. This indicates that incorporation of fibres makes the crack propagation difficult. When the fibres are arranged longitudinally, tearing takes place normal to the fibre orientation and tear strength depends largely on the obstruction offered by the fibres to the advancing tear.

As expected, the incorporation of fibres increases the composite hardness markedly. Hardness is related to the toughness and modulus of composite. The density of the composite increases with fibre content due to the close packing of fibres.

(c) Effect of fibre orientation

Orientation of fibres relative to one another plays a vital role in the performance of the composites. With respect to orientation two extremes are possible. These include the parallel alignment of the longitudinal axis of the
fibres in a single direction and the totally random alignment. Longitudinally oriented composites are inherently anisotropic and the maximum strength and reinforcement are achieved along the direction of fibre alignment. In the transverse direction, reinforcement is virtually non-existent and therefore fracture usually occurs at low tensile stress. In randomly oriented composites, strength lies between these two extremes.

The SEM photographs given in Figures 3.9a and 3.9b show transverse and longitudinal orientation of fibres in PALF/LDPE composites. The figures indicate that the fibres are well oriented during the processing of the composites. It can be seen from Figure 3.10 that longitudinally oriented composites show better tensile strength properties than transversely and randomly oriented composites. When the fibres are aligned perpendicular to the direction of force (transverse) fibres are not in conjunction with the matrix in increasing the strength of the composite. As expected, randomly oriented composites show intermediate values. The same trend can be seen in the modulus curve as shown in Figure 3.11. It is clear that a slight misalignment of fibre from the direction of force may lead to drastic decrease in the modulus.

![SEM photographs showing (a) transverse and (b) longitudinal fibre orientation. Samples were cut perpendicular to the direction of applied force.](image)

**Figure 3.9** SEM photographs showing (a) transverse and (b) longitudinal fibre orientation. Samples were cut perpendicular to the direction of applied force.
Figure 3.10  Effect of fibre orientation on tensile strength of PALF/LDPE composites.

Figure 3.11  Effect of fibre orientation on Young's modulus of PALF/LDPE composites.
Effect of orientation on tear strength can be seen in Figure 3.12. Here also it is observed that longitudinally oriented composites exhibit higher properties than randomly oriented and transversely oriented specimens. As explained earlier when fibres are oriented longitudinally, the failure takes place normal to the fibre orientation. But in the case of composites with transverse fibre orientation, the resistance offered by the fibre to the propagating tear is even less than that of matrix. As expected random composites show intermediate values.

![Figure 3.12](image)

**Figure 3.12** Effect of fibre orientation on tear strength of PALF/LDPE composites.

The effect of orientation on the tensile strength of composites at elevated temperature is shown in Figure 3.13. It is clear from the figure that longitudinally oriented composites exhibit better properties than transversely and randomly oriented composites. The tensile properties of transversely oriented composites are very little affected by temperature.
Effect of orientation on tensile strength of PALF/LDPE composites with varying temperature.

(d) *Effect of test speed*

Stress-strain characteristics of polymers in general give an indication of the strength of the material as well as its toughness. Stress-strain behaviour of the composite is controlled by the characteristics of fibre and matrix. The deformation behaviour of the composite under an applied load can be understood from the stress-strain curves. Since polymers are viscoelastic, the mechanical properties of composites based on them are also greatly influenced by the rate of strain. Changing the strain rate may lead to some degree of alignment along molecular segments. Such alignment will lead to anisotropy of properties.

Stress-strain curves of randomly oriented PALF/LDPE composites at different strain rates, are plotted in Figures 3.14 and 315. With increasing test speed, the initial portion of stress-strain plot becomes steeper resulting in higher modulus.
Figure 3.14  The stress-strain behaviour of randomly oriented PALF/LDPE composites at different test speeds (Fibre loading 10%, temperature 28°C).

Figure 3.15  The stress-strain behaviour of randomly oriented PALF/LDPE composites at different test speeds (Fibre loading 30%, temperature 28°C).
Effect of test speed on the tensile properties of randomly oriented PALF/LDPE composites can be observed from Table 3.5. As expected, both strength and modulus increase and elongation at break decreases with increasing strain rate. The relatively low strength and modulus at low strain rate depends on the uncoiling of chains.

The influence of strain rate on the mechanical properties can be explained by considering the polymer chain as random coils whose segments in a cross section. During testing, by the application of stress, each segment that passes through the cross section aids in supporting the stress.

### Table 3.5. Effect of test speed on tensile properties of PALF/LDPE composites (Fibre loading: 30%; temperature 28°C).

<table>
<thead>
<tr>
<th>Test speed (mm/min)</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
<td>520</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>13</td>
<td>570</td>
<td>6.0</td>
</tr>
<tr>
<td>500</td>
<td>15.5</td>
<td>790</td>
<td>5.1</td>
</tr>
</tbody>
</table>

At low strain rates, the molecular network chains move very slowly as the composite is extended. The viscous forces will be very small. The chains will not lag far behind their equilibrium elongation for the stress at any given instant. The chains will therefore exhibit the strength characteristic of their fully extended, essentially motionless state.\(^{45}\)

As the test speed is increased, (or as the temperature is decreased) the chains will not elongate as fast as the test requires due to large viscous (retarding) forces. At the instant of failure each chain would be still uncoiled. Thus for a given cross section there would be several bonds from each chain holding the load.
Under slow speed the chains are nearly fully extended upon breaking. Hence, each chain provides only one bond to hold the load on a given cross section.

(e) **Effect of temperature**

Composites show much greater sensitivity to temperature than to strain rate. The stress-strain response and the mechanism of failure may also change as a result of temperature variation. Figures 3.16 and 3.17 show the stress-strain curves of LDPE and 20% fibre filled longitudinally oriented PALF/LDPE composites at different temperatures at a crosshead speed of 50 mm/min.

![Figure 3.16](image)

*Figure 3.16* The stress-strain behaviour of LDPE at different temperatures (Test speed 50 mm/min).
Figure 3.17 The stress-strain behaviour of longitudinally oriented PALF/LDPE composites at different temperatures (Fibre loading 20%, test speed 50 mm/min).

At low temperature, the initial modulus is high and as the temperature is increased the modulus decreases and the material shows ductile behaviour. Reduction in the modulus with increase of temperature is associated with the softening of matrix at higher temperatures. In the case of pure LDPE, elongation is quite high and increases with temperature exhibiting a maximum elongation. Similar trend is observed in the stress-strain behaviour of the composite containing 20% fibre but with a considerable reduction in elongation at break and an increase of initial elastic modulus.

The effects of test temperature on the tensile strength of longitudinally oriented PALF/LDPE composites at different fibre loading are shown in Figure 3.18. It is clear that the tensile strength tends to increase as the temperature
is lowered. In general, the mechanical properties of the composite are found to be reduced with increase of temperature. But in the case of composites with higher fibre loading the decrease in strength with temperature (above ambient) is less. On increasing the temperature from 27 to 80°C there is a decrease of about 90% in unfilled system whereas at 30% fibre loading the decrease is only 60%. However, at 80°C the difference in strength of the filled and unfilled systems is marginal because polyethylene approaches its melting temperature (Tm); the matrix fails as a result of viscous flow, accompanied by fibre debonding. In this case, the matrix is insufficient to transfer load to the fibres.

![Figure 3.18](image)

**Figure 3.18** Variation of tensile strength and elongation at break with temperature of longitudinally oriented PALF/LDPE composites at different fibre loading.

The elongation at break is low below room temperature (Figure 3.18). On increasing the temperature elongation at break greatly increases and maximum is found at 40°C. Thereafter it again decreases. The variation of Young’s modulus
with temperature for fibre filled LDPE is presented in Figure 3.19. The modulus decreases with an increase in temperature. Above 40°C the matrix becomes softened and modulus of composite decreases. A levelling off is observed in unfilled system above ambient temperature. The decrease in stiffness in fibre filled system above ambient is associated with the fibre debonding due to the increased viscoelastic deformation of matrix at higher temperature.

The high tensile strength and modulus of composites at low temperature indicate that $T_g$ is being approached. The presence of reinforcing fibres increases the magnitude of this effect. It is possible that the differential fibre/matrix thermal contraction would promote greater frictional force as the temperature is lowered. This would increase the ultimate strength and stiffness of the composites.\(^{37}\)

![Figure 3.19 Variation of Young's modulus with temperature of PALF/LDPE composites at different fibre loading.](image-url)
In order to demonstrate relative changes of strength and modulus and to relate them to more fundamental parameters, ultimate strength and modulus of composite values are normalised by dividing with the same parameter from standard specimen at particular temperature. The LDPE is chosen as standard. The normalised modulus ($E_N$) represents the ratio of moduli between a given specimen and the standard. Similarly, the normalised tensile strength ($\sigma_N$) is the ratio of strength between given specimen and standard at a particular temperature. Figure 3.20 shows the changes of normalised tensile strength with temperature. It is clear that the tensile strength of composite increases with fibre loading. Relative change with loading is less at low temperature. But as the temperature increases, the presence of fibre restricts flow of polymer matrix and this restriction increases with fibre loading. It is observed from the figure that at 30% fibre loading tensile strength of composite is about six times greater than that of unfilled system at a temperature of 80°C. A similar trend is observed in the case of normalised modulus as evident from Figure 3.21. It is clear from the figure that the normalised modulus ($E_N$) increases with temperature and fibre loading. But the increase is maximum at higher fibre loading. The effect of fibre is to maintain high strength and stiffness at elevated temperature even while the matrix becomes deformed. But at low temperature, the effect of fibre is not prominent.

In order to further understand the influence of temperature on the tensile strength of composites, Arrhenius plots are drawn. In Figure 3.22 the logarithm of tensile strength is plotted as a function of reciprocal temperature. Activation energy of a material provides valuable information on the sensitivity of the material towards the change in temperature. Activation energy of the system at different loading is given in Table 3.6. It is clear that the temperature sensitivity decreases on addition of fibre.
Figure 3.20  Normalised tensile strength ($\sigma_N$) of PALF/LDPE composites at different fibre loading.

Figure 3.21  Normalised tensile modulus ($E_N$) of PALF/LDPE composites at different fibre loading.
Figure 3.22  Plot of log tensile strength versus 1/T.

Table 3.6  Activation energy of PALF/LDPE composites.

<table>
<thead>
<tr>
<th>Fibre loading (wt %)</th>
<th>Activation energy x 10^{-2} (cal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.08</td>
</tr>
<tr>
<td>10</td>
<td>1.47</td>
</tr>
<tr>
<td>20</td>
<td>1.41</td>
</tr>
<tr>
<td>30</td>
<td>1.38</td>
</tr>
</tbody>
</table>

(f) Fracture surface morphology

SEM photographs (tensile) of LDPE at different test speeds (5 and 500 mm/min) and temperatures (0 and 80°C) are shown in Figures 3.23 and 3.24.
The fractographs of specimen tested at low speed (Figure 3.23a) reveals a number of folds and wavy structures; several folds are present in the fracture surface of LDPE sample tested at high strain rate (Figure 3.23b). The ductile nature of LDPE at 28°C is thus reflected in these fractographs.

The fractograph of LDPE at 0°C (Figure 3.24) reveals widely separated folds and also few regions of fibrils. They indicate the higher strength and reasonable extensibility of LDPE at 0°C. The fracture surface of LDPE at 80°C exhibits somewhat smooth surface with folds reflecting its lower strength and higher ductility.

The fracture surfaces of composites containing 20% fibre obtained at 0, 28 and 80°C are shown in Figures 3.25a-c. At low temperature, the fibres are held strongly to the matrix resulting in a failure at the interface/fibre ends. As the temperature is increased through 28 to 80°C fibres debonded from a soft matrix are observed (Figures 3.25b and 3.25c) indicating reduced strength and increased ductility.

![Fractographs of LDPE fracture surfaces](image)

**Figure 3.23** Scanning electron micrographs of LDPE fracture surfaces at 28°C: (a) 5 mm/min, (b) 500 mm/min (Magnification x 160).
Figure 3.24  Scanning electron micrographs of LDPE fracture surfaces at a test speed of 50 mm/min: (a) 0°C; (b) 80°C (Magnification x 180).

Figure 3.25  Scanning electron micrographs of failure surfaces of PALF/LDPE composites at 20% fibre loading, test speed 50 mm/min: (a) 0°C; (b) 28°C; and (c) 80°C.
3.2.4 Recyclability of solution mixed composites

One of the important advantages of thermoplastic composites is their recyclability and reprocessability. The recyclability of the solution blended PALF/LDPE composites containing 20% fibre has been analysed by repeated extrusion at 120°C. The properties of the recycled composites are given in Table 3.7. Composite properties remain constant, up to 3rd extrusion. Beyond that the property decreases marginally due to thermal effect and degradation of the fibre.

Table 3.7. Effect of repeated extrusion on the tensile properties of solution mixed PALF/LDPE composites.

<table>
<thead>
<tr>
<th>No. of extrusion</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.8</td>
<td>720</td>
<td>9.2</td>
</tr>
<tr>
<td>2</td>
<td>19.9</td>
<td>775</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>19.1</td>
<td>710</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>17.9</td>
<td>625</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>16.7</td>
<td>530</td>
<td>14</td>
</tr>
</tbody>
</table>

3.2.5 Comparison of pineapple fibre reinforced polyethylene composites with other natural fibres

The tensile properties of LDPE filled with pineapple fibre, sisal\(^{27}\) and jute fibre\(^{46}\) are given in Table 3.8. The results suggest that pineapple and sisal fibre filled composites possess comparable mechanical properties. In the case of longitudinally oriented pineapple fibre filled composites the addition of 10% fibre causes an increase of about 92% in tensile strength whereas in sisal filled
composites the corresponding value is 83%. However, Young’s modulus values of sisal/LDPE composites are superior to PALF/LDPE composites. However, in the case of jute/LDPE composites there is no improvement at low fibre content (≤20%). It is seen that the tensile strength of LDPE is decreased by 30% on adding 20% jute fibre. However, at high jute fibre loading, the tensile properties of LDPE are improved. Among the three composites, PALF/LDPE system shows highest elongation at break values. The superior mechanical properties of pineapple reinforced composites are due to the high cellulose content of pineapple fibres compared to the other natural fibres.47

Table 3.8. Comparison of tensile properties of randomly oriented PALF/LDPE, sisal/LDPE and jute/LDPE composites.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Elongation at break (%)</th>
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<tbody>
<tr>
<td></td>
<td>Fibre loading (Wt %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 20 30</td>
<td>10 20 30</td>
<td>10 20 30</td>
</tr>
<tr>
<td>Pineapple</td>
<td>10.2 (16.3)</td>
<td>11.4 (19.8)</td>
<td>13.0 (22.5)</td>
</tr>
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<td>Sisal</td>
<td>10.8 (15.6)</td>
<td>12.5 (21)</td>
<td>14.7 (31)</td>
</tr>
<tr>
<td>Jute</td>
<td>–</td>
<td>4.99</td>
<td>8.03</td>
</tr>
</tbody>
</table>

*Figures in parentheses correspond to longitudinally oriented composites.

3.3 References