Chapter 9

CONCLUSION AND FUTURE OUTLOOK
9.1 Conclusion

The demand for fibre reinforced plastics for structural and non-structural applications are gaining importance in recent years due to the high specific modulus and strength of the reinforcing fibres. Glass fibre reinforced thermoplastic have been developed for application in high volume markets like the automotive sector. The widely used reinforcing E-glass fibre, however, possess several disadvantages like skin irritation during processing and handling and give slag during burning of the material at the end of its life time. The increased awareness of ecological problems with conventional plastics has turned the attention of manufactures to natural materials. This has motivated various Research and Development organisations and industries for the replacement of glass fibres with agro fibres such as flax, hemp, jute and sisal fibres. Considering the importance of natural fibre reinforcement in thermoplastics a systematic work has been done for the development of short sisal fibre reinforced polystyrene (PS) composites. The composites were prepared by a solution mixing technique in which the fibres are added to viscous slurry of PS that was prepared by adding toluene to melted PS. The mechanical properties, rheological behaviour, viscoelastic properties, dielectric properties and ageing behaviour of the PS-sisal fibre composite were studied in detail.

The tensile properties have been evaluated as a function of fibre length, loading and orientation. Variation of fibre length produces no considerable change in the modulus of PS-sisal composites. However, composite exhibits maximum tensile strength at a fibre length of about 10mm. There is an initial reduction in tensile
strength of polystyrene at 10% fibre loading. Increase of fibre loading to 20% improves the tensile strength of the composite considerably and produces no appreciable change with further loading. The incorporation of sisal fibre considerably improves the modulus of PS. The tensile strength and modulus of the composite was found to follow the order, longitudinally oriented fibre composite > randomly oriented fibre composite > transversely oriented fibre composite. Various theoretical models were used to predict the tensile strength and Young’s modulus of untreated and treated sisal/PS composites. The theoretical predictions were compared with experimental results. The models selected were series, Hirsch, Halpin-Tsai, Bowyer-Border and modified rule of mixtures. Modified rule of mixtures show good agreement with the experimental tensile properties. All models except rule of mixtures are based on the assumption that there is a perfect fibre-matrix interaction and the fibre is perfectly cylindrical having smooth surface characteristics. In the case of real composites, where these factors are not fully obeyed, a deviation from the experimental value was observed.

Variation in fibre loading produces an initial reduction in impact strength at 10% fibre loading followed by increase at 20 and 30% fibre loading. Flexural properties increase with fibre loading. While impact energy of polystyrene-sisal fibre composites increases with fibre length up to 6mm followed by a decrease at 10mm, maximum flexural strength, modulus and strain was observed with 10mm fibre composites.
Various chemical treatments (benzoyl chloride, polystyrene maleicanhydride (PSMA), toluene diisocyanate (TDI), methyl triethoxy silane and triethoxy octyl silane) on sisal fibre were investigated to improve the efficiency of sisal fibre as reinforcement in sisal fibre-polystyrene composites. All fibre modifications improve the tensile properties of the composite but to different extent. The decrease in hydrophilicity of the treated fibre and increased thermodynamic compatibility of the treated fibre with the polymer matrix are responsible for the improvement in the mechanical properties. The maximum improvement in tensile properties was observed with PSMA treatment. SEM studies also suggest strong fibre-matrix adhesion in treated sisal fibre-PS composites. In all cases except PSMA coating, fibre modification decreases the impact strength of the composites and PSMA coating shows an improvement in the impact strength.

Flexural strength of treated composites exhibits an improvement in all cases except benzoylation. Flexural modulus shows a decrease in the case of benzoylated and toluene diisocyanate treated fibre composites and an improvement in the case of silane treated fibre composite. PSMA treated fibre composite, however, shows no considerable variation in flexural modulus. Flexural strain also shows no considerable variation with fibre modification.

The rheological behaviour of short sisal fibre reinforced polystyrene composites has been studied as a function of fibre loading, fibre length, interface modification, shear rate and temperature. These composites exhibit pseudoplastic behaviour and can be represented by the power law equation. At 190 °C, the
addition of fibres increases the viscosity of the system and increase in viscosity is sharper at 30 per cent fibre loading. However, at 180°C, the viscosity follows the order PS< U206 <U106<U306 and this can be explained based on wall-slip effect. Generally, an increase in temperature decreases the viscosity of polymer system. However, PS-sisal composites show the reverse tendency, i.e., the viscosity of the composite increases with temperature. This may be due to the increased interaction between the fibres and polymer molecules at higher temperature. The increased wall-slip due to the presence of longitudinally oriented fibres along the wall-melt interface at lower temperature also contributes to this effect. The flow behaviour index (n*) of the sisal filled PS composite at a given temperature was found lower than that of pure PS suggesting a higher degree of pseudoplasticity for the composite. However, the variation of the flow behaviour index was not linear. Die swell ratio shows a sharp decrease at 10 per cent fibre loading followed by a levelling off at higher fibre loading. The maximum distortion and non-uniformity of the extrudate was observed at 10 per cent fibre loading and becomes uniform at higher fibre loading. SEM studies showed that at low shear rate most of the fibres are oriented along the periphery of the extrudate. At higher shear rates the fibres are uniformly distributed. The effect of chemical treatment of sisal fibres on the rheological behaviour of PS-sisal fibre composites has been studied at different shear rate at 180°C. It is observed that, the modification of fibre surface increases the viscosity of composite due to increased fibre- matrix interaction. The increase in melt viscosity of sisal fibre-polystyrene composites with temperature is more
pronounced in untreated fibre composites than benzoylated sisal fibre polystyrene composites and shows a decrease in viscosity with increase in temperature for polystyrene-maleic anhydride treated sisal fibre composites. The decreased wall slip and increased fibre matrix interaction in treated fibre composites accounts for this behaviour. The decrease in the die swell ratio is more pronounced in the case of treated fibre composites, where the fibres are found to distributed more uniformly than in untreated fibre composites. The flow behaviour index of the treated fibre composites is lower than that of untreated fibre composites indicating a more pseudoplastic nature for treated fibre composites.

The thermal stability of short sisal fibre reinforced polystyrene composites have been studied as a function of fibre loading, fibre length, fibre orientation and fibre modifications. The results showed that the sisal fibre degraded before polystyrene matrix and the composites are more stable than both the components. In the case of sisal fibre the weight loss starts from $60^\circ$C and the major decomposition occurs at $366^\circ$C. For neat PS decomposition starts at $288^\circ$C and is complete at a temperature of $425^\circ$C. In the case of 20% sisal fibre-PS composite, the degradation begins at a higher temperature of $329^\circ$C and decomposition is almost complete at $447^\circ$C. The thermal stability of treated fibre composites were found to be higher than that of untreated fibre composite and can be explained based on the better thermal stability of treated fibres and improved fibre-matrix interactions in treated fibre composites.

The dynamic mechanical properties (storage modulus, loss modulus and tanδc) of neat polystyrene and composites have been studied from 30-150$^\circ$C. In all cases
the storage modulus decreases upon increasing the temperature due to increased segmental mobility. The increase in frequency (0.1 to 100 Hz) increases the storage and loss modulus of PS and composites. The glass transition temperature ($T_g$) of the composite was found to be shifted to lower temperature compared to neat PS and can be attributed to the presence of residual solvent in composites. The addition of 10% fibre to PS matrix increases the storage modulus and loss modulus of the composites followed by a levelling off at higher loading. The increase in the modulus is more pronounced at temperatures above $T_g$ of the matrix. The studies on the effect of fibre length on storage modulus indicated an optimum length of 10mm to obtain the maximum modulus. Above $T_g$, maximum loss modulus is also obtained for 10mm fibre composite. Around glass transition temperature, 2mm fibre composites are found to show maximum loss modulus value. The dynamic properties are strongly influenced by the fibre orientation. Longitudinally oriented fibre composites showed the higher values of storage and loss modulus than transversely oriented fibre composites. Modified fibre composites shows marginally higher storage and loss modulus than that of untreated fibre composites and can be explained based on better fibre-matrix adhesion. Activation energy for the glass transition of neat PS and composites were evaluated and showed an initial decrease at 10% fibre loading followed by an increase above 20% fibre loading. Matrix modification increases the activation energy for glass transition and maximum activation energy was observed with benzoylated matrix composites.
The damping factor $\tan \delta_c$ of the PS is decreased by the addition of fibres and the area and height of the damping peak of the composites were lower and broader than that of neat PS. Fibre modification decreases the height and increases the width of the damping peak. Experimental $\tan \delta$ values were compared with theoretical values and found that experimental values are lower than theoretical values. A master curve was constructed for the storage modulus of composite based on the time-temperature superposition principle.

The dielectric properties of the polystyrene - sisal fibre composites were studied as a function of frequency, fibre loading, fibre length, and fibre–matrix interface modification. The dielectric constant was found to increase with fibre loading. Change in fibre length also affects the dielectric constant values and follows the order $U202 \approx U206 > U2010$ (at lower frequencies) and $U2010 > U206 > U202$ (at higher frequencies). Fibre modification changes the dielectric constant of the composites to varying degrees depending on fibre modification. An increase in dielectric constant of the composites was noticed on silane and PSMA treatment. Benzoylation of the fibre decreases the dielectric constant and can be attributed to the decrease in the number of hydroxyl groups of the fibre. The conductivity of the composites increases with fibre loading and decreases with fibre length. Fibre modifications that improve the fibre-matrix interaction decrease the conductivity values. The loss factor of the composites was found to follow the order $U306 > U206 > U106 > PS$ with fibre loading and $U202 > U206 > U2010$ with fibre length. The effect of fibre modifications on loss factor follows the order
U206 > S206>M206>B206 and is due to lower conductivity loss in the treated fibre composites.

The water absorption behaviour of polystyrene –sisal fibre composites has been studied with reference to fibre loading, temperature and fibre modification. It was found that the uptake of water increased with fibre loading and fibre treatment decreases the water uptake to varying degrees. However, PSMA treatment results in a slight increase of water uptake and follows the order B206 < T206 < Sm206 <Se206<U206< M206. The amount of water sorption increases with temperature. Kinetic parameters such as diffusion coefficient, sorption and permeability coefficients were determined. At higher temperatures, the sorption behaviour follows more Fickian behaviour and it was found that the diffusion coefficient decreases with increase in temperature. The decrease in diffusion coefficient with temperature can be attributed to the lack of hydrogen bonding between water and cellulose hydroxyl groups at higher temperature. Jacobs-Jones Model was used to study the diffusion process in PS-sisal composites and shows good agreement between experimental values and theoretical predictions. The mechanical properties and dimensional stability of untreated and treated sisal fibre reinforced polystyrene composites under different ageing conditions were evaluated. The treated fibre composites showed better dimensional stability and better retention of tensile properties on ageing and can be attributed to the existence of efficient interfacial bond between the fibre and the polymer matrix. However, it is observed that on water ageing untreated fibre composites show minimum decrease in tensile strength compared to treated fibre composites and can be
explained based on the thermal shrinkage of the polystyrene matrix. Based on these studies, it can be concluded that by suitable selection of the fibre treatment sisal fibre-polystyrene composite with superior dimensional stability and mechanical properties can be developed.

Due to the low density and high specific properties of sisal fibres, composites based on these fibres may have very good potential in the automotive and transportation industry. Moreover, reduced equipment abrasion and subsequent reduction of re-tooling costs will make these composites more attractive. These composites could be used as a value added substitute for conventional and non-structural applications. Thus, it can be concluded that with systematic and persistent research there will be a good scope and better future for sisal fibre–polymer composites in the coming years. The possible weight savings in combination with a comparable stiffness compared to glass fibre reinforcement and environmental advantages of these composites makes them potential candidate for applications such as:

- Parcel shelves
- Instrument panels
- Roof liners

9.2 Future outlook

From the present studies, it is clear that sisal fibre can be used as potential filler for the reinforcement of polystyrene. The resulting composites possess good mechanical, environmental and economic properties and can be used as a good
substitute for wood. However, the following areas of research have to be explored for the better utilization of these composites:

- Microstructure of the interface between the fibre and matrix needs to be investigated by single fibre pullout and fragmentation tests.
- The possibility of producing hybrid composites and sisal-textile-reinforced polystyrene composites should be explored to obtain composites with improved properties.
- Production of composites by other methods such as mat reinforcement and extrusion press moulding should be explored.
- Fracture toughness and fracture mechanism of these composites need more investigation.
- New products based on these composites have to be developed.