Conclusions and Future Outlook

The present study reveals that oil palm fibres represent a potential reinforcement in resole type phenol formaldehyde resin. The main benefits of incorporating oil palm fibres in phenolics are decreased shrinkage, reduced thermal stress during curing, improved impact resistance, stiffness and lower costs. Hybridisation of oil palm fibre with glass was tried to make high performance composites.

Structure and properties of the two important oil palm fibres, OPEFB fibre and mesocarp fibres were analysed. Chemical composition of the fibres was determined. The major constituents of these fibres were found to be cellulose. Lignin content is comparatively low. The OPEFB fibre is more cellulosic than the mesocarp fibre. The oil palm mesocarp fibre contains higher percentage of ether soluble and caustic soda soluble matter. Chemical modification of fibres by alkali treatment, acetylation and silane treatment has been carried out. This is to improve the strength and therefore the reinforcing ability of these fibres. Morphological studies revealed that treatment modified the fibre surface. The fine structural changes of the fibres can be seen from the respective scanning electron micrographs. IR studies give evidence for the chemical modification occurred during treatments. Thermal stability and degradation characteristics of the fibres were investigated by thermogravimetry and differential thermal analysis. It is found that alkali and silane treatments increase the thermal stability of the fibres. Fibres are stable up to 300°C without any considerable weight loss.

The silane treated OPEFB fibre showed maximum tensile strength. Alkali treatment slightly decreases the tensile strength. The Young's modulus of the fibre showed enhancement upon silane and alkali treatments. The strength of the mesocarp fibre is less than that of OPEFB fibre. This is due to the high cellulose content of OPEFB fibre. Silane treatment increases the strength of the fibre while alkali treatment decreases. However, the stiffness of the fibre is increased by both alkali and silane treatments. The untreated mesocarp fibre shows very good elongation. Treatment reduces the elongation of the fibre. Microfibrillar angle and strength of the fibres were theoretically predicted. The theoretical strength of the OPEFB fibre was found to be close to the experimental value. However, in the case of mesocarp fibre, there is great deviation from the theoretical strength. It is important to mention that the properties of oil palm fibres are comparable to other natural fibres and therefore they could be used as a potential reinforcing material for polymer matrices.

Oil palm fibres were incorporated as a reinforcement in phenol formaldehyde matrix. Mechanical performance of the matrix is greatly enhanced by the fibrous reinforcement. Chemical treatment of the fibre leads to composites having excellent impact properties. Oil palm fibre is highly hydrophilic due to the presence of hydroxyl groups from cellulose and lignin. Acetylation, isocyanate treatment, silane treatment, acrylation and acrylonitrile grafting lead to strong covalent bond formation thereby reducing the hydrophilicity of the fibre. The scanning electron microscopy and IR studies revealed the physical and chemical modifications occurred to the fibres. Tensile strength of the fibre declined upon various treatments. However, silane treatment and acrylation enhanced the strength. The brittleness of the fibres decreased upon chemical treatments. The Young's modulus and elongation at break of individual fibres increased upon chemical modifications. Optimum mechanical performance is observed for silane treated and acrylated fibre. Latex modification imparts elasticity to the fibres. The fibre elongation properties show sharp increase upon modifications.

Due to the hydrophilicity of PF resin and oil palm fibre, they are highly compatible. Incorporation of the treated fibres in PF matrix reduces the tensile strength of the composite except for permanganate treatment, which exhibit improved tensile strength. Fibre became more hydrophobic upon modifications that reduce the interaction with PF resin, which leads to a decline in interface properties. Extensibility of the composite considerably increased upon treatment. Maximum elongation is observed for latex coated composites. Tensile modulus of the composite shows enhancement upon mercerisation and permanganate treatment. Scanning electron microscopic studies revealed the tensile failure mechanism. Mercerisation, peroxide treatment, permanganate treatment and acrylonitrile grafting resulted in composites having better flexural properties. Decreased hydrophilicity of the fibres upon chemical modifications resulted in composites having very high impact resistance. Latex coating, acetylation, silane and isocyanate treatments led to high impact composites. This is attributed to the relatively poor fibre-matrix adhesion resulting from the hydrophobicity of the modified fibres. This enables the samples to dissipate maximum energy by mechanical friction during failure process. Debonding of the fibres was facilitated upon various modifications and is evident from the scanning electron micrographs. Major failure processes occurred were found to be fibre-matrix debonding leading to fibre pullout and fibre breakage. Thus by reducing the hydrophilic nature of the oil palm fibre, high impact composites could be obtained from PF resin and oil palm fibre.

Mechanical properties of glass/PF and glass/OPEFB hybrid PF composites were studied. Glass effectively reinforces in PF resin and mechanical performance is maximum at 40wt.% loading. Different volume fractions of glass were added to OPEFB fibre/PF composites. Composite properties such as tensile and flexural behaviour showed considerable enhancement by the incorporation of small volume fractions of glass fibre. The tensile and flexural properties of glass/PF and glass/OPEFB hybrid PF composites were studied from the stress-strain curves. Presence of OPEFB fibre enhances the impact strength of the composites. Maximum value of the impact strength was observed for the hybrid composite containing 0.74 volume fraction of OPEFB fibre. The value is greater than glass reinforced PF composites. By replacing the brittle glass fibre by OPEFB fibre the toughness of the composite could be increased. The tensile and impact fracture mechanisms were evident from the respective scanning electron micrographs. On enhancing the glass fibre loading in glass/PF composites the void content increases and this can be understood from the decreased value of experimental density than the theoretically predicted value. Porosity of the composite decreased upon oil palm fibre reinforcement. Void formation associated with the fibre packing defects is minimised upon oil palm fibre addition. Hardness and density of the composite decrease as the volume fraction of OPEFB fibre increases. Phenol formaldehyde gum sample exhibits maximum hardness. Glass fibre reinforcement decreases the hardness while increasing the density of the composite. Hybridisation of glass fibre with 0.74 volume fraction of OPEFB fibre resulted in composites having superior mechanical performance. Positive hybrid effect is observed in impact properties.

Stress relaxation behaviour of oil palm empty fruit bunch fibre and of the oil palm fibre reinforced phenol formaldehyde composites were studied in detail. Fibre surface modifications were carried out inorder to improve the interface properties. Silane treatment, isocyanate treatment, latex coating, mercerisation, acetylation and radiation treatment were attempted to modify the interface. The effect of these treatments on the relaxation behaviour of the fibre was investigated. Latex coating decreases the rate of stress relaxation of the fibre considerably. Other modifications increase the rate of stress relaxation initially, however the relaxation rate is very low at long durations of time as compared to untreated fibre. Thermal aged and water sorbed oil palm fibres were subjected to stress relaxation experiments. Stress relaxation rate is decreased upon both thermal and water ageing of the fibre. Effect of strain level on the relaxation of the fibre was studied. Rate of relaxation is maximum at 10% strain level. Stress relaxation behaviour in oil palm fibre/PF composites was investigated by giving special emphasis to the effect of fibre loading, fibre treatment, physical ageing and strain level. Higher relaxation is observed for 30wt.% fibre loading. Alkali treated composite showed decreased relaxation than untreated composite. Latex coating and introduction of coupling agents increased the relaxation rate of composites. Latex coated composite exhibits maximum relaxation. This is attributed to the decreased fibre-matrix interaction between the less hydrophilic latex coated fibre and more hydrophilic phenolic resin. Water ageing increased the relaxation of the composites. The variation in the relaxation process of aged composites is due to the changes in the interface properties upon ageing. On application of lower strain, the relaxation was comparatively less and on further increase upto 2%, higher relaxation was observed. At very high strain levels the relaxation again decreased. This may be due to the extent of fibre breakage pattern at different strain levels. Interesting results are obtained upon hybridisation of oil palm fibre with glass fibre. Very low stress relaxation is observed for the hybrid composites. Relaxation modulus of the fibre and the composite was also studied. To explain the long-term stress relaxation behaviour of the fibre and composites with respect to strain levels, a master curve is constructed by superimposing points at different strain levels by a horizontal shift along the logarithmic time axis.

Dynamic mechanical behaviour of the oil palm fibre reinforced PF composites and oil palm fibre/glass hybrid PF composites were investigated. Variations in dynamic modulus, loss modulus and mechanical damping parameter were analysed as a function of temperature and frequency. It is found that incorporation of oil palm fibre increases the modulus and damping characteristics of the neat sample. Irregular trend is observed with fibre length. Maximum damping is observed for 20 and 40mm fibre lengths. As the fibre content increases mechanical damping linearly increases. However maximum stiffness is observed for 30wt.% fibre loading. The loss modulus value decreases with fibre loading. Incorporation of oil palm fibre in PF resulted in decrease of glass transition temperature. Lower Tg values are obtained from E" curve. Effect of fibre modification by mercerisation on the dynamic properties of the composites was analysed. Modification improves the interface properties. Highest value of tanδ is observed for 24hrs mercerised composite. As the frequency increases, the tanδ decreases. Latex treated composite exhibits highest damping behaviour. Glass transition shifts to higher temperature with increase in mercerisation time. Stiffness of the composite also increases with treatment. Dynamic modulus of the oil palm fibre/PF composites is increased by fibre treatments. Irregular trend in the variation of loss modulus is observed with treatment time. Acrylated and latex treated composites show lower loss modulus. Effect of hybridisation of oil palm fibre with glass fibre on the dynamic properties was analysed. Hybridisation increases the damping value. The damping increased with relative volume fraction of oil palm fibre. Glass transition temperature of the hybrid composite is lower than that of the unhybridised composite. The storage modulus and loss modulus decrease with increase in relative oil palm fibre volume fraction in hybrid composites after relaxation. However maximum modulus was obtained for composite having 0.3 relative volume fraction of oil palm fibre. This is due to the better fibre dispersion in hybrid composites at lower loading of oil palm fibre. Gradual decrease in loss modulus of the hybrid composites was observed with increase in frequency.

Activation energy required for the major relaxation processes in different composites during dynamic loading were calculated from the Arrhenius relationship. Activation energy for relaxation at glass transition region for PF gum sample is comparatively low. The value increased upon oil palm fibre reinforcement. As the fibre content increased the activation energy decreased. Highest value is observed for the unhybridised composite having 30wt.% fibre loading and 40mm fibre length. Mercerisation for about 48hrs increases the activation energy due to the increased interfacial adhesion. Except mercerisation and permanganate treatments all other treatments decrease the activation energy for relaxation at glass transition region. Activation energy decreases upon incorporation of glass fibre in hybrid composites. Cole-Cole analysis reveals that the composites are not perfectly homogenous. The long term dynamic behaviour of the composites was predicted by master curve based on time-temperature superposition principle.

Water sorption behaviour of both oil palm empty fruit bunch fibre and oil palm mesocarp fibre has been investigated. Sorption behaviour of distilled water, mineral water and salt water at 30, 50, 70 and 90°C was evaluated. Salt water sorption is slightly different from that of distilled water and mineral water and can be understood from the sorption curves. This is due to the presence of ions in salt water. The OPEFB fibre showed higher sorption than oil palm mesocarp fibre. This may be due to higher number of micropores present on the OPEFB fibre surface than mesocarp fibre which facilitates the capillary action. Scanning electron microscopic studies reveal the porous structure of both the fibres. Both the fibres show a higher initial capillary uptake of water. A decrease in uptake with temperature is observed in all systems except for salt water/mesocarp fibre systems.

At lower temperature a two step behaviour is observed for distilled water and mineral water. The effect of OPEFB fibre treatment on the sorption behaviour in distilled water is studied at different temperatures. Treatment reduces the water uptake at all temperatures. The decrease is due to its physical and chemical changes occured to the fibres upon various modifications. Hydrophilicity of the fibre decreased upon modifications and decreases water uptake. The thermodynamics of sorption were studied in detail. The ΔH and ΔS values are found to be negative for all the systems suggesting the sorption process exothermic. The mechanical performance of the fibres decreases upon water sorption and it regains on desorption. However modulus of the OPEFB fibre decreases on sorption and desorption. In mesocarp fibres modulus shows enhancement upon desorption. Treatment reduces the mechanical strength of the fibres. The elongation of the fibres considerably increased upon treatments except silane. Young's modulus shows enhancement upon mercerisation and silane treatment. In swollen stage the stiffness of the fibre is considerably reduced.

Water sorption characteristics of untreated and treated oil palm fibre reinforced PF composites and oil palm fibre/glass hybrid PF composites were studied. The effects of fibre loading, fibre treatment and relative volume fractions of fibres in hybrid composites on the kinetic and thermodynamic parameters of water sorption were analysed. Water sorption parameters of the composites at four different temperatures 30, 50, 70 and 90^{0}C were investigated and compared. Among the untreated composites, highest sorption of water is found to be for systems containing 10 and 50wt.% fibre loaded composites at 30°C. Fibre surface treatment increases water absorption except in alkali treated composite. Most of the treatments make the fibre hydrophobic, which decrease the fibre-matrix adhesion and facilitate water sorption. The decreased fibre-matrix interface facilitates void formation and can enhance sorption. Latex treated composite exhibits maximum water sorption. In hybrid composites, as the relative volume fraction of oil palm fibres is increased, the water sorption linearly increases. It is found that the unhybridised composites, glass/PF and oil palm fibre/PF exhibit less absorption than hybrid composites.

The kinetic parameters of water sorption, n, k, diffusion coefficient, sorption coefficient and permeability coefficient for different composites were calculated. Untreated composites at all fibre loading exhibit Fickian diffusion mechanism. Fibre surface treatment and hybridisation of oil palm fibre with glass deviate the mechanism from Fickian sorption. The diffusion coefficient is found to be increased with increase in the fibre content of the composites. Fibre modification also lead to high values of diffusion coefficient. In hybrid composites the diffusion coefficient values decrease as the volume fraction of glass is increased. Sorption coefficient is found to be higher at lower fibre loading. Latex treated composites have got higher sorption coefficient. Sorption coefficient in hybrid composites shows irregular trend with temperature. Permeability coefficient shows its highest value for 30wt.% fibre loaded composite. Treatments like silane, isocyanate and acrylation raise the value than untreated composite. Highest value of permeability coefficient in hybrid composites is observed for composite with highest volume fraction of oil palm fibre. Activation energies for the permeation and diffusion processes were calculated. The activation energy for permeation becomes higher than that of diffusion in hybrid composites at higher volume fractions of oil palm fibres. The entropy of sorption is found to be negative in all systems. The diffusion coefficient is found to be concentration dependent of the sorbed water. Upto 30-40wt.% sorbed water, the diffusion coefficient increases and thereafter decreases.

Variations in the tensile, flexural and impact properties on water sorption were analysed. In most cases tensile strength values increased upon water sorption. Scanning electron micrographs of tensile fracture surfaces revealed the changes in the fibre-matrix interaction and failure criteria of the composites before and after water sorption. Stiffness of the composites also increased upon water sorption. However flexural strength and flexural modulus were considerably decreased on sorption. Impact strength values change irregularly among treated composites on water sorption.

Environmental effects on the mechanical properties of oil palm fibre reinforced PF composites have been investigated. Ageing effects were compared with those of glass/PF and oil palm/glass hybrid PF composites. Various fibre modifications were carried out and their effect on the ageing process was studied. Thermal ageing, cold water and boiling water ageing, biodegradation and gamma irradiation effects on the composite properties were analysed. Influence of ageing on the tensile, flexural and impact properties of the composites was investigated. The tensile and flexural stress-strain behaviours of the composites were affected by ageing. The tensile strength of the composites decreased upon thermal, biodegradation and gamma irradiation. However, water ageing did not decrease the properties of the composites and in some cases enhancement is observed. The extensibility of the composites decreased upon thermal ageing. However the value increased upon biodegradation, water ageing and gamma irradiation. Thermal and water ageing increased the tensile modulus of composites treated with silane, peroxide, isocyanate and acrylated samples. Biodegradation decreases the modulus values of all systems. Untreated, alkali and peroxide treated fibre composite show enhancement in tensile modulus values upon gamma irradiation. Various tensile failure processes were studied by scanning electron microscopy. The flexural properties of the composites decreases upon water ageing. Thermal ageing leads to higher flexural properties in composites treated with peroxide, latex and acrylic acid. Izod impact strength of the untreated, acrylonitrile, peroxide and isocyanate treated composites increased upon water ageing. Biodegradation, thermal ageing and gamma irradiation decreased the impact resistance of the composite. Scanning electron micrograph of the impact fracture surface revealed the failure mechanism. Finally the thermal stability of the composites was determined by TG and DTG analysis. The study showed that the untreated oil palm fibre/PF composite is thermally stable upto 350°C without any considerable weight loss. The thermal stability can be improved by hybridising the oil palm fibre with small amount of glass fibre.

Electrical properties of oil palm fibre/PF composites and oil palm fibre/glass hybrid PF composites were studied with special reference to the effect of fibre loading, fibre treatment and hybrid fibre ratio. Volume resistivity, dielectric constant, loss factor and dissipation factor of the composites were analysed. Oil palm fibre reinforcement increased the volume resistivity of PF resin. Fibre treatments enhanced the resistivity of the composites. Hybridisation of oil palm fibre with small amount of glass fibre again increased the electrical resistivity of the composites. The changes in the resistivity values were attributed to the inherent electrical resistivity of lignocellulosic oil palm fibres and the interactions at the fibre-matrix interface. With the increase in frequency, the resistivity of the composites decreased linearly. The incorporation of oil palm fibre decreases the dielectric constant, loss factor and dissipation factor of PF resin. This may be due to the lower dielectric values of lignocellulosic fibres. Changes in the polarisability occurring in the composite determine the dielectric properties. Fibre treatments were found to have great influence in the dipole interaction at the fibre-matrix interface. Hybridisation of oil palm fibre with glass increases the dielectric constant, loss factor and dissipation factor. The changes were due to the decreased compatibility between oil palm and glass fibre layers in hybrid composite. The scanning electron microscopic studies gave insight into fibre-matrix interface.

Thus oil palm fibre reinforcement in phenolic resin results in cost effective and environment friendly composite materials. Hybridisation of glass and OPEFB fibre and their reinforcement in PF resin resulted in lightweight composites having good performance qualities. These composites may find applications as structural materials where higher strength and cost considerations are important. By suitable selection of the composition of the reinforcing fibres, high performance composites having better damping and modulus characteristics can be prepared. This composite will be a value-added substitute for conventional structural materials in engineering applications. Also they can be safely used for structural applications in water environment without sacrificing the mechanical strength. They offer high electrical resistivity, which is the most desirable characteristic of an insulator to resist the leakage of electric current in electrical applications. The composite material prepared could be safely used for high impact applications in building and automotive industry. It will be a good candidate for wall panelling and interior room partitioning as a wood substitute in low cost housing. Oil palm fibre reinforced PF composites are lower in cost compared to particleboards from other natural fibre reinforced polymer composites. Their reinforcement costs are negligible. No complicated processing is needed in the preparation of these composites. This makes them less expensive. Since natural fibres are biodegradable compared to other synthetic fibres, natural fibre reinforced thermoset composites can find application in cars of the coming millennium. Low cost, low density, high strength, biodegradability and eco-friendliness make them outstanding among polymer composites.

Future Scope

In order to evaluate the versatile applicable potential of these composite materials, further investigation in this topic is needed to characterise the various aspects of reinforcement.

Flame Retardant Properties:- As the phenolics are highly heat resistant materials, the flame retardant properties of composites should be studied to assess the suitability of the composite material in thermal environments.

Bio-degradability:- Now-a-days, the non-degradable plastic pollution has emerged as a major issue world-wide. Here comes the importance of added biodegradability to composites. The synthetic matrix part in composites can be made more biodegradable by introducing starch onto the polymers. For high performance applications, these composite materials must have high strength coupled with low density and biodegradability.

Textile Composites:- To explore high strength materials, maximum reinforcing action of the fibres could be achieved. This will lead to the preparation of textile composites. Composites with tailor made properties could be achievable by hybrid textile composites.

Other Hybrid Composites:- Oil palm fibres can be hybridised with other natural fibres or with strain compatible synthetic fibres such as polyethylene fibres to achieve better properties. The reinforcing ability of these fibres in other polymer matrices–both thermoplastic and thermoset–has to be investigated. Based on the specific utility, the best composite can be chosen.