Summary and Conclusion
In recent years, there has been a tremendous advancement in the field of science and technology of short fibre reinforced elastomer composites. The low density, high strength, high stiffness to weight ratio, excellent durability and design flexibility of fibre composites are the primary reasons for their use in many industrial components in aircraft, automotive, marine and other industries. There has been an appreciable increase in applications of composites in sophisticated engineering items. The use of composite materials results in 19% weight reduction compared to an identical aluminium airframe.

Besides aerospace industry, chemical, electrical, automobile and sports industries are the other big users, in one form or another, of composite materials. The important differences in the properties and the behaviour of short fibre composites have lead to the development of many new and unique test methods, manufacturing process and design practices for the fibre reinforced composites. The properties and performance of the short fibre composites depend mainly on (a) type of fibre, (b) fibre content, (c) aspect ratio of the fibre, (d) degree of dispersion of the fibre, and (e) addition of the fibre to the elastomeric matrix. Various natural and synthetic fibre reinforced elastomer composites have been analysed as reinforcement. Sisal is a natural lignocellulosic fibre, which is easily available in South India. This fibre has excellent mechanical properties. It is amenable to physical and mechanical surface modifications. In the present study, a detailed and systematic
investigation has been reported on the use of sisal fibre as reinforcement in one of the most important synthetic rubbers, styrene-butadiene rubber (SBR). The composites were prepared in a mixing mill applying a conventional vulcanisation system using accelerated sulphur system.

The mechanical and processing behaviour of untreated short sisal fibre reinforced SBR composites have been studied in detail. The mechanical properties of short sisal fibre reinforced composite have been analysed as a function of fibre length, fibre orientation and fibre concentration. Fibre length of 6 mm was found to be optimum for best balance of properties. Composites containing longitudinally oriented fibres show superior mechanical performance than that of the transverse orientation. The addition of short sisal fibres to SBR offers good reinforcement and causes improvement in mechanical properties. At 35 phr loading of sisal fibre, composite showed maximum properties and mechanical anisotropy is observed at this loading.

The adhesion between the fibre and rubber can be enhanced by the use of resorcinol-hexa bonding system. The improvement in interfacial interaction between fibre and SBR was substantiated by means of SEM studies. From green strength measurements, the extent of fibre orientation was analysed and found that mix containing 15 phr of fibres has better fibre orientation than other mixes due to the better dispersion of fibres during mixing. The extent of fibre alignment and the adhesion between the untreated fibre and SBR matrix with and without bonding agent have been evaluated by swelling measurements.

The effects of different pre-treatments such as hydration, benzene: alcohol mixture, SBR solution and PS-MA coating and chemical modifications like alkali, benzoylation, acetylation, permanganate, peroxide on the tensile properties of sisal-SBR composites were investigated. While analysing these properties, different hypothetical mechanisms for the reaction between the
fibre and the matrix were evaluated. Alkali treated fibre composites showed better tensile properties than untreated composites due to their rough surface topography and increased aspect ratio.

The SEM photographs also support the strong fibre-matrix adhesion in sisal-SBR composites. Peroxide treated composites showed enhancement in tensile properties due to the peroxide induced grafting. Permanganate treated composites also showed a similar trend due to the permanganate induced grafting. The property increase upon various pre-treatments are in the order: SBR solution > PS-MA coating > benzene: alcohol mixture > salt water treatment > water treatment while by chemical modifications in the order: benzoylation > acetylation > mercerisation > peroxide > permanganate treatment. Of these, the bonding agent added mix showed maximum mechanical properties than all other mixes containing treated fibres due to the strong interface developed by the formation of resin adhesion.

On evaluating the anisotropic swelling nature of the SBR composites, it is seen that bonding agent added mix has the maximum slope value followed by the benzoylated and acetylated mixes respectively. Among the various mixes, the restricted equilibrium swelling value indicates that a good interface bonding and better fibre alignment has occurred in mixes containing acetylated and benzoylated fibres and the bonding agent added ones.

The melt rheological and morphological behaviour of extrudates of short sisal fibre reinforced composites has been analysed in order to evaluate the processability of the composites. The effects of shear rate, fibre loading, temperature and the extent of interface bonding on the viscosity of the system has been examined in detail. The sisal fibres undergo severe breakdown during extrusion. All the system showed pseudoplastic behaviour exhibiting decrease of viscosity with increasing shear rate.
The incorporation of treated fibres increased melt viscosity and the viscosity enhancement was due to the increased interfacial adhesion between the fibre and matrix due to the chemical treatments. Of the various chemical treatments, benzoylated fibre reinforced composites showed maximum viscosity among all mixes. The flow behaviour index of the composites was found to decrease and attain a steady value on increasing the concentration of treated fibres. The relative viscosity of the composites was also found to increase with increase of fibre loading.

The extrudate distortion and die swell behaviour of SBR composites was reduced by the addition of short sisal fibres. Short fibres present in the matrix prevents the shape distortion of the extrudates and the increase in fibre content decreased the shape distortion. Die swell values decreased substantially with the incorporation of short fibres. SEM photographs indicated that the increase of short fibres creates discontinuity in the polymer matrix. The fibres were found to be concentrated more on the periphery at low shear rates and on the core at high shear rates.

On comparison of theoretical melt viscosity with the experimental values, it is seen that the experimental viscosity is greater than the theoretical value as a result of better interfacial adhesion and misalignment of the fibres. Moreover, the variation of relative viscosity of composites with fibre loading at different temperatures and shear rates has been fitted into a second-degree polynomial type equation.

The restricted equilibrium swelling behaviour of the short sisal fibre reinforced styrene butadiene rubber composites has been analysed in order to evaluate the interfacial bonding. The results were reported with a special reference to the effect of fibre loading, bonding agent and fibre orientation. The restriction to swelling of SBR composites exerted by the discontinuous fibres as well as the anisotropy of swelling of the composites is evident from
the results from this study. It is confirmed that for fibre-rubber composites containing bonding agent, the measurement of adhesion value is substantially lower than those of without bonding agent.

A greater restriction to swelling is created by the increase in the volume percent of fibres and the use of the two component dry bonding system consisting of a hexamethylene tetramine and resorcinol. This restriction is evident from the strong interfacial adhesion between the fibre and the SBR matrix.

Swelling parameters such as swelling index and swelling coefficient were evaluated in order to study the effect of lignocellulosic sisal fibres on the swelling behaviour of composites. The fibre orientation developed in the fibre-composite, which is evaluated by using restricted equilibrium swelling measurements, showed that the orientation is not perfectly unidirectional.

In well-bonded composites, swelling takes place mainly in the thickness direction. Thus in mixes having high interfacial adhesion showed swelling in the thickness direction due to the capillary action of the fibres and the presence of voids at the interface of the composite. SEM and optical studies also supported the effect of interfacial adhesion on the swelling hindrance. These studies thus open up new avenues for the improvement of better adhesion between the fibre and the rubber by chemical modification of fibres.

The effects of fibre length, fibre loading, temperature, and frequency on the dielectric behaviour of short sisal fibre reinforced SBR composites have been investigated in detail. The electrical properties such as dielectric constant, volume resistivity and dielectric loss factor of sisal fibre reinforced styrene butadiene rubber composites have been studied as a function of fibre length, fibre content, frequency, chemical modification of fibres and the incorporation of the bonding agent. The increased value of dielectric constant
with fibre length is associated with interfacial polarization, the value of which depends upon the number of interfaces. The increased values of dielectric constants with fibre loading were due to increased orientation and interfacial polarizations. The dielectric constants of treated composites were lower than that of untreated composite due to the decreased hydrophilicity of the chemically modified fibres.

The volume resistivity of composites was found to be decreased with fibre loading but increased with chemical modification of fibres while conductivity of the composites decreased with chemical treatment due to the reduction of polar groups in the treated fibres.

The dielectric dissipation factor of composites was found to increase with increase of fibre loading due to the increase in polar groups. Chemically treated fibre composites does not affect the relaxation mechanism, but increases the relaxation magnitude at each frequency. Moreover, these composites could be successfully used in antistatic applications to dissipate the static charges.

The dynamic mechanical thermal properties of short sisal fibre reinforced SBR composites were investigated using Dynamic mechanical thermal analyser. The properties were studied with special reference to the effect of fibre length, orientation, concentration, chemical treatment and bonding agent as a function of temperature and frequency. The storage modulus, $E'$, was found to increase with increase in fibre length, up to 6mm followed by a decrease. This is due to the effective stress transfer between the fibre and the matrix at the critical fibre length of 6mm. Higher fibre length beyond 6mm leads to entanglements and dispersion problems.

The effect of volume percent of fibres on the dynamic properties was analysed. It is seen that by the addition of 17.7 volume percent of fibres, the effective reinforcement takes place and the stress transfer becomes very
efficient and this provides better strength characteristics. This is shown by the increase in $E'$, $E''$ and tan$\delta$ values of the composites with increasing concentration of fibres.

Different chemical treatments were carried out to improve the adhesion between the fibre and the matrix. Among the chemically modified systems, the bonding agent incorporated mix showed the highest storage modulus. The storage moduli varied in the order: untreated $<$ NaCl $<$ NaOH $<$ acetylation $<$ benzyolation $<$ bonding agent. The interface properties have been investigated by increasing the temperature and frequency. Dynamic moduli increased with increasing frequency due to the reduced segmental mobility. The changes in visco-elastic properties with concentration of fibres can be correlated with the morphology of composites. Composites containing longitudinally oriented fibres showed higher modulus than others due to the effective stress transfer between the matrix and fibres.

Time-temperature super position curve was drawn by shifting the curve at a particular temperature to the reference temperature in order to understand the visco elastic behaviour of the material outside the used frequency range. Finally, the cole-cole analysis indicated the heterogeneous nature of the composite.

The thermal behaviour of sisal fibre and the composites has been studied by DSC and TGA with a special reference to fibre concentration, chemical modification of fibres and the incorporation of bonding agent. In the case of sisal fibre at a temperature range of 30-180°C lignin is degraded and at 350°C most of the cellulose is decomposed. The chemically treated fibres showed higher thermal stability than the untreated one. Of the various chemically treated fibres, the benzyolated fibre showed higher thermal stability.
The decomposition of SBR takes place at a temperature of 414°C. In sisal/SBR composites, two peaks were obtained. The minor peak at 494.09°C corresponds to the degradation peak of SBR and major peak at 601.82°C corresponds to the degradation to end products, i.e., the thermal stability is increased in composites due to fibre-rubber interactions.

It was found that the optimal interaction exerted by the chemical treatments makes the composite more mechanically and thermally stable than the untreated fibre composites. The remarkable thermal stability was observed up to 640°C, after which there was a sharp decrease in weight. Thermal decomposition temperature increases as the fibre content increases. The thermal decomposition temperature of treated composites is higher than that of the untreated composites. At 500°C, about 60-80% of the material gets degraded in the case of untreated composites, while 30-50% of the material gets degraded at 610°C in treated ones. Kinetic parameters such as energy of activation, pre-exponential factor and the entropy of activation were also analysed.

DSC studies indicated two distinct $T_g$s corresponding to the transitions of rubber phase and fibre phase. This indicates that the system is heterogeneous and phase separated in all cases.