CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 INTRODUCTION

Vehicles are ubiquitous to modern civilization without them civilization would almost come to stand still, tire are perhaps the most important components of vehicles. In road transport vehicle is powered by petroleum fractions (petrol / Diesel / CNG) that exhaust CO_2 which is perhaps the most singular green house gas responsible for global warming. One of the major concerns of civilization is CO_2 emission. Higher is the fuel consumption more is the emission.

Tire rolling resistance plays an important role in fuel consumption. 20% reduction of tire rolling resistance can save 5% fuel. In the last 20 years, reduction of 20% tire rolling resistance was achieved by the introduction of silica technology. Ever since the introduction of the low rolling resistance tire "green" tire, silica is being used more and more as reinforcing filler in tire applications. Silica when compared to carbon black strongly reduces the rolling resistance of a tire, which in turn leads to a lower fuel consumption of the automobile.

To meet the requirements of European Union (EU) regulation on tire labeling by 2012, silica technology is not enough to meet the target and new technologies are the need of the day.

This investigation was undertaken to make an attempt to address these pressing issues. In this investigation composites based on nano clay (organoclay) were formulated and their efficiency was tested as true tread material for both passenger car radial (PCR) and truck bus radial (TBR) tires. The significant findings and conclusions are listed below sequentially.

8.2 PREPARATION AND CHARACTERIZATION OF NANOCOMPOSITES BASED ON ORGANOCLAY AND BLENDS OF DIFFERENT TYPES OF SBR WITH BR

i. Organoclay has poor dispersibility in SBR/BR rubbers hence a compatibilizer XNBR was required to be used for appropriate dispersion of the filler.

ii. The mechanical and dynamic mechanical properties of the investigated rubber nanocomposites improved as the carboxyl content in XNBR increased.

iii. Among the three mixing techniques used in this investigation internal mixing resulted in the best properties. Moreover, this method is very convenient for industrial applications. The solution method provided better properties than 2 roll mill mixing but removal of solvent was difficult, time consuming and therefore not feasible for industrial applications where as, mixing of clay in 2 roll mill was quite difficult.

iv. For SBR/BR=70/30 blends, the optimum dosages of organoclay and XNBR were found to be 6 and 10 phr respectively.

v. Among three types of SBR investigated, ESBR showed the best mechanical properties followed by SSBR and FSSBR.

vi. All SBR nanocomposites showed slightly lower glass transition temperature and lower Tan δ values at Tg compared to their corresponding gum counter parts in dynamic mechanical testing.

vii. TEM images of SBR nanocomposites prepared by all three mixing technique exhibited mixed intercalated and exfoliated structure of layer silicate in the matrix; however internal mixer showed the best exfoliated morphology.

viii. XRD investigations also supported the intercalated and exfoliated morphology of nanocomposite which was evidenced by the increase of d-spacing of layer silicate and reduction of peaks intensity.

ix. Although organoclay nanocomposite showed excellent mechanical properties but hardness, modulus and other performance properties such as abrasion resistance, tear strength were not sufficient for tire tread application. Further research is required in this field to improve these properties.

8.3 DEVELOPMENT AND CHARACTERIZATION OF HIGH PERFORMANCE NANOCOMPOSITES BASED ON DUAL FILLER SYSTEM AND BLENDS OF DIFFERENT TYPES OF SBR WITH BR

i. Nanocomposites based on SBR/BR blends with organoclay showed remarkable improvement in mechanical properties like hardness, modulus, tensile strength, elongation at break, breaking energy and tear strength compared to gum vulcanizate.

ii. To meet the requirements of tire tread, nanocomposites were developed with organoclay-carbon black and organoclay-silica dual filler systems based on SBR/BR blend using 7% carboxylated nitrile rubber (XNBR) as compatibilizer.

iii. The dual filler nanocomposites showed excellent mechanical properties and are well within the target performance range of passenger car radial tire tread compounds. These blend with dual filler system nanocomposites also fulfilled the requirement of abrasion properties; wet traction and dry traction which are very important for PCR tread application.

iv. Since nanocomposites contain much lower dosage of filler, they show lower hysteresis loss which was reflected in lower Tan δ values at 60°C.

v. Nanocomposite based passenger car tread compounds showed lower rolling resistance without sacrificing other performance parameters like mechanical properties, tear properties, wear properties, wet traction and dry traction.

vi. The properties achieved by dual filler nanocomposites with reasonably small amount of the filler content are close to commercial tread compounds that are highly loaded with fillers.

vii. This investigation revealed the potential of nanocomposites could be used as high performance passenger car radial tread to reduce rolling resistance and improve fuel economy in automotive transport.

8.4 PREPARATION AND CHARACTERIZATION OF NANOCOMPOSITES BASED ON NR/BR BLENDS AND ORGANOCLAY.

Investigations on nanocomposites of NR/BR (70/30) with organoclay (Closite®15A) using XNBR as a compatibiliser reveals the following:

i. NR/BR blends are usually used to formulate TBR tire tread compounds. It was observed that using organoclay as the filler all mechanical properties like modulus, tensile strength and elongation at break increased as the carboxyl content of XNBR increased from NB1(1% carboxyllation) to NB7 (7% carboxyllation). As carboxyl % in XNBR increases, the surface energy of the rubber increases which leads to higher interfacial interaction between filler and polymer (Das *et al*, 2008).

ii. The mixing technique used also influences the organoclay dispersion and ultimately the mechanical properties. Internal mixer lead to the best clay dispersion and mechanical property enhancement followed by solution mixing and 2 roll mill. The mixing temperature (140°C) and high shear force in internal mixer has influence on the filler-polymer interaction which may be the reason for better clay dispersion and properties of nanocomposite compared to solution and 2 roll mill mixing.

iii. The NR/BR-organoclay nanocomposite with 7 phr organoclay was found optimum as it exhibited the best physical properties like hardness, modulus, tensile strength, elongation at break and dynamic mechanical properties. The XRD study of the same nanocomposite reveals the silicate layers were expanded. TEM image also shows the intercalated and exfoliated morphology of the nanocomposite.

iv. The strong interfacial interaction between highly polar XNBR and organoclay played an important role in clay dispersion with in the rubber matrix. Strong interaction between carboxyl group and polar organoclay formed a thermodynamically stable composite and help clay dispersion when mixed with rubber.

8.5 DEVELOPMENT AND CHARACTERIZATION OF HIGH PERFORMANCE NANOCOMPOSITES BASED ON NR/BR BLENDS AND DUAL FILLER SYSTEM

i. Nanocomposites based on NR/BR blends with organoclay showed excellent improvement of mechanical properties when compared with gum vulcanizate for example in the nanocomposite having NR/BR 70:30 and 7 phr organoclay there was 93 % enhancement in 300% modulus; 68% in Tensile strength; 47% in tear strength and 136% in Breaking Energy.

ii. In spite of remarkable improvement of the above mentioned properties, organoclay nanocomposite did not fully meet the requirements of TBR tread compounds because for TBR tire tread applications, hardness, low strain modulus as well as abrasion resistance are very important.

iii. To meet these requirements, nanocomposites based on NR/BR blend were developed with organoclay-carbon black and organoclay-silica dual filler systems. The dual filler nanocomposites showed excellent mechanical properties which are comparable to commercial tread (Control) compounds and also fulfilled the requirements of Hardness, Modulus, Abrasion resistance and Tear strength for tread application. They meet the target performance range for TBR tread compounds.

iv. Tan δ at 60°C indicates lower rolling resistance of the compound and lower the value lower is the rolling resistance. The reduction organoclay-carbon black nanocomposite (NC-20) had 45% less Tan δ_{max} compared to Control-3. Similar reduction of Tan δ_{max} (40%) was observed in organoclay-silica nanocomposite (NS-20) in comparison with Control-4. This clearly shows dual filler nanocomposite (NC-20 and NS-20) will give much lower rolling resistance in tire without sacrificing other performance parameters like mechanical properties, tear properties, wear properties and traction.

v. This investigation revealed the potential of nanocomposites which in future could be used as TBR tire tread to reduce rolling resistance and improve fuel economy in commercial automotive transport.

8.6 ROLLING RESISTANCE SIMULATION OF TIRES USING STATIC FINITE ELEMENT ANALYSIS

i. To investigate tire rolling with the help finite element analysis, a rolling resistance software "***RR code***" was developed and validated with standard tire. One of most practical way to predict rolling resistance of tires using standard finite element analysis was adopted in this investigation. A rolling resistance software "***RR code***" was developed keeping focus on three requirements: (1) easy input data preparation, (2) shorter computation time, and (3) adequate accuracy.

ii. The method implements a steady state rolling simulation (3D non linear elastic analysis using Abaqus software) first and then the strain energy and principal strains thus obtained, together with the loss factors (Tanδ) of the materials determined separately in the laboratory, are used to estimate the energy dissipation of a rolling tire through post processing. In this method loss properties are updated as a function of strain and temperature. Elastic tire simulation was carried out using commercial finite element code Abaqus. The simulation includes several steps like (a) FE tire model generation, (b) Material parameter identification, (c) Material modeling and (d) Steady state rolling simulation

iii. A temperature equation was developed to capture non linear behaviour of Tan δ with variation of dynamic strain and temperature. This equation updates Tan δ value at any strain and temperature during computation of dissipation energy through iterative process. This simulation tool can be used for studying the relationship between compound and design variables and the rolling resistance of tires.

iv. As loss energy representing tire rolling resistance is temperature depended and during service tire gets heated due to conversion of loss energy into heat and reaches a steady state, hence tire temperature distribution in tire to be captured to get accurate rolling resistance value. The temperature distribution in the tire was simulated using standard ABAQUS heat transfer simulation.

8.7 INVESTIGATIONS ON ROLLING RESISTANCE OF NANOCOMPOSITE BASED PASSENGER CAR RADIAL TIRE TREAD COMPOUNDS USING FE SIMULATION TECHNIQUE

i. Prediction of rolling resistance using finite element analysis is a very useful technique which is less expensive and fast and does not require any test tire. This simulation technique would be very useful to improve compound formulations as well as tire design in terms of rolling resistance in the design stage.

ii. In organoclay –carbon black nanocomposites (SC-25 and FC-32) the average reduction of rolling resistance was ~22% compared to carbon black based commercial passenger car tread compound (Control-1).

iii. Similarly ~18% reduction of rolling resistance was observed in organoclay-silica nanocomposites (SS-25 and FS-25) over silica based commercial passenger car tread compound (Control-2).

iv. The difference in rolling resistance between measured and simulated values of Control compounds is attributed to the difference in parameters such as aerodynamic drag, hysteresis loss of reinforcement and environmental conditions which were not incorporated in simulation. Approximately 90% correlation between measured and simulated values is observed which is reasonably precise from simulation perspective.

v. 20% reduction in rolling resistance saves 5% fuel consumption, hence PCR having 18 to 22% less rolling resistance with tread compound with nanocomposite in comparison commercial PCR tread would save around 5% fuel from being consumed.

8.8 INVESTIGATIONS ON ROLLING RESISTANCE OF NANOCOMPOSITE BASED TRUCK BUS RADIAL TIRE TREAD COMPOUNDS USING FE SIMULATION TECHNIQUE

i. Rolling resistance of all three tires; 10.00R20, 295/80R22.5 and 315/80R22.5 with commercial carbon black tread (Control-3) and silica tread (Control-4) were experimentally measured in the drum type rolling resistance testing equipment as well as computed through finite element simulation using *RR Code*. The correlation between measurement and simulation were 94% in 10.00R20, 92% in 295/80R22.5 and 91% in

315/80R22.5. In general more than 90% correlation between simulation and measurement is considered to be very good.

ii. The rolling resistances of all three tires with organoclay-carbon black nanocomposite tread (NC-20) show much lower rolling resistance when compared with their corresponding counter part with commercial carbon black tread (Control-3). The improvement of 37.1% rolling resistance is the highest in 10.00R20 followed by 295/80R22.5 where it is 34.4% and 315/80R22.5 is also very close having value of 32.8%.

iii. Similarly, the improvement of rolling resistances of 10.00R20, 295/80R22.5 and 315 80 R 22.5 tire with organoclay-silica nanocomposite tread (NS-20) when compared with their corresponding sizes with commercial silica tread (Control-4) are 35.2%, 32.8% and 34.4% respectively. In both the cases, the maximum improvement is observed in 10.00R20, however, improvement in 295/80R22.5 and 315/80R22.5 are very close.

iv. In TBR tire average reduction of rolling resistance with nanocomposite tread is ~34.5% which would save ~ 8.6% fuel consumption and reduce environmental pollution. Introduction of silica filler in place of carbon black ~5% reduction of rolling resistance has been achieved. Therefore, dual filler nanocomposites are the future tread compound for extremely low rolling resistance highly fuel efficient truck bus radial (TBR) tire.

The primary objective of development of nanocomposites that can match the prevalent tire tread compounds in term of physical properties while returning much lower rolling resistance without sacrificing other requirements viz. Wet traction, Dry traction, Wear, etc was made. The nanocomposites used as tread show ~20% less rolling resistance in PCR tire which accounts for 5% saving in fuel consumption and ~35% lower in TBR tire which also accounts for ~8.5% fuel saving and reduction of CO_2 emission to save environment.

The secondary objective of prediction of rolling resistance during the design stage through finite element simulation was also made. The good correlation ~90 - 95% was observed between measured and simulated rolling resistance. Using simulations, rolling resistances of tire tread with nanocomposites were predicted with reasonably good accuracy.

8.9 FUTURE WORK

One of the main goals in this project was to develop low rolling resistance passenger car tire tread with SBR/BR-dual filler nanocomposite and truck bus radial tire tread with NR/BR-dual filler nanocomposites. With the newly developed nanocomposite ~ 20-25% reduction of RR in PCR tire and ~30-35% in TBR tire was observed with the help of simulation. However there is ample scope to continue this work further. Some aspects that may be addressed in future are;

i. Produce tire with nanocomposite tread and carry out the indoor testing like endurance, rolling resistance, force and moment and wear characteristics. Presently very high cost of nanoclay is one of the major concerns for its commercial application in tire. In future price of nanoclay may decrease and can find its application in low rolling resistance tire production.

ii. Modification of clay so that no compatibilizer is required especially in SBR

iii. Modification of rubber to have better compatibility with nanoclay

iv. Direct mixing of nanoclay along with conventional filler like carbon black and silica in industrial Banbury mixer.

v. Study of mixing conditions like temperature, rotor speed and mixing time on clay-rubber interaction and investigation of clay exfoliation by TEM and XRD.

This work is the beginning of new era to develop extremely low rolling resistance PCR and TBR tire to reduce CO_2 emission and save precious fuel as well as environmental damage.