CHAPTER 7

PREDICTION OF ROLLING RESISTANCE OF PCR AND TBR TIRES WITH NANOCOMPOSITE TREADS USING FINITE ELEMENT SIMULATION

At a constant speed of 100 km/h a passenger car needs ~50% of its fuel to overcome rolling resistance and the rest of the fuel is used to overcome air drag whereas at a constant speed of 80 km/h a truck needs ~40% of his fuel to overcome rolling resistance. This indicates the importance of tire rolling resistance on fuel consumption. Tire rolling resistance is greatly influenced by viscoelastic behaviour of rubber. Approximate 90% of tire rolling loss may be attributed to hysteresis loss of rubber components and tread rubber alone is responsible for ~40% (Willet 1973, 1974). The different rubber components have its own contribution for tire rolling resistance; tread rubber is a major contributor followed by inner liner and apex in passenger car tires.

Fig. 7.1- TBR tire RR measurement

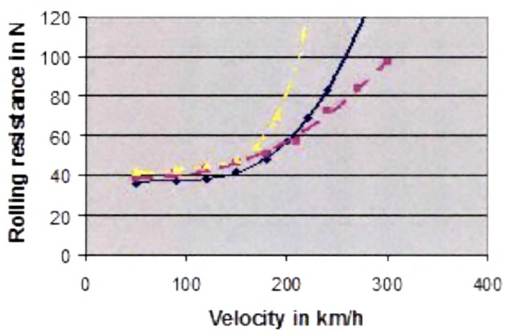

Fig.7.2- PCR tire Speed versus RR

Fig. 7.1 shows the measurement of rolling resistance of TBR tire on rotating drum. At higher speed, tire has higher rolling resistance as shown in Fig. 7.2.

Nanocomposites based on 70/30: SBR/BR blend and dual filler systems were developed for PCR tread application. These nanocomposites show much lower Tan δ at 60°C indicative of low tire rolling resistance when compared with commercial PCR tread compound (Control-1 and Control-2). Similarly nanocomposites based on 70/30: NR/BR have been developed for TBR tread application which also show much lower Tan δ at 60°C when compared with commercial TBR tread compounds (Control-3 and Control-4). The Tan δ at 60°C provides qualitative indication on compound rolling resistance but do not give any quantitative information on rolling resistance in tire. The rolling resistance of nanocomposite tread compounds in the tire could be predicted by using finite element simulation as described in Chapter 6.

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

Tire rolling resistance is very important parameter in passenger car tire as it is responsible for 25% fuel consumption at average speed of 60 kmph. Lower rolling resistance saves a lot of fuel and protects the environment by lowering greenhouse gas emission. European Union has introduced strict norms for tire rolling resistance with effect from 2012. To meet the regulation, further reduction of rolling resistance through innovative tread compound is the need of the hour.

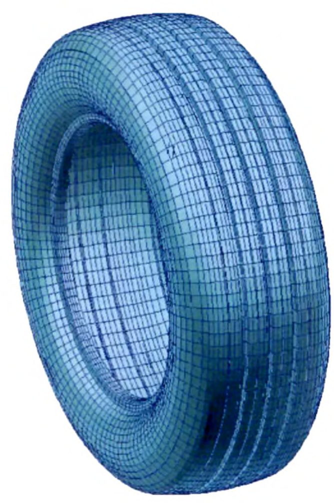

Fig. 7.3- PCR tire model with meshing

To achieve these requirements, nanocomposites based on 70/30: SBR/BR with organoclay-carbon black and organoclay-silica dual filler system were developed. In this investigation commercial carbon black based tread (Control-1) compounds and silica based tread (Control-2) were taken for reference. Tires with Control compounds as well as with nanocomposites were simulated and tire rolling resistances were computed. Rolling resistance of organoclay-carbon black (SC-25 and FC-25) nanocomposites were compared with Control-1 and organoclay -Silica nanocomposites (SS-25 and FS-25) with Control-2.

7.1.1 Mechanical properties

The mechanical properties like hardness, modulus, tensile strength and elongation at break of the nanocomposites are presented in Table 7.1. The typical range of mechanical properties of passenger car tire tread compounds are also listed in the same Table. Mechanical properties of all the nanocomposites were within the typical performance range of passenger car tread compound. The improvement of properties with dual filler system is much more when compared to the individual filler contribution. Dual fillers had synergistic effect in the nanocomposite which resulted in better exfoliation of organoclay, thereby providing superior reinforcement and excellent mechanical properties.

Table 7.1-Mechanical properties of nanocomposites

Compound Reference	100% Modulus (MPa)	Tensile Strength (MPa)	Elongation at Break (%)	Hardness (Shore A)
Target→	(1.5 – 2.5)	12.5 min	350 min	(60 – 70)
Control-1	*1.96*	*18.9*	*510*	*66*
SC 25	1.77	14.5	483	62
FC 25	1.80	14.8	460	62
Control-2	*1.85*	*19.1*	*500*	*65*
SS25	1.61	14.0	484	62
FS 25	1.60	13.0	452	61

7.1.2 Hyper-elastic material properties

Hyper-elasticity is used to model a material the exhibits nonlinear, but reversible, stress strain behavior even at high strains. Properties of rubber material are;

a) large deformation, finite strains
b) Incompressible/ nearly incompressible
c) Final deformation state doesn't depend on load path, load-history
d) Isotropic

Most material models in commercially available finite element analysis codes are designed to describe only a subset of the structural properties of rubber. Stress-strain curves obtained from experiments done at different mode of deformation such as uni-axial, pure shear and bi-axial are fitted to calibrate the material model. The conditions, under which the stress-strain curves are created, are not defined by the material model. Hyper-elastic material properties of Control compounds and nanocomposites are shown in Fig. 7.4.

Hyper-elastic material properties have a great influence on FE elastic simulation results. Control compound had higher stiffness compared to all nanocomposites, however Control-1(CB tread) is stiffer than Control-2 (Silica tread). Lower stiffness of nanocomposites is due to much lower loading of fillers. Organoclay - carbon black nanocomposites (SC-25 and FC-25) showed slightly higher stiffness than organoclay-silica nanocomposites as observed in hyper-elastic stress-strain behaviour. The experimental stress-strain data was fitted in Yeoh's material model implemented in "***Abaqus software***" and hyper-elastic material constants for all the compounds were determined as shown in Table 7.2.

Table 7.2-Yeoh's hyperelastic material constant

	C10	C20	C30	D1
Control-1	0.6541	-0.5738	0.5102	0.0308
SC-25	0.6201	-0.5973	0.5028	0.0325
FC-20	0.5836	-0.5040	0.3994	0.0345
Control-2	0.8202	-0.8605	0.6972	0.0245
SS-25	0.5252	-0.4247	0.3360	0.0383
FS-25	0.5410	-0.3932	0.2970	0.0372

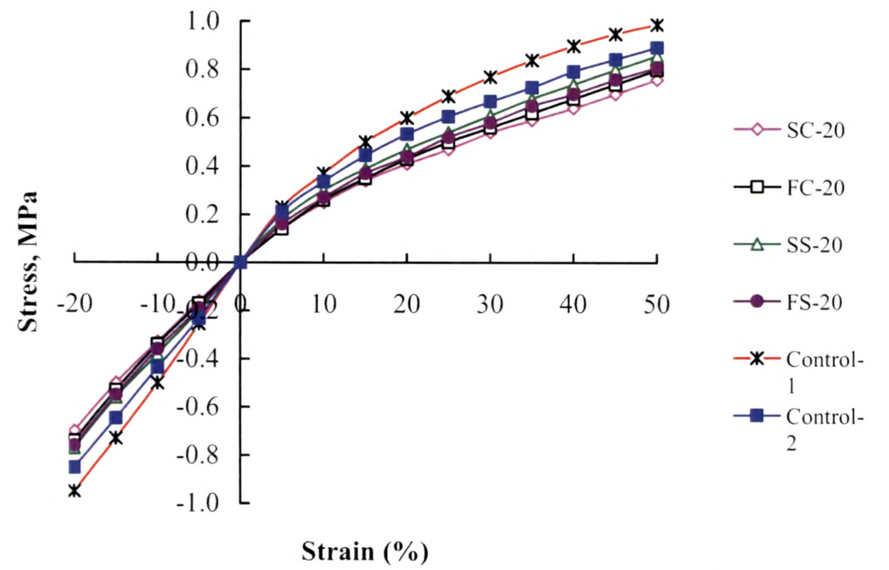

Fig. 7.4- Hyperelastic stress-strain properties of nanocomposites and Control compounds

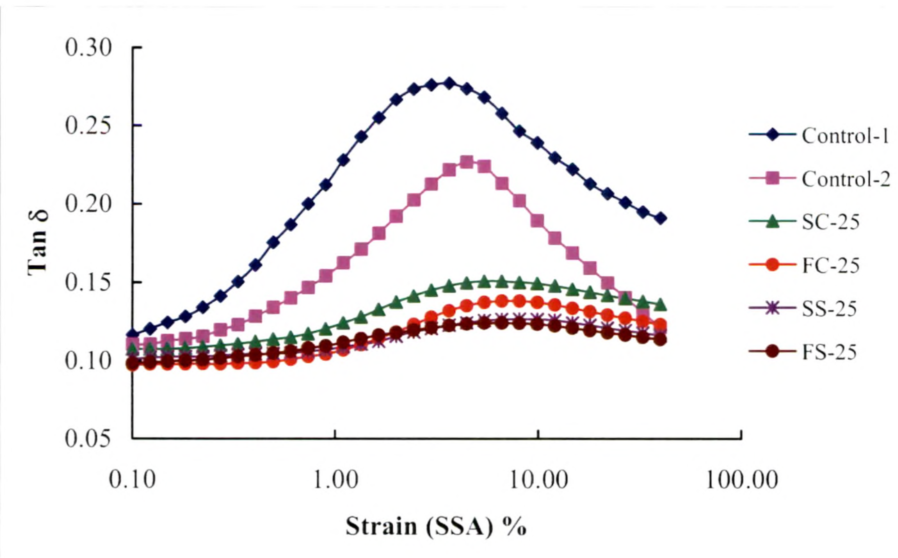

Fig. 7.5- Tan δ versus strain at 10 Hz and 60°C

7.1.3 Viscoelastic Material Properties

During strain sweep, nanocomposites showed much lower Tan δmax compared to the corresponding Control compounds as shown in Fig. 7.5. This behaviour was attributed to lower Filler-filler interaction (Payne's effect) in nanocomposites compared to the respective Control compounds with conventional fillers like carbon black and silica.

7.1.4 Computation of Rolling Resistance

The passenger car radial tires; 205/60R15 and 155/70R14 were investigated for rolling resistance. Rolling resistance of both the tires with carbon black and silica tread were measured in Drum type RR testing equipment and are shown in Table 7.3.

Table 7.3-Rolling resistance of tire with Control compounds at RR M/c.

Tire Size	Load (N)	Pressure (kPa)	Average Rolling Resistance (N)	
			Control- 1	Control- 2
205/60R15	6033	240	52.9	45.6
155/70R14	2827	240	30.7	23.6

Finite element simulation was carried out with both the tire 205/60R15 and 155/70R14. The 2D simulated tires cross-section and foot print of 205/60R15 are presented in Fig. 7.6 and 7.7.

Two Control compounds (Control-1 and Control-2) and four different nanocomposite treads SC-25 and FC-25 (organoclay-carbon black nanocomposites with 70/30, SSBR/BR and FSSBR/BR blends respectively) and FC-25 and FS-25 (organoclay-silica nanocomposite with 70/30, SSBR/BR and FSSBR/BR blends respectively) were used as tread compounds in tire. Rolling resistance of all the compounds were computed through simulation using *RR Code* and presented in Table 7.4 and 7.5.

The reductions of RR of nanocomposites of SC-25 and FC-25 against Control-1 were 21% and 24.9% respectively. Nanocomposite FC-25 (functional Solution SBR) showed more improvement in rolling resistance than nanocomposite SC-25 (Solution SBR). Similarly, the reductions of rolling resistance of nanocomposites of SS-25 and FS-25 against Control-2 were 17.1% and 18.9% respectively. Nanocomposite FS-25 (functional solution SBR) showed more improvement in rolling resistance than nanocomposite SS-25 (solution SBR).

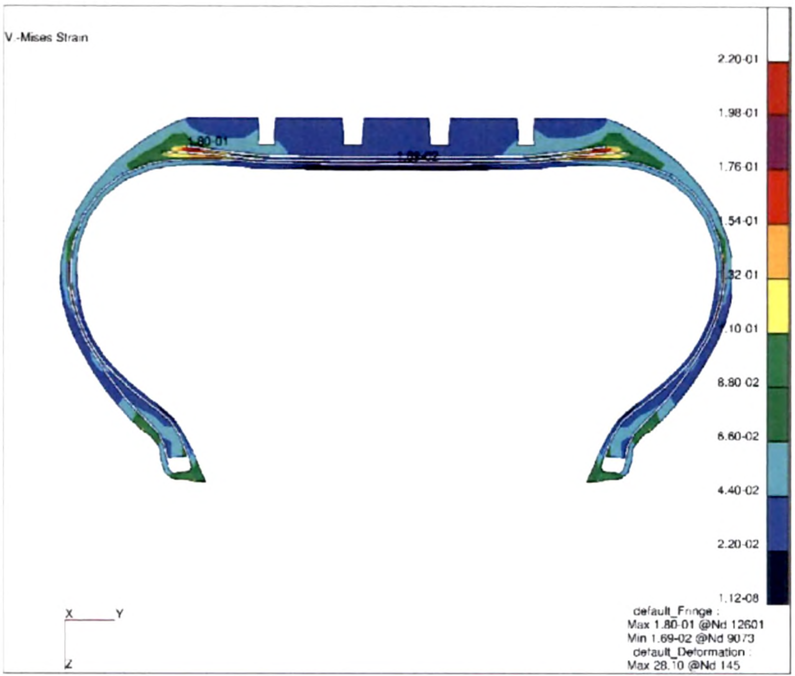

Fig. 7.6- 2D Finite element tire (205/65R15) cross section

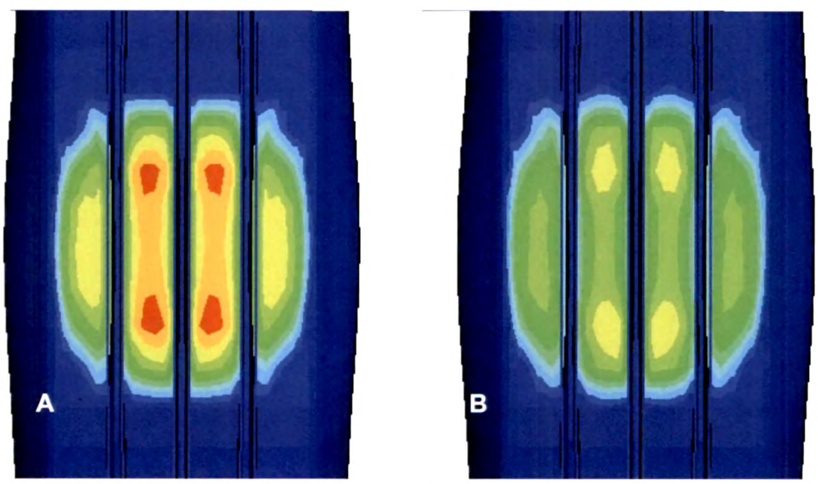

Fig. 7.7- Footprint of PCR tire (A) with silica based commercial tread compound (Control-1) and (B) with organoclay-silica dual filler nanocomposite (SS-25) tread compound

Table 7.4-Rolling resistance by simulation of organoclay –carbon black nanocomposites and Control-1

	Tire Size: 205/60R15			Tire Size: 155/70R14		
	Dissipated Energy (J)	Rolling Resistance (N)	% Reduction	Dissipated Energy (J)	Rolling Resistance (N)	% Reduction
Control 1	98.6	49.7		58.3	29.4	
SC-25	79.8	40.3	19.1	46.2	23.3	21.0
FC-25	75.7	38.2	23.2	43.8	22.1	24.9

Table 7.5-Rolling resistance by simulation of organoclay -silica nanocomposites and Control-2

	Tire Size: 205/60R15			Tire Size: 155/70R14		
	Dissipated Energy (J)	Rolling Resistance (N)	% Reduction	Dissipated Energy (J)	Rolling Resistance (N)	% Reduction
Control 2	88.9	44.8		45.0	22.7	
SS-25	73.9	37.3	16.8	37.3	18.8	17.1
FS-25	72.7	36.7	18.2	36.1	18.2	19.8

This investigation revealed that reduction of rolling resistance was more in case of organoclay – carbon black nanocomposites compared to organoclay-Silica nanocomposites from their respectively Control compounds. Filler-filler interaction (Payne's effect) in silica/silane system is less compared to carbon black with equal filler dosages in the compound. Replacement of equal amount carbon black or silica by small quantity of organoclay from their respective compound would lead to more reduction in Payne's effect in carbon black compound than silica compound. Higher reduction of rolling resistance in organoclay –carbon black nanocomposite from Control-1 could be attributed to higher reduction of filler-filler interaction in this compared to organoclay -silica nanocomposite.

7.1.5 Conclusions

- 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.

- 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).

- 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).

- 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.

- 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.

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

At a constant speed of 80 km/h a truck needs ~40% of its fuel to overcome rolling resistance and rest 60% is consumed to overcome aerodynamic drag. Energy efficient tires having 20% less rolling resistance in comparison to conventional tires reduces the fuel consumption by ~5%. Improvement of 10 % rolling resistance will lead to ≈ 2 g/km less CO_2 emission

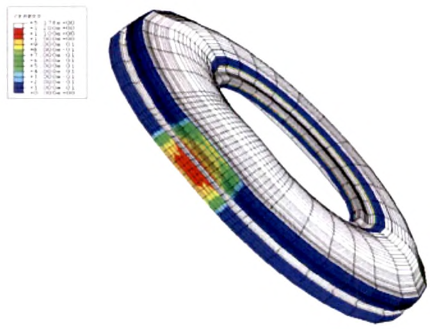

Fig. 7.8- Simulated TBR half tire model

To fulfill the requirements, nanocomposites based on 70/30: NR/BR blends with organoclay-carbon black and organoclay-silica dual filler system were developed. In this investigation commercial carbon black based TBR tread (Control-3) compounds and silica based tread (Control-2) were taken for reference. Tires with Control compounds as well as with nanocomposites were simulated and tire rolling resistances were computed. Rolling resistance of organoclay-carbon black nanocomposite (NC-20) was compared with Control-1 and organoclay-silica nanocomposite (NS-20) with Control-2.

7.2.1 Mechanical properties

The mechanical properties of tire tread rubber like hardness, modulus, tensile strength and elongation at break are critical for tire performance. Beside mechanical properties, abrasion loss, tear properties, hysteresis loss and dynamic properties play vital role in determining tire performances such as tire wear, durability, traction and rolling resistance. The performance properties of nanocomposite treads; NC-20 and NS-20 were compared with respective carbon black tread (Control-3) and silica tread (Control-4) as shown in Table 7.6. The typical range of commercial truck bus radial tread compound properties are also included in Table-7.4 for comparison purpose.

Table 7.6-Mechanical properties of nanocomposites

Properties	Typical range	Control-3	NC-20	Control-4	NS-20
Hardness, Shore A	60 - 70	66	64	64	62
100% Modulus, MPa	1.5 - 2.5	1.82	1.72	1.62	1.50
300% Modulus, MPa	6.0 - 10.0	9.16	7.10	8.32	6.39
Tensile Strength, MPa	22.0 min	23.2	25.8	24.9	28.0
Elongation at Break, %	420 min	554	651	596	646
Tear Strength, N/mm	65 - 110	81.0	68.5	107.0	70.1
Abrasion Loss, mm^3	70 - 110	88.0	94.0	99.0	106.0
Heat Build Up (ΔT), ^{o}C	20 - 30	28.0	18.0	26.0	16.0

Mechanical properties of the nanocomposite tread NC-20 are close to Control-3 and are well within the typical range of TBR commercial tread compounds. The nanocomposite tread NC-20 showed slightly lower hardness, modulus and tear strength than Control-3 but higher tensile strength, elongation at break and much lower heat build up indicate much lower hysteresis loss. The abrasion loss of NC-20 is slightly higher than Control-3 which indicates slightly lower mileage from nanocomposite tread. Nanocomposite tread NS-20 also exhibited the similar trend in properties like NC-20 when compared to Control-4. Lower modulus could be explained by the lower loading of filler in nanocomposite tread than carbon black and silica tread. Higher tensile strength in the nanocomposite is due to higher reinforcement and less hindrance in strain induced crystallization when stretch during tensile test.

7.2.2 Hyper-elastic material properties

For tire elastic simulation, hyperelastic material properties of rubber is required in finite element model. The material properties have a great influence on simulation results. Nanocomposite based tread compound NC-20 showed slightly lower stiffness both in tension and compression mode than Control-3. Similarly, NS-20 organoclay-silica dual filler nanocomposite also showed slightly lower stiffness than Control-4. The lower stiffness of nanocomposite tread compounds is due to the presence of lower volume fraction of filler (25 phr) compared to carbon black or silica treads having 50 phr filler loading. Hyperelastic stress-strain properties of Control compounds and nanocomposites are shown in Fig. 7.9

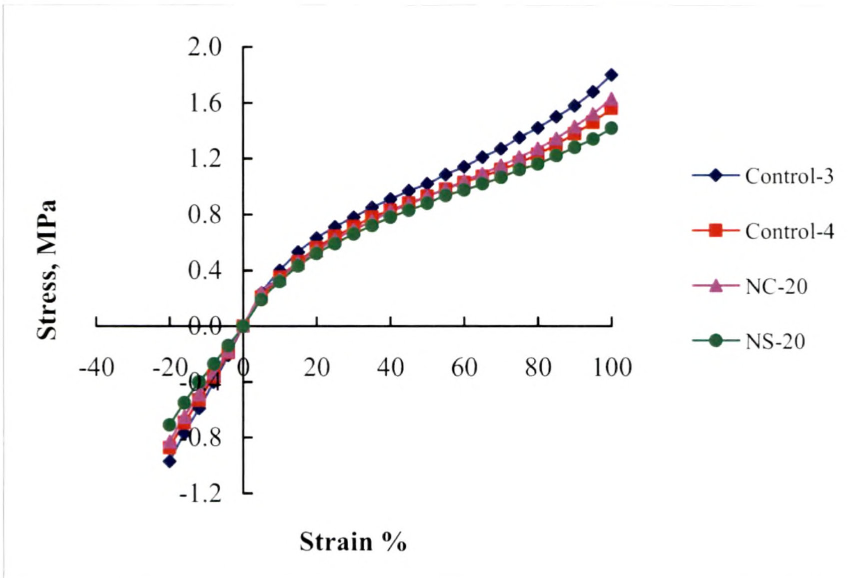

Fig.7.9- Hyperelastic properties of TBR tread rubber compounds

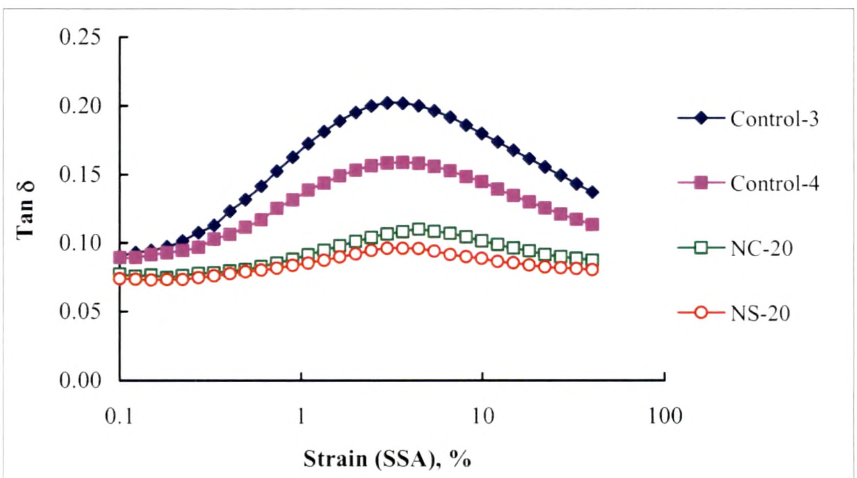

Fig. 7.10: Tan δ versus strain (SSA) at 60°C.

7.2.3 Viscoelastic material properties

The rolling resistance of tire originates from the energy dissipation which is the product of elastic strain energy density and viscoelastic properties of rubber (Tan δ). The Tan δ at any strain and temperature is required to evaluate the energy dissipation (hysteresis loss).

Nanocomposites showed much lower Tan δ values as observed during strain sweep in comparison with Control compounds as shown in Fig. 7.10. The high Tan δ values in Control tread compounds indicate much higher hysteresis losses than tire with nanocomposite treads. This behaviour is attributed to lower volume fraction of filler present in the nanocomposite compared with the Control tread compounds.

7.2.4 Computation of rolling resistance

Simulation is an effective tool to predict the rolling resistance of tire in design stage, using simulation techniques one can study the effect of new compounds and different design aspects on tire rolling resistance. Rolling resistance of three different sizes of tires such as 10.00R20 and two low aspect ratio tires 295/80R22.5 and 315/80R22.5 with commercial carbon tread compound (Control-3) were experimentally measured using drum type rolling resistance testing equipment as shown is Table 7.7.

Table 7.7-Rolling resistance of tire with Control-3 compound measured at pulley wheel machine

	10.00R20	295/80R22.5	315/80R22.5
Rolling Resistance, N	181.05	222.13	236.2

These three tires with Control tread compounds were modeled using finite element simulation techniques and their rolling resistances were evaluated using ***"RR Code".*** The simulated values correlated well with the measured values and approached to 94% of the measured value in 10R20, 92% in 295/80R22.5 and 91% 315 80 R 22.5 as shown in Fig. 7.11. The difference between measured and simulated values is attributed to the difference in parameters such as aerodynamic drag, hysteresis loss of reinforcement, etc. that are not accounted in simulation.

Interestingly the footprint shape of 10.00R20 real tire and simulated one appear very similar as observed in Fig. 7.12.

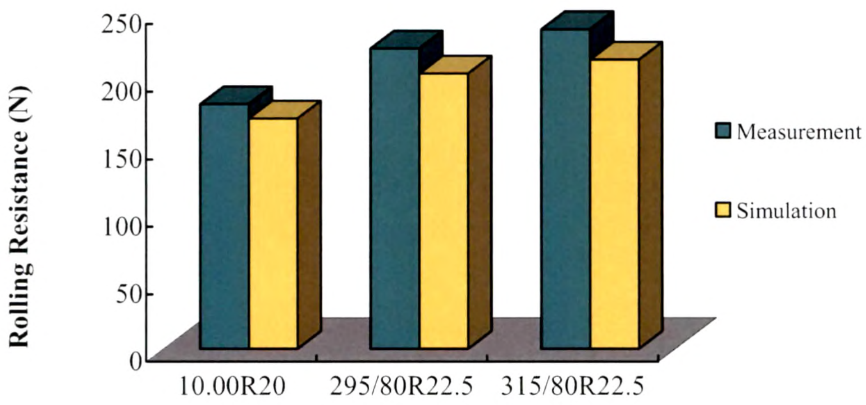

Fig. 7.11- RR results- measurement versus simulation

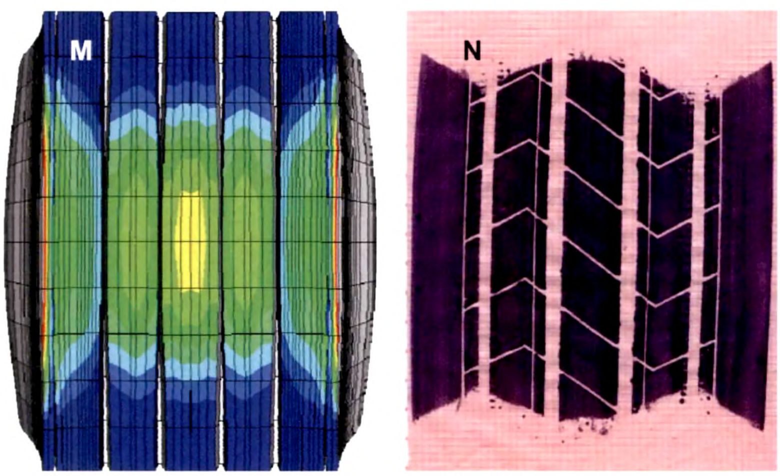

Fig. 7.12- Footprint of 10.00 R20 TBR tire with commercial carbon black tread (M) simulated footprint and (N) measured footprint

All three tires, 10.00R20, 295/80R22.5 and 315 80 R 22.5 with nanocomposite treads (NC-20 and NS-20) were simulated and their rolling resistances were evaluated using ***"RR Code".*** Finite element simulation of all three TBR tires with nanocomposite tread compounds, such as NC-20 and NS-20 were carried out and the rolling resistances were computed using *"RR Code"*. Simulated 2D cross section of 10.00R20 (full section) and 295/80R22.5 (half section) truck bus radial tire with nanocomposite tread (NC-20) are shown in Fig.7.13 and 7.14 respectively.

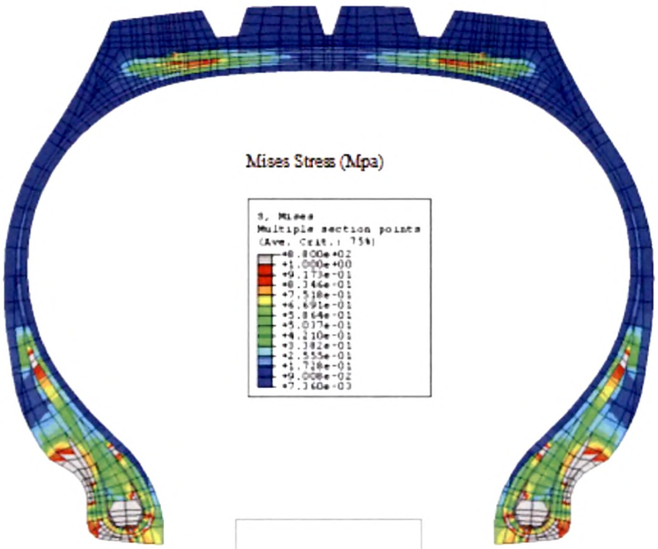

Fig. 7.13- TBR tire (10.00R20) 2D full tire cross section

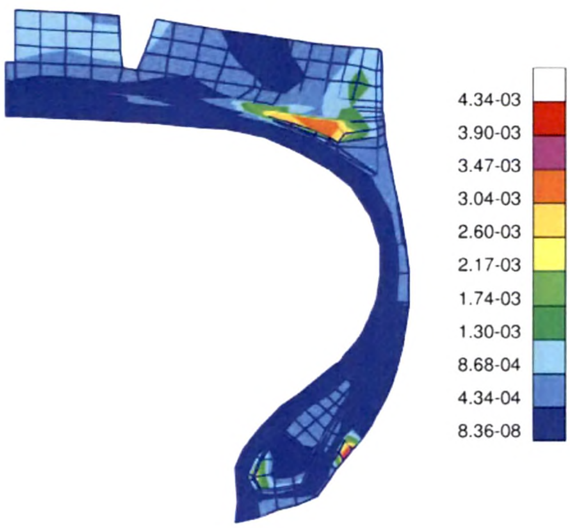

Fig. 7.14- TBR tire (295/80R22.5) 2D half tire cross section

The simulated foot print of 295/80R22.5 TBR tire with commercial carbon black tread (Control-3) and with organoclay-carbon black nanocomposite tread (NC-20) are shown in Fig. 7.15.

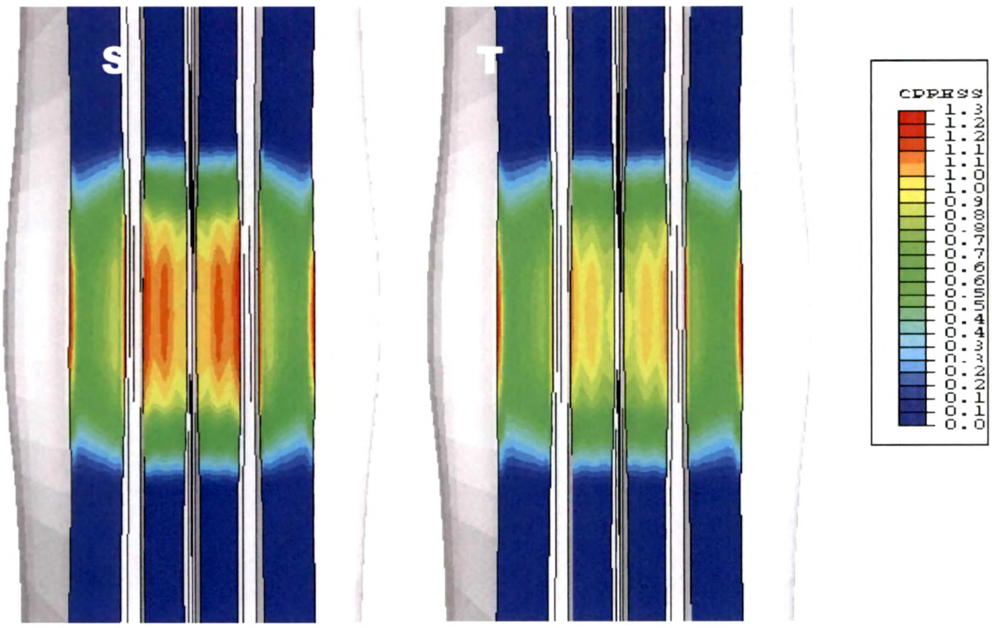

Fig. 7.15- Footprint of 295/80R22.5 TBR tire (S) with commercial carbon black tread, Control-3 and (T) with organoclay-carbon black nanocomposite tread, NC-20.

The rolling resistances of all three tires with organoclay-carbon black nanocomposite tread (NC-20) were compared with corresponding sizes of tires with commercial carbon black tread (Control-3). The nanocomposite tread showed much lower RR values than their corresponding carbon black counter parts for all three tire sizes. In organoclay-carbon black nanocomposite tread (NC-20), improvement of rolling resistance compared to commercial carbon black tread (Control-3) in 10.00R20, 295/80R22.5 and 315 80 R 22.5 are ***37.1, 34.4 and 32.8%*** respectively as shown in Fig. 7.16 and Table 7.6 to Fig. 7.8.

Similarly, the rolling resistances of all three tires with organoclay-Silica nanocomposite tread (NS-20) were compared with corresponding sizes having silica tread (Control-4). The nanocomposite tread showed much lower values than the corresponding Silica counter part in all three sizes. In organoclay-carbon black nanocomposite tread (NS-20), improvement of rolling resistance compared to commercial silica tread (Control-4) in 10.00R20, 295/80R22.5 and 315 80 R 22.5 are ***35.2, 32.8 and 34.4 %*** respectively as shown in Fig. 7.17 and Table 7.6 to Fig. 7.8.

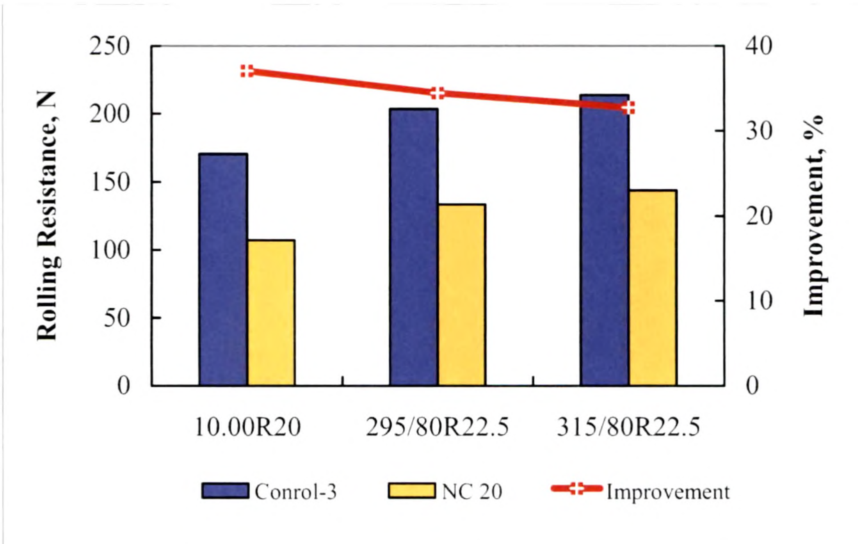

Fig. 7.16- RR results: organoclay-carbon black nanocomposite

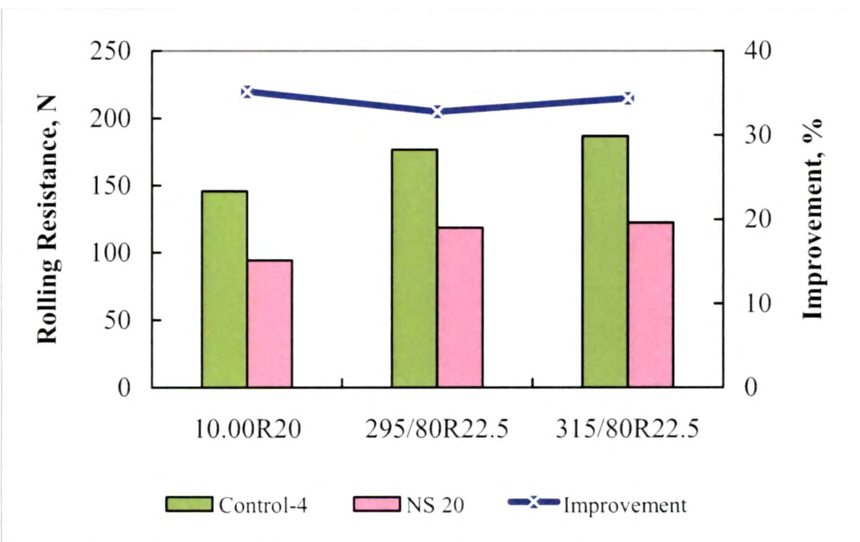

Fig. 7.17- RR results: organoclay-silica nanocomposite

Organoclay-carbon black and organoclay-silica dual filler nanocomposites have shown 32 to 37 % lower rolling resistance than commercially used carbon black and silica treads. Hence introduction of dual filler nanocomposite treads in truck bus radial tire would lead to ~8 to 9 % saving of precious fuel and would reduce environmental pollution. The rolling resistance of the nanocomposites and Control compounds for all three tires are presented in Table 7.8 to 7.10.

Table 7.8-Rolling resistance of 10.00R20 TBR tire predicted by simulation

		Dissipated Energy, N-mm	Rolling Resistance N	Percentage Improvement
10.00R20	Control-3	568443.0	170.4	
	NC 20	357779.2	107.2	37.1
	Control-4	486556.0	145.8	
	NS 20	315381.0	94.5	35.2

Table 7.9-Rolling resistance of 295/80R22.5 TBR tire predicted by simulation

		Dissipated Energy, N-mm	Rolling Resistance, N	Percentage Improvement
295/80 R 22.5	Control-3	679972.0	203.6	
	NC 20	446697.3	133.5	34.4
	Control-4	590998.8	176.6	
	NS 20	397164.3	118.7	32.8

Table 7.10-Rolling resistance of 315/80R22.5 TBR tire predicted by simulation

		Test Load N	Dissipated Energy, N-mm	Rolling Resistance, N	Percentage Improvement
315/80R22.5	Control-3	3403	737380.0	213.8	
	NC 20	3403	498761.2	143.8	32.8
	Control-4	3403	644333.2	186.7	
	NS 20	3403	422480.8	122.5	34.4

Future work would focus on further improvement of clay dispersion in NR/BR blend in industrial mixer and aim to produce tire for indoor endurance and outdoor road tests such as durability, mileage, traction, rolling resistance and fuel efficiency.

7.2.5 Conclusions

The performance properties of nanocomposite treads; NC-20 and NS-20 were compared with respective commercial carbon black tread (Control-3) and silica tread (Control-4). Mechanical properties such as hardness, modulus, tensile strength and elongation at break and critical performance properties like tire wear, durability, traction and rolling resistance of nanocomposites, NC-20 and NS-20 are comparable to their respective Control compounds and are well within the typical performance range.

In hyperelastic material characterization, nanocomposite based tread compounds NC-20 and NS-20 showed slightly lower stiffness both in tension and compression mode than respective Control compounds and this is due to the lower volume fraction (lower phr) of filler in nanocomposites.

Nanocomposites shows much lower Tan δ_{max} values as observed in dynamic mechanical study (strain sweep) in comparison with respective Control compounds. The much higher Tan δ value of Control tread compounds give higher hysteresis loss leads to higher rolling resistance in tire during rolling.

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.

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%.

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.

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.