CHAPTER-5:

CORRELATION OF CARBON BLACK PARAMETERS WITH RUBBER COMPOUND PROPERTIES FOR DEVELOPMENT OF IMPROVED TYRE TREAD COMPOUNDS

5.1 Introduction

Carbon black morphological features refer to its structural characteristics such as presence of micro and macros porosities on particle surface, crystallinity, particle size, surface area, structure, aggregate, aggregate size and shapes, agglomerates etc [1]. Carbon black characteristics with smaller particle size results in high surface area. While the structure of carbon black refers to the extent of aggregation and agglomeration which are the measure of void volume in the carbon black structural units [2]. The primary units of carbon black are aggregates whose size and distribution pattern are considered to be key parameters in line with surface area and the structure of carbon black as described in the previous Chapter-2. It has been described that broadness of aggregate size distribution is expressed by FWHM value of carbon black as well the presence of the bigger size aggregates into the same, which is indicated by differential volume distribution (dV/dD) against corresponding aggregate size. Aggregate size distribution further characterized with different statistical parameters such as mean, mode, d_n value etc [3]. Each of these carbon black parameters has its own importance in the end applications. In this investigation an attempt has been made, to study the effect of different carbon black parameters such as aggregate size, d_n value, aggregate size distribution, structure, surface area on rubber properties and to explore the correlations of the rubber compound properties with different carbon black properties.

5.2 Carbon Black Development

In this study different grades of carbon black were developed based on tailor made morphological characteristics such as surface area, structure and aggregate size distribution. During development of the grade in the furnace process, the surface area of the grades was controlled by monitoring the reactor temperature and the ratio of input CBFS to input oxygen into the reactor, while the structure of the grades was monitored by adjusting the input flow of K+ salt in the reactor. The aggregate size and its distribution pattern were monitored by use of multiple locations for CBFS injection into the furnace. A modified furnace reactor with multiple choke sections was used to develop the experimental carbon black. The details of furnace reactor and the carbon black manufacturing process have been discussed in Section 3.3.1 and 4.1.2. The different grades developed for these studies are based on their unique morphological characteristics and the developed grades are identified as HP01, HP02, HP03, HP04, HP05, HP06 and HP07. The basic carbon black properties of the grades are shown in Table-5.1

Table-5.1: Carbon black characteristics

	Units	HP01	HP02	HP03	HP04	HP05	HP06	HP07
IAN	g/kg	119	118.5	119.0	120.1	119.9	120.6	118.4
OAN	ml/100 g	113.8	114.4	115.9	124	123.5	134.0	110.0
COAN	ml/100 g	97	98.3	95.7	104.7	103.8	108.5	95.8
NSA	m^2/g	112.3	111.5	111.6	113.3	113.5	114.8	112.3

5.2.1 Characteristics of Carbon Black

5.2.1.1 Surface Area and Structure of Carbon Black

Surface area of carbon black is represented by iodine adsorption number (IAN) and nitrogen surface area. It shows that HP06 grade is characterized with maximum iodine adsorption number and nitrogen surface area of 120.6 g/kg and 114.8 m^2/g respectively, while HP02 grade carbon black has the least iodine adsorption number and nitrogen surface area of 118.5 g/kg, 111.5 m^2/g respectively. Since the surface area of carbon black samples are nearly similar with variation of maximum 3% therefore the characteristics of rubber compounds caused by surface area of the different carbon black samples are expected to be similar. The structure of carbon black implies the nature of aggregation and is represented by OAN and COAN values. The highly agglomerated carbon black, known as high structure carbon black and it has high oil absorption number (OAN). The high OAN and COAN values indicate carbon black with highly branched type aggregate and agglomerate skeletons in its morphology and in turn it possesses high void volume.

The presence of void volume in carbon black morphology plays a significant role in rubber compound properties. It has been established that rubber molecules penetrate inside the carbon black voids and lose their mobility, which causes restriction of rubber molecules movement and leads to higher viscosity of rubber compound [4]. Hence, a carbon black structure with greater degree of voids is expected to immobilize rubber molecules to a larger extent and attain greater reinforcement in rubber compounds. In the present study, the OAN of carbon black varies from 110 to 134 ml/100g.

5.2.1.2 Aggregate Size Distribution

The aggregate size distribution of carbon black has been represented by the plot of differential volume distribution (dV/dD) of aggregate versus the diameter of the aggregates assuming spherical shape of the same. The height of the plot represents relative concentration of the corresponding aggregate size, and the width of the plot represents the broadness of the aggregate size distribution as stated previously. The highest peak of the plot indicates maximum occurrence of the aggregates, and the diameter of aggregate corresponds to height peak of plot and is called the 'mode' of the aggregate size distribution. The mean of the aggregate size distribution is the arithmetic average of all the aggregates present in the system, where aggregate size is represented by Stokes's diameter of the aggregates [5]. Hence carbon black with higher mean value suggests presence of a larger extent of bigger aggregate size in the system. The aggregate size distribution parameters of carbon black are shown in Table-5.2, and it indicates that HP06 carbon black is characterized with broadest aggregate size distribution with FWHM value of 90 nm, and HP01 grade is characterized with narrowest aggregate size distribution with least FWHM value of 62nm. The pattern of aggregate size distribution for all the carbon black are portrayed in the distribution plot of the carbon black as shown in Fig-5.2.

The aggregate size distribution parameters are shown in Table5.2, it indicates, HP02 grade carbon black is associated with lower d_{10} value (50 nm) while HP02 grade is associated with larger d_{10} value (65 nm) among all the carbon black. The definition of d_{10} illustrates that for HP02 grade carbon black 10% of aggregate volume is occupied by the aggregates having diameter of maximum 50 nm while for HP07 grade carbon 10% of aggregate have diameter up to 65 nm. Thus, it indicates that HP02 carbon black has more concentration of smaller size aggregates of diameter 50 nm or less compared to HP07 grade carbon black.

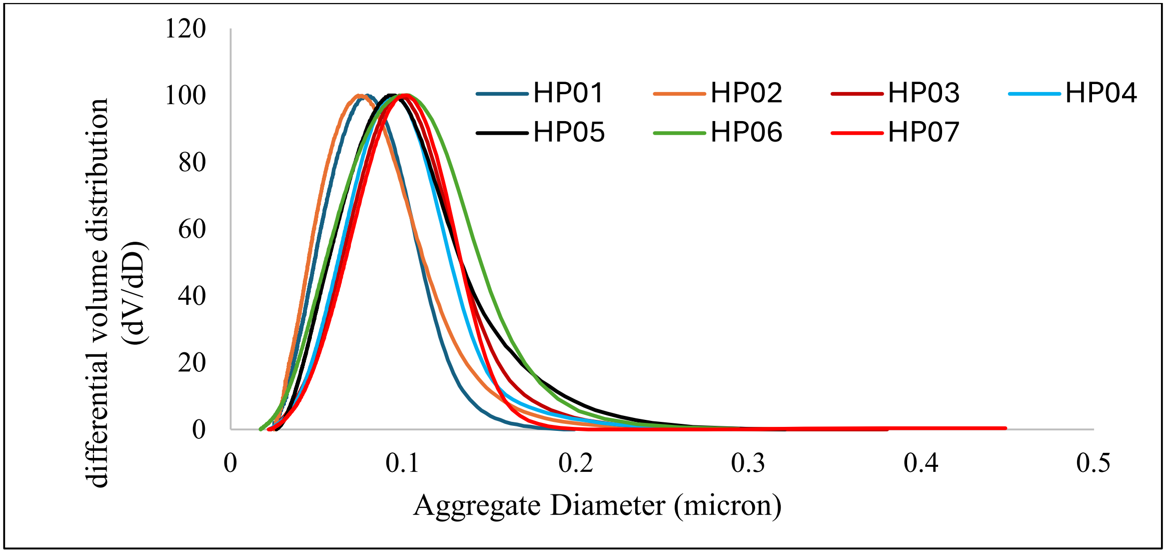

Fig-5.1: *Aggregate size distribution of different carbon black grades (HP01, HP02, HP03, HP04, HP05, HP06, HP07)*

Table-5.2: Aggregate size distribution parameters of carbon black

	Units	HP01	HP02	HP03	HP04	HP05	HP06	HP07
Mean	nm	82	87	103	100	106	105	102
Mode	nm	79	74	98	94	91	104	100
FWHM	nm	62	67	69	66	77	90	67
d_{10}	nm	51	50	64	63	61	59	65

5.2.1.3 High Resolution Transmission Electron Microscopy and Structural Morphology

High resolution transmission electron microscopic study of the grades was carried out to investigate the nature of aggregation and the size of carbon black particles. It has been described that the grades are characterized by similar surface area however, dissimilar in structure properties as measured by nitrogen surface area and OAN respectively. The development of the grades based on dissimilar features of aggregate characterization and the same has been portrayed by aggregate size distribution.

The HRTEM analysis the carbon black is shown in Fig-5.2, which signifies above carbon black are characterized with similar particle size distribution within the aggregate having particle size from 20 nm to 40 nm. It demonstrates similar nitrogen surface area for the grades HP01 to HP07.

The images of aggregate structural units show the extent of branching associated with the grades. It shows carbon black grades HP03 to HP06 are characteristics with highly branched aggregation with association of more inbuild void volume within the aggregate structure which results in higher COAN values for the respective grades.

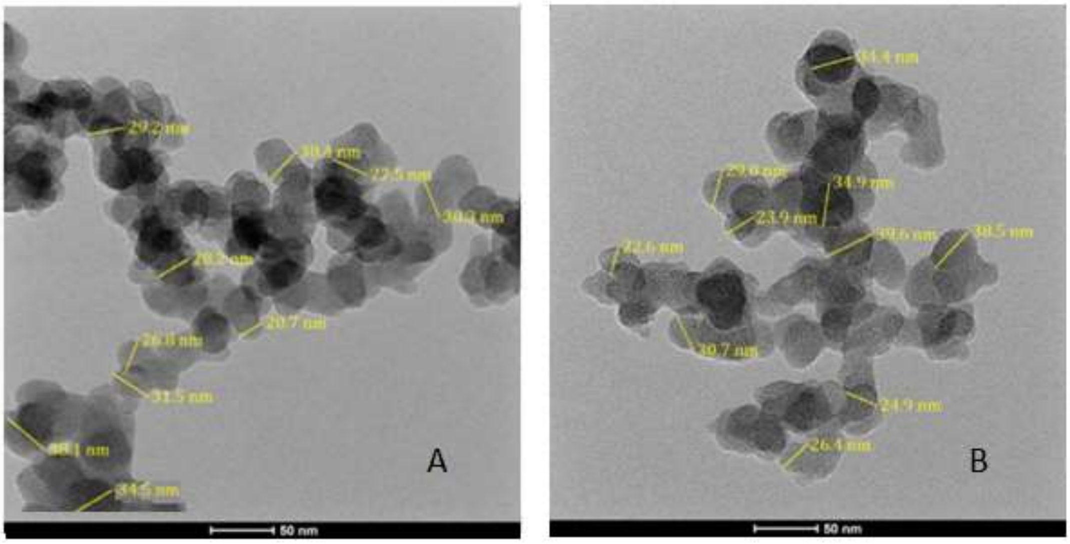

Fig-5.2: (A and B): *HRTEM images and characteristics of particle size of carbon black grade (A) HP01 grade (B) HP02 grade.*

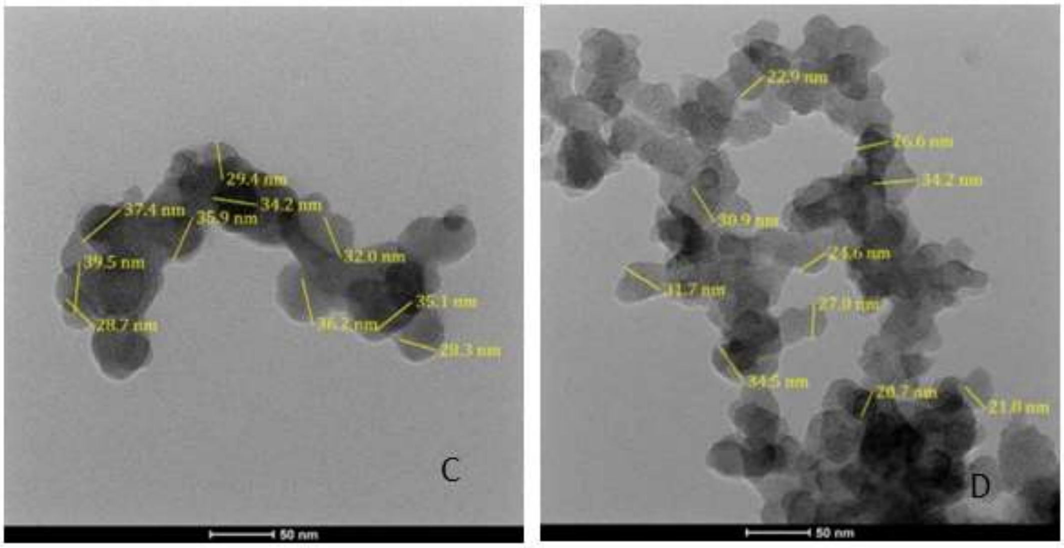

Fig-5.2 (C & D): *HRTEM images and characteristics of particle size of carbon black grade (C) HP03 grade (D) HP04 grade.*

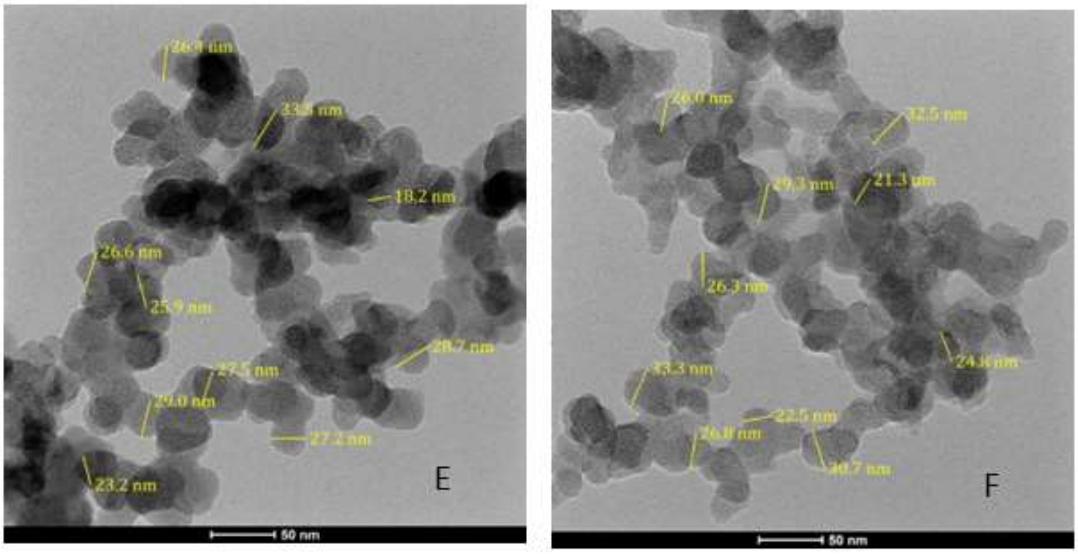

Fig-5.2 (E & F): *HRTEM images and characteristics of particle size of carbon black grade (E) HP05 grade (F) HP06 grade.*

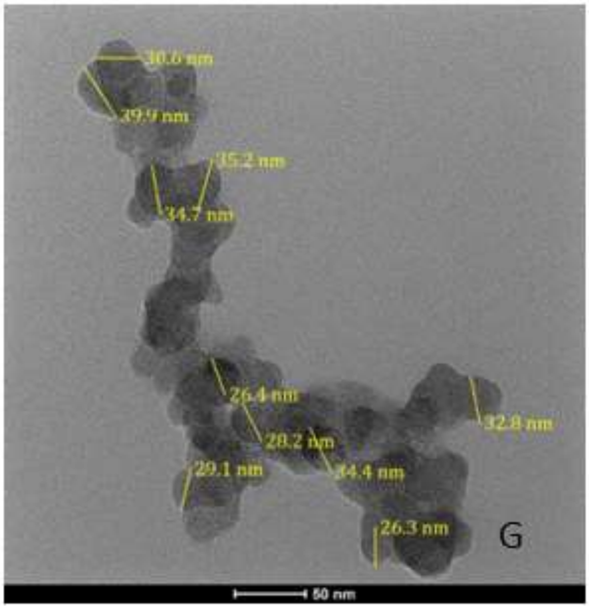

Fig-5.2 (G): *HRTEM images and characteristics of particle size of carbon black (G) HP01 grade*

5.3 Rubber Compound Properties and Their Relationship with Carbon Black Parameters

5.3.1 Rubber Compounding and Mixing

The performances of the above carbon black were studied in a model passenger car tyre tread formulation based on SBR1712-BR with 70 phr of SBR and 30 phr of BR was taken. The carbon black loading was taken for 60 phr. Loading of rest of the chemicals and the curing agents for each of the compound are similar (5 phr ZnO, 3 phr Stearic acid, 1 phr TMQ, 1 phr 6 PPD, 1.2 phr CBS and 1.5 phr sulphur). The rubber compounds associated with HP01, HP02, HP03, HP04, HP05, HP06 and HP07 grade carbon black are identified as HP01C, HP02C, HP03C, HP04C, HP05C, HP06C and HP07C respectively. The mixing and compounding was done by a Laboratory Banbury and by a Two roll mill mixing machine and the details of mixing procedure are described in Chapter 2.

5.3.2 Processing and Curing Characteristics

It has been discussed earlier that carbon black with high structure is associated with highly branched aggregates as well as agglomerates and causes large void volume in its structural morphology. During mixing and compounding of carbon black with rubber, there is possibility of rubber molecules penetrating inside the voids of carbon black and lost its mobility. Due to this constraint in molecular movement, the Mooney viscosity and minimum torque value of the rubber compound is increased [6]. The rheological characteristics of rubber compounds is tabulated in Table 5.3, and it is seen that carbon black HP06 resulted in high Mooney viscosity and high 'minimum torque' value in the rubber compound compared to other grades of carbon black. One of the potential reasons for this observation is the high structure of HP06 grade carbon black in comparison to the other samples of carbon black. Broad aggregate size carbon black assists in the ease of processability and results in lower Mooney viscosity of the rubber compound while narrow aggregate size distribution of carbon black results in high Mooney viscosity and high ML value [7]. In the present study, HP04 and HP05 carbon black are characterized with narrow aggregate size distribution compared to HP06 grade carbon black. This pattern of aggregate size distribution justifies the comparable Mooney viscosity and ML value of HP04C and HP05C rubber compound with HP06C compound despite having relatively lower structure of the corresponding carbon black HP04 and HP05 respectively compared to HP06 grade carbon black. The scorch time and optimum cure time of the compound are comparable. However, carbon black associated with high structure results in marginal fast curing phenomena as the same provides inbuild heat generation during the MDR measurement and which causes relatively faster curing.

Table-5.3: Processing and Curing characteristics of rubber compounds.

	Unit	**HP01C**	**HP02C**	**HP03C**	**HP04C**	**HP05C**	**HP06C**	**HP07C**
Mooney Viscosity	MU	61	61.5	61	63.5	63	64	61.2
Minimum torque	lb-in	2.1	2.0	2.2	2.4	2.4	2.5	2.1
Maximum torque	lb-in	10.7	10.9	11.0	11.2	11.4	11.9	10.5
Delta torque	lb-in	8.6	8.9	8.8	9.1	9.2	9.4	8.4
Scorch time (ts2)	Minutes	6.8	7.0	7.0	6.5	6.3	6.1	6.7
Curing time (T_c50)	Minutes	8.4	8.6	8.6	8.1	7.9	8.0	8.2
Curing time (T_c90)	Minutes	12.8	13.5	13.0	13.2	12.8	12.6	13.2

5.3.3 Payne Effect of Rubber Compound and its Relationship with Aggregate Size

Carbon black exhibits a tendency of network formation in the rubber compound due to the existence of filler-filler interaction. The presence of filler network in the rubber compound induces strain dependent shear modulus. This phenomenon was extensively studied by Payne [8]. It was demonstrated that on application of shear strain, the strain dependent shear modulus falls steadily due to the breakdown of filler-filler interaction, this is called Payne effect. It was also described that higher extent of filler-filler interaction present in rubber compound causes higher Payne effect in the rubber compound.

Several investigations have reported their studies on the filler-filler interaction and the network formation ability of carbon black in the rubber matrix. Wang et al., [9] extensively studied on that network formation ability of carbon black in rubber matrix and observed that it is determined by attractive potential of carbon black and the distance among the carbon black aggregates. In order to investigate the inter-particle distance of filler in rubber matrix, they have established an equation, which expressed interparticle distance (δ_o) of filler in term the particle diameter (d_p), where each particle was considered as spherical in shaped and the equation is as given below.

$$\delta_o = \left(\mathrm{k}\varphi^{-1/3} - 1\right)\mathrm{d_p} \quad \textbf{(5.1)}$$

where 'k' is a constant, which is determined by the arrangement of filler particles and 'φ' is the fraction of filler in rubber matrix.

In the case of carbon black, the basic and discrete units are aggregates which do not exist in spherical shape but are branched, and irregularly shaped particle entities. Due to the irregular shape in nature, aggregates possess internal void volumes in their structure and in the reinforcing mechanism the rubber molecules penetrate in the voids of aggregates and thus the same (voids) are occupied by the rubbery materials. The rubbery parts occupied inside the voids are assumed to act as an integral part of the filler, and as a result the effective filler fraction in rubber matrix is considered to have increased and it is denoted by 'φ_{eff}'. Considering aggregates as discreate units of carbon black the inter-aggregate distance (δ_{agg}) of carbon black in the polymeric matrix is expressed in term of the aggregate diameter (d_{agg}) and thus the above equation (5.1) is expressed as follows.

$$\delta_{\mathrm{agg}} = \left(\mathrm{k}\varphi_{\mathrm{eff}}^{-1/3} - 1\right)\mathrm{d_{agg}} \quad \textbf{(5.2)}$$

The above equation shows that the distance between the aggregates has a potential relationship with aggregate size, and the same reduces when aggregate diameters are smaller. On lowering of the aggregate diameter, the carbon black aggregates come closer in the rubber matrix and as a result it provides high Van der Walls force of interaction among the aggregates [10]. Hence carbon black possessing lower aggregate size may result in high propensity of filler-filler interaction due to high Van der Waals force of interaction.

The shear modulus of rubber compounds steadily falls on application of strain sweep because of breakdown of filler-filler network. The trend of shear modulus of rubber compound with strain sweep is shown in Fig-5.3 and it shows that while the strain sweep is increased the shear modulus steadily falls and after a certain level strain sweep a plateau pattern of shear modulus is seen, which indicates almost complete breakdown of filler-filler interaction. Comparing the trend of shear modulus among all the rubber compounds, it is seen that HP07C rubber compound provides least shear modulus value at lower strain region and thus it leads to least decline of shear modulus on strain sweep.

Payne effect of the rubber compound is measured by subtracting the shear modulus at higher stain amplitude from the shear modulus at low strain amplitude. In this study the Payne effect of rubber compound is measured by subtracting the shear modulus of 100% strain amplitude from the same at 0.1% strain amplitude [11].

It is seen that HP07C rubber compound is associated with least shear modulus at the lower strain region among all the compound and it has least fall of shear modulus on the strain sweep as a result HP07C is characterized with least Payne effect among all the compounds.

In this part of the study an attempt has been made to interpret the Payne effect of rubber compound using the aggregate size distribution parameters of carbon black and to do so d_{10} value of aggregate size distribution parameters has been considered. It has been described that d_{10} value of carbon black signifies maximum size of aggregate which occupies 10% of aggregate volume, and carbon black with lower d_{10} value indicates the presence of higher extent of smaller size aggregates into it as compared to the same associated with higher d_{10} value.

Equation-5.2, demonstrates that the interaggregate distance among carbon black aggregates is low while in the rubber matrix while the carbon black consists of smaller sized aggregates. In this study, it is seen that carbon black HP02 is characteristic with least value d_{10} among all the carbon black samples and hence it is associated with higher extent of lower size aggregates among all the carbon black. As a result, HP02 carbon black provides lower interaggregate distance in rubber matrix compared to rest of the carbon black.

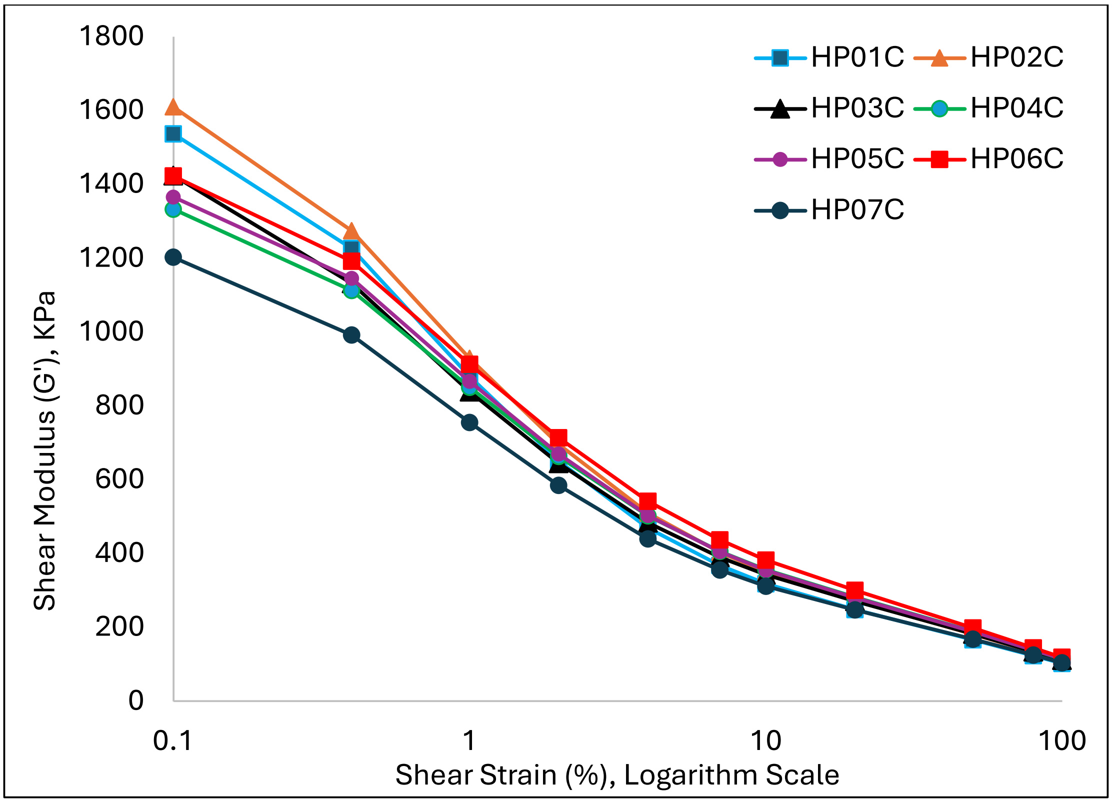

Fig- 5.3: *The trend of shear modulus with shear strain sweep of different rubber compounds*.

It was clarified that lower inter-aggregate distance among the aggregates causes high Van der Waals force of interaction in the rubber matrix and leads to higher propensity of filler-filler interaction in the rubber matrix and as a result it causes high Payne effect. The Payne effect of rubber compounds is shown in Table-5.4, and it is seen that high Payne effect observed with HP02C rubber compound due to the presence of greater amount of small size aggregates in the corresponding carbon black HP02.

Table-5.4: Shear modulus of rubber compound at different strain and Payne effect of rubber compounds.

	Unit	HP01C	HP02C	HP03C	HP04C	HP05C	HP06C	HP07C
G'@0.1 %	KPa	1537	1610	1424	1333	1366	1423	1202
G'@100 %	KPa	102	110	111	115	115	119	104
Payne Effect	KPa	1434	1500	1250	1218	1251	1304	1122

Thus, one of potential aspects of Payne effect in rubber compound is the size of carbon black aggregates, more specifically the d_{10} value of carbon black aggregate size distribution parameters. To describe the effect of d_{10} value, Payne effect of rubber compound is plotted with d_{10} values of the corresponding carbon black as shown in Fig-5.4. It is observed that the Payne effect of the rubber compound declines linearly with increasing d_{10} values, indicating that carbon black with low d_{10} value provides high Payne effect and with increasing the d_{10} value Payne effect of rubber compound is reduced. Hence it is established that carbon black associated with higher extent of smaller size aggregates results high filler-filler interaction in rubber compound and consequently has high Payne effect.

The correlation between Payne effect and d_{10} value of corresponding carbon black is statistically indicated by the R-square value at 95% confidence level, which demonstrates a significant correlation of Payne effect associated with the d_{10} value of aggregate size distribution parameter of corresponding carbon black.

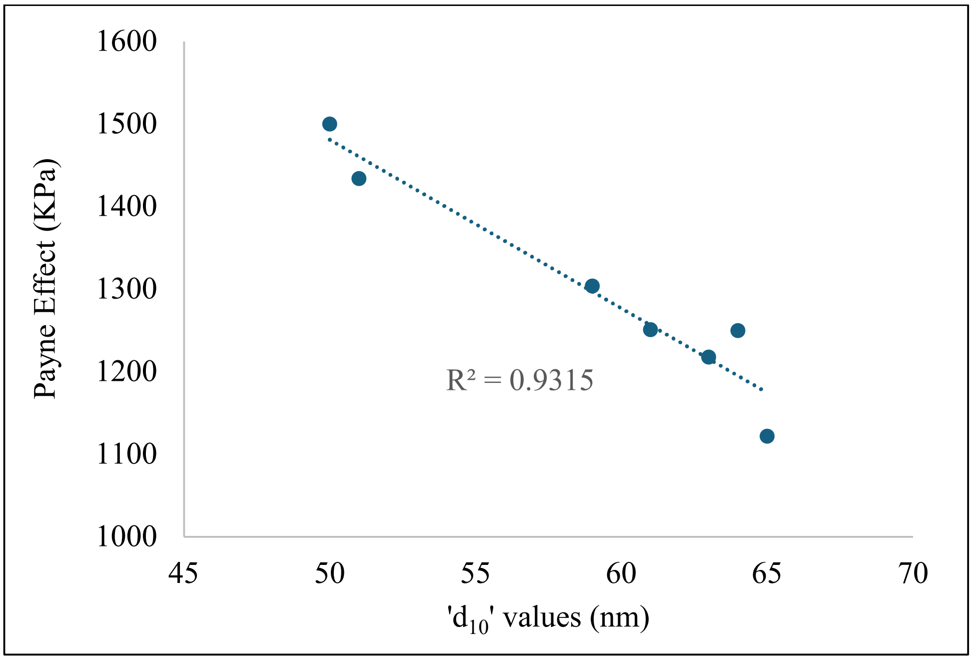

Fig-5.4: *Payne effect of the rubber compounds with* d_{10} *value of corresponding carbon black*

5.3.4 Heat Buildup in Rubber Compounds and Effect of Payne Effect

Heat buildup is the rise in temperature due to the generation of heat in rubber compounds subjected to cyclic deformation when the rubber compound experiences an oscillating compressive stress or strain. There are several reasons associated with heat buildup in rubber compounds such as molecular friction among rubber molecules during the deformation, breaking of filler-filler interaction in rubber matrix as well as subsequent reorganization of filler particle networks, hysteresis energy loss of rubber compounds etc [12].

In practice heat buildup is caused primarily due to incorporation of filler in rubber compound and the same is increased with increase in filler loading e.g., carbon black loading. However, rubber compounds with fixed carbon black loading, the characteristics of carbon black play a crucial role on the heat buildup of a defined rubber system. In fact, surface area and structure of carbon black are key parameters which determines the heat buildup in carbon black filled rubber compound and heat buildup of rubber compound increases with increased surface area as well as structure of the carbon black [13-14].

As described, the inter-aggregate links of carbon black in rubber matrix readily breakdown on application of strain and leads to Payne effect in the rubber compound. On application of shear strain, the weak links between carbon black aggregates break down steadily even on application of lower shear strain, while the strongest links start breaking as strain progresses to the higher region. One of potential causes of heat buildup in rubber compound has been identified as the breakdown of filler network in the rubber matrix. Hence while filler-filler network breaks in the cyclic deformation, it emits energy and causes heat buildup in rubber compound. [15]. A rubber compound associated with higher extent of filler network thus tends to generate high heat buildup in rubber compound because of larger extent of filler-filler network breakdown under the deformation. Payne effect is the measure of filler-filler interaction in rubber compound, hence the same can be correlated with the heat buildup of rubber compounds. In this part of the study heat buildup of rubber compound is compared with Payne effect and the same is represented graphically in Fig-5.5.

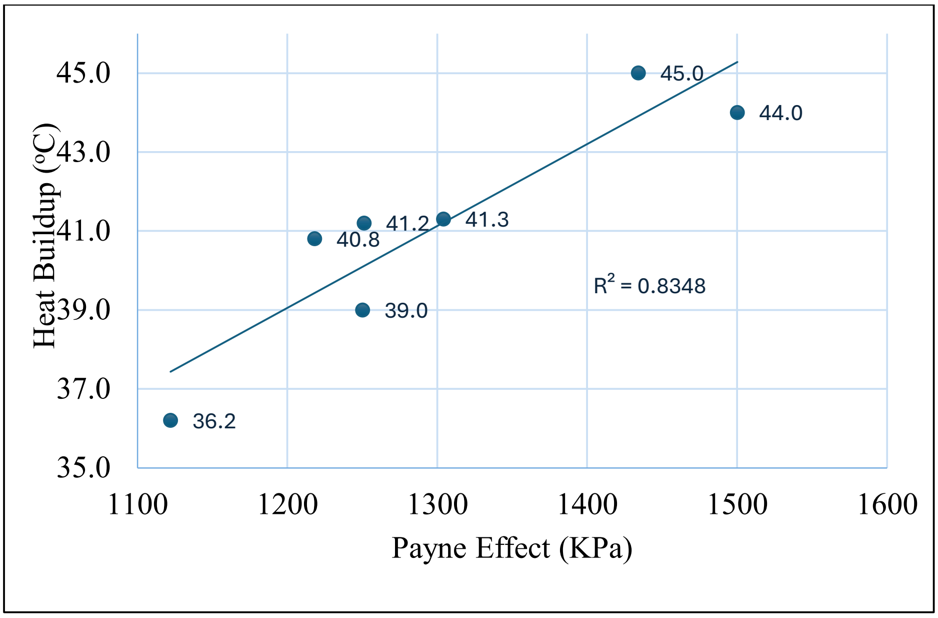

Fig-5.5: *Trend of heat buildup property (rise in sample temperature) with Payne effect*

It reveals that heat buildup of rubber compound is increased with increase in Payne effect of rubber compound and it appears that a linear relationship between the Payne effect and the heat buildup exists. The correlation factor (R-square value) of the relationship is measured and is limited to 0.83. The co-relation factor of the relationship indicates that Payne effect of rubber compound has a substantial relationship with heat buildup of rubber compound but there are other factors associated in rubber compound which significantly influences the heat buildup property, as a result, the correlation factor is limited to 0.83.

In the above section we have seen the correlation of Payne effect with d_{10} value of corresponding carbon black, and it has been seen, Payne effect of the rubber compound has significant correlation with the 'd_{10}' value of corresponding carbon black. Thus, it is not inappropriate to presume that d_{10} value as one of potential parameters of carbon black to affect the heat buildup property of rubber compound. Heat buildup of rubber compound is corelated vis-a-vis with d_{10} value of corresponding carbon black, and it is seen that heat buildup increases with decreasing d_{10}, which has a linear relationship as shown in Fig-5.6. This demonstrates carbon black associated with higher extent of smaller size aggregate leads to higher heat buildup in rubber compound and same reduces while extent of smaller size aggregates reduces. Therefore, it can be interfered that in line with surface area and structure property, the aggregate size distribution parameters, d_{10} value of carbon black could be considered a significant parameter which impacts on heat buildup of rubber compound.

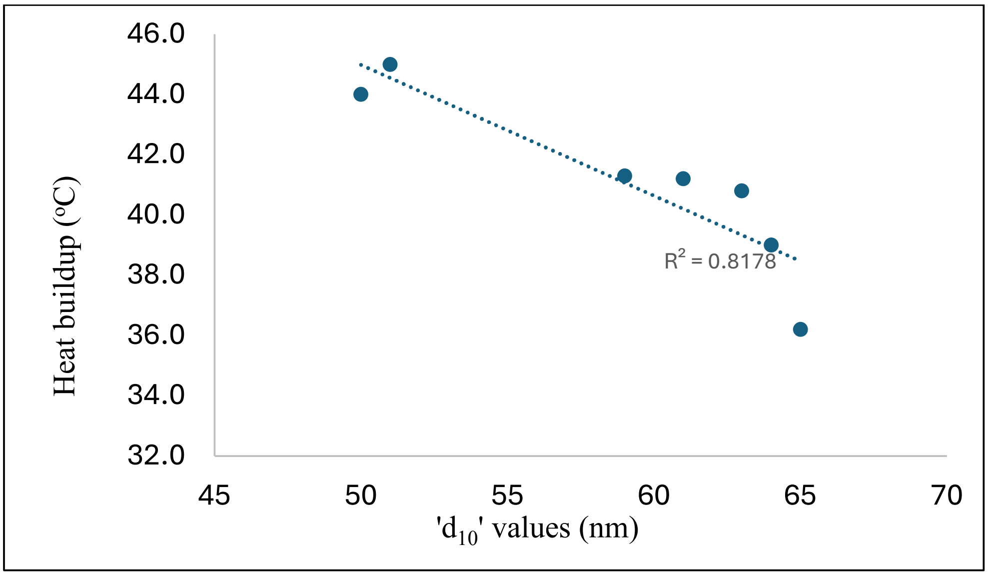

Fig- 5.6: *Trend of heat buildup property with d_{10} value of carbon black aggregate size distribution.*

5.3.5 Hysteresis Loss of Rubber Compound as Dependent on Aggregate Size Distribution

Hysteresis loss is a fundamental feature of rubber compounds; it is greatly influenced by the characteristics of carbon black used in a specific rubber system. Carbon black characterized with high surface area provides higher hysteresis loss in rubber compounds and consequently results in high rolling resistance in tyre tread application [16-17]. In this study the carbon blacks are characterized with similar surface area however, the same are characterized with dissimilar aggregate size distribution. In the previous chapter it has been shown carbon black characterized with broad aggregate size distribution and possessing large extent of bigger size aggregates results in lower hysteresis loss in the rubber. Thus, along with aggregate size distribution the size of carbon black aggregates simultaneously effects hysteresis loss of rubber compounds. Thus, the effect of aggregate size distribution on the hysteresis energy loss of rubber compound turns to be a combined effect of aggregate size distribution pattern and aggregate size of carbon black, the pattern of aggregate size distribution is represented by FWHM and while the size of aggregates is represented by the mean value of carbon black.

To demonstrate the combined effect of aggregate size distribution and aggregate size, an ‘aggregate size distribution co-efficient (A)’ parameter has been introduced, which is expressed as a function of FWHM and means ($\bar{X}$) value of carbon black, which is shown in equation (5.3), where ‘a’ and ‘b’ are the integer coefficients.

$$A = \sqrt[n]{a\mathrm{FWHM}^2 + b(\bar{X})^2} \tag{5.3}$$

The ‘A’ value for each carbon black was calculated for specific values of ‘a’ and ‘b’ and the same (A) is correlated with hysteresis loss (tanδ, measured at 60°C) of corresponding rubber compound. A graphical plot of tanδ values of rubber compounds with aggregate size distribution co-efficient (A)’ parameter of corresponding carbon black is shown in Fig-5.7, where a and b values are 2 and 1 respectively. It is observed that tanδ decreases with increasing ‘A’ value of carbon black, which indicates carbon black with high ‘A’ value would lead to reduce hysteresis loss in rubber compound.

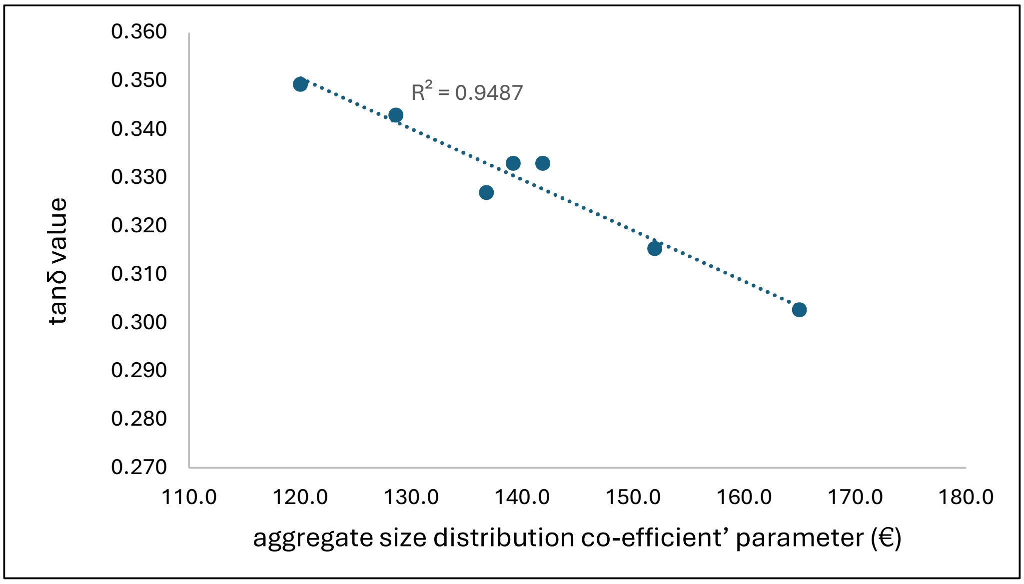

Fig-5.7: *Trend of tanδ values with ‘aggregate size distribution co-efficient’ parameter (A) where n=1, a=2, b=1.*

The R-square value of the plot changes with change in value of ‘a’ and ‘b’, and it has been seen that while value of ‘a’ is 2 and the same of ‘b’ is 1 the R-square value of the plot stood at 0.948 with a confidence level of 95%. Thus, it signifies, there has a strong relationship of hysteresis loss (tanδ) of rubber compound with ‘A’ value corresponding carbon black.

Here ‘A’ values of different carbon black have been calculated by using different set of a and b values and corresponding ‘R square’ values of the plot obtained, have been tabulated in Table-5.5 along with corresponding ‘a’ and ‘b’. It is seen that with the specific values of a and b, the ‘R square’ value of the plot changes from 0.824 to 0.951, from which it can be interfered that the effectiveness of the co-relation between tan delta and ‘A’ is greatly influenced by the values of integer constants a and b values. In this relationship the interesting fact is that the R-square value of the plot becomes high while a>b. Hence it demonstrates that FWHM is predominant parameter of carbon black over mean value in controlling the hysteresis loss of rubber compound.

Table-5.5: R-square value of tan delta vs aggregate size distribution co-efficient parameters with different value of n, a, and b

Values of ‘a’	1	1	1	2	2	2	3	3	3
Values of ‘b’	1	2	3	1	2	3	1	2	3
R-square value for n=1	0.930	0.866	0.824	0.951	0.931	0.896	0.940	0.949	0.931

5.3.6 Abrasion Resistance Property and Structure Co-efficient Parameter

Abrasion resistance property of rubber compound refers to the loss of rubber compound due to friction of the same with solid surface. Carbon black provides enhanced abrasion resistance in rubber compound, which is increased with high-surface-area and high structure properties of the same. It is established that carbon black with high surface area, results increased filler-rubber interfacial adhesion, and causes resistance towards the abrasive loss of rubber compound while on rubbing with solid surface [18-19]. Price and Aboytes [20] demonstrated that abrasion resistance of rubber compound increases with increase structure of carbon black and the same phenomenon becomes more intense while the structure of carbon black is below oil absorption number value of 110 ml/100g. Chang et al. [21] further demonstrated abrasion resistance of carbon black filled rubber compound increases with increase of surface area and structure of carbon black.

In the present research the carbon blacks are characterized with similar range of nitrogen surface area property, hence in such case the structure properties of carbon black become predominant factor for controlling the abrasion resistance of rubber compound. To correlate the abrasion resistance of rubber compound with corresponding carbon black characteristics, a 'structure co-efficient parameter (Ŝ)' has been introduced, which is function of primary structure as well as secondary structure of carbon black and is defined in the equation (5.4).

$$\hat{S} = \sqrt{OAN^2 + COAN^2} \qquad \textbf{(5.4)}$$

The abrasion resistance of rubber compounds is expressed in terms of abrasion resistance index and high abrasion resistance index of rubber compound represents enhanced abrasion resistance of the same.

The abrasion resistance index of rubber compound is plotted graphically with the 'structure co-efficient parameter of corresponding carbon black and same is represented in Fig-5.8. It is seen that a linear correlation observed with an intense correlation factor with R-square value above 0.99 at a 95% confidence level. Hence carbon black structure is considered as the prime and predominant parameter to investigate the abrasion resistance property of rubber compound while the surface area of the carbon black remains in similar range, though to explore the same, a consideration of primary structure as well as secondary structure is highly desired.

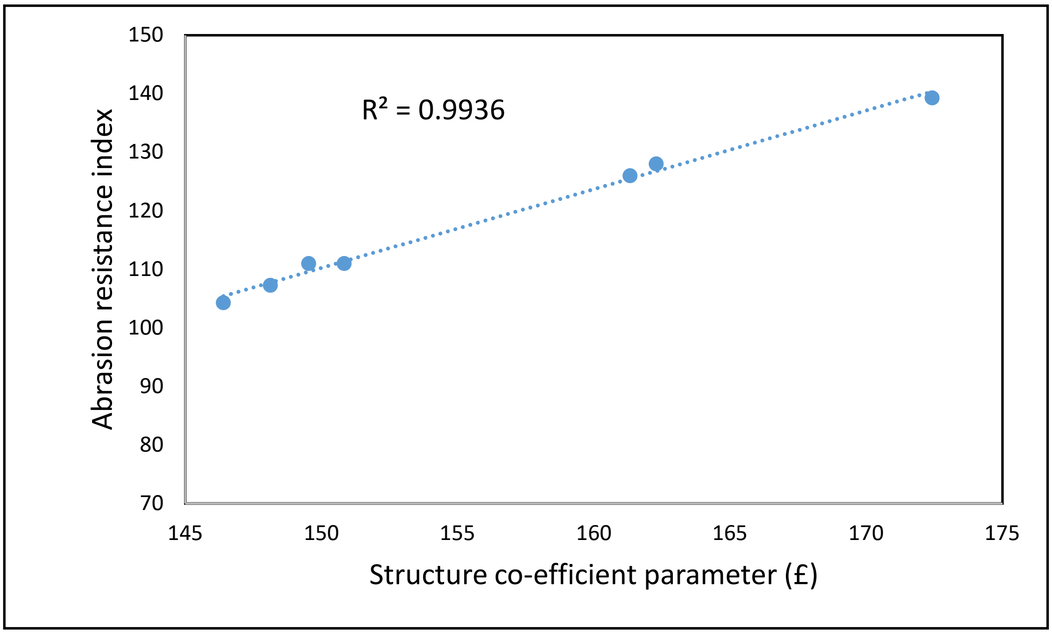

Fig-5.8: Trend of abrasion resistance index of rubber compound with 'structure co-efficient parameter (Ŝ) of carbon black

The abrasion resistance of individual rubber compounds shown in Fig-5.9 in term of abrasion resistance index, which demonstrates carbon black HP06 provides highest abrasion resistance property in rubber compound due to its highest structure property while HP03 provides least abrasion resistance due to its lower structure property. It has been seen that aggregate size distribution of carbon black also affects the abrasion resistance of rubber compound. Diehl and Niedermeier [22] demonstrated that carbon black with narrow aggregate size distribution provides improved abrasion resistance compared to similar carbon black with broad aggregate size distribution. It is seen HP02 and HP03 carbon black have similar surface area, structure and FWHM value, however, HP02 carbon black provided marginally superior abrasion resistance compared to HP03 grade carbon black. The probable cause for the same could be dissimilar characterization of aggregate size present in individual carbon black. It is noticed that HP02 carbon black is characterized with lower mode and lower mean values as compared to HP03 carbon black. Lower mode and lower mean value of HP02 grade carbon black indicates presence of larger extent of smaller size aggregates in HP02 grade carbon black as compared to the HP03 grade carbon black and it results in improved abrasion resistance property for the HP02 carbon black in rubber compound. The smaller size aggregate can lead to formation of high carbon black network in rubber matrix and could increase the rigidity of rubber compound and consequently lead to high abrasion resistance property.

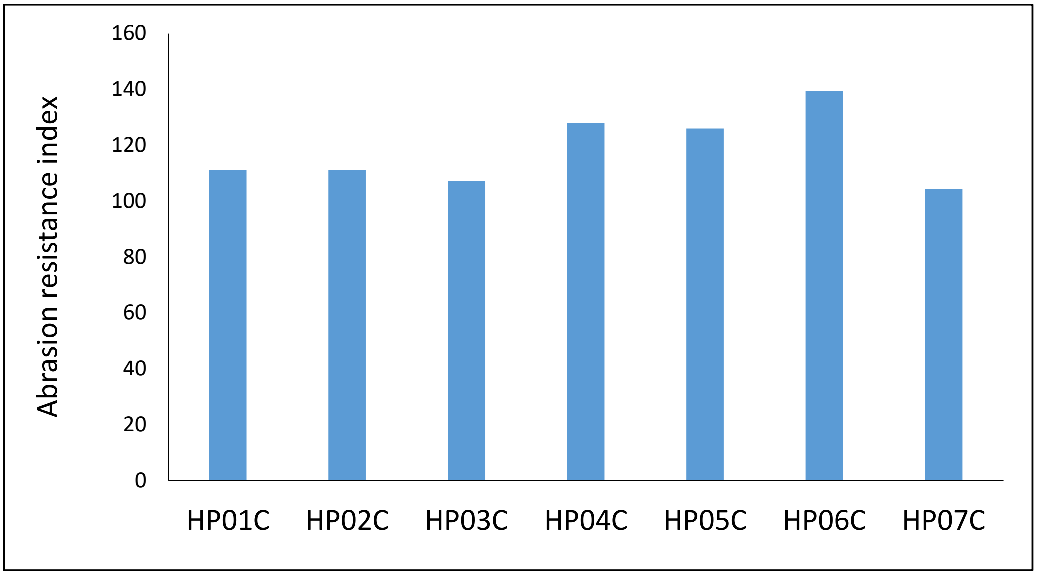

Fig- 5.9: Abrasion resistance Index of rubber compounds

5.4 Conclusions

Carbon black is characterized by surface area, structure, and different aggregate size distribution parameters such as mean, mode, FWHM, 'd_n' value etc. Each of these parameters affects the rubber compound properties. HRTEM analysis validates carbon black characterized with similar range of particles size would provide similar external surface area. In this study it is demonstrated that carbon black aggregate size has a significant influence on Payne effect and heat buildup property of rubber compound. Carbon black possessing lower aggregate size has strong affinity to form filler-filler network and leads to high Payne effect in rubber compound. The same phenomenon also influences the heat buildup property of rubber compounds. The d_{10} value is a potential parameter of carbon black, which represents lower size aggregates present in carbon black and lower value of the same indicates presence of large extent of lower size aggregate in carbon black as a result it provides high Payne effect and high heat build in rubber compounds.

The aggregate size distribution of carbon black has a considerable impact on hysteresis loss of rubber compound. To demonstrate hysteresis loss of rubber compound, a novel aggregate size distribution coefficient parameter, termed as aggregate size distribution co-efficient' has been introduced which is function of mean and FWHM on hysteresis property. It has been established that the hysteresis property of rubber compound is reduced with increasing 'aggregate size distribution co-efficient' parameter, this demonstrates increase of mean aggregate size or FWHM value or both parameters of carbon black favor in achieving low hysteresis property of rubber compounds and it is also demonstrated FWHM is predominat parameter on hysteresis compared to mean value. Hysteresis loss in the present study was represented by tanδ value measured at 60°C, which is a measure of rolling resistance for tyre tread compound. Hence carbon black development with tailor made aggregate size distribution can significantly limit the rolling resistance for tyre tread compound.

The abrasion resistance property of the rubber compound is predominantly controlled by the structure property of carbon black while the surface area of the same remains in the similar range. However, it has been observed that to express the abrasion resistance property of rubber compound by structure property of carbon black a combined consideration of primary and secondary structure is preferable. To investigate the same here a unique 'structure co-efficient parameter ($\hat{S}$) has been introduced, which is a function of primary structure as well as secondary structure of carbon black. It demonstrates that carbon black with high 'structure co-efficient parameter value results in enhanced abrasion resistance property of rubber compounds. Aggregate size distribution parameters also play certain effect on abrasion resistance property and in this case, carbon black with lower mean aggregate size and lower mode value has potential to enhance the abrasion resistance property of rubber compound as compared to carbon black having relatively higher mean and mode values.

Thus, to achieve high durable, low rolling resistance tyre tread compound for new generation tyre technology, carbon black with a tailor-made aggregate size distribution and suitable combination of colloidal properties are essential. Present study indicates that by accomplishing those carbon black properties, produced in furnace process, a perfect tyre tread compound can be made.

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