

# Impact of Silicas with Different Surface Areas on Tire Performance

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## Abstract

This study investigates the relationship between the surface area of silica used in rubber compounds and tire performance. As efforts to improve safety and fuel efficiency continue, optimizing the reinforcing fillers, particularly the BET surface area of silica, has become a crucial strategy. This paper examines the influence of silicas with varying surface areas on physico-mechanical properties,  $\tan \delta$  behavior in DMA analysis, rolling resistance, and traction performance on wet and snowy surfaces, based on literature review and experimental data.

Although numerous studies have been conducted on the performance of tire tread compounds, information regarding the effect of silica reinforcing fillers on wet traction and rolling resistance remains limited. It is well known that the transition from carbon black to silica as a filler improves tire tread performance. In addition to reducing rolling resistance, improving wet grip of the tread is a critical safety and performance factor. The friction, traction, and slip resistance of tire treads on various surfaces under dry and wet conditions have been the subject of extensive experimentation and modeling. In this study, three different types of highly dispersible silica were compared to investigate the influence of specific silica surface area on tire performance. Among the structural parameters of silica, specific surface area (measured by BET and CTAB methods) plays a key role in determining its interaction with the rubber matrix.

*Keywords:* Braking performance; Rolling resistance; Silica; Surface area

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## 1. Introduction

Carbon black is widely regarded as one of the earliest manufactured materials, with documented use tracing back to ancient Chinese and Egyptian civilizations. In those periods, it served as a pigment in India ink and wall paints. The most consequential development for its industrial application and a pivotal milestone for the tire and automotive sectors was the discovery of its reinforcing effect when incorporated into natural rubber. employed as a reinforcing filler, carbon black dramatically extended tire service life, enabling driving ranges on the order of tens of thousands of kilometers [1].

Since the early nineteen-forties, carbon blacks have been complemented by the group of highly active silicas. Technological reasons have long prevented silicas from being used in tire compounds. Conventionally, carbon black is considered to be a more effective reinforcing filler for rubber tire treads than silica, if the silica is used without a coupling agent. In comparison with carbon black there tends to be a lack of, or at least an insufficient degree of physical and/or chemical bonding between the silica particles and the rubber. This is necessary to enable the silica to become a reinforcing filler for the rubber for most purposes, including tire treads. To overcome such deficiencies, additives capable of reacting with both the silica surface and the rubber molecules, generally known as coupling agents became a necessity during compounding [2].

Silica offers several advantages over carbon black. When used in tire treads together with an appropriate silane, silica can deliver improved wet grip and reduced rolling resistance. Because both rubber and carbon black are hydrophobic, their co-mixing is generally compatible but can occasionally present issues. Michelin pioneered silica technology and, in 1992, introduced the first generation of low fuel consumption “Green Tires” by partially substituting carbon black with silica. Nonetheless, when silica is compounded with widely used non polar olefinic hydrocarbon rubbers, hydrogen bonding among surface silanol groups within silica agglomerates predominates over silica rubber interactions, creating significant compounding challenges. Consequently, chemically modifying precipitated silica surfaces to enhance compatibility with hydrocarbon rubbers has become a focal point. To this end, bifunctional organosilanes are widely employed. At present, the most commonly used organosilane in tire applications is bis(triethoxysilylpropyl) tetrasulfide (TESPT) [3]. Figures 1 and 2 illustrate representative silica–silane salinization reactions.

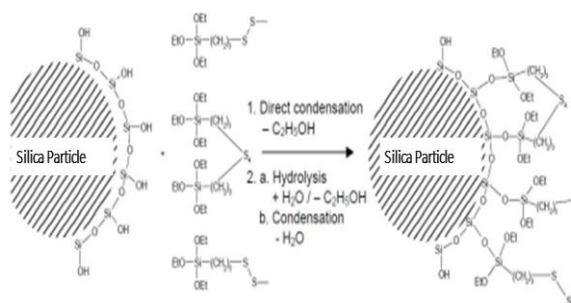


Figure 1. Silica silane 1. reaction mechanism [2]

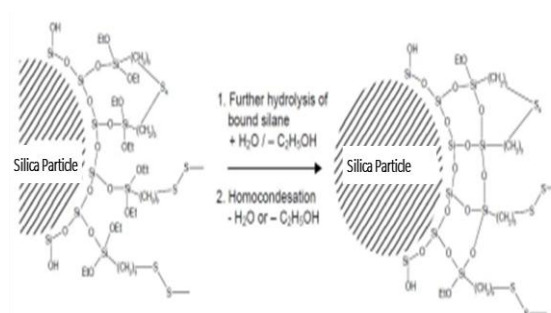


Figure 2. Silica silane 2. reaction mechanism [2]

The use of silica can deliver a 20% or greater reduction in rolling resistance compared with carbon black. Provided tire inflation pressures are properly maintained and variable speeds and driving characteristics are taken into account a 20% decrease in rolling resistance translates to roughly a 5% improvement in fuel economy.

Specific surface areas measured by Brunauer–Emmett–Teller (BET) and cetyltrimethylammonium bromide (CTAB) methods characterize the accessibility of the silica surface to probes of different sizes relatively small molecules such as nitrogen for BET, and relatively larger species such as polymers for CTAB [4,5]. The BET value is a measure of the “total” surface area, whereas the CTAB value corresponds to the “external” surface area of silica, as illustrated in Figure 3. The BET/CTAB ratio is commonly used to compare different silica grades. In practice, obtaining a large disparity between these two specific surface areas is challenging. For most silica types, the BET/CTAB ratio ranges from 0.8 to 1.2; however, higher values (e.g., 1.5 to 2.4) have also been reported in the literature [2,6].

In our study, as shown in Table 1, trial compounds were prepared using silicas with BET surface areas of 90 m<sup>2</sup>/g, 115 m<sup>2</sup>/g, and 175 m<sup>2</sup>/g in formulations D32, D38, and D40, respectively, while keeping all other raw materials constant. These formulations were mixed in internal mixers, tires were manufactured from the resulting compounds, and their performance was evaluated via rolling resistance, wet-braking, and snow-braking tests.

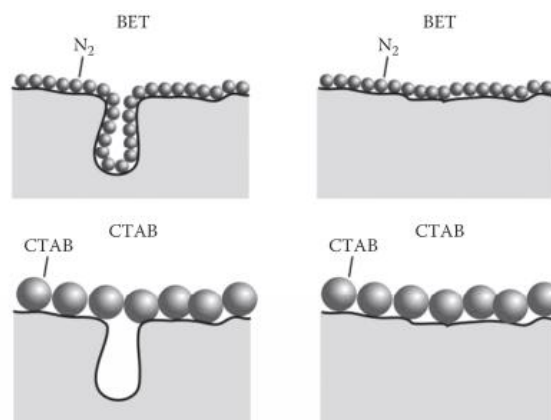


Figure 3. Difference between BET and CTAB surface area measurements [9]

## 2. Experimental Methods

To evaluate the influence of silica surface area on tire performance particularly braking distance trial formulations expressed in phr (parts per hundred rubber) were prepared using three silicas with distinct BET surface areas, as shown in Table 1, and mixed in a Banbury-type internal mixer. In each compound, the polymer matrix, coupling agent (TESPT), plasticizer, and vulcanization system were held constant so that only the effect of silica morphology would be isolated by design. After mixing, the compounds were processed by extrusion, followed by tyre building. Specimens were then cured in molds under identical temperature and pressure conditions.

The cured specimens were tested for physico-mechanical properties via the ring test method, Mooney viscosity, dynamic mechanical analysis (DMA) with  $\tan \delta$  measured at 0 °C and 60 °C, and  $\tan \delta$  by RPA. The finished tires were subsequently subjected to rolling resistance (RR), wet-braking, and snow-braking performance tests.

Table 1. Trial compounds formulations

Raw Materials	Trial Recipes		
	D32 (1.Recipe)	D38 (2.Recipe)	D40 (3.Recipe)
Natural Rubber	40,00	40,00	40,00
Strien Butadien Rubber	60,00	60,00	60,00
Silica 1 (90 m2/g)	80,00		
Silica 2 (115 m2/g)		65,00	
Silica 3 (175 m2/g)			65,00
Tespt Silane	4,00	4,70	6,00
Oil	20,00	20,00	20,00
Zinc Oxide	2,50	2,50	2,50
Stearic Acid	1,50	1,50	1,50
Resin	1,00	1,00	1,00
Antioxidant	1,00	1,00	1,00
Antiozonant	1,50	1,50	1,50
Sulphur	1,80	1,80	1,80
Accelerator 1	1,60	1,60	1,60
Accelerator 2	1,00	1,00	1,00

### 2.1. Evaluation of Compounds Test Results

#### 2.1.1. Evaluation of Compound Mooney Viscosity (ML 1+4)

#### 2.1.2. Evaluation of Tensile Properties

Tensile strength provides insight into the robustness of interactions between filler particles and polymer chains under high deformation. When filler–polymer interactions are weak, polymer chains adsorbed on or entangled with the filler surface undergo interfacial slippage under load and may desorb from the filler surface. Such molecular slippage at the filler–polymer interface is also well documented for carbon-black-filled elastomers [7,8]. For example, in a formulation where a silane is used but silica itself is absent, the fillers generally exhibit relatively low reinforcing capability: tensile strength remains low while elongation at break is high. By contrast, when polymer chains are covalently tethered to the filler surface (e.g., via a silane), slippage is suppressed; elongation at break decreases and tensile strength increases.

With increasing CTAB/BET surface area, the tensile strength of vulcanized compounds rises. As aggregate size decreases i.e., as surface area increases more polymer is adsorbed onto the filler surface, which can, in some cases, lead to higher elongation at break [1]. Figure 4 illustrates rubber–silica–silane bonding.

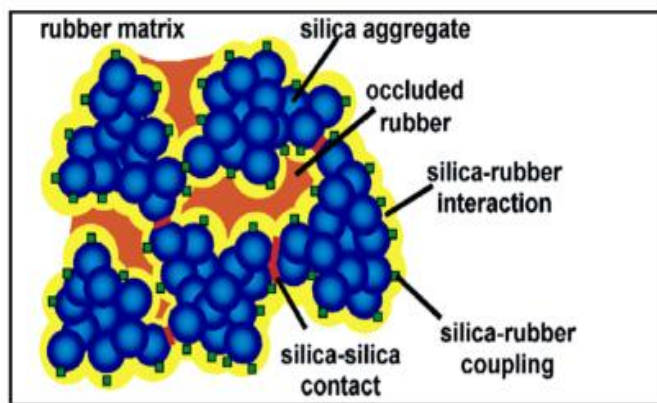


Figure 4. Rubber and silica-silane bonding [9]

As summarized on an index basis in Table 3, the formulation D38 prepared with the lowest-surface-area silica exhibits the lowest tensile strength and elongation at break. In contrast, the formulation D40 containing the highest-surface-area silica shows the highest tensile strength and elongation at break.

Table 3. Ring test results of the trial compounds

Trials	Tensile Strength	Elongation At Break
D32 (90 m2/g)	16,80	320,06
D38 (115 m2/g)	19,49	371,27
D40 (175 m2/g)	22,58	430,22

### 2.1.3. Evaluation of Polymer-Filler Interaction-The Payne Effect

The Payne effect [10] can be used as an indicator of filler-filler interactions. It is an indirect method that enables assessment of these interactions, which are partly dependent on the dispersion of the filler within the polymer matrix. The Payne effect is commonly expressed in terms of the ratio of storage to loss moduli,  $\tan \delta$ . A decrease in the specific surface area of silica or an increase in particle size reduces the extent of the filler-filler network and thus leads to a lower Payne effect. Therefore, a lower RPA  $\tan \delta$  value indicates a lower Payne effect.

The polymer-filler interactions of the compounds were tested using the RPA device, and the results are presented in Table 4. Accordingly, it was observed that formulation D32, which contains the lowest surface-area silica, exhibits the highest polymer-filler interaction, the lowest filler-filler interaction, and therefore the lowest Payne effect.

Table 4. RPA test results of the trial compounds

Trials	RPA( $\tan \delta$ 60°C )
D32 (90 m2/g)	0,120
D38 (115 m2/g)	0,126
D40 (175 m2/g)	0,144

### 2.1.4. Evaluation of Dynamic Mechanical Properties (DMA)

In the DMA response, the  $\tan \delta$  peak height decreases as aggregate size diminishes that is, as specific surface area increases. As silica aggregates become smaller (i.e., surface area increases), filler-filler interactions intensify. At the same time, polymer chain mobility becomes more constrained with decreasing aggregate size (increasing surface area).

As shown in Figure 5, the compound containing the lowest-surface-area silica (90 m<sup>2</sup>/g; formulation D32) exhibits the highest tan δ peak in the DMA trace. This is followed by the compounds formulated with 115 m<sup>2</sup>/g and 175 m<sup>2</sup>/g BET silicas (D38 and D40, respectively).

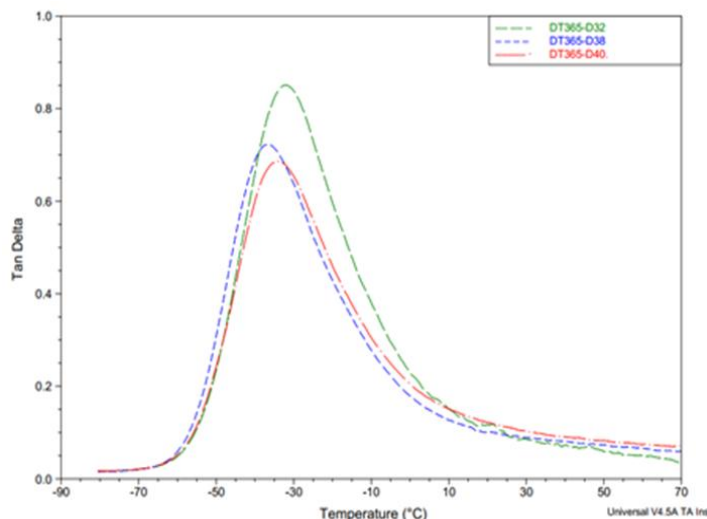


Figure 5. DMA graphs of trial compounds

#### 2.1.4.1. Evaluation of tan δ at 60 °C: Indicators of Rolling Resistance

Rolling resistance may be defined as the resistive force acting opposite to the direction of motion when a circular object rolls over a surface. Approximately 30% of the energy released by fuel combustion in a vehicle’s engine is expended to overcome the tires’ rolling resistance. The predominant cause of this energy loss is hysteresis. A strong correlation exists between a tire’s rolling resistance and the loss tangent (tan δ) of the tread rubber measured between 60–80 °C; accordingly, rolling resistance was estimated from dynamic mechanical analysis (DMA) data collected in temperature-sweep mode.

A low tan δ measured at rolling-temperature conditions indicates low rolling resistance. The greater the filler–filler interactions, the higher the hysteresis values not only in the 0–20 °C range but also at elevated temperatures. As the amount of polymer chains adsorbed on the filler surface increases, hysteresis decreases at both high and low temperatures. Fundamentally, hysteresis arises from (i) the breakdown and reformation of filler aggregates (the filler–filler network) under dynamic strain and (ii) interfacial slippage of polymer chains along the filler surface due to weak filler–elastomer interactions.

Assuming an average vehicle speed of 70 km h<sup>-1</sup> and a tire size of 255/65 R16, the characteristic deformation frequency in a rotating tire is on the order of 10 Hz. The hysteresis of the rubber compound raises the tire temperature to approximately 60 °C during service. The load applied by the vehicle is estimated to produce about 2–6% deformation in the tread. Therefore, measuring tan δ at 10 Hz, 2% dynamic strain, and 60 °C provides a reliable indicator of rolling resistance. Under these conditions, a lower tan δ corresponds to a lower predicted rolling resistance. Silicas with higher specific surface areas tend to agglomerate more within the polymer matrix, intensifying the Payne effect. Consequently, due to their higher specific surface areas and smaller aggregate sizes, higher-surface-area silicas yield markedly higher tan δ values at 60 °C.

When the DMA tan δ values of the compounds at 60°C (the temperature simulating rolling resistance) were examined in Table 5, it was predicted that the formulation containing the lowest surface-area silica (D32) would exhibit the lowest tan δ value and therefore the lowest rolling resistance. This is followed by the formulations employing silicas with BET surface areas of 115 and 175 m<sup>2</sup> g<sup>-1</sup> (D38 and D40, respectively).

Table 5. DMA tan δ 60°C test results of compound trials

Trials	DMA (tan δ 60° )
D32 (90 m <sup>2</sup> /g)	0,119
D38 (115 m <sup>2</sup> /g)	0,133

D40 (175 m2/g)	0,180
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**2.1.4.2. Evaluation of  $\tan \delta$  at Low Temperatures: Indicators of Wet-Traction Performance**

While rolling resistance is of paramount economic importance, braking performance is directly linked to safety. Shortening braking distance significantly enhances traffic safety on both dry and wet surfaces. A fundamental distinction, however, is that braking distances on wet surfaces are substantially longer than on dry ones. It is widely accepted that the dynamic properties of tread compounds particularly  $\tan \delta$  at low temperatures and high frequencies serve as indicators of wet-traction behavior, because the dynamic strain during wet braking is inherently high-frequency in nature.

When low-hysteresis tread compounds (i.e., “green tires”) were introduced, they were shown not only to reduce rolling resistance but also to deliver improved wet performance. This enhancement in wet grip was achieved by replacing carbon black with a silica–silane system. The improvement can be attributed to two effects:

1. The dynamic properties of the silica-filled tread compound, and
2. The hydrophilic surface characteristics of the silica-filled tread.

The first phenomenon reflects intrinsic differences in dynamic behavior between silica-filled and carbon-black-filled rubbers. The principal distinction is that silica-containing formulations typically exhibit higher hysteresis at low temperatures and lower hysteresis at elevated temperatures.

As depicted in Figure 6, the temperature windows used in DMA can be mapped onto tire performance parameters. In particular,  $\tan \delta$  values measured between  $-10^{\circ}\text{C}$  and  $+10^{\circ}\text{C}$  are generally regarded as indicators of wet-traction performance for the tread. Higher  $\tan \delta$  values within this temperature range simulate better wet-grip performance.

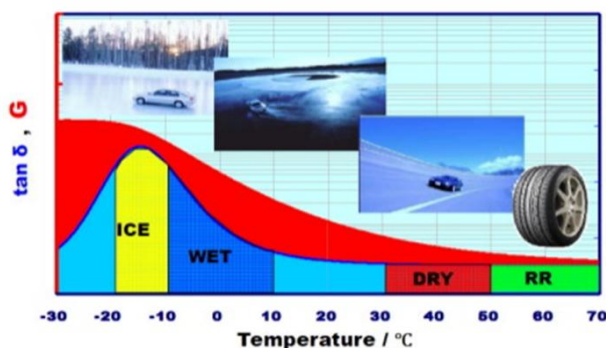


Figure 6. DMA Curve and temperature ranges simulating tire performance [11]

The DMA  $\tan \delta$  results at  $0^{\circ}\text{C}$  for the prepared trial formulations are presented in Table 6. Accordingly, formulation D32, which contains the lowest surface-area silica, exhibits the highest  $\tan \delta$  at  $0^{\circ}\text{C}$  and is therefore predicted to provide the best wet-grip performance.

Table 6.  $0^{\circ}\text{C}$  DMA  $\tan \delta$  test results of trial compounds

Trials	DMA ( $\tan \delta$ $0^{\circ}\text{C}$ )
D32 (90 m2/g)	0,422
D38 (115 m2/g)	0,333
D40 (175 m2/g)	0,329

**3. Characterization Methods**

- Mooney viscosity (ML (1+4)) was measured at  $100^{\circ}\text{C}$  on an MV 2000E Mooney viscometer (Alpha Technologies) in accordance with ASTM D1646.
- Payne effect measurements were performed on an RPA 2000 in the pre-vulcanization state, following Petlas RPA internal standard procedures.
- Mechanical properties of the specimens were tested using an Instron tensile testing machine in accordance with ISO 37.
- Dynamic mechanical analysis (DMA) was conducted in tensile mode using a Metravib DMA 2000 dynamic spectrometer.

#### 4. Results and Discussion

##### 4.1. Evaluation of Rolling Resistance

The rolling resistance test is carried out in Petlas’s accredited in-house laboratories. For a C1 class passenger vehicle, the fuel consumption label values and regulatory limits are presented in Table 7.

Table 7. Rolling resistance test label values

Fuel efficiency class	C1 tyres (RRC in N/kN)	C2 tyres (RRC in N/kN)	C3 tyres (RRC in N/kN)
A	$RRC \leq 6.5$	$RRC \leq 5.5$	$RRC \leq 4.0$
B	$6.6 \leq RRC \leq 7.7$	$5.6 \leq RRC \leq 6.7$	$4.1 \leq RRC \leq 5.0$
C	$7.8 \leq RRC \leq 9.0$	$6.8 \leq RRC \leq 8.0$	$5.1 \leq RRC \leq 6.0$
D	$9.1 \leq RRC \leq 10.5$	$8.1 \leq RRC \leq 9.0$	$6.1 \leq RRC \leq 7.0$
E	$RRC \geq 10.6$	$RRC \geq 9.1$	$RRC \geq 7.1$

Rolling-resistance test results for the compounds evaluated on a Petlas 225/55 R17 101V GLACIER W661 tire are presented in Table 8. Accordingly, the tire produced with the trial compound formulated using the lowest-surface-area silica (D32) exhibits the lowest rolling resistance. The rolling-resistance outcome corroborates the DMA-based prediction. Low rolling resistance indicates low fuel consumption.

Table 8. Rolling resistance test results of trial tires

Trials	DMA (tan 60°C )	Rolling Resistance
D32 (90 m2/g)	0,119	6,85 (B)
D38 (115 m2/g)	0,133	7,04 (B)
D40 (175 m2/g)	0,180	7,23 (B)

##### 4.2. Wet-Braking Performance Test

As shown in Table 9, the compound formulated with the lowest-surface-area silica (D32) delivers the best wet-braking performance.

Table 9. Wet braking distance (m) test results of trial tires

Trials	Wet Braking Distance (m)
D32 (90 m2/g)	29,26
D38 (115 m2/g)	31,12
D40 (175 m2/g)	32,46

##### 4.3. Snow-Braking Performance Test

To evaluate snow performance, tires produced with the three trial compounds were subjected to braking tests at Kayseri–Erciyes and Bolu–Kartalkaya. A photograph taken during testing is shown in Figure 5. Examination of the compound–snow braking distance data in Table 10 indicates that the trial tire formulated with the lowest-surface-area silica (D32) delivered the best snow-traction performance. Overall, the assessment of snow-braking performance shows that decreasing silica surface area enhances the tire’s braking capability on snow.

Table 10. Snow brake distance (m) test results of trial tires

Trials	Snow Brake Distance(m)
D32 (90 m2/g)	6,85
D38 (115 m2/g)	6,91

D40 (175 m <sup>2</sup> /g)	7,27
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## 5. Conclusions

The experimental data demonstrate a clear relationship between the BET surface area of silica and critical tire performance parameters. Compounds containing silica with higher BET surface area exhibited a more pronounced Payne effect, indicating a stronger filler–filler network structure. Consequently, these formulations showed lower  $\tan \delta$  values at 0 °C and, therefore, inferior wet-grip performance.

By contrast, lower-surface-area silicas provide a reduced Payne effect and easier processing. The balance between processability and performance is crucial. Snow-braking tests reveal that silicas with lower BET surface areas improve braking performance on snow by approximately 10–15% relative to higher-BET silicas.

Our study indicates that silica surface area plays a significant role in rubber compound properties—particularly tire braking performance. Higher-surface-area silicas can lead to processing challenges and increased viscosity. Moreover, in terms of snow performance, the best braking results were obtained with the tire formulated using the lowest-surface-area silica.

Accordingly, optimal silica selection should aim to maximize the performance balance while maintaining processing efficiency.

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