Rational Design of High-Performance Nanomaterials for Electric Vehicle Tires

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Abstract. In today's society, the market limitations of electric vehicle tires are relatively poor wear resistance and rolling resistance. These two problems restrict the further development of electric vehicles, accelerate energy consumption and environmental pollution, and bring hidden dangers to users. In this paper, the principle of tire wear resistance and the cause of excessive rolling resistance related to tire deformation are analyzed from the perspective of materials. At present, these two problems can be improved by adding nanomaterials to automobile tire materials (natural rubber and synthetic rubber). The tire's thermal conductivity and wear resistance can be improved by inserting Silica and a small amount of nano-diamond. This paper will also discuss the unique advantages of carbon black with different particle sizes as filler by analyzing the effects of modified Silica and carbon black on the molecular rubber chain. On this basis, this paper will also explain the drawbacks of nanofiller materials.

Keywords: Nanotechnology, nanomaterial; tire, electric vehicle.

1. Introduction

The automobile has become one of the most commonly used means of transportation in real life. With the continuous development of the automobile industry, people put forward higher and higher requirements for the quality and performance of automobiles. The pursuit of more perfect, more convenient and more satisfactory manufacturing has become the goal of major automobile manufacturers. However, there are still many unavoidable difficulties and dangers in using automobiles. For example, insufficient tire friction coefficient leads to excessive fuel consumption, or poor tire grip leads to vehicle skidding. According to the relationship between the rolling resistance of automobile tires and fuel economy, it is pointed out that due to the insufficient rolling resistance of the tires, the elastic hysteresis loss of the tires is caused, and the automobiles need to consume 3%~7% of energy at the same mileage. According to incomplete statistics in the Research Report on Analysis of Automobile Tire Accidents in Traffic Accidents in 2019, the automobile accident rate caused by tire problems in China in 2019 is as high as 39% [1]. Currently, most of the automobile tires used in the market are traditional. Many tire companies have improved the wheel hub's structure and material and the carcass's pattern. A few tire companies have added an appropriate amount of cis-1,4-polybutadiene rubber to the carcass material to improve the wear resistance, but the effect is not obvious, and they cannot effectively solve the problem of excessive tire rolling resistance. Therefore, it is urgent to improve the technology of traditional tires. This paper hopes that refitting the tires currently in use will not only reduce the vehicle accident rate, but also improve fuel efficiency and reduce unnecessary energy consumption. It not only achieves objective economic benefits from the perspective of vehicle users but also achieves the goal of green transportation from the perspective of environmental protection [2]. By analyzing the influence of nanomaterials on the composition, structure and performance of automobile tires (mainly tread and carcass), this paper attempts to further optimize the tires on the current market. Due to the extensive application of nanomaterials in automobile tires, this paper mainly introduces two important methods to fill nanomaterials to change tire performance. Next, the reasons for poor wear resistance and high rolling resistance of tires are introduced from the point of view of mechanics and materials, and how to use nanomaterials to solve these two problems is shown.

2. The increased share of electric vehicles in the automotive market

In transportation, the electrification of vehicles has gradually become a trend. Electric vehicles can significantly improve energy conversion efficiency and also help reduce greenhouse gas emissions, air quality, and noise pollution by replacing traditional fossil energy with electric energy from diverse sources. In addition, the electrification of vehicles can also improve the country's energy security, achieve sustainable development, and meet the requirements of various policies. In 2017, the global sales of electric vehicles exceeded 1 million, an increase of 54% over 2016 and a record high [1]. Electric vehicles accounted for 39% of new vehicle sales in Norway. In terms of sales share, Norway is the largest electric vehicle market in the world. Iceland and Sweden ranked second and third, and the sales share of electric vehicles reached 11.7% and 6.3% in 2017. China accounted for more than half of the global electric vehicle sales, more than twice the world's second-largest electric vehicle market (the United States), and 2.2% of the total automobile sales. In addition to passenger cars, the electrification of other vehicles, such as two-wheeled vehicles and buses, is also developing rapidly in the transportation industry. In 2017, the global sales of electric buses reached 100000, and the sales of electric two-wheeled vehicles reached 30 million [2]. China accounted for most of the sales. From the perspective of China, since the entry of electric vehicles into the market, cars have become an ordinary commodity that can be driven away with only a down payment of 20000 yuan. Since then, people's lifestyles, life concepts, and quality of life have changed due to electric cars.

3. Disadvantages and limitations of current traditional tires

Compared with other means of transportation, new energy vehicles have the characteristics of unlimited number, unlimited travel, fast acceleration, and no exhaust pollution, so it is used more and more. In today's huge electric vehicle market, various electric vehicle companies pay great attention to how to improve the performance of electric vehicles. Among them, how to improve tires is an important issue that various companies consider. With the establishment of the highway network, people are generally concerned about the driving safety of tires. Most automobile manufacturers in North America believe that the safety of tires is more important than life. However, the reliability and safety of tires are not a problem. Among the early damaged tires in the former Soviet Union, 10% were damaged due to delamination and blocked falling, and no more than 2% were damaged due to carcasses or belt cords [2].

In 1991, Baumgardner D, the former Firestone, urged tire companies to solve the problems existing in the current tire technology at a tire industry conference. He pointed out that 80% of tire-related injuries and 70% of lawsuits filed with tire manufacturers were mainly caused by the following reasons: i) the steel bead of Multi Strand Bead was broken; ii) Belt delamination of radial tires for some cars and light load vehicles; iii) Some medium-sized truck radial tires (mostly with low cross-section) are easy to burst when re-inflated after running short of air; iv) tire load capacity formula and coefficient K are out of date. In 1994, the American Tire Association also specifically discussed the zipper-type explosion problem that suddenly appeared on the sidewall of medium and light truck radial tires when inflated. Some automobile companies (such as Callway Corvettos) choose Goodyear's "EMT" (extended mobility tire) and Bridgestone's "Expedia" as the original tires and replacement tires for high-class cars [3]. These tires can still travel a certain distance after air leakage. The service life of tires needs to be further improved. How to reduce tire wear is a big problem. Compared with the wear of tires, excessive rolling resistance will cause unnecessary negative effects on cars. When the vehicle is running, the load applied to the tire will cause the tire to deform. Because the rubber formula used for tire manufacturing has viscoelastic properties, when the tire is deformed, this type of material will lose part of the energy, and the lost energy will be converted into the form of heat. The repeated tire deformation continuously causes energy loss, which is the main reason for the tire's rolling resistance, accounting for about 90%-95% of the total rolling resistance of the tire. For an electric vehicle, the battery supplies energy, so the tire's rolling resistance directly affects the

power consumption. Moreover, excessive rolling resistance will aggravate tire wear and reduce tire life.

4. Analyzing the reason for low tire strength from the point of view of material mechanics

It can be seen from the representative tire structure design theories proposed in recent years that most of them are traditional strength theories based on material mechanics [4]. For example, many chemical research companies and institutions such as ITTC in Tianjin only take the stress (or strain) generated by the static load as the characteristic parameter of the mechanical state, only include stress in the strength condition, and also consider the stress concentration generated by material defects or inhomogeneity.

Tire Research Institute of the former Soviet Union is also based on material mechanics, stress, and strain of smooth components. Of course, compared with the EOT theory of the mainland, they have made great progress because they are all based on the fatigue strength of the specimen under the combined influence of dynamic and static strains under the complex stress state, which includes the deformation energy obtained by using the dynamic linear deformation amplitude and the dynamic deformation shear component amplitude [4]. Mechanics of materials solves the safety design of components from the following three aspects: i) calculating stress σ (or/and strain); ii) determining the ultimate stress of the material according to the static test σ. Then divide it by a generally discounted safety factor with poor pertinence to obtain the allowable stress [σ]. iii) Finally, the strength condition is established at $\sigma \leq [\sigma]$ [5]. Because this strength theory does not consider the defects of materials and the concentration of stress at this point, it is only applicable to small components with constant static load and low-strength materials. It can only ensure that the components will not be damaged due to elastic instability, excessive deformation, or flexure. For fatigue damage under alternating load, this theory is not applicable because most materials have defects (it makes the actual strength of polymers 100-1000 times lower than the theoretical strength, and the size of concentrated stress in this area is proportional to the square root of the defect size). Therefore, the data is scattered when only stress (or/and strain) is used to determine fatigue strength and life [5]. The double logarithm plot of the stress amplitude s versus the number of life cycles n drawn is often some parallel curves because the sample has original defects of different sizes. The influence of internal defects on fatigue life is not considered in material mechanics.

5. Mechanical causes of tire rolling resistance

When the wheel rolls, the area where the tire contacts the road surface deforms, and the corresponding supporting road surface also deforms. Due to the relative stiffness of tires and supporting pavement, their deformation characteristics are also different. Figure 1 shows the rolling of wheels on different road surfaces. Figure 1(a) shows the rolling of the elastic tire on a hard road surface. At this time, the deformation of the tire is the main one, and the hard pavement (artificial pavement such as concrete and asphalt) hardly deforms when it bears the load, which can be regarded as rigid approximately. The rolling resistance of the wheel mainly comes from the elastic hysteresis loss of the tire. Figure 1(b) shows the rolling of an elastic tire on a soft road surface. Soft pavement (earth road, sand road, snow road, etc.) forms rutting deformation during wheel rolling, and at the same time, the tire itself also has a certain small amount of elastic deformation. The rolling resistance of the wheel comes from the deformation of the soft pavement and the elastic hysteresis loss of the tire (the energy consumed by rutting formation is far greater than the elastic hysteresis loss of the tire) [5].

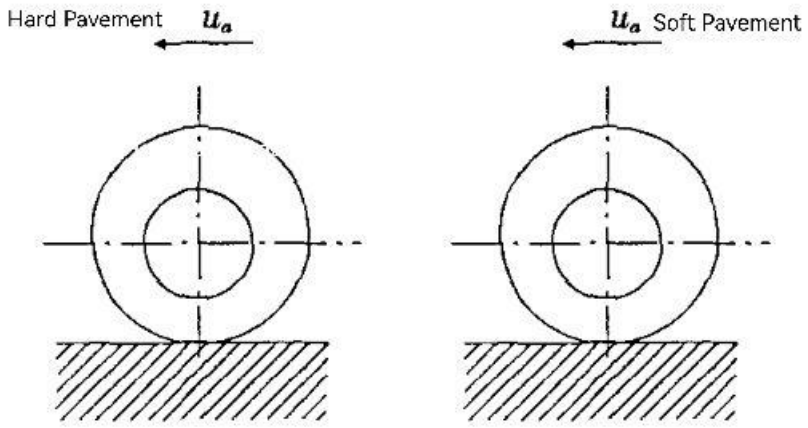


Figure 1. Wheel rolling on the road [6].

Starting from the radial deformation process of tires, the formation of rolling resistance of elastic tires when rolling on hard roads will be further analyzed. When the elastic tire rolls on the hard road, the change in the working state of each tiny elastomer on the tire can be regarded as the radial loading and unloading in turn (Figure 2). Figure 2(a) is an elastic tire with a radial load Q: if a section 2-2 is cut on the tire, the section completes a loading and unloading process when the tire rolls for one cycle. The truncated surface on the left of the normal lines 1 to 4 rolls toward the ground step by step, which is a loading (compression) process. The deformation curve is equivalent to the OCA curve in Figure 2(b). When the cutting surface is located at position 4-4, it has the largest deformation. When the cutting surface is on the right side of 4-4, the deformation gradually decreases and is in the unloading (recovery) process. The deformation curve at this time is equivalent to the EDA curve in Figure 2(b). The whole tire can be regarded as a process of continuous loading (compression) and unloading (recovery) of countless sections. It can be seen from Figure 2 that the work done to the tire during loading (equivalent to area Cabo) is not equal to the work released when the tire recovers deformation during unloading. The difference between the two is the energy loss during tire deformation, called the elastic hysteresis loss of the tire [6].

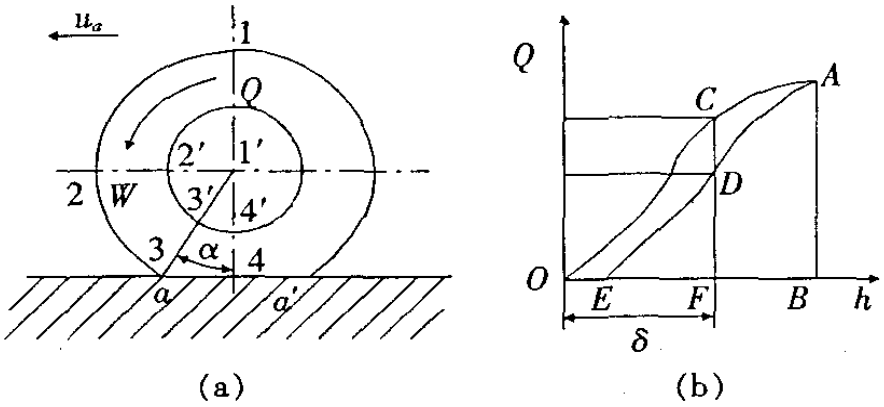


Figure 2. Elastic wheel rolling on the hard road [6].

6. Effective strategies for performance improvement of car tires

6.1. Method of inlaying nanomaterials

The final effect of reducing power consumption and saving energy can be achieved by reducing tire resistance and improving the wet traction of the tire tread. It is very important in the tire industry to improve rolling resistance without damaging wet traction and tread wear. One solution is to mix nano-diamond (ND) into Silica and fill the product into styrene butadiene rubber/butadiene rubber

[7], the main material of tire tread, to achieve this effect. First, exposed carboxylation of ND was to hot air, and then propyltrimethoxysilane was to modify its surface. The obtained product is mixed with SBR / BR mixture with a weight ratio of 75/25; half Silica, silane, half aromatic oil, and half process resin are added. This process uses a two-roll grinder for mixing to promote a sufficient silanization reaction [7]. Here is the schematic diagram of the hydrolysis and carboxylation of propyltrimethoxysilane and silylation of ND [8]. In order to test the effect of carboxylated ND on the strength of rubber, it can be compared with the rubber doped with vulcanized ND. The Fourier transform infrared spectroscopy data of these two substances is shown in Figure 3.

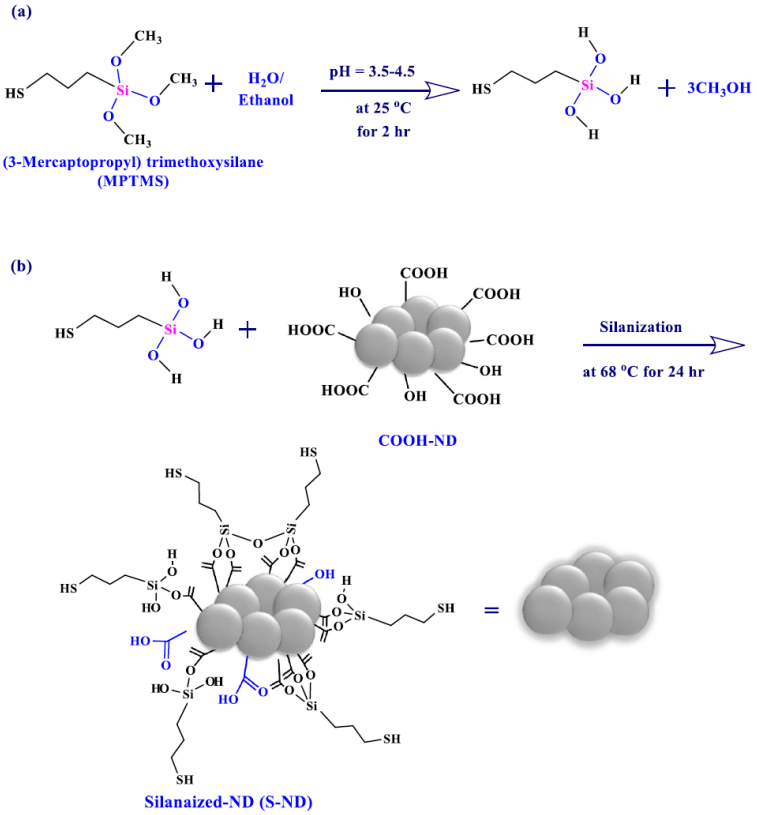


Figure 3. Schematic representation of (a) hydrolysis of MPTMS and (b) silanization of COOH-ND [7].

The strength of carboxylated ND is stronger. The reason can be attributed to the better dispersion state of carboxylated ND in rubber matrix, while vulcanized ND sacrifices slightly during dispersion. Uniformly dispersed ND impedes the movement of polymer chains and improves cross-linking [9]. It is worth noting that the formation of more agglomerates and higher accelerant adsorption on the surface of vulcanized ND resulted in a slightly lower cross-linking density. That is, carboxylated ND containing nano SiO_2 fills the nanocomposite with the best concentration in SBR/BR compound (Figure 4).

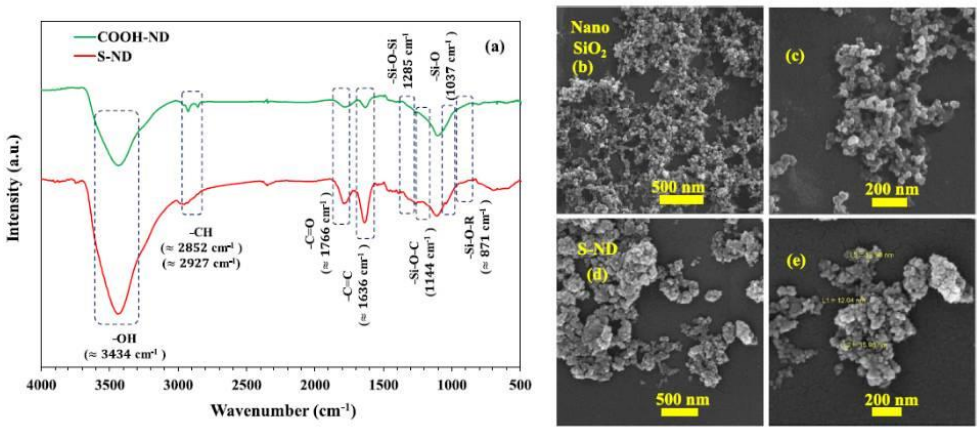


Figure 4. (a) FTIR spectra of COOH-ND and S-ND, FESEM images of (b, c) nano-SiO2 and (d, e) S-ND [9].

In addition, this nanomaterial also has good thermal conductivity. Rubber composites with high thermal conductivity can transfer heat more effectively and prolong service life. ND is incorporated into rubber compounds due to its excellent thermal conductivity (~ 3000 w/m/k). The hybridization of ND and nano SiO_2 results in that most of the silica-filled SBR/BR nanocomposites having properties between ND, and nano SiO_2-filled compounds, thus improving the thermal conductivity of rubber. This is attributed to the fact that ND improves the hardness and thermal conductivity of the silica-filled styrene butadiene rubber/CIS butadiene rubber compound and reduces the temperature rise in dynamic analysis. In a word, replacing a small amount of well-prepared Silica particles with ND in the tire tread compound has favorable performance, which will be a major achievement of the tire tread compound formulation [9].

6.2. NR filled with Silica with moderate particle size

See Figure 5 for the stress-strain curve of NR vulcanizate. It can be seen that the carbon black N330 (particle size = 0.03 μm) Under the same strain, greater stress is given. Because the carbon black used has a small particle size, few polar surface groups, and a large number of carbon double bonds, all of which leads to a strong interaction with NR, thus obtaining a large reinforcement effect. It is worth pointing out that Silica-peg2000-0.9 and PSilica-0.4 have comparable reinforcing effects; Silica-Si-69-0.6 and PSilica-Si-69-0.4 have equivalent reinforcing effects and are better than PEG2000-modified Silica [10]. The surface polarity and particle size of white carbon black are larger than that of carbon black, resulting in its interaction with NR being smaller than that of carbon black, so the reinforcement effect is smaller than that of carbon black. However, it can be seen that although the reinforcing effect of small-sized Silica is better than that of large-sized Silica, the modified large-sized Silica can be used to replace the small-sized Silica, that is, eliminating the surface polarity of Silica and increasing the affinity with non-polar rubber is very important to enhance the reinforcing effect of Silica because the smaller the particle size, the larger the agglomeration effect, and the more significant the influence of the filler network will affect the rubber composite's dynamic performance. The modified Silica with a slightly larger particle size but a reinforcement effect equivalent to that of the Silica with a smaller particle size will be conducive to improving or even improving the dynamic performance [11].

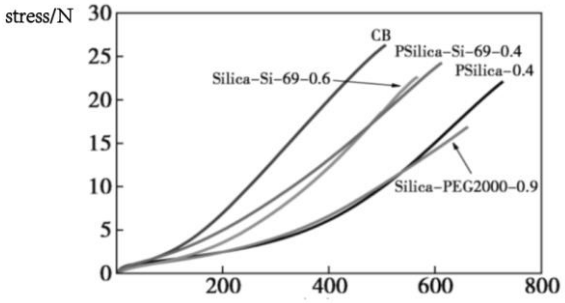


Figure 5. Stress-strain curve of NR vulcanizate [11].

It can also be seen that the positions of the stress suddenly increase points of carbon black and vulcanizates filled with white carbon blacks are different. The stress sudden increase points of carbon black are the most front, Silica-Si-69-0.4 and Silica-Si-69-0.6 are the second, and PSilica-0.4 and Silica-PEG2000-0.9 are the last. Under small strain, the molecular chain's deformation is small, mainly due to the small movement of the side groups or branches of the molecular rubber chain. When the strain exceeds a certain value, due to the large particle size and small specific surface area of Silica-PEG2000-0.9, the surface of PSilica-0.4 is not modified, the physical cross-linking points formed with the molecular rubber chain are less, and the chain segments of the molecular rubber chain move more freely. Therefore, PSilica-0.4 and Silica-PEG2000-0.9 have a longer flattening period, and the stress is slightly lower than that of the vulcanizates of Silica-Si-69-0.9 and PSilica-Si-69-0.4. However, carbon black and molecular rubber chains undergo chemical and physical adsorption. The chemical and physical cross-linking points formed are not easy to disentangle or slip during the stretching process, and the movement of rubber molecular segments is limited. Therefore, the strain of carbon black vulcanizates is small when the stress suddenly increases, and the stress is higher than that of white carbon black filled vulcanizates. Under the repeated compression of periodic pressure, the temperature of the rubber material itself will increase greatly. This phenomenon is called compression heat generation [11]. Factors such as the destruction and reconstruction of the filler network, the internal friction between the macromolecular segments, and the destruction and rearrangement of the sulfur cross-linked network are directly related to the degree of temperature rise. In this experiment, no softener such as filling oil was added to the vulcanization formula so that the influence of slightly larger particle size (hundreds of nanometers) white carbon on network structure, internal friction between macromolecular segments, destruction and rearrangement of the sulfur cross-linked network could be investigated through measurement of compression heat generation. See Figure 6 for the influence of various fillers on temperature rise. The Silica-Si-69-0.6 filling system gives the lowest temperature rise [11].

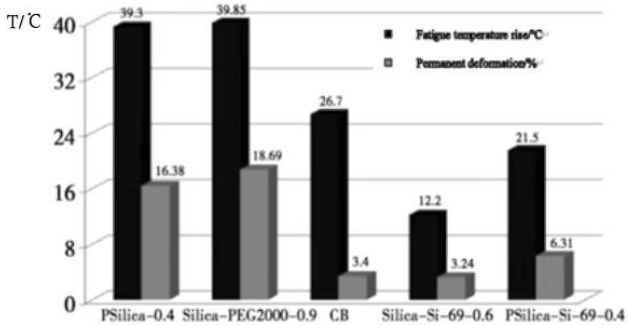


Figure 6. Effect of white carbon black on compression heat generation properties of NR Composites (stroke: 4.45 mm) [12].

The results in Figure 4 are very meaningful. The results can explain from one side (particle size) why white carbon black can play a reinforcing role like carbon not only black but also effectively reduce the compression heat generation of rubber materials [13]. There is a strong interaction between CB (n330-0.3) with a particle size of 30nm and rubber, and the reinforcing effect is excellent.

However, due to the small particle size, the degree of agglomeration is bound to increase. Under the action of periodic stress, the damage (large Payne effect, Figure 6) and reconstruction of the filler network are obvious, and the temperature rise is large. Silica-Si-69-0.6, with a particle size of 600 nm, also has a strong interaction with rubber, which has considerable reinforcing ability. However, the aggregation phenomenon of Si-69 surface-modified silica with this particle size is much smaller, resulting in a relatively low Payne effect, which gives a relatively low-temperature rise [13].

7. Conclusion

This research aims to solve the problems of poor wear resistance, easy deformation and excessive rolling resistance faced by traditional tires in the current market because they will increase tire wear, reduce tire life, reduce vehicle safety, and cause excessive energy consumption and environmental pollution. The rolling resistance of the wheel mainly comes from the deformation of the soft road surface and the elastic hysteresis loss of the tire (the energy consumed by rutting is far greater than the elastic hysteresis loss of the tire). Adding **S**ilica and ND to the tire tread can effectively improve the thermal conductivity of natural rubber/synthetic rubber, avoid the excessive local temperature of the tire, reduce tire deformation, and reduce rolling resistance. At the same time, the uniformly dispersed ND effectively prevents the movement of the polymer chain, which is conducive to improving the tire's wear resistance. SiO_2-Si-69-0.6 is a good filler material because it has a low Payne effect and the possibility of forming a filler network, reducing the elastic hysteresis loss of tires.

This paper clearly explains how to use nanomaterials to improve tires to reduce rolling resistance and wear resistance, but it also raises the problem of environmental pollution caused by nanomaterials themselves. This paper lacks research on the environmental pollution caused by nanomaterials themselves. Generally speaking, nanomaterials can reach the environment through material processing and wear. If material fragments are released into the environment, they may degrade faster than nanomaterials. Therefore, nanoparticles can persist in the environment as aggregates or aggregates. The organic components in worn rubber degrade slowly in the environment, although their low concentrations in tire rubber may accumulate in the soil. This means that inorganic nanoparticles can be released into the environment from the rubber matrix of worn tires. Based on the research content of this paper, researchers should pay attention to how to reduce the environmental pollution caused by nanomaterials entering the environment through processing and wear. However, there is little information on the type and extent of potential risks of these nano pollutants.

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