

Effects of Resins on the Abrasion Resistance of Natural Rubber Composites under Harsh Service Conditions

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Abstract Tread wear of aircraft tires is governed by harsh service conditions and material composition, which directly affect their service life. However, insufficient understanding of abrasion mechanisms under harsh service conditions imposes restrictions on the design and preparation of rubber materials with high abrasion resistance and low heat build-up. In this study, coumarone resin (CMR) and two types of *tert*-octyl phenolic resins, namely resole (PR45) and novolac (PR68), were introduced into natural rubber (NR) composites owing to their good compatibility with NR. To clarify the separate effects of large slip angle and high speed, the abrasion behavior of NR composites with different resins was evaluated under large-slip-angle abrasion (20° slip angle, 2.5 km/h) and high-speed abrasion (5° slip angle, 45 km/h) using a Laboratory Abrasion Tester 100 (LAT 100). The results showed that large-slip-angle abrasion was much more severe than high-speed abrasion, indicating that a large lateral force resulting from a large slip angle is much more detrimental to abrasion resistance than the surface temperature rise from high speed. Compared with CMR, both PR45 and PR68 improved the abrasion resistance of the NR composite under large-slip-angle conditions. The NR composite with PR68 also exhibited the lowest heat build-up among the three composites owing to its high cross-link density and uniform filler dispersion. Considering the abrasion resistance under a large slip angle and the overall performance, the PR68 composite exhibits great potential for extending the service life of aircraft tire treads.

Keywords Resins; Abrasion resistance; Aircraft tires; Large slip angle; High speed

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INTRODUCTION

As the key component of an aircraft in contact with the runway, aircraft tires bear loads, buffer impacts, and transmit forces during landing and cornering.^[1,2] Given that the wear performance of aircraft tires has a substantial impact on their service life and flight safety, many researchers are dedicated to investigating the factors affecting wear performance, thus obtaining tire treads with high wear resistance.^[3,4] The wear performance of tires is determined by the harsh service conditions and material composition of the tire treads. The service conditions of aircraft tires mainly involve the load, velocity, slip ratio, and yaw angle (slip angle) connected with cornering or crosswind.^[5–7] During aircraft steering maneuvers of taxiing process, aircraft tires are subjected to heavy load, extremely low velocity^[8] and large slip angle.^[9–11] In contrast, the service condition of aircraft tires during landing is characterized by heavy load, high speed^[12] and limited slip angles achieved through landing maneuvers,^[13,14] exhibiting distinct differences from the service condition during steering maneuvers.

The effects of load, velocity, and ambient temperature on

wear loss and temperature rise during landing were investigated using the thermo-mechanical coupling mechanism.^[15–17] Chen *et al.*^[18] employed a high-speed friction test apparatus to study the effect of slip angle on the abrasion loss and temperature rise under heavy load (120 N) and high speed (500 r/min). When the slip angle reached 18°, the abrasion loss of the rubber tire was more than 45 times that under a small slip angle, which was attributed to the increased friction work and rapid rise in surface temperature. In addition, distinct furrows were observed in the contact area and a rough contact surface was formed. In our previous research,^[19] the synergistic effects of the slip angle and speed on the abrasion volume were systematically investigated using a Laboratory Abrasion Tester 100 (LAT 100) by varying the slip angle (6°–15°) and speed (15–45 km/h). A logarithmic relationship between the abrasion volume, friction work, and surface temperature rise was established, verifying a thermo-mechanical coupling mechanism for the abrasion loss.

Considering practical aircraft tire service conditions, during large-slip-angle steering with extremely low speed, aircraft tires are likely to suffer from high lateral forces, leading to the aggravation of tire wear. In addition, high speeds occur during takeoff and landing with a low slip angle, resulting in a high surface temperature. Therefore, a large slip angle and high speed seldom occur simultaneously during aircraft tire

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services. In this study, large-slip-angle abrasion and high-speed abrasion were investigated and compared to separately evaluate the effects of slip angle (lateral force) and speed (surface temperature) on abrasion.

Natural rubber (NR) has been widely used in aircraft tires owing to its outstanding tensile strength, modulus, and strain-induced crystallization.^[20–22] Recently, the application of resins in tire treads has gained considerable attention, as resins are generally used to modulate the viscoelastic properties and wet skid resistance.^[23–28] However, research on the wear performance of aircraft tire treads with different resins remains inadequate. Mohanty *et al.*^[29] explored the impact of resin structure on the abrasion resistance of NR tread composites through DIN abrasion tests. The NR composite with terpene phenol resin exhibited higher abrasion resistance than the other samples owing to its good compatibility with natural rubber. However, the DIN abrasion test condition (5 N, 40 m) is inadequate for aircraft tire service conditions. Indriasari *et al.*^[30] used terpene phenol resin and C9 hydrocarbon resin to fully replace aromatic oil and improve the abrasion resistance of NR composites. Kujur *et al.*^[31] prepared a phenol-cardanol-formaldehyde resin as a co-curing agent to enhance the abrasion resistance of NR composites, accompanied by the deterioration of the static mechanical properties with increasing resin content.

Compared with traditional phenolic resins, phenolic resins with alkyl chains of certain lengths and branching degrees exhibit improved compatibility with natural rubber owing to their reduced polarity. Resole phenolic resins with abundant methylol groups serve as crosslinking agents to improve the heat resistance of rubber composites.^[32] Novolac phenolic resins, as linear oligomers, can improve filler dispersion as plasticizers. In addition, through the formation of intermolecular hydrogen bonds between phenolic hydroxyl groups on the rubber surface, novolac phenolic resins can also enhance adhesion strength, serving as tackifiers. Coumarone resin, a commonly used industrial tackifier that is compatible with natural rubber, can improve the processability and tackiness of natural rubber composites.

In this study, coumarone resin (CMR) and two types of *tert*-octyl phenolic resins, resole (PR45) and novolac (PR68), which are widely used in tires and exhibit good compatibility with NR,^[33] were chosen to achieve high abrasion resistance and low heat build-up of NR composites. To clarify the effects of a large slip angle and high speed separately, the abrasion behavior of NR composites with different resins was evaluated using LAT 100 under two typical service conditions: large-slip-angle abrasion (20° slip angle, 2.5 km/h) and high-speed abrasion (5° slip angle, 45 km/h). In addition, the dynamic and static mechanical properties and dynamic compression temperature rise (heat build-up) were investigated. The results showed that PR68 has potential applications in aircraft tire treads with high abrasion resistance under harsh service conditions and low heat build-up.

EXPERIMENTAL

Materials

Natural rubber (NR) was purchased from the Yunnan Natural Rubber Industry Group Co., Ltd. Carbon black N234 (CB) was

provided by Cabot Chemical Co., Ltd. Silica VN3 was obtained from Evonik Industries AG. Coumarone resin (CMR) was obtained from Shanghai Yuanxiang Industrial Co., Ltd. Novolac *tert*-octyl phenolic resin (PR68) and resole *tert*-octyl phenolic resin (PR45) were obtained from SI Group (Shanghai) Co., Ltd. The chemical structures of the selected resins are shown in Fig. 1. The main difference between resin PR68 and resin PR45 was the end group, and the end group of PR45 was the methylol group. All the other experimental materials were commercially available.

Preparation of NR Composites with Different Resins

The formulations of the CMR, PR68, and PR45 compounds with the corresponding resins are presented in Table 1. To explore the influence of different resins on the abrasion resistance of NR compounds, all the compounds were prepared with the same amount of resin using a two-stage mixing process. The first stage was performed in an internal mixer (RM-2000C-300 mL, Harpo Electric Technology Co., Ltd.). The initial temperature of the mixer was set to 100 °C at a starting speed of 60 r/min. NR was plasticized for 40 s, followed by addition of CB, silica, accelerator D, and Si69. When the torque stabilized, the corresponding resin was added and evenly blended. Finally, the rubber compounds were heat treated at 145–150 °C for 3 min before discharge.

In the second stage, the resultant rubber was sequentially mixed with stearic acid (SA), zinc oxide (ZnO), antioxidants, sulfur, and accelerators in a two-roll mill (XK-160, Jiangnan Rubber & Plastic Machinery Co., Ltd.) at room temperature. After the rubber compounds with different resins were homogeneously mixed, they were cured in a compression molding press at 143 °C under a pressure of 15 MPa. The optical curing time was determined using a rotor-less curemeter.

Characterization Techniques

Curing characteristics

The curing characteristics of the NR compounds with different resins were evaluated at 143 °C for 60 min using a rotorless curemeter (M-3000A, Gotech Testing Machines, China) in accordance with ISO 6502-3:2025. The swing frequency was 1.7 Hz, and the swing amplitude was 0.5°. The curing time was determined from the corresponding vulcanization curves. The cross-link density was preliminarily assessed based on the torque difference (ΔM) from the vulcanization curves. The torque difference was defined as the maximum torque (M_H) minus the minimum torque (M_L). The optimum cure time t_{90} (time to 90% state of cure) and scorch time t_{10} (time to 10% state of cure) were also calculated.

Cross-link density

To validate the cross-link density results preliminarily assessed by the torque difference from the vulcanization curves, the equilibrium swelling method was employed.^[34,35] Three samples of each composite were tested independently. The rectangular samples were weighed (m_0) and then immersed in toluene at room temperature for 3 days. After reaching swelling equilibrium, all the samples were wiped with filter paper and weighed (m_1). The samples were dried in a forced-air drying oven at 60 °C to constant weight (m_2). The volume fraction of the rubber in the swollen sample (V_r) was calculated using Eq. (1). The cross-link density (V_e) was calculated using the Flory-

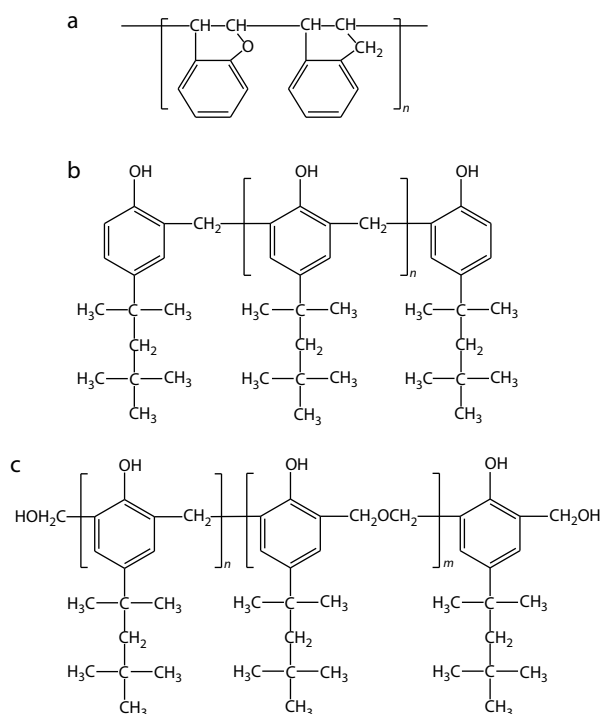


Fig. 1 Chemical structures of resins: (a) CMR, (b) PR68 and (c) PR45.

Table 1 Formulas of NR composites with different resins (phr).

Sample	CMR	PR68	PR45
NR	100	100	100
CB	40	40	40
Silica	10	10	10
Si69	2	2	2
CMR	2	—	—
PR68	—	2	—
PR45	—	—	2

Note: phr: parts per hundred parts of rubbers; Each material includes stearic acid 5 phr, zinc oxide 2 phr, antioxidants 4.5 phr, sulfur 1.6 phr and accelerators 2 phr.

Rehner equation (Eq. 2).

$$V_r = \frac{m_0 \cdot \varphi \cdot (1 - a)}{\rho_r} \quad (1)$$

$$\frac{m_0 \cdot \varphi \cdot (1 - a)}{\rho_r} + \frac{m_1 - m_2}{\rho_s}$$

$$V_e = -\frac{\ln(1 - V_r) + V_r + \chi V_r^2}{V_s \cdot \left(\frac{1}{V_r^3} - \frac{2V_r}{f} \right)} \quad (2)$$

In Eq. (1), φ is the volume fraction of pure NR in the vulcanizate, a is the mass-loss ratio of the dried sample, ρ_r is the density of NR, ρ_s is the density of toluene. In Eq. (2), V_s is the solvent molar volume, f is the functionality of the crosslinks, and χ is the Flory-Huggins interaction parameter for NR-toluene.

Abrasion resistance and surface abrasion pattern

To investigate the abrasion resistance of NR composites under two typical abrasion conditions (high-speed abrasion and large-slip-angle abrasion), the Grosch sample wheels prepared by the

corresponding NR compounds were tested using a Laboratory Abrasion Tester 100 (LAT 100, VMI Group, Holland) in accordance with ISO 23233-2016. The geometric parameters of the Grosch sample wheels were as follows: outer diameter of 84 mm, inner diameter of 35 mm, and thickness of 19 mm. During the abrasion tests, each sample wheel was set at precise slip angles adjusted by a linear motor and cylinder. Subsequently, it was pressed against the abrasive disc under a controlled vertical load. When the motor-driven abrasive disc began rotating, its rotation was transmitted to the sample wheel through friction, causing the test piece to rotate. The side force and surface temperature of the sample wheels were measured in real time using a force sensor and an infrared pyrometer, respectively. To counteract smearing and maintain an efficiently cleaned abrasive disc surface, the anti-smearing powder, a mixture of magnesium oxide (MgO) and alumina (Al₂O₃) at a volume ratio of 2:1, was fed into the contact area between the test piece and abrasive disc. A suitable anti-smearing powder feed rate was adopted according to the abrasion behavior of each sample wheel. To eliminate the errors caused by uneven wear, both the left and right sides of each sample wheel were tested once, and the average value of the test results was adopted. To acquire a stable abrasion loss of the samples, the running distance of each abrasion condition was designed to be long enough to reach a stable longitudinal friction force, side force, and surface temperature.

The abrasion test conditions are listed in Table 2. The applied load was 100 N, and the ambient temperature during testing was 23 °C. For the large-slip-angle abrasion, the slip angle was 20°, corresponding to sharp cornering, and the speed was very low, 2.5 km/h. For high-speed abrasion, the speed was 45 km/h, and the slip angle was set to 5°. Given the size parameters of the test pieces, the rolling frequency of 45 km/h was 47.4 Hz, which corresponded to the maximum frequency during aircraft taxiing. All abrasion tests were performed at room temperature on Corundum 60 type disc.

As the abrasion volume can avoid the effect of the density of different composites, the abrasion resistance index (ARI) correlated with the abrasion volume was used to compare the abrasion resistance of different composites. ARI, side work (W_s), longitudinal friction work (W_f), and total friction work (W_T) were calculated using Eqs. (3)–(6), respectively:

$$ARI = \frac{\Delta V_{REF}}{\Delta V_{SAM}} \times 100 \quad (3)$$

$$W_s = F_s \times \sin \alpha \quad (4)$$

$$W_f = F_f \times \cos \alpha \quad (5)$$

$$W_T = W_s + W_f \quad (6)$$

The abrasion mass is the average value of the mass loss per unit running distance for both sides of the test pieces. The abrasion volume ($\Delta V_{abrasion}$) was determined by dividing the abrasion mass by the density of the corresponding NR composite. ΔV_{REF} represents the average abrasion volume of the reference sample. ΔV_{SAM} represents the average abrasion volume of the test sample. F_s , F_f , α are the side force, longitudinal friction force, and slip angle, respectively. To evaluate the ARIs of the NR composites with different resins, the CMR composite was chosen as the reference sample, owing to the

Table 2 Test conditions of LAT 100 abrasion.

Testing condition	Load (N)	Slip angle (°)	Speed (km/h)	Running distance (m)
Large-slip-angle abrasion	100	20	2.5	250
High-speed abrasion	100	5	45	2500

common practice of CMR as an industrial tackifier.

The abrasion surface morphology (surface abrasion pattern) was obtained using a Canon 70D camera with an EF of 100 mm f/2.8L macro lens.

Payne effect

For the uncured NR compounds, a strain sweep in the range of 0.28%–200% was tested using an RPA 2000 (Alpha Technologies Co., USA) according to ASTM D8059-19. The test temperature was 60 °C and the frequency was 1 Hz. For the cured composites, the storage shear modulus (G') was measured at 60 °C with a test frequency of 10 Hz and a strain range of 0.28%–42%. To evaluate the Payne effect and filler dispersion in vulcanizates, the storage shear modulus difference ($\Delta G'$) of uncured compounds and vulcanizates was separately calculated using Eqs. (7) and (8).

$$\Delta G'_{\text{uncured}} = G'_{0.28\%} - G'_{200\%} \quad (7)$$

$$\Delta G'_{\text{cured}} = G'_{0.28\%} - G'_{42\%} \quad (8)$$

In Eq. (7), $G'_{0.28\%}$ and $G'_{200\%}$ represent the storage modulus of the uncured compounds at 0.28% strain and at 200% strain, respectively. In Eq. (8), $G'_{0.28\%}$ and $G'_{42\%}$ represent the storage modulus of cured vulcanizates at 0.28% strain and at 42% strain, respectively.

TEM observation

Transmission electron microscopy (TEM, FEI G2 F30, Thermo Fisher Scientific, USA) was used to observe filler dispersion at an acceleration voltage of 300 kV. The test samples were cut into ultrathin sections using liquid nitrogen freezing.

Viscoelastic properties

Dynamic mechanical analysis tests were conducted using a dynamic mechanical thermal analyzer (VA3000, Metravib Corporation, France) in the tension mode at a heating rate of 3 °C/min from –80 °C to 80 °C. The test frequency was 10 Hz and the strain amplitude was 0.3%. The glass transition temperature (T_g) was determined from the loss factor ($\tan\delta$)–temperature curve, in accordance with ISO 4664-3.

Static mechanical properties

The static mechanical properties were measured using an electrical tensile tester (AI7000-S1, Gotech Testing Machines, China) in accordance with ISO 37:2024.

Heat build-up

The heat build-up of the rubber composites was measured using a compression flexometer (Gotech Testing Machines, China) in accordance with ISO 4666-3:2022. The test conditions were 55 °C chamber temperature, 5.71 mm stroke, pre-stress of 1 MPa, and frequency of 30 Hz.

RESULTS AND DISCUSSION

Separate Effects of Speed and Slip Angle on Abrasion Behavior

To clarify the individual effects of high speed and large slip an-

gle on the abrasion, and further analyze the underlying abrasion cause, high-speed abrasion at low slip angles (45 km/h and 5° slip angle) and large-slip-angle abrasion at low speed (20° slip angle and 2.5 km/h) were measured, and the corresponding ARIs were calculated. Further, the surface temperature rise, friction work, and abrasion surface patterns are discussed below.

High-speed abrasion

ARI was used as an indicator to estimate the relative abrasion resistance, with a higher ARI value indicating better abrasion resistance. Fig. 2(a) presents the ARI and surface temperature of the NR composites with different resins at 45 km/h and a 5° slip angle. Compared with CMR, PR45 showed an 8% increase in ARI, and the three composites exhibited comparable surface temperatures, for example, 49.6–50.6 °C. The high speed led to an increased surface temperature on the abrasion surface.

To elucidate the cause of the underlying abrasion, the longitudinal friction work (W_f) and side work (W_s) are shown in Fig. 2(b). W_f and W_s accounted for approximately 46%–48% and 54%–52% of the W_t , respectively. This indicates that both W_f and W_s play equally important roles in high-speed abrasion processes. Owing to the low slip angle, W_t with friction force was maintained at a low level of approximately 6 kJ/km, leading to a low abrasion loss (33–35 mm³/km) under high-speed abrasion.

Surface abrasion pattern images are depicted in Fig. 2(c), and discontinuous shallow striations appeared on all abrasion surfaces at 45 km/h and a 5° slip angle, owing to the low total friction work. The PR45 composite exhibited abrasion patterns with the shallowest striations and discontinuous ridges with uneven heights circled by blue dashed lines, thus verifying the ARI results. The abrasion patterns of the CMR and PR68 composites are similar.

Large-slip-angle abrasion

Fig. 3(a) presents the ARI and surface temperature of NR composites with different resins at a 20° slip angle and 2.5 km/h. Both the PR68 and PR45 composites showed an 8% increase in ARI compared to the CMR composite, indicating that PR68 and PR45 exhibited better abrasion resistance than CMR under large-slip-angle abrasion. Meanwhile, the contact abrasion surface temperatures of the three composites were close (39.9–40.8 °C), indicating that friction also resulted in increased abrasion surface temperature.

The total friction work and abrasion volume are shown in Fig. 3(b). At a 20° slip angle, the total friction work was approximately 31 kJ/km, which is approximately 5 times that at high speed (approximately 6 kJ/km). The large friction work led to a much larger abrasion volume of 1910–2070 mm³/km, approximately 55–59 times that at high speeds (approximately 33–35 mm³/km). Furthermore, the contribution of side work to the total friction work is overwhelmingly 96%–98%, compared to longitudinal friction work, which is completely different from the high-speed case.

The surface abrasion patterns are shown in Fig. 3(c). Although the abrasion distance was 250 m, which was much

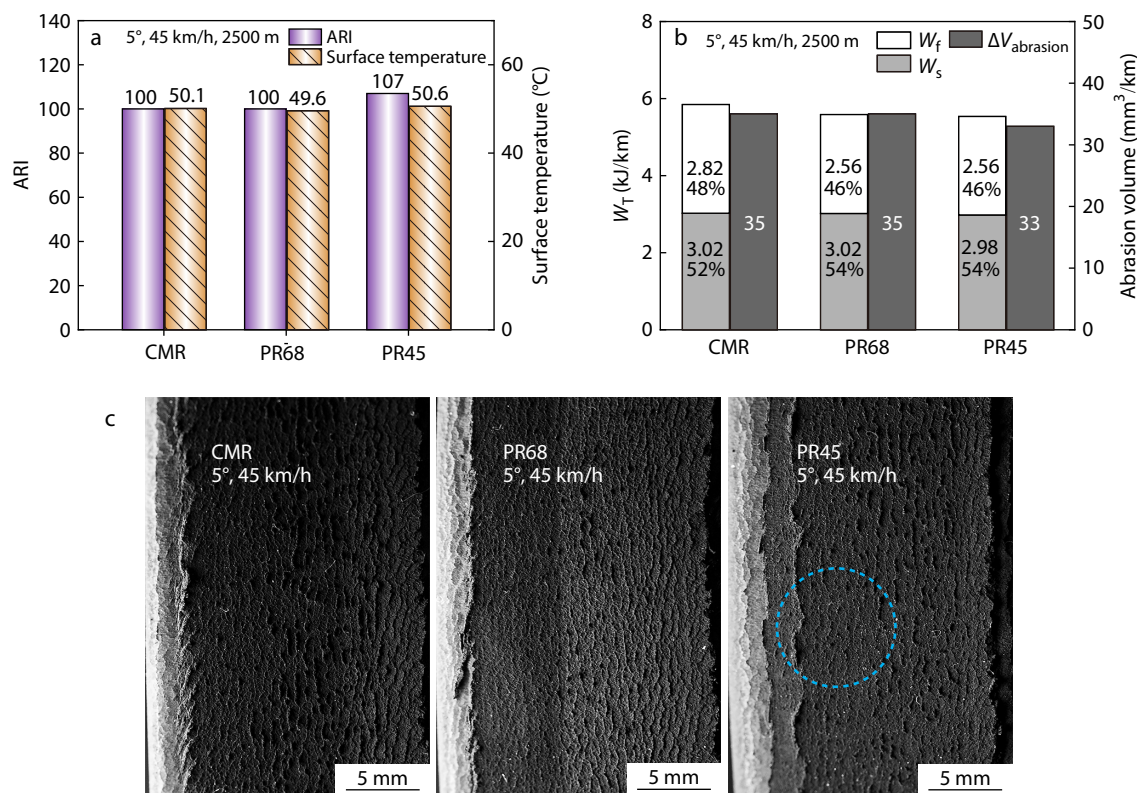


Fig. 2 (a) ARI and surface temperature; (b) Total friction work with longitudinal friction work and side work contributions, abrasion volume; (c) Abrasion surface morphology of three NR composites under high-speed abrasion.

less than 2500 m in the case of high-speed abrasion, continuous wider and higher ridges could be observed for the three composites compared to the cases in Fig. 2(c). These results also verified that the large lateral force resulting from the large slip angle was much more detrimental to abrasion resistance than the surface temperature rise from high speeds.

To further elucidate the underlying reason that PR45 and PR68 exhibited better abrasion resistance than CMR at large slip angles, the cross-link densities, filler dispersion, filler networks, mechanical properties, and heat build-up of the three composites were also investigated in detail.

Cross-link Density of NR Composites

The cross-link density of the composites can be preliminarily assessed using the torque difference from the vulcanization curve.^[36] The vulcanization curves of NR compounds with different resins are shown in Fig. 4, and the corresponding torque differences are presented in Table 3. Compared to the CMR compound, the PR68 compound exhibited a higher torque difference, indicating a higher cross-link density. The cross-link density was further determined using the equilibrium swelling method, and the test results are listed in Table 3. The PR68 composite exhibited an increase in the cross-link density by 9% compared to the CMR composite, which agreed with the cross-link density assessed by the torque difference. The PR45 and CMR composites exhibited a close cross-link density.

As shown in Fig. 4, compared to the PR68 composite, the PR45 composite exhibited a vulcanization delay with prolonged t_{10} , prolonged optimum cure time t_{90} , and lower cross-link density. This observed effect could be attributed to

the possible reaction between the methylol groups of PR45 and the C=C bonds of NR,^[37,38] leading to a reduction in the available sites for sulfur crosslinking and consequently delaying the vulcanization process.

Filler Dispersion and Filler Network

The filler dispersion and filler network can be evaluated by characterizing the Payne effect of the filled rubber using RPA.^[39] The curves of the storage modulus (G') versus strain are shown in Fig. 5. G' of the PR68 compound was lower at low strains (<1%) than those of the CMR and PR45 compounds, indicating better filler dispersion. With increasing shear strain, the filler networks gradually break, resulting in a decrease in G' . At sufficiently large strains (>100%), the filler networks of the compounds were destroyed and the trapped rubber was released from the filler agglomerates. $\Delta G'$ (calculated using Eqs. 7 and 8) is connected to the filler dispersion and filler network, with a larger $\Delta G'$ indicating poorer filler dispersion and a stronger filler network. The $\Delta G'$ values of the three uncured compounds are also presented in Fig. 5(a), and the order of $\Delta G'$ was PR68 < PR45 < CMR, indicating that PR68 exhibited the best filler dispersion and weakest filler network. The RPA results of the three vulcanizates are shown in Fig. 5(b), PR68 also exhibited the lowest G' and $\Delta G'$ values, suggesting that curing has little effect on filler dispersion.

The filler dispersion in the NR matrix can also be directly observed by TEM, and TEM images of the three composites are shown in Fig. 6. The dark regions represent filler agglomerates, and the brighter background refers to the NR matrix. For the CMR composite in Fig. 6(a), the dark regions were

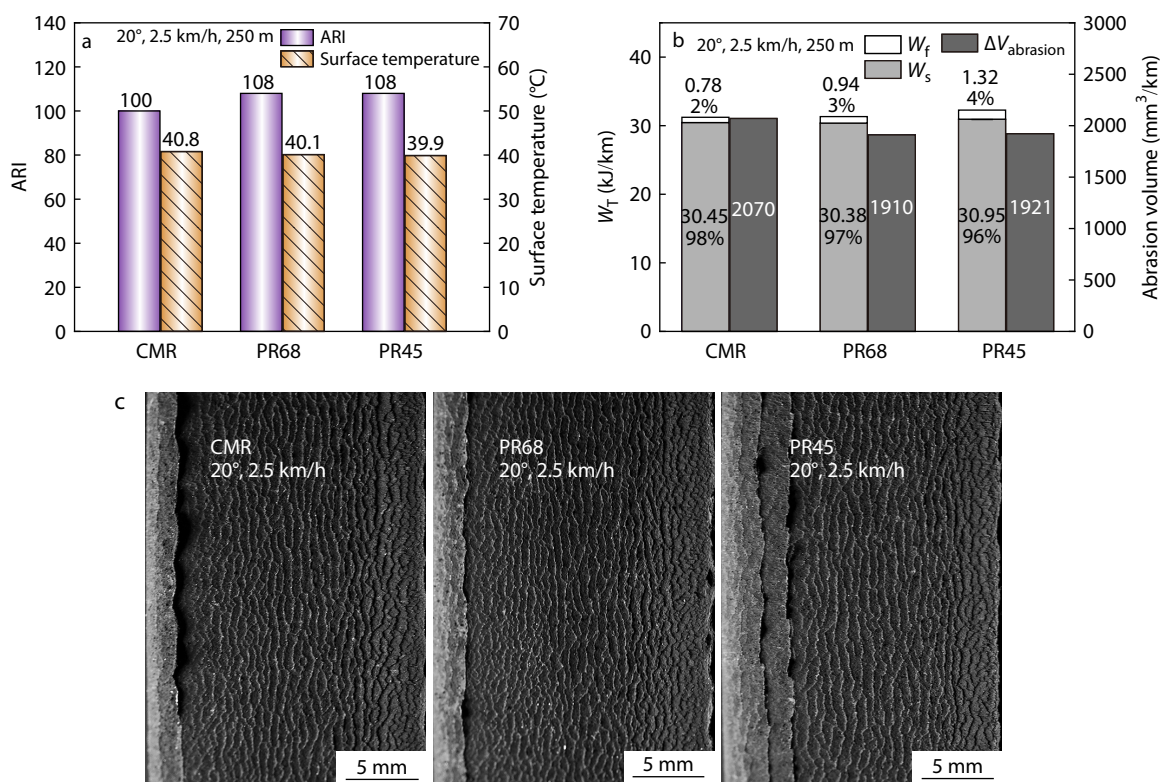


Fig. 3 (a) ARI and surface temperature; (b) Total friction work with longitudinal friction work and side work contributions, abrasion volume; (c) Abrasion surface morphology of three NR composites under large-slip-angle abrasion.

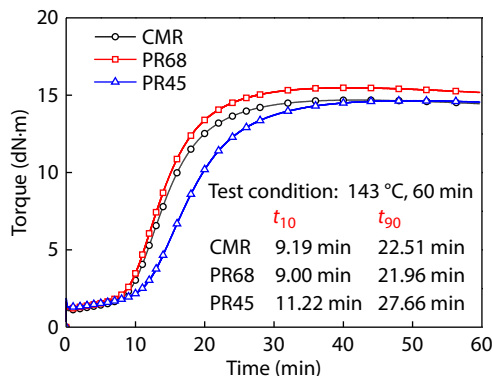


Fig. 4 Vulcanization curves of three NR compounds.

Table 3 Cross-link density of NR composites with different resins.

Sample	ΔM (dN·m)	V_e (10^{-4} mol/cm ³)
CMR	13.36	$2.42_{-0.01}^{+0.01}$
PR68	14.04	$2.64_{-0.04}^{+0.03}$
PR45	13.10	$2.50_{-0.01}^{+0.01}$

large, and the white regions were uneven. Compared with the CMR and PR45 (Fig. 6c) composites, the PR68 composite exhibited uniform filler dispersion, with smaller dark and white regions (Fig. 6b). This is consistent with the results of RPA.

Filler-polymer Interactions in NR Composites

Dynamic mechanical analysis provides insight into the activa-

tion energies for glass transition and the number of chain segments participating in glass transition by characterizing the glass transition temperature (T_g) and maximum loss factor ($\tan\delta$), thus indirectly reflecting filler-polymer interfacial interactions.^[40,41] The curves of $\tan\delta$ versus temperature are shown in Fig. 7(a). The CMR, PR68, and PR45 composites exhibited glass transition temperatures of -42.8 , -43.2 and -43.9 °C, respectively, indicating comparable energy for activating the movement of the polymer segments. Because the $\tan\delta$ peak height (max $\tan\delta$) was correlated with the contribution of the movable rubber fraction,^[42] the lower $\tan\delta$ peak height indicated that fewer rubber chains participated in the glass transition. The PR68 composite exhibited the lowest $\tan\delta$ peak height, demonstrating that in the PR68 composite, the filler surface restricted the movement of the rubber molecular chains, resulting in reduced mobile rubber chains. This demonstrated that the PR68 composite exhibited the strongest filler-polymer interactions among the three composites.

The stresses at 100% and 300% strain are shown in Fig. 7(b). The PR68 composite exhibited the highest stress at 100% and 300% strain among the three samples, verifying the enhanced filler-polymer interactions obtained from the DMA test results.

Heat Build-up of NR Composites

For aircraft tire treads, low heat build-up is also an important requirement. The results of the compression fatigue temperature rise (heat build-up) of the three composites are shown in Fig. 8. The order of the heat build-up was PR68 < CMR < PR45. It is generally accepted that the dynamic heat build-up is mainly de-

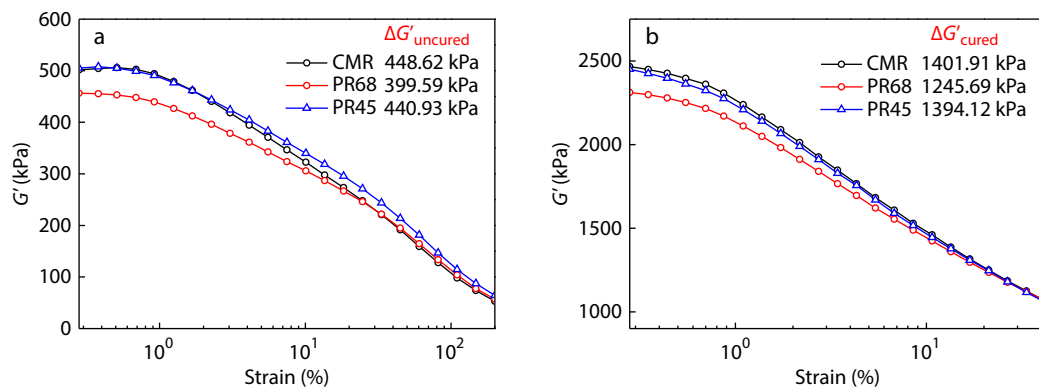


Fig. 5 G' -strain curves of (a) the uncured compounds and (b) vulcanizates.

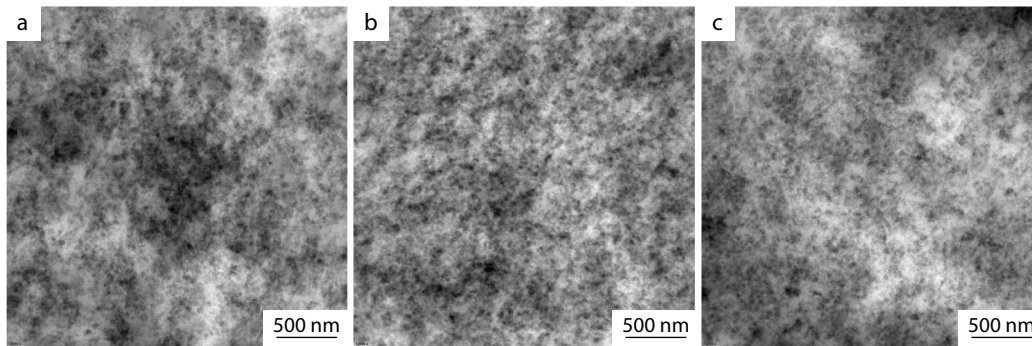


Fig. 6 TEM images of (a) CMR composite, (b) PR68 composite and (c) PR45 composite.

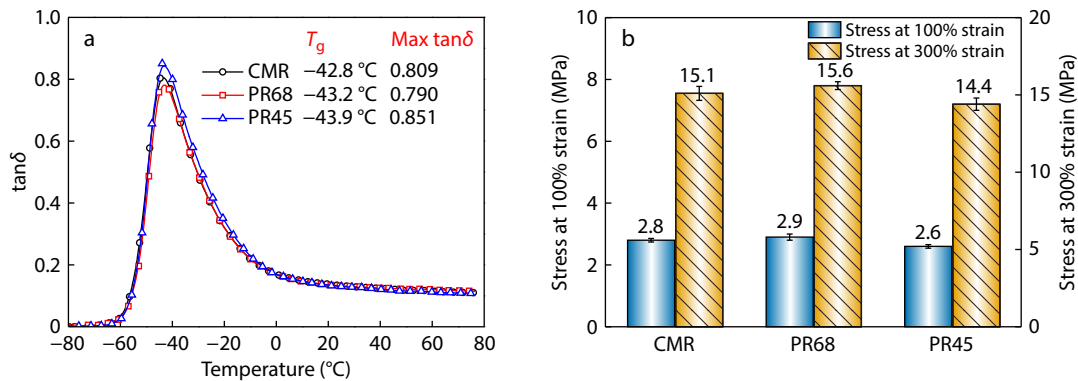


Fig. 7 (a) Temperature dependence on loss factor ($\tan\delta$) and (b) stress at 100% and 300% strains of NR composites.

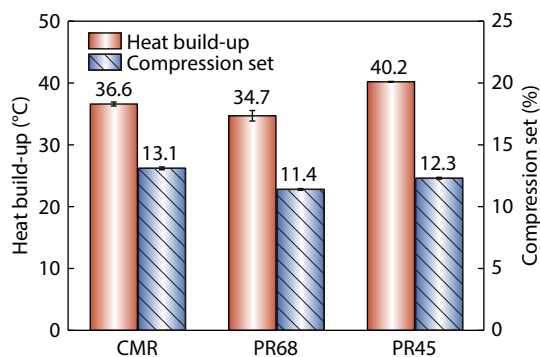


Fig. 8 Heat build-up and compression set of three NR composites.

derived from the filler-filler, filler-polymer friction under dynamic conditions.^[43–45] Novolac resin PR68, which serves as a plasticiz-

er, improves filler dispersion and maintains strong filler-polymer interfacial interactions and a relatively high cross-link density. Under dynamic compression, the internal filler friction, which is correlated with filler dispersion and filler-polymer interactions, was relatively mild during the destruction and rebuilding of the filler network, leading to lower heat build-up. The PR68 composite also exhibited the lowest compression set, which was consistent with its highest cross-link density and weakest filler network. For resole resin PR45, the resin crosslinking agent with abundant methylol groups and phenolic hydroxyl groups, the hydrogen bond formed between phenolic hydroxyl groups and silanol groups hindered the coupling reaction between Si69 and silica.^[46,47] During vulcanization, the resin curing reaction involving the methylol groups of resole resin PR45 and C=C of NR interferes with sulfur vulcanization, thus leading to a low cross-link density. With uneven filler dispersion and a weak filler-poly-

mer interface, the filler-filler frictions were stronger, resulting in higher heat build-up.

CONCLUSIONS

In this study, the abrasion resistance of NR composites with three different resins was measured separately under two typical service conditions: large-slip-angle abrasion and high-speed abrasion. Compared with high speed, the high friction work from a large slip angle mainly contributed to the substantial abrasion loss, indicating that the large side force was profoundly destructive. Among the three composites, the PR68 composite exhibited the highest cross-link density without a delay in vulcanization, uniform filler dispersion, and the strongest filler-polymer interfacial interactions. With better static mechanical properties and less heat build-up relative to the PR45 composite, the PR68 composite is more suitable for application in aircraft tire treads under large-slip-angle abrasion conditions.

Conflict of Interests

The authors declare no interest conflict.

Data Availability Statement

The data supporting the findings are available from the corresponding author upon reasonable request.

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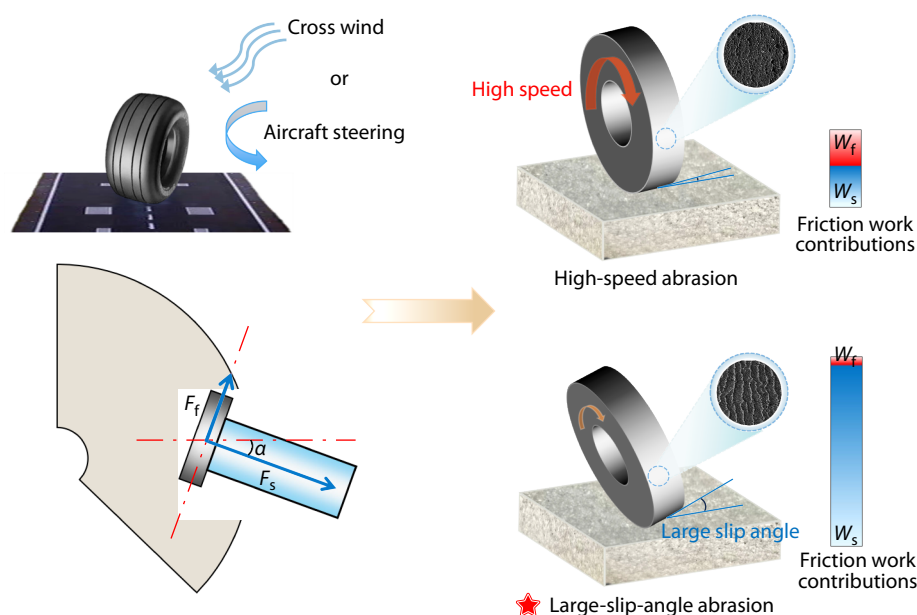
Graphical Abstract

Effects of Resins on the Abrasion Resistance of Natural Rubber Composites under Harsh Service Conditions

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For abrasion resistance, high friction work resulting from a large slip angle is much more detrimental than that resulting from high speed.



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