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# Evaluation of friction mechanisms and wear rates on rubber tire materials by low-cost laboratory tests

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ABSTRACT

The tire–pavement contact is part of a complex tribo-system with several variables. Once the pavement surface and the rubber tire are directly and indirectly related to transportation safety, fuel consumption, wear rate, noise generation, and others, it is possible to state that a better understanding of tribo-logical variables may provide a deeper knowledge of friction and wear phenomena. In this study, low-cost tests were carried out for the purpose of evaluating these phenomena. In addition, statistical analysis of friction and wear rates was accomplished, allowing their correlation with parameters such as surface energy and wear pattern spacing. Therefore, it was possible to validate the existence and relevance of the adhesion mechanism at friction, which is frequently neglected in the literature. It was also possible to verify the indirect methods of evaluating wear and friction performance of rubber tire materials.



## 1. Introduction

The pavement surface represents the contact medium between the tire and the pavement itself. It is related to aspects such as transportation safety, skid resistance, fuel consumption, noise generation, wear rate, and other variables, and may be ruled by the friction mechanism, which is intimately correlated with the pavement surface condition and the rubber properties of the tire. In this paper, Moore's friction formulation [1] was used, which describes friction as a sum of two mathematically independent components: hysteresis and adhesion, which will be better explained in Section 2.

Although the pavement texture analysis is not directly related to this paper's scope, its influence on the friction is significant. According to Wambold et al. [2], the pavement texture is classified into five categories, and may be approximated by sine curves with different wavelengths and amplitudes. Each texture category is related to distinct phenomena. The macrotexture category, for example, was demonstrated to be significantly correlated with car accident rates in the United States [3], and the megatexture and macrotexture influence noise generation [4]. Therefore, it is observed that the pavement surface analysis provides a better understanding of rubber friction.

On the other hand, excessive friction physically damages the tire, compromising its performance. Some studies forecast that world tire demand may reach 3.3 billion units of tire by 2015 [5] while others emphasize that rubber is not a biodegradable material [6]. Besides this environmental issue, analyzing rubber properties is also important to understand the wear rate generated in the tire–pavement contact.

Thus, it is possible to state that besides the wear rate mechanism, friction also has an important role in vehicle performance and it has been deeply studied in the past years from Amontons and Coulomb until more recent researchers such as Persson [7] and Klüppel [8,9], who developed more complex friction models. Despite the fact that some authors completely neglect the adhesion component in the friction mechanism [10,11], in this paper the adhesion is evidenced under different laboratory test conditions and is not neglected. Laboratory tests were carried out, providing measures of wear rate, friction, energy surface and wear pattern spacing in rubber samples.

The present study focused on contributing to the evaluation of friction and wear rates with low-cost methods in different rubber tire compounds, with statistically significant correlations between the measures obtained. The British Pendulum equipment, used to evaluate the friction phenomena at two surfaces contact, has a low operational cost with easy and practical handling. As well as the British Pendulum Tester, the Rotary Drum Abrader, which is the equipment used to evaluate the wear rate of different rubber materials, has also a low operational cost with easy handling. Furthermore, this study presents the importance of adhesion

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mechanism in tire–pavement interaction as well as the influence of viscoelastic properties of the rubber compounds on friction and wear rate phenomena.

## 2. Modeling adhesion

The rubber–pavement contact interaction is modeled, for this paper, as the result of two distinct and mathematically independent components: (i) hysteresis and (ii) adhesion. This formulation of friction was proposed by Moore (1975). Even though more complex models have been proposed [7–9], the separation of two friction mechanisms is still widely used on friction modeling [8,9], contact interaction evaluation, and will be further explored in this paper.

The hysteresis component of friction is the result of the rubber material draping over the surface asperities. This component of friction is dependent not only on the surface texture, including asperities shapes and relative distribution over the contact area, but also on the rubber viscoelastic properties. The delayed viscoelastic response of the rubber material results in energy dissipation, which is temperature dependent and has an important role on tire pavement interaction.

The adhesive component of friction is the result of adhesive forces attracting the body and the counter body together. The sources of adhesive forces are here classified into five different categories: (i) chemical, (ii) dispersive, (iii) electrostatic, (iv) diffusive, and (v) microhysteresis. The five adhesion sources are briefly detailed as follows.

The first listed adhesion source is the chemical one, which takes place when the two surfaces are joined by compound, swapping electrons, thus forming ionic bonds, or sharing electrons, thus forming covalent bonds [11]. The second listed adhesion source is the dispersive mechanism, which is the formation of van der Waals forces. These intermolecular forces hold the two surfaces together [12]. The third source, electrostatic adhesion, forms attractive forces as the two surfaces swap electrons, forming a negative surface and a positive one that attract each other [11]. When two soluble polymeric materials interact, the interpenetration of polymeric chains generates adhesive forces, which result in the fourth mechanisms of adhesion, the diffusive one [11]. Finally, the fifth source of adhesion is the microhysteresis, which is the result of viscoelastic dissipation over the surface microtexture. This mechanism is similar to the hysteresis component of friction, yet on a microscale. It was initially proposed by Moore [1] as an alternative approach to understand friction on micro-roughness.

In the tire–pavement contact interaction, the most important sources of adhesion are the dispersive and electrostatic [11] ones. The electrostatic mechanism is highly dependent on humidity, leaving only the dispersive adhesion as a source of adhesive forces in the tire–pavement interaction. Even though some authors propose that adhesion is almost insignificant [13,14] or neglect the adhesive forces entirely [10,11], this work proposes not to neglect the adhesion, or more specifically, the dispersive mechanism in the tire–pavement contact.

According to Moore's formulation, the adhesive component of friction is dependent on the adhesion capacity of the tribo-system. Initially consider a rubber body sliding on a rigid surface. In the initial stage, adhesive forces cause the junction of the rubber surface and the rigid surface on a given asperity contact. This initial stage is named “the stick phase”. As the relative motion between the two surfaces continues, the junction stress eventually exceeds the junction bonding resistance. At this point, the second stage named “the separation stage” takes place. Part of the energy, which was stored as an elastic deformation to accommodate the junction bonding with the relative motion of the two surfaces, is restored. Part of the energy is lost, dissipated due to the bulk viscoelastic properties of rubber, and part of it is lost due to the surface friction itself during the recovery phase. Note that the junction may fail due to in-plane shearing, approaching a stick–slip phenomenon, or to normal traction, approaching a stick–snap phenomenon. When the surface junction fails, at the separation stage, it is considered that a pair of new surfaces is created, which were previously joined together by adhesive forces.

Considering two solid unit area surfaces joined together, work is required to separate them and create two unit area surfaces (adapted from [15]). This work, namely, the work of adhesion, may be estimated by the geometric mean of the surfaces energies, as indicated by Eq. (1), where $\gamma_1$ and $\gamma_2$ are the surface energies for the contacting bodies [15].

$$W_{adh\ 12} = 2\sqrt{\gamma_1\gamma_2} \tag{1}$$

The relationship between surface energy and the mechanical work required to separate a contact had already been predicted by Johnson et al. [16]. Using a fracture mechanics analogy, it is possible to use an energy balance, considering strain energy, potential energy and interface energy. Modeling the junction failure as crack propagation in mode 1, similar to the formulation proposed by Maugis and Barquins [17], Eq. (2) may be derived [18]. $G$ represents the energy release rate for a junction failure, $f$ is proportionally constant. This allows the adhesive friction to be connected to the surface energy.

$$G = W_{adh\ 12} = \varphi' = 2f\sqrt{\gamma_1\gamma_2} \tag{2}$$

Eq. (2) represents an equilibrium condition, as the energy release rate equals the work of adhesion. The energy required to create a new infinitesimal surface is $W_{adh12}dA$. The energy released when two infinitesimal surfaces are separated is $GdA$. When the condition of bonding two surfaces is energetically more favorable, $G < W_{adh}$, the contact area is increased by forming new junctions. When breaking junctions is more favorable, slipping or snapping takes place in order to reduce the total contact area. This formulation, therefore, allows connecting adhesive friction to the surface energy and also considers the occurrence of surface instabilities on the rubber.

## 3. Schallamach waves

A simple and immediate way to analyze which rubber material has higher abrasion loss is observed in the spacing pattern created by the Rotary Drum Abrader Test [19], as Muhr and Roberts [20] and Gent [21] affirm, the ridge height and the spacing increase with increasing severity of abrasion. It is possible to confirm this point of view through the results reached by Fukahori and Yamazaki [22–24] and Uchiyama and Ishino [25] in Fig. 1.

Furthermore, Fukahori and Yamazaki [22–24] described an empirical equation, credited to Schallamach [26] and Ratner et al. [27], which presents once more direct relationship between the rate of abrasion ($\dot{V}$) and pattern spacing ($s_p$), Eq. (3), where $k$ and $n$ are constants.

$$\dot{V} = k \times s_p^n \tag{3}$$

Even though the formation of Schallamach waves is still an unsettled subject, which may be related to a local change of the rubber modulus, a possible formation mechanism for the abrasion pattern is related to the stick slip phenomenon. According to Fukahori et al. [28], at certain conditions of sliding velocity and contact pressure, the formation of the abrasion pattern is related to a periodic stick–slip motion of the rubber. Following this approach, the existence of the abrasion pattern signals the relevance of adhesive friction in the contact. The absence of this pattern, although, does not indicate the absence of adhesive effects, as the pattern is only