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Design, construction, and evaluation of a modified rolling pendulum to measure energy dissipation in rubber

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ABSTRACT

A practical method to measure the energy dissipation in rubber vulcanizates under rolling condition has been considered. For this purpose, a modified rolling pendulum device was designed and constructed to eliminate the shortcomings of an initial design by Gent. This modified device has a working table, heated rolling plate, symmetric pendulum and an ultrasonic sensor for accurate measurement of the roller travel distance and calculation of rolling resistance parameters for rubber. Performance of this new device was evaluated by measurement of the rolling resistance force and coefficient for rubber vulcanizates containing un-modified and silane-modified nano-silica under different conditions. The device could successfully show the effects of strain, temperature and silica surface modification on rubber rolling resistance parameters, as reported by other researchers.
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1. Introduction

Tire rolling resistance is defined as the energy dissipated in rolling of a tire per unit normal load and unit distance traveled [1]. Another definition of tire rolling resistance is the force resisting the rolling movement of a tire on the road. Tire rolling resistance dissipates fuel energy causing increased fuel consumption and vehicle emissions [2–4].

One of the methods for comparing rolling resistance of tires is measurement of the distance traveled by an automobile in neutral gear from a known speed (coast-down) [5]. The major source of tire rolling resistance is the hysteresis due to the viscoelastic behavior of rubber, especially tire tread vulcanizates [6,7]. Designing low-rolling-resistance tires needs devices to measure and compare energy dissipation in rubber vulcanizates under rolling conditions. Dynamic analyses in strain or temperature sweeps are normally employed to quantify loss factors as measures of energy dissipation in rubber [8,9]. However, these devices operate in a simple shear mode which is very different from the actual loadings (compression, shear, tension) in a tire during rolling. Providing a continuous flat surface for rolling is a challenge in measuring devices, therefore rolling of tires against a rotating drum with complex mechanical and electronic devices has been applied [10]. The major challenges in such devices are the curved contact surfaces [11], losses in gears and motors, and complexity in measurements of resisting forces or torques. In addition, there is no such device on a laboratory scale for measuring rubber rolling resistance.

Gent et al. presented a simple method to measure the energy dissipation of rubber under rolling conditions in the laboratory [12,13]. It takes advantage of a rolling pendulum oscillating over a flat rubber sheet. A pendulum oscillates and makes a rigid cylinder roll back and forth across a rubber sheet, and its energy dissipates due to the viscoelastic hysteresis of rubber. The design had a simple mechanical and electrical set up, but the device had a few shortcomings which prevent it from being practically used in the laboratory. First, the asymmetric pendulum was the source of deviation of the roller from a straight rolling path.

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As a result, torque asymmetry could reduce the reproducibility and accuracy of measurements. Second, oscillating motion of the pendulum mass was measured with an ultrasonic sensor which limited the working angle of the pendulum. Ultrasonic sensors measure distances from perpendicular surfaces accurately, however their accuracy reduces as the angle between the surface and the sensor beam deviates from being perpendicular. Third, the rolling resistance of rubber could not be measured as a function of temperature, although it is highly temperature dependent [1,14].

The present work, discusses the design, construction, and evaluation of a modified rolling pendulum, based on the Gent's original design, but with improved features for more accurate measurements of the energy dissipation in rubber. Using nano silica-SBR vulcanizates, performance of the device was evaluated and the effects of silanization of silica, vertical load and temperature on the energy dissipation of rubber were investigated.

2. Design and construction of the device

A photograph of the machine is shown in Fig. 1, and a schematic diagram of the machine and its components is shown in Fig. 2.

As shown in Fig. 2, a symmetric pendulum is attached to a rolling cylinder which rolls back and forth on a rubber sheet as a result of the pendulum oscillation. Using a working table with a horizontal rolling plate,

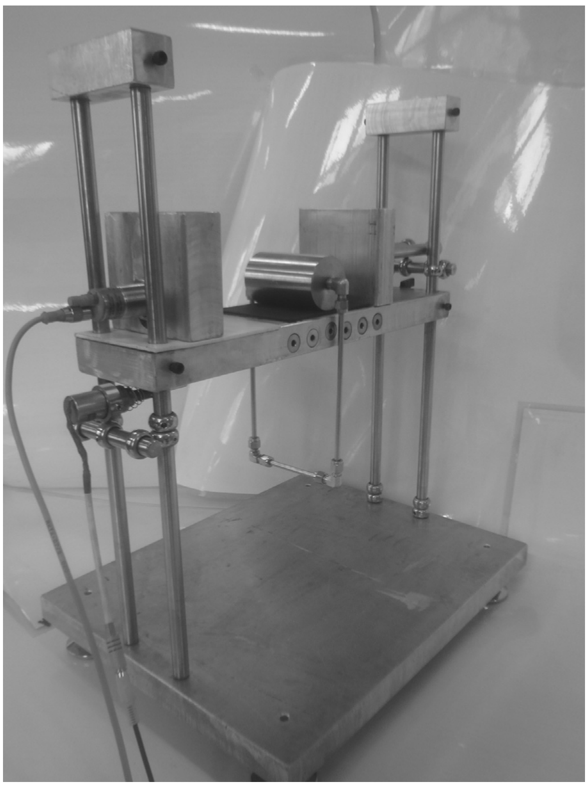

Fig. 1. Photograph of the modified rolling pendulum device.

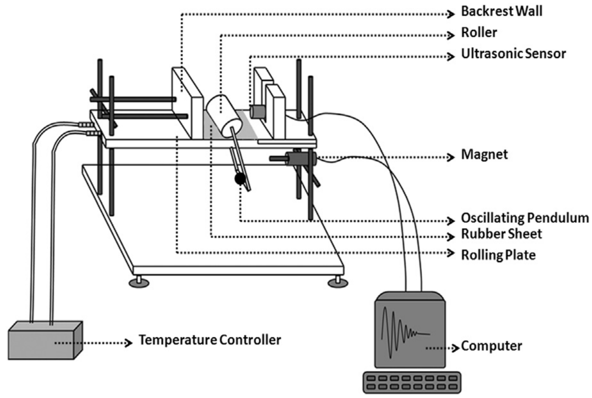

Fig. 2. Schematic of the modified rolling pendulum device.

along with a symmetric pendulum, provides a balanced straight path of rolling which improves reproducibility of the measurements. Employing a vertical backrest plate which defines the starting position of the roller, and a computer-controlled magnet which triggers oscillation of the pendulum from a defined height, add to the accuracy of measurements. The ultrasonic sensor was positioned so that displacement of the roller could be measured rather than that of the pendulum, as Gent's device did. In this position, the sensor measures displacement of the roller in a horizontal path more accurately. Computer software calibrates the ultrasonic sensor and records variation of the roller's displacement versus time, as shown in Fig. 3.

The vertical axis in Fig. 3 is the distance of the roller from the ultrasonic sensor, and the horizontal axis is the testing time in seconds. Rollers with different sizes and weights were prepared and used to alter the applied strain on the rubber sheet. The rolling plate is equipped with channels for oil circulation in order to heat up the plate and the rubber sheet placed on it. This design allows measurement of the energy dissipation as a function of temperature. Since there is no gear, motor or other dissipating parts in the device, the pendulum's potential energy dissipates only in the rubber sheet as a result of the viscoelastic hysteresis in the rubber vulcanizate.

3. Calculation of energy dissipation rate

Consider the experimental arrangement sketched in Fig. 4. A rigid cylinder with mass 'M' and radius 'R' rolls back and forth on the rubber surface due to oscillation of the attached pendulum with mass 'm' and light connecting bars of length 'L'.

As shown in Fig. 4, the distances of the roller's surface from the ultrasonic sensor at the beginning and the end of the first period are termed 'a_0' and 'a_1', respectively. Also, the initial and final angles of the pendulum from the vertical line in the first period are termed 'θ_0' and 'θ_1', respectively. Similarly, the distances and angles for the n^{th} and $n+1^{th}$ period of oscillation will be 'a_n', 'a_{n+1}', 'θ_n', and 'θ_{n+1}', respectively. The final distance of the roller at stop (midline) is termed 'a_∞', at which $\theta_\infty = 0$.

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