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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.

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.

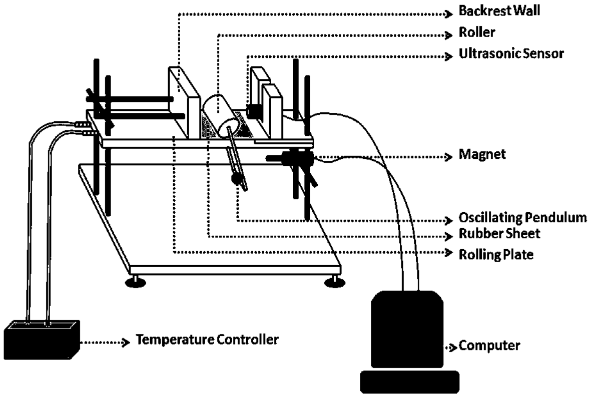

Fig. 2. Schematic of the modified rolling pendulum device.

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 $\theta_\infty = 0$.

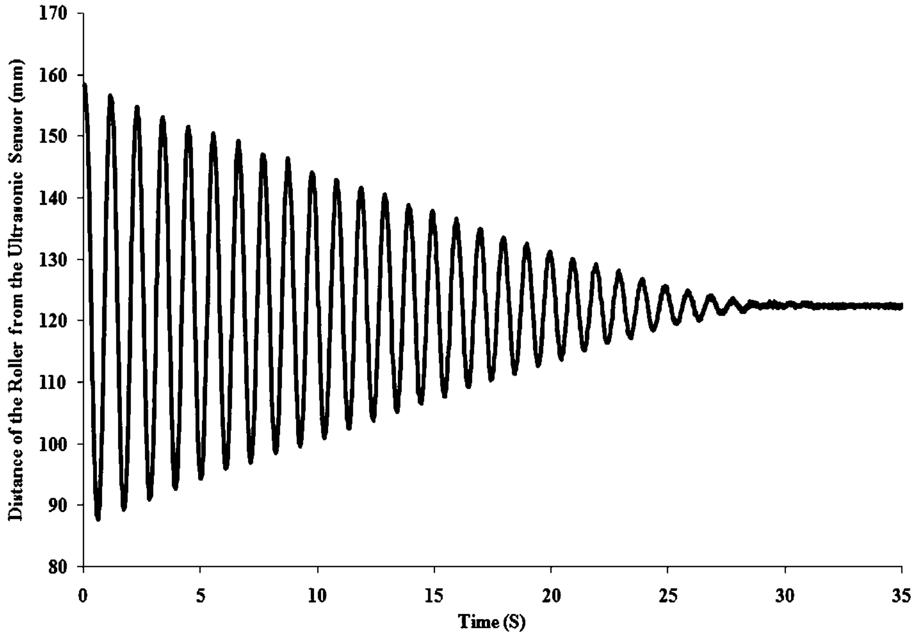

Fig. 3. Displacement of the roller versus time.

Traveled distance of roller from the midline at the nth period is: $A_n = |a_n - a_\infty|$; then the distance traveled between nth and n + 1th period is: $A_{[n,n+1]} = A_n + A_{n+1}$.

The initial angle of the pendulum from the vertical line and at the nth period is '$\theta_0 = A_0/R$', and '$\theta_n = A_n/R$', respectively. Initial potential energy of the pendulum is $mgL(1 - \cos\theta_0)$ and at the nth period will be $mgL(1 - \cos\theta_n)$; then the energy loss in each period will be: $\Delta W_{[n,n+1]} = mgL(\cos\theta_{n+1} - \cos\theta_n)$, where 'g' is the gravitational acceleration. Energy dissipated in one cycle, between nth and n + 1th period, per distance traveled will be:

$$F_x[a, a+1] = \frac{\Delta W_{[n,n+1]}}{A_{[n,n+1]}} = \frac{mgL(\cos\theta_{n+1} - \cos\theta_n)}{A_n + A_{n+1}} = \frac{mgL\left[\cos\left(\frac{A_{n+1}}{R}\right) - \cos\left(\frac{A_n}{R}\right)\right]}{A_n + A_{n+1}}$$

This can also be considered as the rolling resistance force. Rolling resistance (RR) as total energy dissipated per total distance traveled will be:

$$RR = \frac{W_0}{A_{total}} = \sum_{n=0}^{n=\infty} \frac{mgL\left[1 - \cos\frac{A_n}{R}\right]}{A_n} = \frac{mgL\left[1 - \cos\left(\frac{|a_0 - a_\infty|}{R}\right)\right]}{\sum_{n=0}^{n=\infty} |a_n - a_\infty|}$$

where, W_0 is the total potential energy of the pendulum and A_{total} is the total displacement of the roller. Rolling resistance coefficient (RRC) is given as the rolling resistance per unit normal load which is obtained as:

$$RRC = \frac{RR}{F_y} = \frac{RR}{(M+m)g}$$

4. Evaluation of the device performance

4.1. Materials and preparation of rubber vulcanizates

A rubber compound was designed based on styrene butadiene rubber (SBR1502, BIPC, Iran) according to Table 1. Compound ingredients were fumed silica (Aerisil200,

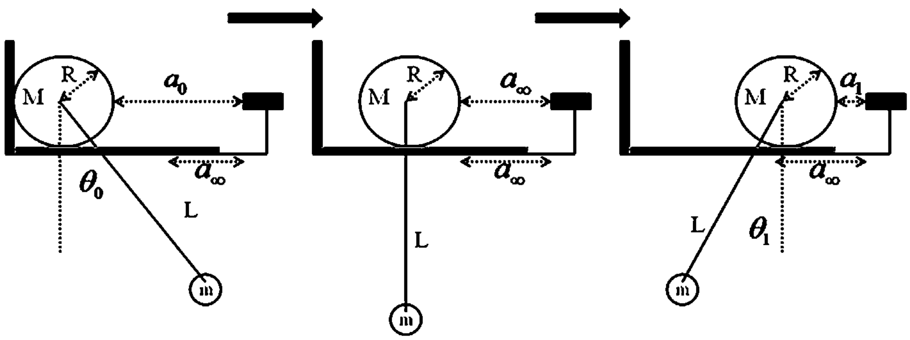

Fig. 4. Distance of the roller from the ultrasonic sensor and the angle of the pendulum from the vertical line in the first period of oscillation.

Table 1
Recipe of SBR compound.

	Function	Phr*
Styrene Butadiene Rubber	Base Elastomer	100
Nano Fumed Silica	Nano Filler	20
Zinc Oxide	Activator	0.5
TBBS	Accelerator	3
6PPD	Antioxidant	1
Sulfur	Curing Agent	2.5

* Phr: weight parts per 100 parts of rubber.

Evonik-Degussa, Germany), zinc oxide (ZnO, Pars Techno, Iran), sulfur (Crystex OT20, Flexsys, Germany), TBBS (Santocure NS, Flexsys, Germany), 6PPD (Bayer, Germany) and 3-Mercaptopropyltrimethoxysilane (Dynasilane MTMO, Evonik-Degussa, Germany).

Silanization of silica was started with dispersion of nano-silica in toluene by an ultrasonic mixer. Excess amount of silane was added to the suspension. The mixture of silica-silane-toluene was heated at 60 °C and stirred for 6 hours. Then, it was dried in air followed by 8 hours in an oven at 80 °C. The dried powder was dispersed in ethanol and centrifuged to remove the un-reacted silane. The remaining modified silica was dried in a vacuum oven at 110 °C for 8 hours.

A melt mixing method was employed for compound preparation using a Brabender laboratory two-roll mill with a friction ratio of 1:1.4 at room temperature. Rubber samples were vulcanized in an electrically heated hydraulic press at its optimum cure time obtained from a Monsanto Oscillating Disk Rheometer at 160 °C. The vulcanized rubber sheet was attached to the rolling table with double-sided adhesive tape.

4.2. Test conditions

Rolling resistance tests were performed on the rubber sheet at 25 °C and 60 °C with two different rollers weighing 0.610 and 2.280 kilograms. The ultrasonic sensor was positioned across the center of the roller. The initial position of the roller was set by resting it against the backrest wall while the attached pendulum was connected to the magnet with a known initial release angle (θ_0). The test was started via the designed software by triggering the magnet and releasing the pendulum. The ultrasonic sensor measures the position of the roller, and the software records it against time. Each test was repeated for five times and the average rolling resistance force and coefficient were calculated by a Matlab program and reported.

5. Results and discussions

Fig. 5 shows position of the roller from the midline versus time for two different roller weights for the vulcanizate containing un-modified silica. The positive values of position are toward the backrest wall from the midline and the negative values are toward the ultrasonic sensor. Comparing Fig. 5a and b, it is clear that the heavier roller stops in a shorter time than the lighter one. In other words, the rate of energy dissipation, i.e. slope of the line connecting peaks, in the rubber for the heavier roller is higher. This is due to larger strains for the heavier roller.

The average rolling resistance force and rolling resistance coefficient for the un-modified silica filled rubber vulcanizate with two different rollers at two different temperatures are shown in Fig. 6. Rolling resistance force (Fig. 6a) increases with increasing vertical load and decreasing temperature. Vertical load increases the strain magnitude which

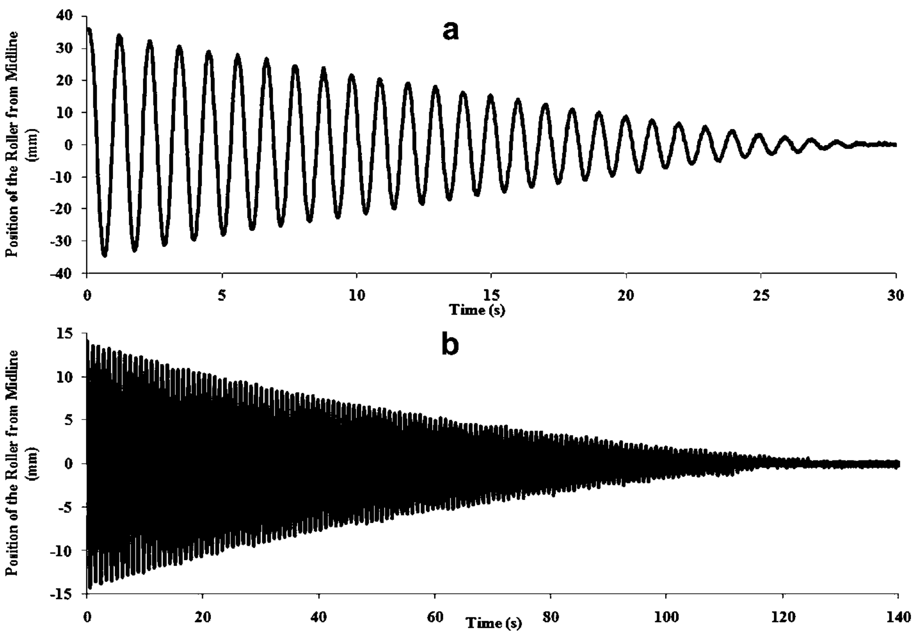

Fig. 5. Position of the roller from the midline a) heavier roller and b) lighter roller.

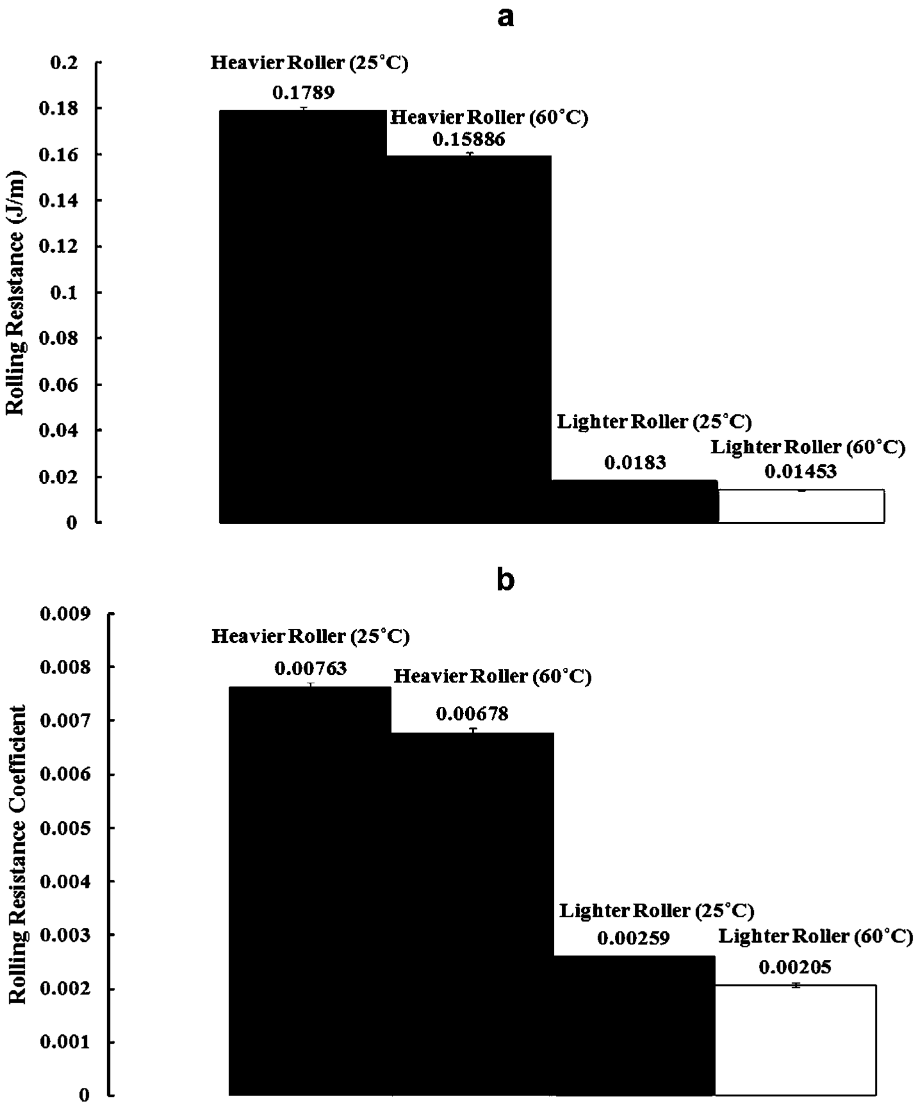

Fig. 6. a) Rolling resistance force and b) rolling resistance coefficient for the SBR vulcanizate filled with un-modified silica.

is related to the energy dissipation in the rubber. Supposing a linear viscoelastic behavior for rubber, energy loss (W) over a single cycle is proportional to the square of strain as:

$$W = \int_0^{\frac{2\pi}{\omega}} \sigma\dot{\gamma}dt = \pi\gamma_0^2 G''$$

where σ is stress, γ_0 is the dynamic strain magnitude and G'' is the loss modulus of the rubber vulcanizate. It has been shown that the loss modulus of rubber vulcanizates decrease with temperature above the glass transition temperature [15]. Therefore, rolling resistance force decreases with temperature, as shown in Fig. 6a.

On the other hand, Fig. 6b compares the rolling resistance coefficient for the same conditions. RRC is also higher at lower temperature of 25 °C and for the heavier roller.

Comparison between rolling resistance of the un-modified and the silane-modified silica filled samples with

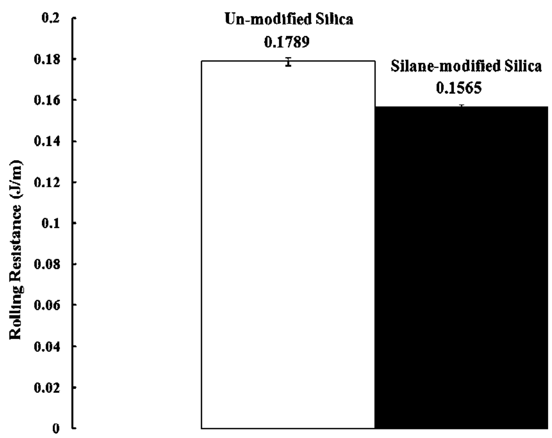

Fig. 7. Rolling resistance force of SBR vulcanizates containing un-modified and silane-modified silica with heavier roller at 25 °C.

the heavier roller at 25 °C are shown in Fig. 7. As it can be seen in this figure, silanization of the nano-silica has reduced the energy dissipation due to rolling resistance in the rubber vulcanizate by about 12.5%. Effect of silica surface modification by silane on reduction of the tire rolling resistance to this extent has previously been proven [8,9].

6. Conclusions

Due to importance of the rolling resistance in Green Tire Technology, and measurement of the energy dissipation in rubber vulcanizates designed for such tires, the need for a practical method to compare vulcanizates in the laboratory has been more recognized. For this purpose, an improved rolling pendulum, based on an initial invention proposed by Gent, was designed and constructed. This improved device has new features which eliminates shortcomings of the initial design and allows for practical measurement of the energy dissipation and the rolling resistance parameters of rubber vulcanizates in the laboratory. Accurate measurements of the distance travelled by the roller on the rubber sample provided the means for calculation of the rolling resistance force and coefficient.

Performance of the improved device was evaluated using nanosilica-SBR vulcanizates under two different roller weights (strains) and two different temperatures. Lower temperature and higher normal load resulted in higher measured rolling resistance force and coefficient. Also, the results showed that the effect of nano-silicasilanization on the reduction of energy dissipation in rubber vulcanizates is of the same magnitude as its effect on the rolling resistance of tires. The modified rolling pendulum device can successfully be employed in the laboratory to measure the energy dissipation in rubber vulcanizates in order to predict their performance in green tires.

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