International Journal of Pharmaceutics 392 (2010) 107–110

Contents lists available at ScienceDirect

International Journal of Pharmaceutics

journal homepage: www.elsevier.com/locate/ijpharm

The coefficient of rolling resistance (CoRR) of some pharmaceutical tablets

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ARTICLE INFO

Article history:
Received 19 January 2010
Received in revised form 11 March 2010
Accepted 15 March 2010
Available online 20 March 2010

Keywords:
Tablet
Coefficient of rolling resistance
Discrete element method

ABSTRACT

Experiments have been conducted to measure the coefficient of rolling resistance (CoRR) of some pharmaceutical tablets and several common materials, such as glass beads and steel ball bearings. CoRR values are required as inputs for discrete element method (DEM) models which can be used to model particulate flows and solid dosage form manufacturing processes. Until now there have been no CoRR data reported for pharmaceutical materials, and thus these new data will help to facilitate more accurate modeling of pharmaceutical systems.

1. Introduction

In discrete element method (DEM) models of particulate systems, several material inputs (e.g., shear modulus, Poisson ratio, and particle density) are required for the accurate prediction of contact forces (Bharadwaj et al., 2006; Kruggel-Emden et al., 2007; Ketterhagen et al., 2009; Kodam et al., 2009). In addition, material interaction parameters (e.g., coefficient of restitution, coefficient of sliding friction, coefficient of rolling resistance) that describe how materials behave when they contact one another are also required. The coefficient of rolling resistance (CoRR), as the name suggests, defines the ratio of the force opposing rolling motion to the normal force acting between two contacting materials. This rolling resistance, or rolling friction, for spherical or cylindrical bodies has been attributed to hysteretic losses (Tabor, 1955), especially in cases where deformable materials such as rubber are considered. However, in many DEM models, the modeled materials are not necessarily "soft", but a rolling resistance is included nevertheless to help account for the resistance to rolling due to slightly non-spherical particles (Ketterhagen et al., 2007) as depicted in Fig. 1. The torque due to rolling resistance $\boldsymbol{M}_R$ has been included in DEM models via several approaches (Beer and Johnson, 1976; Brilliantov and Pöschel, 1998; Iwashita and Oda, 1998, 2000; Zhou et al., 1999), but typically follows a form similar to the following:

$$\boldsymbol{M}_R = -\mu_R \boldsymbol{F}_N \frac{\boldsymbol{\omega}}{|\boldsymbol{\omega}|} \quad (1)$$

where μ_R is the CoRR, $\boldsymbol{F}_N$ is normal force, and $\boldsymbol{\omega}$ is the particle angular velocity.

The inclusion of rolling resistance has been shown to be important (Zhou et al., 2002; Estrada et al., 2008; Ji et al., 2009) but, because there is a very limited theoretical basis for the prediction of these values, the CoRR values must typically be measured experimentally. Values of the coefficient of restitution (Foerster et al., 1994; Gorham and Kharaz, 2000) and the coefficient of sliding friction (Tomlinson, 1929; Beare and Bowden, 1938) can be found in the literature for common materials such as glass, steel, aluminum, *etc.* but, aside from limited exceptions (e.g., Hancock et al., 2010), almost no data is available for pharmaceutical materials. Further, little data has been reported for CoRR values for any materials (Beer and Johnson, 1976; Kudrolli et al., 1997; Williams, 2005; ASTM, 2009). The objective of this work was to measure and report CoRR values for several common materials and some pharmaceutical tablets so that the data can be used as inputs for DEM models and thus permit more accurate predictions of the processing behavior of pharmaceutical samples. These values are important because rolling resistance may affect bulk flow characteristics in pharmaceutical processing operations, for instance, the flow pattern and mixing in a tablet film coating pan or the flow of tablets in a packaging line (Zhou et al., 2002).

2. Materials and methods

2.1. Derivation of CoRR

Consider a spherical ball of mass m, rolling (assume that there is no sliding/slipping between surfaces) down an inclined plane of height h. The ball rolls down the incline from A to B and then comes to rest at C after rolling a distance d, as depicted in Fig. 2. From the

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doi:10.1016/j.ijpharm.2010.03.039

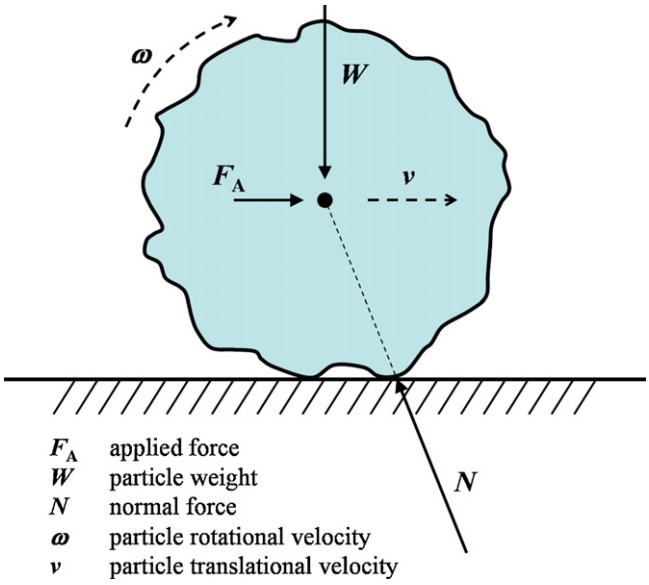

Fig. 1. Schematic showing the rotation of a spherical particle with exaggerated roughness.

Fig. 2. A schematic showing a test material in a rolling resistance measurement.

law of conservation of energy, the total energy of the system at A is equal to the total energy of the system at B. Thus, the potential energy of the system at A is equal to the kinetic energy at B plus the losses from rolling A to B:

$$mgh = \frac{1}{2}mv_B^2 + \text{loss}_{AB} \tag{2}$$

If we assume that the losses during rolling from AB are significantly less than the total energy of the system, we obtain from Eq. (2)

$$v_B = \sqrt{2gh} \tag{3}$$

The ball rolls from B to C with an initial velocity of V_B and deceleration a. Using simple equations of motion from BC we obtain:

$$v_C^2 - v_B^2 = -2ad \Rightarrow 0 - v_B^2 = -2ad \Rightarrow v_B = \sqrt{2ad} \tag{4}$$

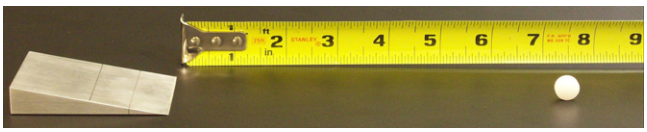

Fig. 3. A photograph showing the simple setup for measuring CoRR of a Teflon ball using a ramp of height h and measuring the distance traveled on a flat substrate d.

From Eqs. (3) and (4), the deceleration of the ball due to the resistance to its rolling motion is given by:

$$a = \frac{gh}{d} \tag{5}$$

The subsequent retarding force F_r that is due to frictional rolling resistance on the ball is given as:

$$F_r = ma = m\left(\frac{gh}{d}\right) \tag{6}$$

The force of rolling resistance F_r is also given as:

$$F_r = \mu_r W \tag{7}$$

where W is the weight of the ball (=mg), and μ_r is the coefficient of rolling resistance. Setting Eqs. (6) and (7) equal to one another, the coefficient of rolling resistance is given as:

$$\mu_r W = \frac{mgh}{d} \Rightarrow \mu_r(mg) = \frac{mgh}{d} \Rightarrow \underline{\underline{\mu_r = \frac{h}{d}}}$$

2.2. Measurement procedure

A measurement procedure based on that described in the ASTM Standard (ASTM, 2009) was used. The sample (ball, disc or tablet) was placed at the top of a smooth ramp of height h. The sample was released and allowed to roll down the incline and onto a flat, level substrate (Fig. 3). The total distance traveled on the flat substrate before the sample came to rest d was measured. The CoRR was calculated as the ratio h/d. A flat planar ramp was used for the tablet and disc samples, whereas a ramp with a V-shaped groove was used for the spherical samples. In both cases, frictional losses between the samples and the ramp were neglected. Five tests were conducted for each sample-substrate pair. The five tests were then repeated in the opposite direction to determine the effect (if any) of unevenness of the substrate. For each pair, the mean values and standard deviations were calculated. In some instances, the tablet trajectory did not follow a straight line. This typically only happened when the tablet was not released straight down the incline. When this occurred, the data from that trial was discarded because rolling was not the sole energy dissipation mechanism, and the trial was repeated.

Table 1
Summary of test materials with the given diameter, D, cylinder thickness or length, T, tablet hardness, H, and solid fraction, ϕ.

Test material	Diameter, D (mm)	Thickness, T (mm)	Hardness, H (kp)	Solid fraction, ϕ (–)
Stainless steel ball bearing	5.6			
Glass bead	2.0			
Glass bead	5.0			
PTFE ball	6.0			
Acrylic disk	8.0	5.3		
MCC tablets with 0.25% MgSt at several different compression forces				
Flat-faced (277 mg)	9.62	4.72	4.3	0.52
Flat-faced (277 mg)	9.61	3.96	9.8	0.62
Flat-faced (277 mg)	9.60	3.61	13.6	0.68
Flat-faced (277 mg)	9.54	2.72	44.6	0.91
SRC (500 mg)	11.28	7.57	5.4	0.50
SRC (500 mg)	11.27	6.56	10.4	0.59
SRC (500 mg)	11.22	5.28	30.4	0.77

MCC, microcrystalline cellulose (Avicel PH102); MgSt, magnesium stearate lubricant; SRC, standard round convex.

Table 2
Summary of the CoRR values measured for the spherical samples where the mean (*M*), standard deviation (SD), and relative standard deviation (RSD = M/SD) are given.

Substrate: 6.4 mm thick aluminum plate		Test material	5.6 mm stainless steel ball	5 mm glass bead	2 mm glass bead	6 mm PTFE ball	8 mm acrylic disk
Ramp height 1 (h = 3.2 mm)	Replicate 1	M		0.0047	0.0070	0.0054	0.0102
		SD		0.0004	0.0007	0.0003	0.0004
		RSD (%)		8.1	10.4	5.0	4.2
	Replicate 2	M		0.0048	0.0065	0.0060	0.0104
		SD		0.0006	0.0006	0.0004	0.0005
		RSD (%)		12.1	9.4	7.0	4.6
Ramp height 2 (h = 1.6 mm)	Replicate 1	M	0.0026	0.0037	0.0060	0.0047	
		SD	0.0002	0.0004	0.0006	0.0001	
		RSD (%)	7.4	10.2	10.5	2.8	
	Replicate 2	M	0.0023	0.0043	0.0058	0.0049	
		SD	0.0001	0.0006	0.0008	0.0002	
		RSD (%)	2.4	14.3	14.0	4.7	
Substrate: 12.8 mm thick polycarbonate plate		**Test material**	**5.6 mm stainless steel ball**	**5 mm glass bead**	**2 mm glass bead**	**6 mm PTFE ball**	**8 mm acrylic disk**
Ramp height 1 (h = 3.2 mm)	Replicate 1	M					
		SD					
		RSD					
	Replicate 2	M					
		SD					
		RSD					
Ramp height 2 (h = 1.6 mm)	Replicate 1	M	0.0022				
		SD	0.0001				
		RSD (%)	6.1				
	Replicate 2	M	0.0022				
		SD	0.0002				
		RSD (%)	9.2				

2.3. Materials

Several model particles (glass, steel, and polytetrafluorethylene (PTFE) (Teflon) balls, and acrylic discs) and a variety of round pharmaceutical tablets were tested in combination with two different substrates (aluminum and polycarbonate). To minimize the confounding influences of surface roughness effects, the samples and substrates were selected to be as spherical/round and smooth as possible. The model particles were obtained from McMaster-Carr (Elmhurst, IL) and the tablets were manufactured from a common excipient (microcrystalline cellulose) by direct compression. Compacts manufactured from microcrystalline cellulose have smooth surfaces and sharp edges, and thus they are ideal for the determination of CoRR values. The tablets were manufactured in two shapes (flat-faced discs and standard round convex tablets) and several solid fractions to determine the effects (if any) of differences in these tablet properties. The properties of all the samples are summarized in Table 1. The substrates were selected because they were representative of materials commonly used for pharmaceutical processing equipment (that is, they were smooth metal and polymer surfaces) and they were readily available in large flat sheets. The substrates were cleaned with alcohol wipes to remove any dust, oil, *etc*. prior to conducting the tests.

3. Results

The measured CoRR values for the model particles are reported in Table 2. Most of the CoRR values for these materials were quite small (0.002–0.006) and replicate measurements were fairly consistent, with RSDs less than 15% for all material pairs. The acrylic disk exhibited a somewhat larger CoRR (≈0.010), and this was thought to be due to the contact area differences between sphere-plate contacts (point contact) and cylinder-plate contacts (line contact). It could also have been due to differences in surface roughness of the samples.

The CoRR results for the MCC tablets – bi-convex and flat-faced – are reported in Figs. 4–7. They were all in the range from 0.004 to

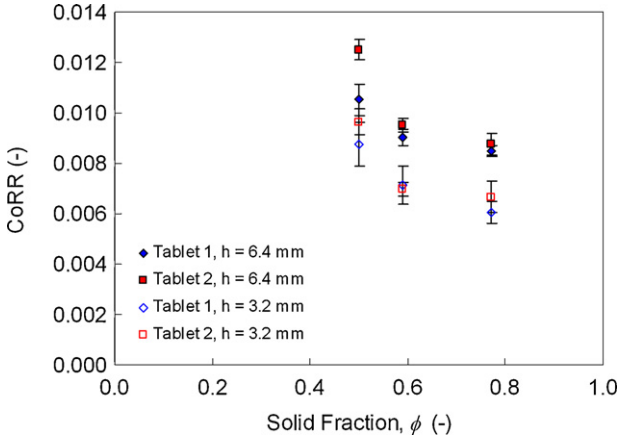

Fig. 4. CoRR values measured for SRC shaped tablets on the aluminum substrate.

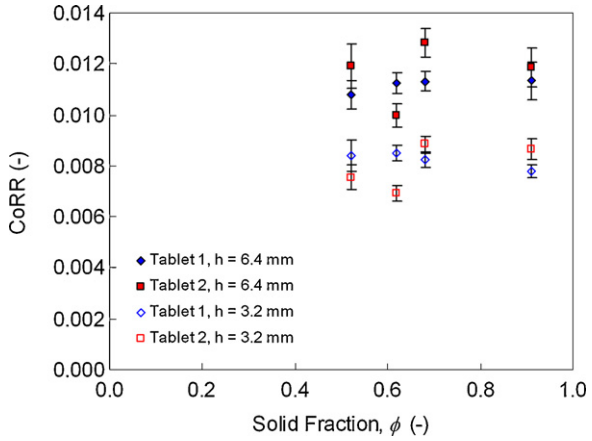

Fig. 5. CoRR values measured for flat-faced tablets on the aluminum substrate.

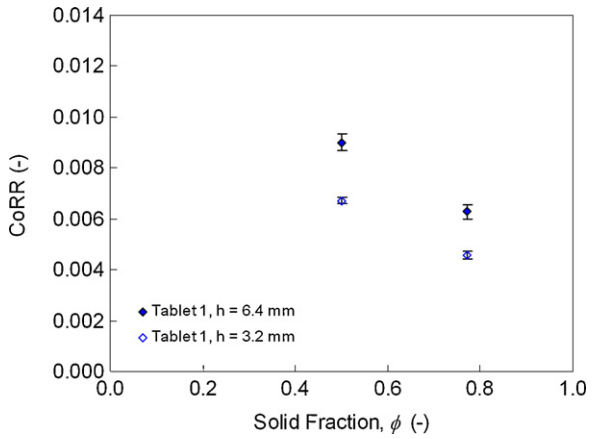

Fig. 6. CoRR values measured for SRC shaped tablets on the polycarbonate substrate.

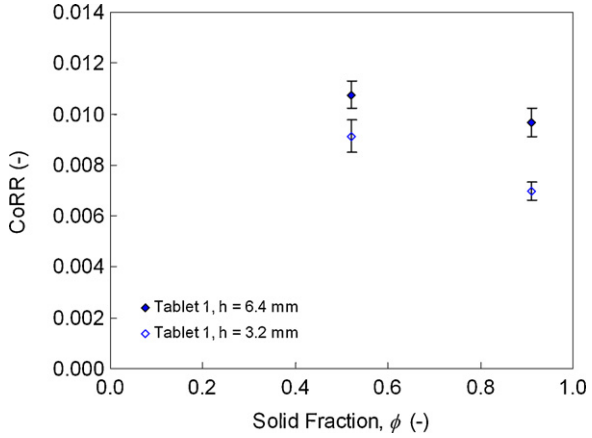

Fig. 7. CoRR values measured for flat-faced tablets on the polycarbonate substrate.

0.013, and there was only a small effect (5–15%) due to the direction of testing (data not shown). For the bi-convex tablets (Fig. 4), the CoRR values tended to decrease slightly with increasing tablet solid fraction, which is probably due to decreasing thickness of the tablet band. In contrast, the flat-face tablets (Fig. 5) did not show a clear trend with tablet solid fraction. The CoRR values for the aluminum substrate were typically equal to or very slightly greater than those for the polycarbonate substrate.

The CoRR values were always greater for tests with larger h (Table 1 and Figs. 4–7). The samples may lose some energy at the transition between the ramp and the flat substrate, and based on experimental observations of the samples 'bumping' at the transition point, it is speculated that this loss is relatively greater for measurements taken at larger h. The larger these losses are, the shorter distance the tablet will roll, and the larger the apparent h/d value.

It appears that test conditions (ramp height), substrate material, and surface smoothness all play some small role in determining the CoRR. However, the range of CoRR values obtained for pharmaceutical and model materials in this work was relatively narrow (0.004–0.013) and is typical of the values previously reported (ASTM, 2009). This narrow range is not expected to have a large affect on bulk flow characteristics such as tablet motion in a film coating pan or a packaging line. Rather, other parameters such as tablet shape and sliding friction coefficient (Hancock et al., 2010) may have a more significant effect. Notably, the range of CoRR values determined experimentally spans the default value (0.010) used by at least one commercial DEM software application (EDEM^{TM}, DEM Solutions, Edinburgh, Scotland).

4. Conclusions

Measurements of the CoRR were conducted for several model materials as well as placebo tablets of varying shapes and solid fractions. Very little CoRR data exists in the literature, and what does exist is for very limited combinations of common materials. The data obtained in this work fill an important gap and can be used as inputs to discrete element method (DEM) models of pharmaceutical systems, thereby helping to improve the accuracy of the DEM model predictions. The range of measured CoRR values obtained in this work was relatively narrow and was similar to that of other non-pharmaceutical materials. The results were slightly affected by changes in the tablet solid fraction, substrate material, and the test conditions (ramp height).

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