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Friction properties of cork

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The friction coefficient, μ, of cork sliding on another material (glass and steel in most experiments and also cork) was measured for various compressive stresses and sliding velocities. There is a strong effect of stress and a negligible effect of velocity on the friction coefficient. Values of μ are in the range 0.4 to 1.2. The effect of moisture content of cork was also evaluated. For dry cork (6% moisture content) there is anisotropy of the friction coefficient related to the orientation of the sliding plane of cork, with larger values for sliding in the tangential plane (compression in the radial direction) as compared to sliding in planes perpendicular to this. At larger moisture contents, the anisotropy of μ decreases. No in-plane of sliding anisotropy was detected. The friction coefficients for sliding on glass and on steel are comparable, but an effect of roughness was detected. The friction coefficients for sliding on glass and on steel are comparable, but an effect of roughness was detected. The friction against cork is large, with μ close to unity. The interplay between the friction coefficient and the compression properties of cork is discussed. © *1998 Chapman & Hall*

1. Introduction

The friction properties of cork are important in a number of its applications, from shoe soles to stoppers for bottles. Cork agglomerates are widely used in floor covering in part because of their favourable friction properties. Data on the friction coefficient of cork against common materials are not available in the literature. The friction coefficient of a cork stopper in a common wine bottle, is, however, easily estimated from the measured pull-out force which is around 300 N. The (relaxed) compressive radial stress of the (wet) cork in the bottle neck is around 0.3 MPa [1] and the area of contact (i.e. the surface area of the inserted stopper) is typically 20 cm^2. This gives a coefficient of friction around 0.5.

Cork is a transversally isotropic cellular material, the radial direction in the tree (R-direction) being a direction of symmetry. This is a consequence of its cellular structure (see Fig. 1) with the prismatic closed cells arranged in columns parallel to the radial direction [2, 3], which is also the direction of the lenticels (pores) in cork. The directions perpendicular to the radial direction (which we term non-radial or NR-directions), including the axial (tree axis) and tangential directions, are in principle, equivalent because of the random orientation of the lateral faces of the prismatic cells.

The friction coefficient of an anisotropic material sliding on another (isotropic) material depends on the direction of compression, which is normal to the sliding surface, and on the direction of sliding. The friction force F_f is in general not parallel to the sliding direction [4]. The friction coefficient is defined as

$$\mu = \frac{F_f}{F_0} \qquad (1)$$

where F_0 is the force of compression. For a fixed direction of compression, the friction force depends on the direction of sliding, and a second order tensor has been used to define the in-plane friction coefficient [4]. Anisotropy of friction has been experimentally observed in many crystalline solids [e.g. 5–7] and also in wood [8]. These studies usually consider friction in different sliding directions on the same contact plane, but do not address the anisotropy related to the plane of sliding. As for other properties of anisotropic materials (e.g. the surface energy), the value of the friction coefficient for an arbitrary combination of the directions of compression and sliding cannot be obtained from its value for a finite number of combinations of these two directions, even for a fixed value of the compressive force, F_0.

In this experimental study of the friction of cork we investigated the anisotropy of friction by determining the coefficient μ for sliding on surfaces parallel and perpendicular to the radial direction. We also investigated in-plane of sliding anisotropy. The various combinations that were experimentally studied are schematically shown in Fig. 2. The measurement of the friction coefficient was undertaken for cork sliding on three different materials (glass, steel and cork) at various values of the sliding velocity and of the compressive stress. The effects of the roughness of the counter-surface and of the humidity of cork were also studied and measurements of the pin temperature were undertaken. Uniaxial compression tests of cork specimens were carried out to obtain and compare simple mechanical properties of the dry and humid cork, in an attempt to correlate them to the friction properties.

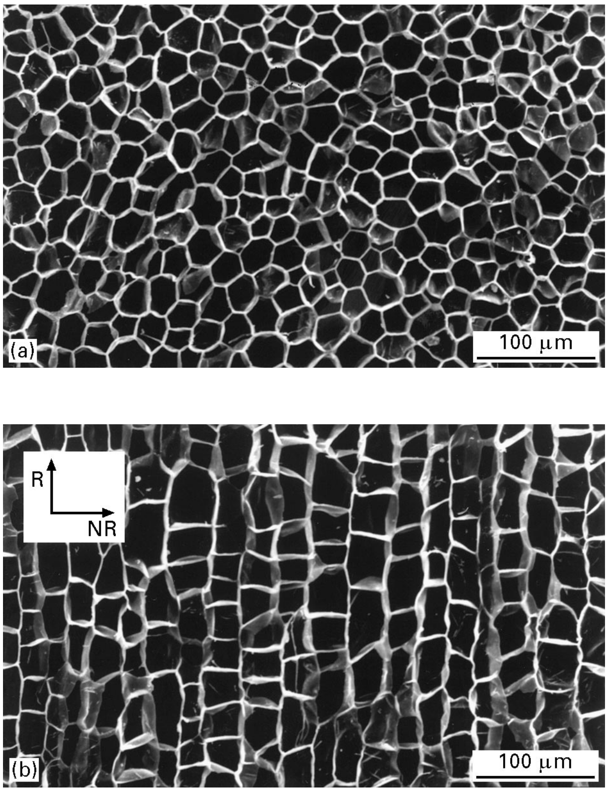

Figure 1 The cellular structure of cork: (a) section perpendicular to the radial direction (tangential section); (b) section containing the radial direction, which is vertical in the figure (scanning electron microscopy).

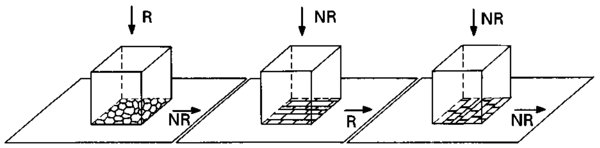

Figure 2 The three main types of friction tests of cork, with a schematic representation of the cork cellular structure in the plane of sliding. The direction of compression and the direction of sliding are indicated in each drawing by arrows. R denotes the radial direction and NR a direction perpendicular to the radial direction (non-radial direction).

2. Experimental procedure

The cork used in most experiments was a good quality cork with a small incidence of lenticels (less than 5% by volume). All pins were cut from the same corkboard. The moisture content of laboratory air equilibrated samples was 6%, measured by drying to constant mass at 102 °C (to be referred to as dry cork). Specimens of the same cork were also equilibriated in a humid atmosphere (the vapour of a saturated solution of K_2SO_4) to a moisture content of 15% (to be referred to as humid cork).

Uniaxial compression tests were carried out for compression in the radial direction and in non-radial directions (the axial and tangential directions). Cube specimens were used. The stress–strain or $\sigma(\varepsilon)$ curves for compression in these three directions at a strain rate of $1.6 \times 10^{-3}\,s^{-1}$ are shown in Fig. 3 for the two moisture contents. They clearly show the transition

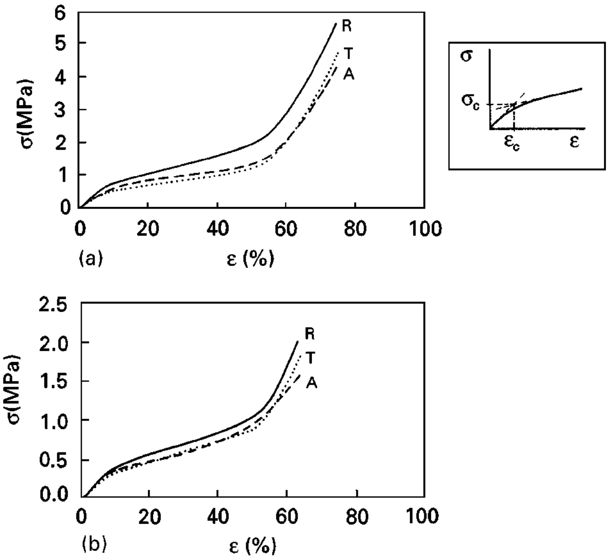

Figure 3 Stress (σ)–strain (ε) curves of the cork used in the friction experiments: curve R compression in the radial direction; curve A compression in the axial direction; curve T compression in the tangential direction. (a) Moisture content 6% (dry cork); (b) moisture content 15% (humid cork). The insert shows how to determine the collapse stress and strain.

TABLE I Compression properties of cork used in the friction experiments

Direction of compression	Moisture content 6% Radial	Moisture content 6% Axial/tangential	Moisture content 15% Radial	Moisture content 15% Axial/tangential
E (MPa)	10.0	7.0	5.9	5.2
σ_c (MPa)	0.75	0.63	0.36	0.33
ε_c (%)	9.1	11.5	8.5	11.0

from initial elastic behaviour to a regime of smaller $d\sigma/d\varepsilon$ in which cell wall collapse occurs by buckling [2, 9]. Table I indicates the values of the Young's modulus, E (calculated from the average slope of the stress–strain curve between strains of 0 and 5%) and of the collapse (or buckling) stress, σ_c, and collapse strain, ε_c at the initiation of the plateau region of the $\sigma(\varepsilon)$ curve. The corresponding point in the $\sigma(\varepsilon)$ curve was defined at the intersection of the elastic and cell buckling regions of the curve (see insert in Fig. 3). In dry cork, the radial direction is appreciably stiffer than the non-radial directions. The difference between the radial and non-radial directions is considerably smaller in humid cork which also shows a smaller compression strength than dry cork. The two NR-directions tested (axial and tangential) were found to be nearly equivalent, with a slightly larger strength in the axial direction in dry cork. The values in Table I are average values for the two NR-directions. These results for dry cork agree with those in the literature [9].

The friction coefficient of cork was measured with a pin-on-disc machine, with continuous record of the friction force. The machine measures the component of the friction force parallel to the sliding direction, which coincides with the friction force F_f in the case of in-plane isotropy. The cork pins had either circular or square cross-section. Four levels of compressive stress, namely 0.12, 0.46, 0.80 and 1.40 MPa were used in different experiments. These were achieved by varying the compressive load (between 10 and 50 N) and the area of the cross section (between 20 and 400 mm^2). In a few cases, such as for cork sliding on rough discs, lower stresses were used.

Pins with their axes parallel to each of the principal directions of cork (radial, axial and tangential) were used in different experiments (Fig. 2). Within the experimental scatter, no difference was found in the friction behaviour between the two NR-directions tested. The results will therefore be indicated indistinctly for any of these NR-directions.

Three sliding velocities were used in different experiments: (in m s^{-1}) 0.2, 0.66 and 1.33. These correspond to angular speeds of the disc of 60, 200 and 400 rot./min.

Smooth glass and steel discs were used in most experiments. The glass surface was very smooth and its asperities could not be detected with the profilometer available (sensitivity of 5 μm). The roughness of the smooth steel plate was $R_z = 12$ μm. The effect of roughness on the sliding friction was assessed with other discs of the same materials (glass and steel) but of larger roughness ($R_z = 70$ μm for rough steel; $R_z = 55$ μm for rough glass). A few tests for cork sliding on cork were also undertaken.

3. Results

A typical curve of variation of the friction coefficient, μ, with sliding distance is shown in Fig. 4. There is an initial period during which μ increases, occasionally with fluctuations; until it reaches a constant value. It is this constant value that will be indicated.

There was an appreciable scatter in the values of μ obtained with different pins under the same conditions. This scatter in the mechanical properties is usual with cork and can be attributed to the heterogeneity of its structure with cell sizes that vary along the radial direction [9]. To avoid the scatter inherent to different specimens, experiments were made, when possible, using the same cork pin. For example, the effects of the compressive load and velocity were evaluated using the same cork pin in the same orientation. There is, of course, wear of the pins, implying that the contact surface is changing as the pin slides. Nevertheless, a constant μ is reached after an initial transient.

We discuss in turn the effects of the various intervening parameters on the friction coefficient of dry cork (6% moisture content) sliding on smooth glass and steel. The effects of disc roughness and of moisture content and results for cork sliding on cork will be indicated subsequently.

3.1. Effects of sliding velocity

Fig. 5 shows the variation with sliding velocity of the friction coefficient μ_R of a cork pin under compression ($\sigma = 0.12$ MPa) in the radial direction. The pin was the same for all velocities. The friction coefficient is not much affected by the sliding velocity, for velocities between 0.2 and 1.33 m s^{-1}, although a small tendency for μ to increase with sliding velocity was detected. The same behaviour was found for other compressive stresses applied either in R and NR directions.

3.2. Effect of compressive stress

Measurements of μ_R on glass using compressive stresses of 0.12, 0.46, 0.8 and 1.4 MPa gave the results shown in Fig. 6. The cork pin was the same for the four stresses. The sliding velocity was 1.33 m s^{-1}. Fig. 6 indicates a clear decrease of μ_R with stress. A similar effect was found for compression in NR directions.

3.3. Antisotropy of friction

For cork sliding on planes perpendicular to the R-direction, no anisotropy of μ is expected in virtue of the symmetry of the radial direction. However, in-plane anisotropy for sliding on planes containing the radial direction cannot be excluded, since the in-plane R and NR-directions are not structurally equivalent.

Experiments were carried out in which the sliding direction was changed by rotating a pin about its axis and μ measured for each direction. In all cases, the friction coefficient increases initially, when a new sliding direction is tested, and stabilizes after a transient.

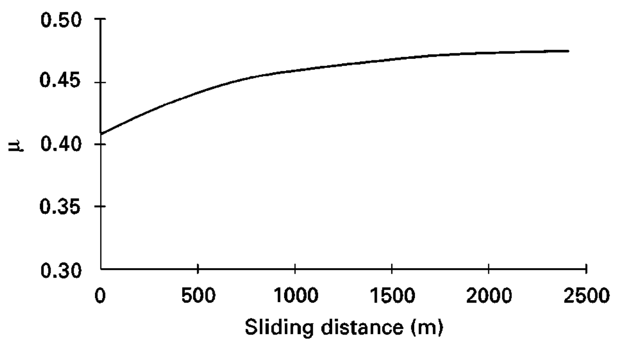

Figure 4 Variation of friction coefficient with sliding distance for cork on smooth glass. Compressive stress 0.12 MPa in NR-direction; sliding velocity; 1.33 m s^{-1}.

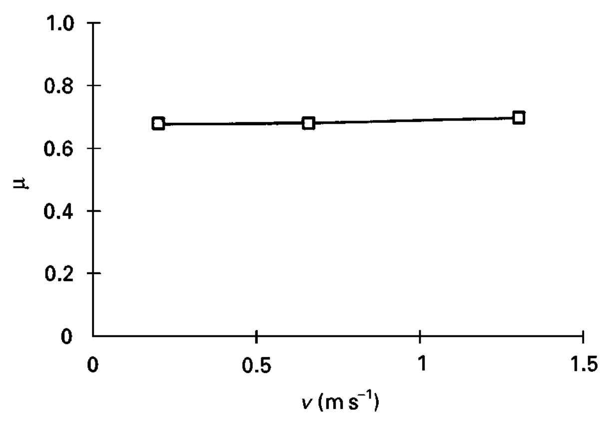

Figure 5 Variation of friction coefficient with sliding velocity for cork on smooth glass. Compressive stress 0.12 MPa in R-direction.

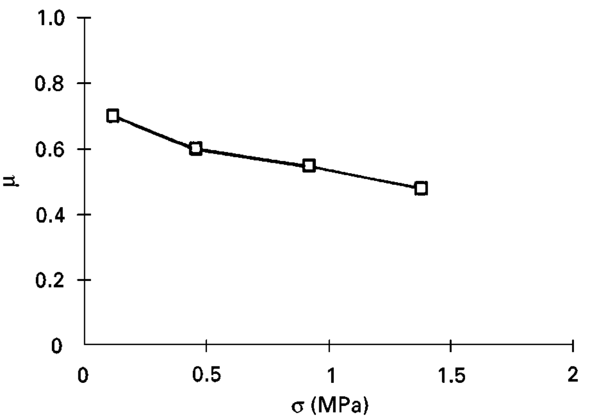

Figure 6 Variation of friction coefficient (against smooth glass) with compressive stress. Compression in R-direction; sliding velocity: 1.33 $m s^{-1}$.

The experiments were carried out for pins with their axes along R and NR-directions. The change in μ with direction of sliding was always very small and uncorrelated with the direction of sliding. In conclusion, no in-plane of sliding anisotropy was detected, even for pins with their axes along a NR direction.

In order to investigate possible anisotropy related to the direction of compression, i.e. radial or non-radial, we measured the coefficients μ_R and μ_{NR}, respectively, of dry cork. Because of the unavoidable scatter of results in these measurements, twenty cork pins were used to measure μ_R and different twenty other cork pins to measure μ_{NR} on smooth glass. The results are shown in Fig. 7 for $\sigma = 0.46$ MPa and $v = 0.66\ m s^{-1}$. A statistical analysis of the data was made based on t (Student's parameter). It was found that with a confidence larger than 99.95%, the populations (radial and non-radial) are different, with μ_R larger than μ_{NR}. The average values and standard deviations for the 20 measurements that were carried out are $\mu_R = 0.55 \pm 0.06$ and $\mu_{NR} = 0.46 \pm 0.08$. We conclude that there is anisotropy of the friction coefficient related to the orientation of the contact surface, but there is no in-plane anisotropy.

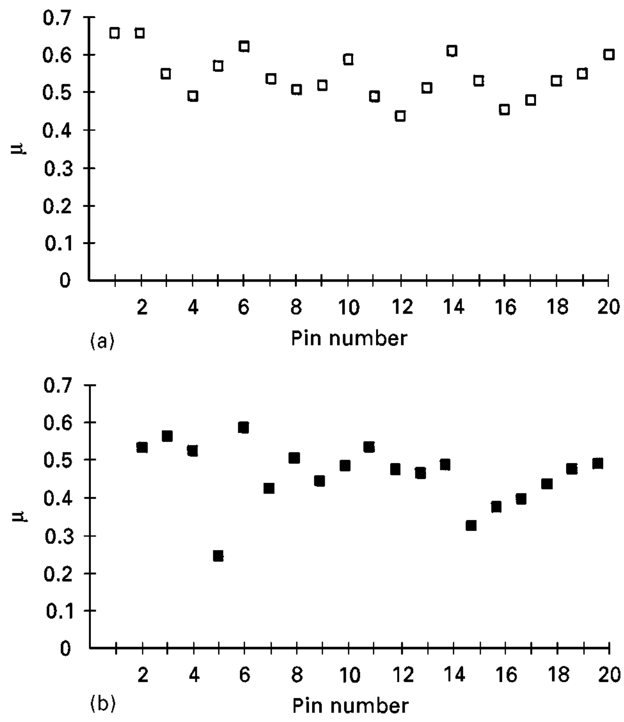

Figure 7 Friction coefficients of twenty different cork pins sliding on smooth glass: (a) compression in the radial direction □ *R*; (b) compression in a non-radial direction. $\sigma = 0.46$ MPa and $v = 0.66\ m s^{-1}$ ■ NR.

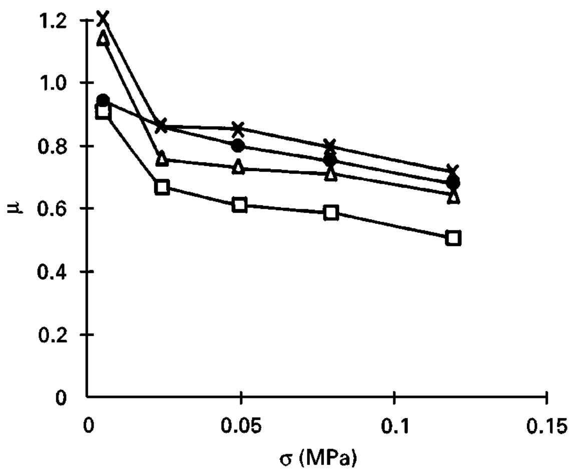

Figure 8 The effect of compressive stress (in a non-radial direction) on the friction coefficient of cork sliding on smooth glass (□), rough glass (●), smooth steel (△) and rough steel (×) $v = 0.6\ m s^{-1}$.

3.4. Effects of disc roughness

Tests were made with the same cork pin sliding on smooth glass, rough glass, smooth steel and rough steel, for a sliding velocity of 0.66 $m s^{-1}$ under various compressive loads. The compression load was applied in a non-radial direction. The results obtained are indicated in Fig. 8. For example, the friction coefficient in rough glass is 0.67, in smooth glass 0.50, in rough steel 0.71 and in smooth steel 0.64, under the same stress (0.12 MPa) and the same velocity (0.66 $m s^{-1}$). Compressive stresses smaller than usual were used in these experiments, because the wear rate is high in rough discs and four friction tests (two materials, two roughnesses) with the same pin were required. The friction coefficient increases with increasing disc roughness and is larger for steel than for glass of comparable roughness.

3.5. Effects of moisture content

In preliminary experiments, the friction coefficients for the 15% moisture cork (humid cork) sliding on glass were compared with the values for the 6% moisture cork (dry cork) using different cork pins, under the same applied stress and velocity. These experiments showed the usual large scatter in μ, but with a tendency for smaller μ in the humid cork.

Other tests were conducted using the same cork pin (a cube of cork) in the dry condition and in the humid condition. The friction coefficient was first measured for the moisture content of 6%, successively in R and

TABLE II Effect of moisture content on friction coefficients (cork-glass, $\sigma = 0.12$ MPa; $v = (0.66\ \mathrm{m\,s^{-1}})$

Pin	Moisture content 6%		Moisture content 15%	
	μ_R	μ_{NR}	μ_R	μ_{NR}
1	0.73	0.54	0.57	0.50
2	0.75	0.59	0.55	0.54

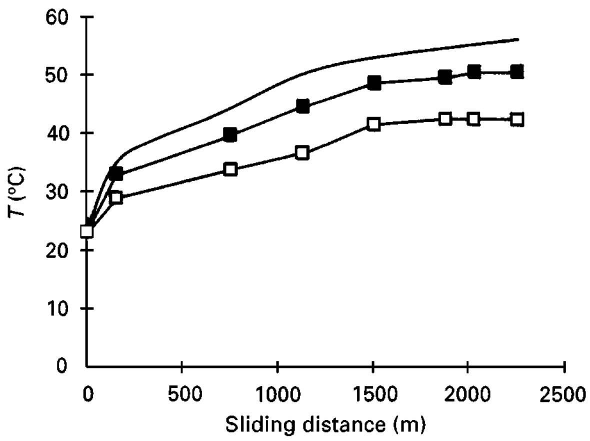

Figure 9 Variation of temperature with sliding distance. Measured temperature at 4 (■) and 10 mm (□) from the sliding surface and estimated temperature at the sliding surface (—) are plotted. $\sigma = 0.12$ MPa and $v = 1.33\ \mathrm{m\,s^{-1}}$.

NR compression; the pin was then equilibrated to a moisture content of 15% and the friction coefficient was again measured for the same two orientations of the sliding surface. Results are indicated in Table II for two cork pins. There is a large reduction in μ_R and a small reduction in μ_{NR} due to the increase in humidity. As a result, the anisotropy of the friction coefficient of humid cork is relatively small.

3.6. Temperature of cork spin

The temperature of a cork pin sliding on smooth glass was measured with two thermocouples placed at approximately 4 mm and 10 mm from the contact surface. Fig. 9 shows the variation of temperature with sliding distance for a velocity of $1.33\ \mathrm{m\,s^{-1}}$ under a stress of 0.12 MPa. There is an effect of velocity on the temperature, with an increase of approximately 4 °C (in the temperature at both positions) between the extreme velocities used. The temperature at the contact surface was calculated assuming a linear temperature profile in the pin. The estimated temperature at the contact surface is also shown in Fig. 9. It increases from the initial value ($\sim$25 °C) to a constant, maximum temperature between 50 and 70 °C in different experiments. It is apparent, by comparing Fig. 9 with Fig. 4, that the transient in temperature has approximately the same duration as the transient in μ.

3.7. Friction of cork sliding on cork

A few experiments were undertaken for dry cork sliding on a disc covered with a 2 mm thick plate of natural cork. The plate was cut perpendicular to the radial direction of cork. The friction coefficient is large with values $\mu_R = 0.97$ and $\mu_{NR} = 0.77$, for $\sigma = 0.12$ MPa and $v = 0.66\ \mathrm{m\,s^{-1}}$.

4. Discussion

Experimental results on the friction properties of cellular materials are very scarce in the literature and seem to be limited to wood [8, 10–13]. Atack and Tabor [10] measured the friction coefficient of balsa wood sliding on steel and polytetrafluoroethylene (PTFE). When balsa was the material of the disc they observed an increase in μ from 0.6 to 0.65 for a steel sphere (diameter 1.58 mm) with increasing compressive load from 2 to 10 N. When balsa was the material of the spherical "pins", there was no effect of the compressive stress. These results contrast with the effect of compressive stress on μ observed with cork in the present work.

The friction of lignum vitae was studied by McLaren and Tabor [11] and found to resemble that of balsa, though with smaller μ. Murase [13] studied the frictional properties of wood (western hemlock) sliding on various materials under different stress and moisture contents. The friction coefficient between Swedish woods and steel was determined by Guan *et al.* [8]. They studied the effect of moisture content, sliding velocity and smoothness of the steel surface. Anisotropy of friction in wood associated with the orientation of the contact surface was also detected by Guan *et al.* [8], confirming the observations done by Coulomb in the eighteenth century.

Two contributions to friction were identified in these experiments [8, 10–13]: one caused by adhesion and the other caused by deformation of the wood caused by sliding.

The mechanics of the static contact of a cellular material with a compact surface is a complex problem and a detailed analysis is still lacking. It is, of course, a prerequisite to understanding the sliding behaviour of a cellular material. In the following we discuss briefly these two problems (contact and friction) without attempting any quantitative predictions. We consider, as previous authors, two contributions (adhesion and deformation) to friction.

A free surface in cork contains cut cell walls connected at edges. The adhesion contribution to the friction force is related to the actual area of contact A_{cont}, of the cut cell walls with the counter-surface. This area is related to the number of cell walls in contact and increases with the applied compressive stress σ. If the increase in contact area with σ is less than linear, the friction coefficient decreases as σ increases. It will be shown elsewhere that this is indeed the case for a system of discrete rods, which simulate the cut cell walls, that is pressed against a rough surface, inducing linear elastic deformation of the rods. As the global compressive force increases, more rods contact the counter-surface but the number of rods in contact, per unit applied stress, decreases. Buckling of the rods at a critical load will also contribute to a decrease of μ with σ.

The initial increase observed in the friction coefficient can also result from the increase in the area of contact that occurs because of the "polishing" of the original surface of contact. The more protuberant asperities will be eliminated by wear and the area of contact will increase. An increase in contact area is also expected to result from creep of the cell walls in contact with the disc. Finally, the increase in temperature that occurs during the transient in μ can also contribute to an increase in μ, if μ increases with temperature, as it is the case with some polymers [e.g. 14]. More experimental work is required to explain the observed transient behaviour of μ.

The sliding of cork on a compact surface S can be visualized as a stick-slip process of the cut cell walls in contact with S [15]. While they are sticking on S and pushed in the sliding direction, the walls gradually bend to a configuration where they jump to a new position ahead. The stored elastic energy of bending is lost in the stick-slip process. It is this mechanism that gives the deformation contribution to the friction force and explains the observed increase of μ with surface roughness [15].

The experimental results on the anisotropy of μ relative to the direction of compression and of the effect of humidity of cork, when compared with the properties measured in uniaxial compression tests, suggest a correlation between μ on one hand and E (and σ_c) on the other, with μ increasing as E (and σ_c) increase, as also observed in wood [8]. This could be caused by an increase of the deformation contribution to μ, which would result from an increase in E and of the corresponding increase in the energy dissipated in cell wall bending for the same deflection (same roughness of the disc). However, in this argument we are not taking into account the different arrangement of the cut cell walls in the two contact planes (perpendicular and parallel to the radial direction). In addition, a possible effect of moisture content of cork on the adhesion force cannot be ruled out.

Finally, the experimental result of virtually no effect of sliding velocity on the friction coefficient is somehow unexpected, considering the appreciable strain rate sensivity of cork, measured in uniaxial compression, with a value of the coefficient $m = \mathrm{d}\ln\sigma/\mathrm{d}\ln\dot{\varepsilon}$ of 0.08 [9]. If the strain rate of the deforming cell walls during sliding is proportional to the sliding velocity, one could expect an increase by a factor 1.13 in the sliding force required for deformation at velocities that differ by a factor of 6, as is the case in our experiments. The corresponding increase in the deformation contribution to the friction force would be 1.13. This is far more than the measured increase in the friction force, and would suggest a very small contribution of deformation to friction.

5. Conclusions

The following are the main conclusions of this experimental study of the friction of cork sliding on glass and on steel:

1. The friction coefficient of cork is virtually independent of sliding velocity for velocities between 0.2 and 1.33 $\mathrm{m\,s^{-1}}$.
2. When sliding on glass or steel the friction coefficient of dry cork decreases with increasing compressive load.
3. The friction coefficient of dry cork is anisotropic, with larger values for sliding in the tangential plane (perpendicular to the radial direction) as compared to those for sliding in planes perpendicular to this (parallel to the radial direction), that is, $\mu_R > \mu_{NR}$.
4. No anisotropy of the friction coefficient occurs when the sliding plane is perpendicular to the radial direction, since this is a direction of symmetry in cork. No anisotropy was detected for sliding in a plane containing the radial direction, in spite of the structural anisotropy of the sections of cork by such planes.
5. The pin temperature at the contact surface with the disc increases to values up to 70 °C, for a sliding velocity of 1.33 $\mathrm{m\,s^{-1}}$. The increase in temperature may contribute to the initial rise in μ.
6. The friction coefficients of dry cork sliding on glass and on steel were found to increase with increasing roughness.
7. As the moisture content of cork increases from 6 to 15% both μ_R and μ_{NR} decrease in such a way that the anisotropy of the friction coefficient becomes less pronounced.
8. Two contributions to the sliding friction of cork on a compact solid can be identified, one related to adhesion and dependent on the contact area and friction coefficient of the broken cell walls, and the other related to deformation by bending of the cell walls, caused by sliding, which depends on the roughness of the counter-surface and on the bending stiffness of the walls. The friction coefficient seems to correlate with the Young's modulus (E) and collapse stress (σ_c) measured in uniaxial compression tests, increasing as E and σ_c increase. However, the interpretation of the experimental results requires a more complete analysis of the contact and friction mechanisms of cellular solids.

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