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Characterization of cigarette hardness and tobacco filling power

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Summary

The hardness measurement is not specific to the tobacco world. It can be found in areas as diverse as engineering, ergonomics, fruit and vegetable farming, etc. In addition, the way in which the consumer judges the quality of this parameter varies greatly. It would thus be utopian to think of designing a universal device capable of reproducing this tactile sensation. Generally, the various methods used call on the same principle: the application of a set force over a given period and the observance of the resulting crushing. Applied to cigarettes, this method has the merit of being simple but does not give full information on the capacity of the product tested to react to the force. We envisage a new method of characterizing hardness, based on a three-parameter physical model. This model takes into account the elastic and plastic deformation together with the relaxation phenomenon. For tobacco, it applies equally well to the measurement of cigarette hardness and to the measurement of the blend filling power. Associated with a regression software program, it provides the means for fully characterizing the deformation of the product tested under a force and is the subject of experimental validation.

1. Introduction

It has been known for a number of years [1] that the requirements for manual assessment of hardness or firmness depend on the product and the assessors. Thus, the applied force is greater when the product is firmer and women generally apply a lower force than men for a given product. Therefore, it would seem misleading to try to develop a device capable of reproducing human behavior accurately for the assessment of hardness. On the other hand, a force is applied and a displacement is felt. Thus, in order to evaluate hardness using a device, the capacity to apply a force and to measure a displacement is a prerequisite. In this case, hardness is measured by crushing. Many devices, based on this principle, have been developed for the food-processing and tobacco industries [2,3,4]. For a given physical principle, the force, the contact points and the crushing time differ greatly from one device to another [5].

The filling power of tobacco is also based on the application of a force and the measurement of crushing after a given period of time [6]. In this way, analysis of the hardness of cigarettes and of the filling power of tobacco can be performed simultaneously.

The aims of this study were to examine the behavior of cigarettes or of tobacco when submitted to a crushing force, to evaluate the limits of currently employed methods and to propose a new method for the characterization of hardness and of filling power.

2. Theory

Devising a model to study crushing is based on an inventory of the physical phenomena that play a role when a force is exerted on a cigarette or tobacco. Three main phenomena are observed:

- → plastic deformation
- → elastic deformation
- → relaxation of internal forces

The approach adopted to take each of these phenomena into account, within one and the same model, was to search for the equivalent in an electrical circuit. Plastic deformation, which induces a loss of input energy, can be represented by an electrical resistance that dissipates energy when a current passes through it. Elastic deformation, which corresponds to a store of energy capable of being released, can be represented by a capacity capable of charging or discharging when submitted to voltage changes. Finally, relaxation, which constitutes a loss of accumulated energy, can be represented by a resistance connected in parallel to the capacity, inducing a leakage current when the capacity is charged.

We have shown that it is relatively easy to make an analogy between mechanical and electrical phenomena. The following table shows the equivalences between these phenomena.

Mechanical phenomena	**Electrical phenomena**
Application of a force, F(t)	Application of a tension u(t)
Speed of displacement v(t)	Current i(t)
Input energy; $\int_0^t F(t).v(t).dt$	Input energy; $\int_0^t u(t).i(t).dt$
Dissipated energy	$\int_0^t R.i^2(t).dt$, R = resistance
Accumulated energy	$\frac{1}{2} \times C \times u^2(t)$, C = capacity

Table 1 - Analogy between physical and electrical phenomena

The electrical circuit corresponding to these analogies is represented in Figure 1. The resistance, R1, corresponds to the plastic deformation, the capacity, C, corresponds to the elastic deformation and an additional resistance, R2, corresponds to the phenomenon of relaxation.

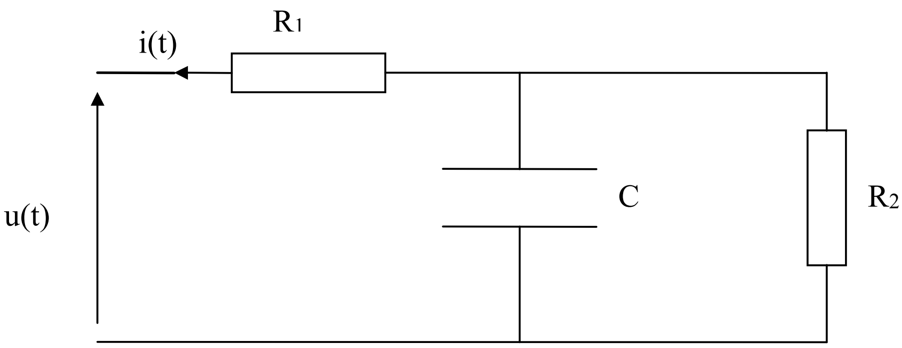

Figure 1 - Electrical model equivalent to a cigarette or tobacco rod submitted to a crushing force.

The response of a cigarette or tobacco to a force F(t) can be calculated, by measuring the response of the electrical circuit to a tension u(t). In general, it can be calculated using the Laplace transformation.

Assuming that the force is applied instantaneously i.e. the tension, u(t), is a voltage step of magnitude U, the following results are obtained;

$$i(t) = \frac{U}{R_1}\left[1 - \frac{R_2}{R_1 + R_2} \times \left(1 - e^{-\frac{R_1+R_2}{R_1 \times R_2 \times C} \times t}\right)\right]$$

which is, by analogy, for the speed of displacement;

$$v(t) = \frac{F}{p_1}\left[1 - \frac{p_2}{p_1 + p_2} \times \left(1 - e^{-\frac{p_1+p_2}{p_1 \times p_2 \times p_3} \times t}\right)\right]$$

F = crushing force applied
p_1 = parameter characteristic of energy dissipation at the time of deformation
p_2 = parameter characteristic of relaxation of the force at the time of crushing
p_3 = parameter characteristic of the energy accumulation at the time of deformation

and for displacement;

$$d(t) = \int_0^t v(t).\,dt \equiv \int_0^t i(t).\,dt$$

$$d(t) = \frac{F.p_2^2.p_3}{(p_1 + p_2)^2} \times \left(1 - e^{-\frac{p_1+p_2}{p_1.p_2.p_3} \times t}\right) + \frac{F}{p_1 + p_2} \times t \qquad (1)$$

The response can be calculated, irrespective of the tension applied, using the electrical circuit and the Laplace transformation. We have reported, in the annex, the displacement obtained when the force increases linearly up to $t = t_0$ and then reaches a constant level.

The modeling of the displacement is drawn in Figure 2, for the two previous cases (instantaneous or linear application of force), for F=355 N, $p_1 = 4$ N.s.mm^{-1}, $p_2 = 400$ N.s.mm^{-1}, $p_3 = 0.4$ mm. N^{-1} and $t_0 = 3$s.

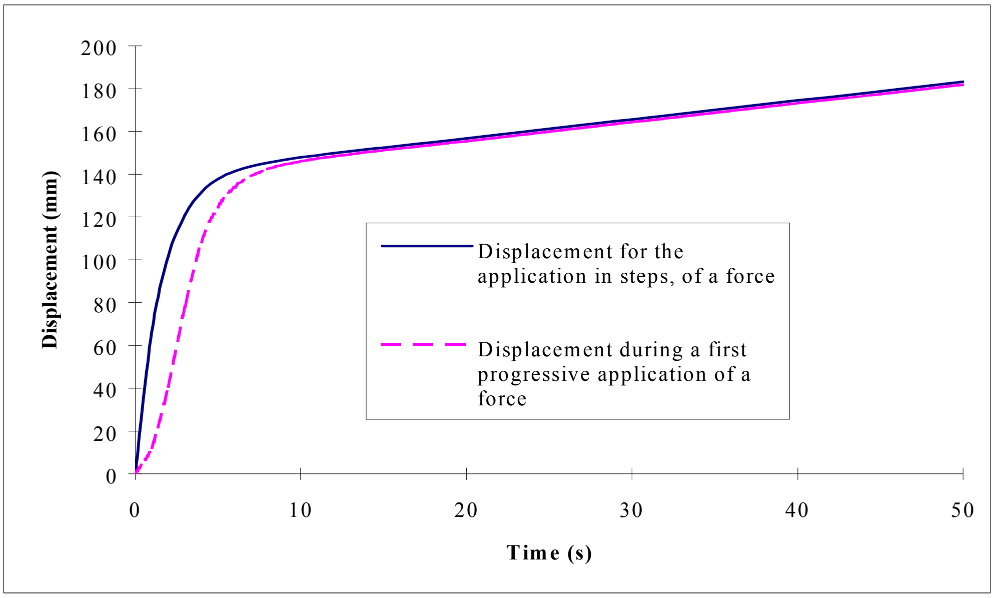

Figure 2 - Modeling of the displacement during crushing

Figure 2 shows that relaxation induces a linear displacement, after a major deformation. Our findings are in agreement with those of B. Kluss *et al.*[6] concerning filling power. The model for deformation proposed by Buisson [3], equivalent to a circuit composed of only one resistance and capacity, does not take relaxation into account. To improve the adjustment of this model to the measurements, Buisson *et al.* were compelled to propose an empiric logarithmic model which could not be applied at time t = 0. The model that we propose gives a better representation of the physical reality since it is based on an enumeration of phenomena and then, more representative of firmness rather than hardness.

New methods for the characterization of firmness and of filling power, permitting the determination of three parameters directly linked to the physical properties of cigarettes or tobacco could be based on this model. Nevertheless, the model needs to be validated experimentally.

3. Experiments

The experimental equipment utilized remains the same as that already used in currently employed methods for measurement of firmness or of filling power. However, with the method proposed in this study, both the applied force and the displacement must be known or recorded during the period of crushing. The theoretical displacement, which is adjusted to the measured displacement, can be simulated using the model, since the force applied over time is known. It should be noted, however, that a law for the application of a simple force *e.g.* a force in steps, considerably simplifies the modelling of displacement and therefore the adjustment step. Exploitation of the data is carried out by adjusting the theoretical model to the experimental results. Adjustment is achieved with the help of a non-linear multi-regression software program which can be based on various minimization algorithms such as that of Newton Raphson, of the maximum slope or that of Levenberg-Marquardt. In the latter case, uncertainty can be expressed for the three parameters p_1, p_2 and p_3 of the model.

In order to set up experiments that allow the validation of the proposed theoretical model, the following elements are required:

→ A method for applying a known force on the object to be characterized *e.g.* weight, force sensor etc.

→ A method for recording the crushing *e.g.* a digital oscilloscope, a recorder connected to a displacement sensor etc.

→ A non linear multi-regression application program *e.g.* statistics software etc.

The practical application of the method was carried out for measuring firmness using a Sodim compacimeter installed on a SODIMAT measuring unit, a digital oscilloscope and a software program for statistical analysis of the data. Likewise, the method was applied for measuring filling power using a Borgwaldt D51 densimeter, a digital recorder and a software program for statistical analysis of the data. 3.1.

3.1. Characterization of cigarette firmness

In order to validate the proposed method, it was applied to a real case of crushing of a cigarette, using a Sodim automatic compacimeter. We recorded crushing over time, (contrary to the standard procedure) of a cigarette submitted to a level of force equivalent to 300g (2.943N). In order to perform this, a digital oscilloscope was connected to the displacement sensor of the compacimeter. The following results were obtained for the first 2.5 seconds of crushing:

Time (s)	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.50	0.60	0.80
Crushing (mm)	0	0.20	0.32	0.44	0.56	0.65	0.72	0.79	0.83	0.90	0.93	1.00

Table 2 - Measurement of crushing of a cigarette over time

Adjustment of the model to these data with the help of a standard multi-regression tool, allowed the characterization of the crushed cigarette and determination of the value of the three parameters:

$p_1 = 0.72 \pm 0.01$ N.s.mm^{-1} to 95%

$p_2 = 37 \pm 4$ N.s.mm^{-1}

$p_3 = 0.348 \pm 0.004$ mm.N^{-1}

The precision of the parameters can be improved by increasing the number of sampling points.

Adjustment of the model is shown in Figure 3 where the model and the experimental data are represented by a continuous line and dots, respectively. The adjustment is good (correlation coefficient of $R^2 = 0.9991$) and validates the physical model (Eq. 1) for characterization of the firmness of cigarettes.

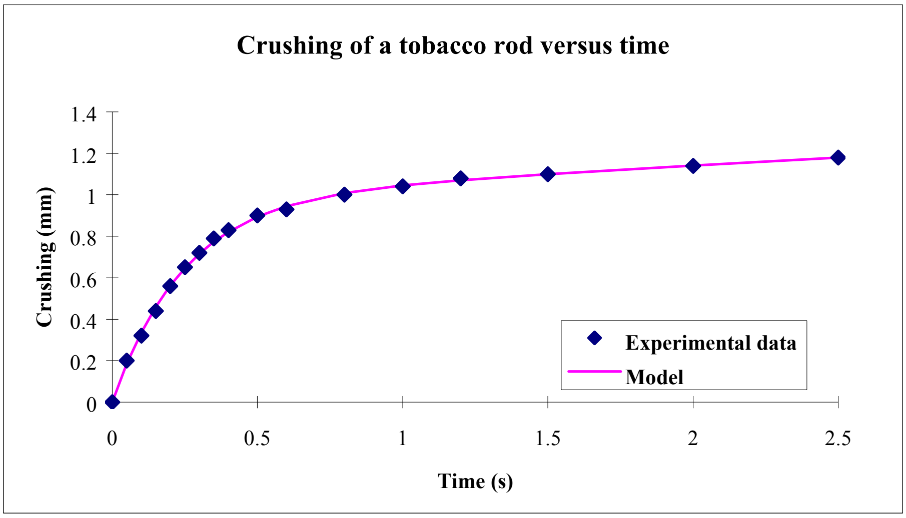

Figure 3 - Adjustment of the model (Eq. 1) to the measurement of displacement during the crushing of a cigarette

3.2. Characterization of the filling power of tobacco

The second validation experiment of the model concerns the measurement of the filling power. We connected a digital recorder to the displacement sensor of a Borgwaldt D51 densimeter in order to determine the crushing of a quantity of tobacco under a load of 11.4kg (111.8N) over the initial 10 seconds. The following results were obtained:

Time (s)	0	1	2	3	4	5	6	7	8
Crushing (mm)	0	55.00	82.20	98.70	113.90	125.70	131.60	139.80	145.7

Table 3 - Measurement of crushing of a quantity of tobacco over time

Adjustment of the model to these data with the help of a standard multi-regression tool, allowed the characterization of the crushed tobacco and determination of the value of the three parameters:

$p_1 = 1.63 \pm 0.07$ N.s.mm^{-1} to 95%

$p_2 = 18 \pm 2$ N.s.mm^{-1}

$p_3 = 1.06 \pm 0.04$ mm.N^{-1}

The precision of the parameters can be improved by increasing the number of sampling points.

Adjustment of the model is shown in Figure 4, where the model and the experimental data are represented by a continuous line and dots, respectively. The adjustment is good (correlation coefficient of $R^2 = 0.9986$) and validates the physical model of deformation (Eq. 1) for the characterization of the deformation of a tobacco sample.

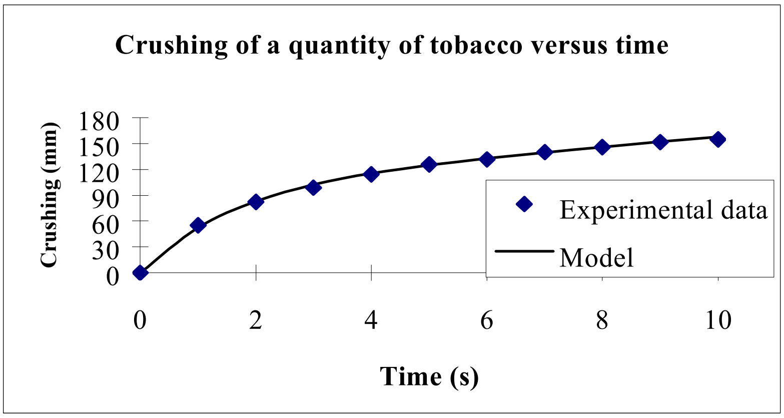

Figure 4 - Adjustment of the model (equation 1) to the displacement during the crushing of a quantity of tobacco.

4. Conclusion

The methods currently practiced for the characterization of the hardness of cigarettes, of filters and of filling power are based on the same physical principle *i.e.* the product to be characterized is placed between two jaws and is submitted to a force capable of provoking crushing. Consequently, the amplitude of the resulting deformation is measured after a given time and is directly correlated to the characteristic properties commonly called hardness and filling power. Therefore, the currently practiced methods compare these characteristic properties to a magnitude of crushing. Characterization of hardness or of filling power by a magnitude of crushing is a simple means but is far from providing a detailed description of the behavior of the product when it is subjected to a force. In fact, crushing is the result of plastic and elastic deformation, and relaxation of the internal forces of the product. However, the magnitude of crushing after a given time provides no information on these three physical phenomna. The methods currently employed are not discriminative enough as they lack a detailed characterization of the mechanical properties of the product. The method we propose in this study, is based on a physical model and provides information on the three phenomena; elastic deformation, plastic deformation and relaxation during the process of crushing. This method is thus much more discriminative than currently practiced methods and more representative of firmness rather than hardness. Besides, with the new procedure, results are collected from the initial seconds of crushing. Therefore, they are obtained more quickly than in the currently practiced methods based on measurement of the magnitude of crushing. Finally, the measurement method proposed in this study is presented for the characterization of tobacco but can also be applied to various other products such as the mousses, bread, fruit and vegetables and all other products that can undergo a similar process of deformation.

Annex

If the force F(t) is not applied instantaneously, but increases linearly before reaching a maximum value "a" at the end of time t_0, a more complex relationship is obtained:

$$d(t)=\frac{a\times p_1\times p_2^3\times p_3^2}{(p_1+p_2)^3}\times\left(e^{-\frac{p_1+p_2}{p_1\cdot p_2\cdot p_3}\times t}-1\right)+\frac{a}{2.(p_1+p_2)}\times t^2+\frac{a\times p_2^2\times p_3}{(p_1+p_2)^2}\times t-$$
$$\left[\frac{a\times p_1\times p_2^3\times p_3^2}{(p_1+p_2)^3}\times\left(e^{-\frac{p_1+p_2}{p_1\cdot p_2\cdot p_3}\times(t-t_0)}-1\right)+\frac{a}{2.(p_1+p_2)}\times(t-t_0)^2+\frac{a\times p_2^2\times p_3}{(p_1+p_2)^2}\times(t-t_0)\right]\times H$$

a = speed of increase of tension between $t = 0$ and $t = t_0$ ($a = F/t_0$)
H(t) = step function

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