Beiträge zur Tabakforschung · Band 8 · Heft 5 · März 1976

DOI: 10.2478/cttr-2013-0392

A Structural Model of Reconstituted Tobacco Substantiated by Ultrasonic Interrogation*

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INTRODUCTION

In recent years theoretical model building has become a respectable and profitable approach in many industries. No technical problem is ever solved without some type of model. In many cases, when the variables significant to the mission are few in number, the appropriate model describing the system will simply exist in the mind of the problem solver. Situations of this type do exist in the tobacco industry, however, they are rare. When dealing with the physical aspects of tobacco materials in connection with "events" occurring in processing one must resort to some degree of abstraction.

Generally speaking, analysis of tobacco material (as reflected by the literature) has been restricted to quasi-static testing procedures (1). This may be due to the complex structure of the material and/or the lack of suitable methods and technologies. Typically, the approaches (2) have involved inducing deformations which, in most instances, are assumed to have achieved their equilibrium values. Approximations of this type are valid only when the time required to establish equilibrium is short in comparison to the observation time. Nonetheless, it is often tempting to use results from measurements of this type to infer or predict dynamical behavior.

It certainly is not the authors' intent to imply that quasi-static measurement methodologies are useless. When the conditions for which these techniques were originally devised are rigorously adhered to, they provide a powerful means of analysis. The authors also recognize that because we must deal with "real life" problems, certain extrapolations and gross inferences are a practical necessity.

The processing of tobacco materials involves a variety of forces. Common to *any installation* are forces which arise from operations such as cutting, conveying, etc. In addition, the materials are subjected to processing steps which involve the addition of water, additives and various drying procedures. These combinations lead to changes in the physical state of the tobacco materials. Thus, information concerning the state of the material, the nature of the forces exerted on the material, and the type of material are necessary in order to develop a reasonable processing model.

The above statements underscore the complexities facing the model builder. However, starting from fundamentals, certain communalities may be identified. First, to a large extent the structural properties of the material are an important factor to consider when dealing with any of the above-mentioned processing "events". Second, the forces predominantly encountered will vary both in time and magnitude. These observations imply that physically the effects must be considered in terms of stress wave propagation within the material.

This first paper will deal with one particular phase of the overall problem of process modelling. In the ensuing, we will confine our attention to the structural aspects of reconstituted tobacco sheets. This restriction is predicated primarily on the fact that in comparison to lamina, reconstituted tobacco materials are relatively simple. Equally important, in simplifying our mission is that a wealth of information can be drawn upon from the published work of several accomplished researchers (3).

The first section will deal with the basic concepts of elasticity theory. Knowledge of the elastic properties of tobacco materials (in general) provide insight into cigarette firmness, tobacco smoking quality, and tobacco expansion (4—6). The argument should serve as an overview for many researchers or, alternatively, as a primer for those working in the tobacco industry who are not familiar with these specific concepts. The fundamentals of wave propagation will be introduced and coupled with the concepts of elastic theory (7). A one-dimensional model will be assumed so that the type of waves which arise experimentally can be most easily understood (8).

Production of stress waves, for material testing purposes, may be systematically accomplished by employing ultrasonic techniques. In using ultrasonic wave propagation methodologies, phase relations must be kept in mind. Because the test material is finite in length, boundary conditions (just as in the optical analogue) give rise to phase reversals. The phase conditions involved in dealing with reflected and transmitted waves are illustrated in terms of the material's parameters (9). These arguments are simple but will aid the researcher in interpreting the signals arising

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* Presented, in part, at the CORESTA/26th TCRC Joint Conference, Williamsburg, Virginia, 1972, and the 28th TCRC Conference, Raleigh, North Carolina, 1974.

from the stress waves as they are propagated through reconstituted tobacco.

The structural model which has been tested experimentally will be discussed in context of the previously introduced concepts. Fundamentally, the model assumes that reconstituted tobaccos fall into one of two general classes ... that is, either isotropic or orthotropic materials.

The second section will deal with the experimental approach. Ultrasonic techniques and "how to use them in testing reconstituted tobacco materials" is the central theme. "Tricks of the trade" are discussed. Although one may regard the principles as somewhat trivial, nonetheless the pragmatics of dealing with bonding, mode selection, etc. are not.

The final section will deal with the results of ultrasonically interrogating several reconstituted tobaccos. These results will be examined in terms of the theoretical framework presented. In addition, the implications of structure, and the formation of that structure from a fabrication viewpoint will be discussed. Experimental data will be presented only for a specific set of environmental test conditions. In a later paper we will present the results of changing variables such as temperature and relative humidity.

THEORETICAL CONSIDERATIONS

Elasticity — Elastic Limit

When forces are applied to solid bodies, deformations are observed. Depending on the magnitude of the force, the body may or may not return to its original configuration upon removal of the force.

In Figure 1, the region OA illustrates the case where the relation between stress and strain is linear. The stress and strain relations are governed by *Hooke's* law. Point A is called the elastic limit of the body. Consequently, if the magnitude of the stress does not exceed that value corresponding to A, the body will always return to its original dimensions. On the other hand, if the stress is increased to the corresponding region B and then "turned off", the body retains, to a degree, the associated strain. This region is sometimes termed the region of "plasticity" (10). If the stress is increased beyond that value at region B, to point C, the body would finally break.

Figure 1. Stress-strain relation for typical solids.

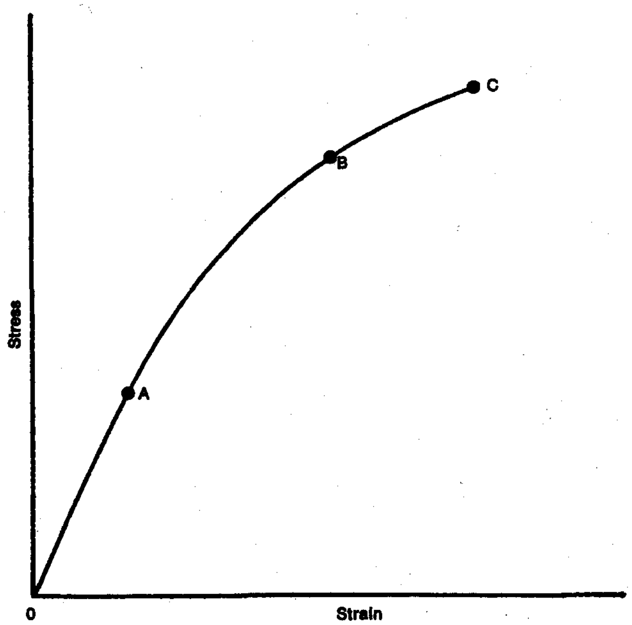


Figure 2 illustrates the stresses which are involved in the x_1 direction for a material in the form of a cube. There are three sets of couples (i. e. two forces of equal magnitude and opposite direction whose lines of action are parallel but non-coincident) which act on the six faces of the body. The generalization of *Hooke's* law is most simply displayed by employing tensor notation (11),

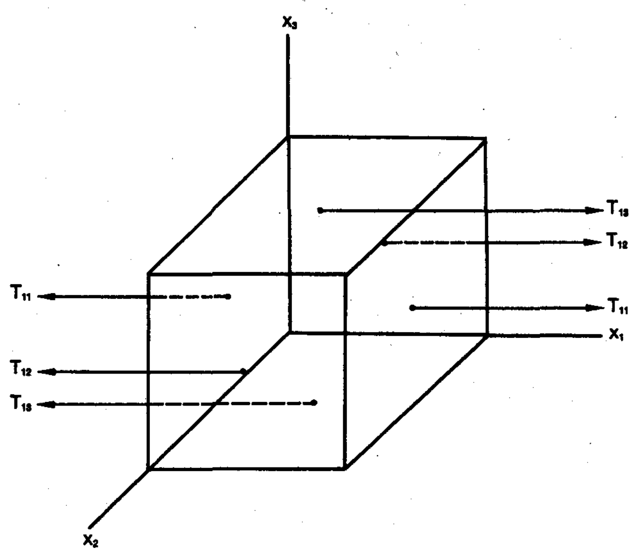
$$T_{ij} = \varepsilon_{ijkl} S_{kl} \quad , \qquad [1]$$

where i, j, k, l = 1, 2, 3. In equation 1, T_{ij} is called the stress tensor, S_{kl} the strain tensor, and ε_{ijkl} the elasticity tensor. The elements T_{ii} are the normal stresses while the elements T_{ij}, $i \neq j$, are the shear stresses. Symmetry and energy constraints on T_{ij} and S_{kl} allow a reduction of the number of independent elements of ε_{ijkl} from 81 to 21. The number of independent elements may be reduced further by spacial symmetry conditions exhibited by the material. For example, a body possessing orthorhombic symmetry has 9 independent elements while materials with cubic or isotropic symmetries have 3 and 2 elements respectively.

The classical theory of elasticity leads to a description of *Young's* moduli, E and G, in terms of the *Lamé* constants, λ and μ (12). For example, consider an isotropic body with one force acting in the x_1 direction. The stress tensor reduces to only one term,

$$T_{11} = E\, S_{11} \, , \qquad [2]$$

Figure 2. Three elements of the stress tensor associated with the x_1 direction.



where E is defined by

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} . \quad [3]$$

In addition we have that

$$S_{22} = S_{33} = -\nu S_{11} , \quad [4]$$

$$\nu = \frac{\lambda}{2(\lambda + \mu)} , \quad [5]$$

ν being the *Poisson's* ratio. Equation 3 indicates that a body under stress in the x_1 direction undergoes a contraction in the transverse direction. The ratio of the two associated strains is simply *Poisson's* ratio. In the case of an isotropic body, a simple relation exists between G and E, namely,

$$E = 2G(1 + \nu) . \quad [6]$$

Wave Equation

The quantities λ and μ arising in the classical theory of elasticity may be related to the velocity of mechanical waves propagated through a solid material. In general, all materials exhibit some degree of inhomogeneity. Typical of reconstituted tobacco are the various pores and random defects in the structure arising from fabrication methods. At ultrasonic frequencies, the presence of these inhomogeneities tend to act as scattering centers and/or absorbers of mechanical waves. Thus, experimentally, one observes a distorted or attenuated sound pulse emerging from the material. As long as the attenuation is not too severe, one may describe the phenomena by the one-dimensonal wave equation:

$$\varrho \frac{\partial^2 u}{\partial t^2} = E \frac{\partial^2 u}{\partial x^2} + f(u, \dot{u}) . \quad [7]$$

In [7], ϱ is the *density* of the *material* through which *waves are propagated,* E is *Young's* modulus and u is the particle displacement. The term $f(u, \dot{u})$ is (the dot denotes differentiation with respect to time) a dispersive/dissipative term. The function encompasses the phenomena of scattering and attenuation of sound waves in solids (13). For the present we will assume that

$$f(u, \dot{u}) = 0 . \quad [8]$$

With condition 8, equation 7 reduces to the well-known homogeneous wave equation

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 u}{\partial t^2} , \quad [9]$$

where

$$v^2 = E/\varrho . \quad [10]$$

The above form of the wave equation describes one particular mode of wave propagation, that is the longitudinal mode. It can be shown, however, that other elastic modes exist (14). In general, the propagation of *elastic waves in solids* can be divided into two distinct categories, longitudinal and transverse waves. The former type describes extensional or compressional motion while the latter describes twisting or shearing motions of the material. In practice, when one deals with materials such as reconstituted tobacco, local disturbances (defects, etc.) generally tend to give rise to both longitudinal and transverse waves. Consequently, one may start with a pure longitudinal wave and observe mixed modes. The intensity of these modes are several orders of magnitude less than that of the initial wave and may be ignored. In this case (the isotropic limit), the sonic velocity is related to the elastic constants λ and μ via

$$v^2 = \frac{\lambda + 2\mu}{\varrho} . \quad [11]$$

In the strictest sense equation 11 is only an approximation. When the test material's width, d, bears the following relation to the wavelength, λ,

$$d \geqq 5\lambda , \quad [12]$$

equation 11 must be replaced by (15)

$$v^2 = \frac{E}{\varrho} \left\{ (1 - \nu) / (1 + \nu)(1 - 2\nu) \right\} . \quad [13]$$

The principal concern with longitudinal wave propagation in reconstituted tobacco is for samples in the shape of a strip or thin line. For such configurations, the *sonic modulus* as determined by equation 11 is found to be more than adequate. A similar situation exists for paper materials. Several acoustical measurements in paper have been reported. On the basis of work on cellulosic sheets by *Horio* and *Onogi* (16), *Craver* and *Taylor* (17) concluded that the correction term in equation 13 could be ignored.

Phase Relations

When testing material by ultrasonic methods, one must take into account the relative phases of the associated pressure waves to properly interpret the signal information. Consider two materials with a common boundary (say tobacco and nickel). The reflection coefficient, r, and transmission coefficient, t, are defined by

$$r = \frac{\varrho_2 v_2 - \varrho_1 v_1}{\varrho_1 v_1 + \varrho_2 v_2} , \quad [14]$$

and

$$t = \frac{2\varrho_2 v_2}{\varrho_1 v_1 + \varrho_2 v_2} . \quad [15]$$

In the above relations, v_i is the longitudinal sonic velocity in the material of density ϱ_i. Three conditions may exist at the boundary, that is

$$\varrho_1 v_1 > \varrho_2 v_2 ,$$

$$\varrho_1 v_1 < \varrho_2 v_2 ,$$

$$\varrho_1 v_1 = \varrho_2 v_2 .$$

If the first condition is satisfied, the reflected wave is said to be 180° out of phase with respect to the incident wave. If, on the other hand, the second condition is true, the reflected and transmitted waves are in phase. The last relation depicts the ideal case of perfect transmission across the boundary. The last condition, although not as important as the first two for signal identification purposes, has important practical implications. Experimentally, one does not connect the exciting media (magnetostrictive rod) directly to the material under investigation (reconstituted tobacco). In practice, one must find a suitable bonding material so that waves may be coupled into the tobacco material with minimum reflection. The above arguments are oversimplifications of reality. However, they, as do their optical analogues, serve to illustrate the physics of the experiment.

Anisotropy of Tobacco Sheet

In the measurement of any mechanical parameter of a material, symmetry considerations must not be ignored. In general, materials such as crystals, reflect their fundamental lattice parameters via symmetry. These parameters provide insight into the very nature of formation or structure of the solid. Similarly, the determination of reconstituted tobacco symmetry provides valuable information concerning the fabrication and processability of these materials.
The property of anisotropy has received a great deal of attention in the paper making industry (18). The variation of elastic moduli as a function of "making direction", to a large degree, influences many of the important material processing characteristics. The authors, upon a review of the pertinent literature, found that a similar directional model is applicable to reconstituted tobacco.
The model is based on the assumption that reconstituted tobacco can be described by orthotropic symmetry. When a material exhibits such symmetry, two principal directions situated at right angles to one another exist. In general the elastic moduli as a function of angle are related by (19):

$$\frac{1}{E(\Theta)} = \frac{\cos^4\Theta}{E_\perp} + \left\{\frac{1}{G_{\parallel,\perp}} - \frac{\nu_{\perp,\parallel}}{E_\perp} - \frac{\nu_{\parallel,\perp}}{E_\parallel}\right\}\sin^2\Theta\cos^2\Theta + \frac{\sin^4\Theta}{E_\parallel}\ . \quad [16]$$

In [16] the symbol $\parallel$ denotes "machine direction" and $\perp$ the perpendicular direction. $G_{\parallel,\perp}$ is the in-plane shear modulus, and ν the corresponding *Poisson's* ratio. If

$$\frac{1}{G_{\parallel,\perp}} = \frac{1+\nu_{\perp,\parallel}}{E_\perp} + \frac{1+\nu_{\parallel,\perp}}{E_\parallel}\ , \quad [17]$$

it then follows that

$$E(\Theta) = \frac{E_\parallel \cdot E_\perp}{E_\perp \sin^2\Theta + E_\parallel \cos^2\Theta}\ . \quad [18]$$

The validity of equation 18 has been investigated for a large variety of reconstituted tobacco materials. In the context of the present work on reconstituted tobacco, equation 18 has been tested in the following way:

1. The sonic modulus of elasticity was measured in the $\parallel$ and $\perp$ directions.
2. Using [18] the angular dependence at $\Theta = 45°$ was calculated.
3. The value calculated via [18] was compared to the experimental value.

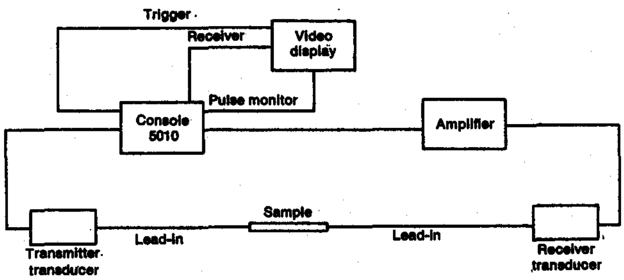
The above approach does not lead to a complete test of the orthotropicity of reconstituted tobacco. Nonetheless, an agreement with the general form of equation 18 implies that relation 17 holds true as well.

EXPERIMENTAL APPROACH

Apparatus and Methods

The heart of any ultrasonic experiment is the transmitter-receiver transducer system. For the measurements described herein a Panametrics 5010 console with magnetostrictive transducers (20) provided the required capabilities. Auxiliary equipment consisted of a Tektronix 1121 Broadband Amplifier and a Tektronix 7504 Oscilloscope. Figure 3 is a block diagram of a typical arrangement incorporating the above-mentioned modules. The 5010 is capable of providing an ultrasonic pulse of (3 to 30 µs wide) at a pulse repetition frequency (PRF) of 60 or 120 pulses per second. All measurements were performed at a PRF of 60. The transducers used can produce two modes, that is either pure extensional or combinational (extensional — torsional).

Figure 3. System block diagram.



Echo Mode

The echo mode is the most basic ultrasonic method (21) in use. In this mode only one transducer is required since the transmitter output point is switched to a combination transmitter output-receiver input junction. Operation is as follows: the transmitter provides an electronic pulse, at a selected amplitude and pulse

Figure 4. Echo mode without sample.

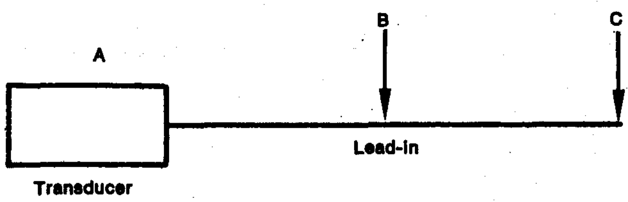
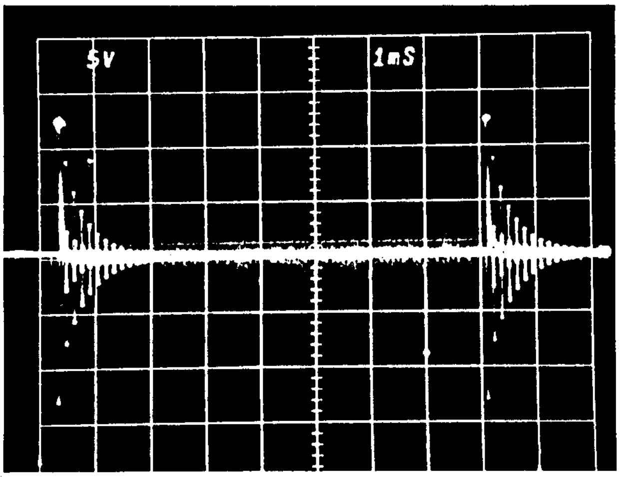


Figure 5. Decaying reverberation pattern in magnetostrictive lead-in.



width, to transducer A (see Figure 4). The transducer converts this pulse to an ultrasonic pulse which travels along the axis of the lead-in (B) toward its end (C). Assume a pure extensional mode for clarity. Transverse waves will be discussed later. When the pulse reaches the end of the lead-in (C) (assume no sample is attached), nearly total reflection occurs. At the transducer, the pulse is partially converted back to an electrical signal which is then fed to the receiver.

A portion of the ultrasonic pulse is not converted but is reflected and again travels toward the end of the lead-in. It should be noted that the ultrasonic pulse travels through the lead-in at the velocity of sound in the medium (nickel). The pulse continues reverberating in the lead-in, decaying in time (Figure 5). The portion of the echo signal which is sent to the receiver is amplified to permit proper operation of the gating circuit and to provide a usable signal for viewing on the oscilloscope. The gating circuits provide pulses which can be varied to correspond to two echo peaks and in turn provide a visual readout of *the time between the two peaks.* This visual readout is dis-

Figure 6. Typical ultrasonic spectrum. Upper trace corresponds to signal information; lower trace is associated with internal timing gates.

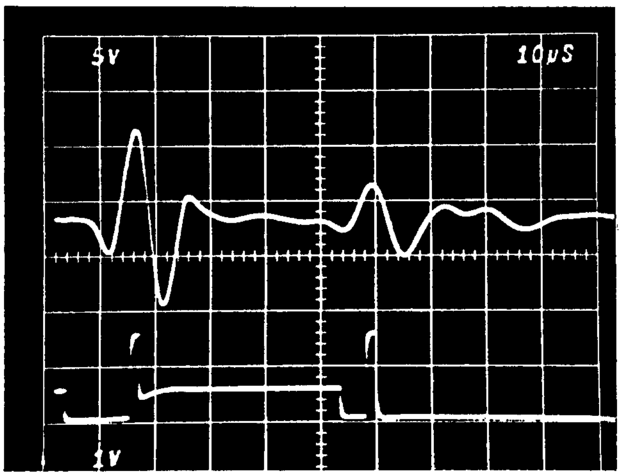
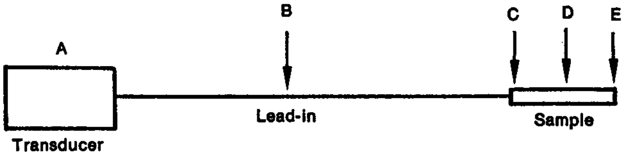


Figure 7. Echo mode with sample.



played by Nixie tubes located on the front of the console. By measuring the time between the initial drive pulse (main bang) and the first echo, and measuring the length of the lead-in, one can calculate the velocity of sound in the lead-in material (see Figure 6). Extremely accurate time measurements are thus available (± .1 µs).

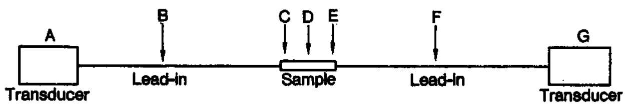
Now assume a sample (D) is attached to the end of the lead-in (Figure 7). As the pulse reaches the boundary (C), part of the signal is coupled into the sample (D) and part of it is reflected. The amount of coupling is a function of the material bonded to the lead-in and the means used for bonding (boundary impedance). The transmitted signal propagates through the sample, is reflected at its end (E) and returns toward the lead-in. At that point it is again partially reflected and transmitted. Note the transmitted signal lags the initial reflection from the lead-in junction by an amount equal to the travel time back and forth in the sample. By measuring the time between these pulses along with the length of the sample, and by accounting for the two-way trip, one can determine the speed of sound in the sample material. This cycle is repeated 60 times each second with the ensuing reverberations damped well before a succeeding pulse is generated.

Transmission Mode

In the transmission mode, the initiation and detection is accomplished by utilizing a symmetric transducer configuration (22) (see Figure 8). The transmitter output is isolated from the receiver which now obtains its input from the receiving transducer (G). Only signals which are transmitted through the sample are amplified, therefore, the signal reflected back toward the transmitter transducer (A) from the first junction point (C) is disregarded.

Following one ultrasonic pulse through the system will provide a good understanding of this mode. As in the echo mode, the signal travels through the transmitter transducer lead-in (B) and is partially transmitted and reflected at the lead-in sample boundary (C). The transmitted signal continues through the sample (D) and is partially reflected and transmitted at the sample receiver transducer lead-in boundary (E). The pulse propagates through the lead-in (F) and is converted by the receiving transducer (G), providing the first

Figure 8. Configuration for transmission or combination mode.



reference pulse. The reflected signal from this second junction point (E) travels back through the sample (D) and is reflected and transmitted again at the first junction (C). This reflected portion returns toward the second junction (E) where it is reflected and transmitted as before. The transmitted pulse is converted by the transducer (G) and used as the second reference point. Note that the difference between the two pulses represents the travel time back and forth in the sample only, and thus can be used to calculate the speed of sound in the media.

Echo-Transmission Mode

This particular mixed mode of operation was conceived by the authors during the course of this work. Subsequent utilization of this approach has generated much interest in testing material of similar acoustical properties.

The echo-transmission mode (E–T Mode) is, as the name implies, a combination of the echo mode and the transmission mode. In this mode, both the echo pulse and the transmitted pulse are received and utilized. As in the echo mode, the transmitter output is also the receiver input. In addition, the receiver obtains a signal from the receiving transducer (G); therefore, two signals are introduced into the receiver.

Again, for the sake of clarity, a pulse will be traced through the measuring system (Figure 8). The initial echo from (C) is amplified and used as reference. The portion of the pulse which is transmitted through the sample (D) and the lead-in (F) is amplified and used as the second reference pulse. Note that in this instance the difference between the first and second pulse represents the difference in travel time from point (C) to point (A) and point (C) to point (G) which primarily occurs because of the difference in the velocity of sound in the sample (D). The lead-in wire (F) is purposely made longer to provide a difference in the time even when the two lead-ins are directly coupled together. This time increment is, of course, still included in the time difference between the two pulses and must be taken into consideration when calculating the velocity in the test material.

Bonding Considerations

The method and material used in bonding the sample to the lead-in are of extreme importance in performing the measurements. The ratio of reflection to transmission at each boundary is a function of the bonding material as well as the sample. Factors which must be considered are: strength, thickness, attenuation, configuration of the lead-in, sample junction and ease of bonding.

If the thickness of the bond becomes too great, then time of travel in the bond itself becomes critical. In the E–T Mode, the thickness of the bond and hence the time of travel is accounted for somewhat in the determination of the travel time differences in the lead-ins . . . the configuration of the lead-in end and the

Figure 9. Bonding configuration.

sample affects the percent of transmission at the boundaries. Experimentation determined that the best junction to use in these measurements was the overlapping joint (see Figure 9). This arrangement was selected because of the geometry of the material. To achieve optimal transmission, the condition $\varrho_1 v_1 \approx \varrho_2 v_2$ must be satisfied. In practice, one need not worry about obtaining echos since these occur readily, but obtaining good transmission is sometimes difficult. Various materials were tried as bonding agents. Since information is lacking on many materials with respect to attenuation coefficients and acoustical impedances, trial and error emerge as the only solution. Apiezon W provided a practical bond which satisfied the necessary acoustical properties for tobacco substances.

Display and Phase Effects

During a measurement, the oscilloscope provides a visual display of the acoustical patterns occurring in the lead-in sample system. The usefulness and accuracy of the whole experiment depends on the ability to correctly read this display. The slightest bend in the lead-in, a kink in the sample, poor lead-in sample junctions, all provide unnecessary pulses and reverberations. Sometimes these spurious signals can be eliminated, at other times, they are unavoidable. The pulses which are of interest are those occurring because of the sample boundaries. It is essential to not only distinguish which peaks are the primary peaks but also to recognize their relative phases. To obtain accurate time measurements, the differences between corresponding points on two signals must be measured. This is complicated by phase changes and differentiation effects (23).

The pulse induced in the lead-in by the transducer and, likewise, the signal induced in the transducer by the lead-in are results of a changing current and a changing magnetic field respectively. These induction effects convert the square drive pulse from the transmitter to a negative peak and a positive peak. The negative peak corresponds to the leading edge of the square wave while the positive peak corresponds to the lagging edge. Therefore, since differentiation occurs twice, the video display consists of four peaks, two positive and two negative. In general, it should be remembered that a phase change accompanies the reflected pulse at the boundary of a material possessing a larger acoustic impedance.

EXPERIMENTAL PROCEDURE

Six different types of reconstituted tobacco were selected. Over three hundred individual measurements were made on these samples. These reconstituted

Table 1. Summary of results.

Sheet	I	II	III	IV	V	VI
Average extensional elastic modulus*	4.1	3.7	4.4	3.0	2.6	1.8
Transverse shear modulus*	1.6	1.4	1.7	1.0	.95	.6
Elastic constant A direction*	3.9	3.7	3.8	3.1	2.9	1.6
Elastic constant B direction*	4.2	3.8	4.8	3.0	2.4	1.8
Elastic constant C direction*	4.1	3.6	4.5	2.7	2.6	1.8
Calculated elastic constant C direction*	4.0	3.7	4.3	3.1	2.6	1.7
Density g/cm³	1.48	1.48	1.66	1.39	1.46	1.32

* The relative values of E are within 5 %. Additional stages of amplification obtained subsequent to the experiment reported above will reduce this error to approximately 2 %. The elastic moduli in Table 1 are in units of 10^{10} dynes/cm².

materials were selected on the basis of their varied composition and processing. The different reconstituted tobaccos will be referred to as I, II, III, IV, V, and VI (see Table 1). All samples were conditioned to ambient laboratory temperature and humidity. The temperature was approximately 75° F and the relative humidity was approximately 54 %.

Extensional Measurements

The *Young's Modulus* of a material may be multi-valued if the material is anisotropic or single valued if isotropic. It follows that a material's directional properties must be considered if a thorough understanding of its elastic behavior is to be ascertained. The ultrasonic method described provides a simple, accurate and non-destructive method of determining a material's directional properties.

In consideration of the possible anisotropic behavior of reconstituted tobacco, it was necessary to establish a directional convention, such that a measurement in the A direction for one sample was the same A direction of another sample. It is not assumed on an a-priori basis that direction A, B, or C of Sheet III is in the casting direction. In sheets I, II, IV, V, and VI, A was in the casting direction, B was perpendicular to A. C is associated with $\Theta = 45°$ (see equation 18).

The E-T Mode was chosen for both the longitudinal wave and the transverse wave experiments. This mode was used because of the relatively high attenuation of the acoustical pulses by the material. Before a measurement could be made, the time difference between the two lead-ins was established. This was accomplished by joining the two lead-ins with a bond similar to that used to hold the sample sheet during measurements. Care was taken to obtain a representative bond. By using the oscilloscope, the time between the echo from the junction and the transmitted pulse through the junction was measured. Various measurements showed this time to be 14.5 µs.

To make a measurement, a piece of reconstituted tobacco, approximately 3.0×0.3 cm, was bonded to each end of the lead-ins so that it bridged the gap between them. The visual display on the oscilloscope along with the Panatherm 5010 was adjusted so that a time interval between pulses could be measured. The sample was then removed and retained for surrogate measures.

Transverse Shear Measurement

The shear wave measurements were performed in a different fashion from the extensional measurements. Instead of using two extensional transducers, two combinational units (24) were employed. Whereas the extensional transducer produced only an extensional mode pulse, the combinational produced both longitudinal and shear waves. In order to properly view both pulses and provide for viewing their echos so that time intervals could be measured, longer lead-ins were used. This increased the reverberation time and prevented confusing the reverberation echo with the shear wave which propagates at a lower velocity than the longitudinal wave.

Bonding and sample size were similar to those used in the extensional measurements; however, for these tests the density of each particle was not measured. Instead, the velocities of both the longitudinal waves and the shear waves were measured and their ratios calculated.

SUMMARY

The theoretical model and experimental results, as tabulated in Table 1, lead to the following conclusions concerning the elastic and structural properties of the examined reconstituted tobaccos:

a. The magnitudes of the moduli for the materials interrogated were different (statistically significant).

b. Type I material, although in principle the same as Type II material, displays orthotropic symmetry. This structural difference was induced by slightly changing process operating parameters.

c. Type II materials can be classified as belonging to the isotropic group.

d. Type III material is orthotropic. This particular material was developed using a higher degree of fiber content, consequently fiber orientation was manifest in the mechanical structure.

e. Type VI material has the lowest modulus. This property is derived from the various input/binder materials.

f. Type V material is orthotropic. In this material a relatively high fiber content was used, coupled with a variation in processing.

g. Type III material possesses the largest moduli for the entire collection of reconstituted tobaccos tested.

The higher elasticity as well as its anisotropy can be linked with the input material and method of fabrication.

The vehicle of ultrasonic interrogation of reconstituted materials proved to be efficacious. In total, the authors observed the advantages of this mode of experimentation to be:

1. Inherent accuracy in the measurement of the ultrasonic pulses.
2. The method is non-destructive; consequently, allowing the actual test sample to be used in other analyses.
3. Direct measurement of material properties with the option of observing contributions arising from "mechanical defects".
4. The ability to make real time observations. This degree of freedom is particularly useful when the test specimen is deliberately perturbed.

ZUSAMMENFASSUNG

Das theoretische Modell und die experimentellen Ergebnisse, wie sie in Tabelle 1 dargelegt sind, führen zu den im folgenden aufgeführten Schlußfolgerungen hinsichtlich der elastischen und strukturellen Eigenschaften der untersuchten Tabakfolien:

a. Die Größen der Moduln der untersuchten Materialien waren statistisch signifikant verschieden.

b. Das Material vom Typ I zeigt orthotrope Symmetrie, obwohl es im Prinzip dem Material des Typs II gleicht. Dieser strukturelle Unterschied beruht auf einer leichten Veränderung der Herstellungsparameter.

c. Die Materialien des Typs II können der isotropen Gruppe zugeordnet werden.

d. Typ III ist orthotrop. Dieses Material insbesondere wurde unter Verwendung eines höheren Fasergehaltes entwickelt, wodurch die Ausrichtung der Faser in der mechanischen Struktur sichtbar war.

e. Typ VI hat den niedrigsten Modul. Diese Eigenschaft wird durch die verschiedenen Zusatz/Bindemittel-Stoffe herbeigeführt.

f. Typ V ist orthotrop. Bei diesem Material wurde ein relativ hoher Faseranteil verwendet in Verbindung mit einer Modifikation bei der Verarbeitung.

g. Typ III verfügt von allen untersuchten Tabakfolien über die größten Moduln. Sowohl die höhere Elastizität als auch seine Anisotropie können dem Zusatzstoff und dem Herstellungsverfahren zugeschrieben werden.

Die Methode der Ultraschalluntersuchung erwies sich bei Folientabaken als wirksam. Insgesamt beobachteten die Autoren bei diesem experimentellen Verfahren die folgenden Vorzüge:

1. Inhärente Genauigkeit bei der Messung der Ultraschallimpulse.
2. Die Methode arbeitet nicht destruktiv, wodurch das der Analyse unterworfene Probenmaterial auch für andere Untersuchungen benutzt werden kann.
3. Direkte Messung der Materialeigenschaften mit der Möglichkeit der Beobachtung von Beiträgen „mechanischer Fehler".
4. Die Fähigkeit des Verfahrens zu echter Zeitbeobachtung. Diese Möglichkeit ist besonders nützlich, wenn das Untersuchungsobjekt absichtlich gestört ist.

RESUME

Le modèle théorique et les résultats expérimentaux comme indiqués dans le tableau mènent aux conclusions suivantes, en ce qui concerne l'élasticité et les propriétés structurelles des tabacs reconstitués en feuille examinés:

a. Les magnitudes des modules des substances interrogées diffèrent d'une manière statistiquement significative.

b. La substance du type I démontre une symmétrie orthotropique, quoiqu'en principe la substance est la même que celle du type II. Cette différence structurelle a été provoquée par une légère modification des paramètres impliqués dans l'opération.

c. On peut classer les substances du type II comme faisant partie du groupe isotropique.

d. La substance du type III est orthotropique. On a mis cette substance spéciale au point en utilisant un pourcentage plus élevé de fibres, par conséquent l'orientation des fibres est apparente dans la structure mécanique.

e. La substance du type VI a le module le plus bas. Cette propriété découle de la variété de substances incorporées comme liant.

f. La substance du type V est orthotropique. Pour cette substance-ci on a utilisé un pourcentage relativement élevé de fibres, associé à une modification du traitement.

g. La substance du type III contient les plus grands modules sur l'ensemble des tabacs reconstitués en feuille testés. Sa plus grande élasticité ainsi que son anisotropie peuvent être associées aux substances incorporées ainsi qu'à la méthode de fabrication.

La méthode d'interrogation ultrasonique de matériaux reconstitués semble s'avérer efficace. Favorables à ce mode d'expérimentation, les auteurs concluent les avantages suivants:

1. Précision inhérente dans la mesure des pulsations ultrasoniques.
2. La méthode n'est pas destructive, par conséquent l'échantillon-test peut être réemployé pour d'autres analyses.

3. Mesure directe des propriétés des substances comprenant l'option d'observer les contributions provenant de «défauts mécaniques».

4. La possibilité de réaliser des observations de temps réel. Ce degré de liberté est particulièrement utile lorsque le spécimen-test est perturbé délibérément.

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Acknowledgments

The authors would like to thank Mr. Carl B. Jenkins and Dr. N. D. Heitkamp for devising the necessary hardware/techniques and measurements of the absolute densities of all the reconstituted tobaccos used in this study.

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