Engineering Techniques for Nondestructive Quality Evaluation of Agricultural Products

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ABSTRACT

A number of nondestructive methods have been developed to detect defects and evaluate physical characteristics associated with quality of agricultural products. The methods involve the application of a well-characterized source of energy (such as x-rays, light, infrared radiation, or sonic energy) to the test object. Because of the composition and condition of the material, the input energy is modified in some unique manner. The difference between the input energy and energy response can be measured and recorded, and may provide a basis for development of empirical relations and correlations for assessing quality-related factors. This paper reviews some of the nondestructive techniques which have been developed for testing agricultural products.

Quality is often thought of as the degree of excellence of a product. Kramer and Twigg (48), however, defined quality as "...the composite of those characteristics that differentiate individual units of a product, and have significance in determining the degree of acceptability of that unit to the buyer." Thus, quality may be specified in terms of a number of factors or characteristics, such as size, shape, color, tenderness, hardness, sweetness, each of which may be defined and evaluated independently. Grade standards of the United States Department of Agriculture (USDA) are based largely upon such quality factors (36,81). Quality evaluation instruments have been developed in an attempt to improve the objectivity of methods used to assess factors of quality. This paper highlights some of the nondestructive engineering techniques used to evaluate physical characteristics associated with quality of agricultural products.

THE NONDESTRUCTIVE TESTING CONCEPT

A simplified concept of the principles involved in nondestructive testing is illustrated in Fig. 1. Nondestructive tests (NDT) have been used for many years to evaluate engineering materials (6,99), and many of these tests can be adapted to measure agricultural products. Nondestructive implies that the sample is not damaged or destroyed during measurement.

Nondestructive testing commonly involves application of a well-characterized source of energy to the test object or sample (Fig. 1). This energy may be in the form of x-rays, ultraviolet, visible (light), or infrared radiation, microwaves, sonic or ultrasonic energy, etc. The type of energy to use as a source depends upon a number of factors, such as the material to be tested and the physical characteristics or anomaly which is of primary interest (2,6,99). The energy which reaches the test object (Fig. 1) interacts with it and is modified in some unique manner because of the chemical and/or physical properties of the object. Generally, the input energy is reflected, transmitted, and/or absorbed by the object. The difference between the input energy and the energy response is measured and recorded, and provides a basis for development of empirical relations and correlations to predict product quality.

An element which is crucial to performance of the entire test system is the receiving transducer or the energy detector (Fig. 1), and its interface with the test object. The transducer converts the energy response into an electrical signal. Zurbrick (99) emphasizes that the receiving transducer is responsible for efficient, low-noise, high-compliance reception; also, it should have
long-range stability, precision, and high sensitivity. A major consideration in the design of any NDT instrument, therefore, must focus upon matching detector performance to the energy response characteristics of the test object. Norris (59, 60) and others (62, 74, 88) have discussed factors to consider in the selection of detectors for light-transmission and reflection measurements; and Finney (25) has described the effect which detectors may have upon the measured sonic vibration response of fruits.

The final component of the NDT system is the readout device (Fig. 1). This unit processes the electrical signal from the detector and enables the investigator to interpret the measurement. A wide variety of electronic signal processing and display equipment is available, from simple digital or analog meters to sophisticated computer-controlled systems. The readout device or system should be designed to match the test situation. For basic studies that require energy response data over a range of frequencies, the readout device should be able to record and display spectra or differences in spectra for different samples. Such systems have been developed for spectrophotometric studies (55, 72). They include a computer to record, store, and calculate correlations and regression relationships between measured variables. In other instances, when the basis for a measurement has been previously established, the readout system may simply be the pointer on a meter or a digital indicator. Birth and Norris (14), for example, used a special recording spectrophotometer to obtain information that was then used in the design of an abridged instrument to indicate directly the chlorophyll concentration in fruit.

Many NDT methods have been developed and used to evaluate agricultural products. Some of the applications are listed in Table 1, according to the type of energy used to interrogate the product. The discussion that follows further illustrates some of the principles involved in nondestructive quality evaluation.

**NONDESTRUCTIVE TEST METHODS**

**Light techniques**

External appearance and internal color are important factors to consider in the quality evaluation of agricultural products; and they can be objectively

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**TABLE 1. Nondestructive techniques for evaluating some of the factors of quality in agricultural products.**

<table>
<thead>
<tr>
<th>Commodities</th>
<th>Defects or quality factors</th>
<th>X rays</th>
<th>Ultraviolet</th>
<th>Light</th>
<th>Infrared</th>
<th>Microwaves</th>
<th>Nuclear magnetic resonance</th>
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*The methods indicated are applicable; but selection is influenced by such considerations as geometry, structure, and composition of the commodity, defect orientation, and equipment cost.*
measured by use of visible radiation (light). A number of techniques are available for isolating narrow beams of light of a specific wavelength and measuring that which is transmitted, reflected, or absorbed by the sample \((13, 59, 62, 88)\). Instruments have been designed to specifically measure the color of agricultural products; that is, the spectral reflectance of specified wavelengths in the visible region \((20, 43, 69, 96)\). For some quality evaluations, however, internal characteristics may be of equal or even greater importance than external appearance. Chlorophyll content in the flesh of apples and peaches, for example, is correlated with maturity and ripeness \((13, 14, 76, 93, 95)\). Quality defects such as hollow heart in potatoes \((12, 67)\) and watercore in apples \((15, 68)\) exist internally without any external evidence of abnormality. These internal quality factors can affect the USDA grade, and light-transmittance instrumentation can be used for their detection \((14)\). Chlorophyll in flesh is associated with a specific type of pigmentation; hollow heart, with discoloration; and water core, with light scatter within the product. Thus, the energy transmitted by the product in selected portions of the visible region of the spectrum can provide an empirical basis for separating desirable products from those which are not. The principles and methods involved in applying these NDT techniques to evaluate interior quality of agricultural products have been described in a number of publications \((13, 14, 56, 59, 71, 94, 95)\).

**Infrared techniques**

Radiation in the infrared and near-infrared region of the spectrum (wavelengths longer than 780 nm) can provide information related to the chemical composition of agricultural products. Water, for example, is an important component of most agricultural commodities, and has strong absorption bands at 0.76, 0.97, 1.19, 1.45, and 1.94 \(\mu m\) \((21)\). These bands can be used to measure the moisture content of seed, grain, and meat preparations \((10, 11, 39)\), and of whole, intact products \((29, 63)\).

Fat content of meat and meat products can be estimated rapidly from infrared reflectance and transmittance measurements. Ben-Gera and Norris \((11)\) identified two prominent absorption bands for fat at 1.725 and 1.76 \(\mu m\). Measurements made at these bands provided a correlation coefficient of 0.974 with percent fat. A simple table model instrument has been developed to measure the intensities of the moisture and fat absorption bands in ground beef and to convert the measurements to fat content, which is displayed directly on a panel meter \((69)\).

During recent years, infrared reflectance techniques have been extended to evaluate other quality factors important in agriculture. Absorption bands within the wavelength region from 1.0 to 2.4 \(\mu m\) have been correlated with the oil and protein content of soybeans \((41, 44, 61, 70)\), protein in cereal grains \((44, 92)\), and with the nutritional quality of forages \((65)\). By use of special optical components and digital processing equipment, table model instruments have been developed to provide a direct quantitative readout of such quality factors as oil, protein, and moisture in less than 2 min \((92)\). Such instrumentation for rapid compositional analyses could have a marked influence upon the system for marketing cereal and feed grains \((4)\). In each of these applications, the basic design of the test instrumentation is based upon an empirical relation between the energy response of the sample to a well-defined source of near-infrared radiation and the quality factor of interest.

**X-ray techniques**

The energy generated by x-ray tubes and radioactive sources, such as cobalt-60, iridium-192, cesium-137, is highly penetrating to biological materials. The material-energy response tends to be especially sensitive to structural discontinuities (such as voids and cracks), density differences or variations, and shape or geometry \((2)\). In agricultural products, those quality factors which are associated with mass-density variations may often be evaluated nondestructively by x-rays. Hollow heart of potatoes, for example, is not visible externally, but can be detected clearly in an x-ray picture \((27, 67)\). Radiographic techniques have been used for a number of years to detect this defect nondestructively, and recently a scanning technique has been suggested for automatic sorting of hollow heart potatoes \((30)\). X-rays have been used also to sort stones from potatoes on the basis of density differences \((77, 79)\).

Significant correlations have been established between density and maturity of lettuce \((33, 50)\). Lettuce becomes firm and dense as it matures; and the density change provides a basis for nondestructive evaluation of lettuce maturity by use of x-rays, and hence for selective mechanical harvesting \((33)\).

The density and x-ray absorption properties of the fat content of meat differ significantly from those of lean meat. The specific gravity of meat, for example, is significantly correlated with the percentage of fat \((91)\), and the absorption of x-radiation by ground meat has been linearly related to the percentage of fat \((54)\). These empirical relationships provide a basis for evaluating the fat content of meat nondestructively \((34)\).

Nondestructive x-ray techniques have been developed to sort frost-damaged, granulated oranges from good quality fruit \((3, 27)\). Frost damage or internal granulation in oranges is known to cause changes in the specific gravity of the fruit \((66)\). Cells within the fruit tend to become dry, and the air-filled voids cause mottling of the x-ray image. A normal fruit, on the other hand, shows fairly uniform absorption characteristics across the projected area of the fruit.

These examples indicate the applicability of x-ray energy to evaluate quality nondestructively. In these applications, response of the product to the input energy tends to reflect mass-density characteristics associated with internal voids or structural variations.
Sonic techniques

The response of materials to sonic energy is influenced by such factors as elasticity, mechanical resistance, mass, and geometry of the material (2). Finney and Abbott (28) have reviewed a number of techniques for applying sonic energy to agricultural products and measuring their responses. Response is usually measured in terms of vibration amplitude, frequency, and damping characteristics. Results of sonic vibration studies indicate that the natural resonant frequency of fruits decreases as they soften (1,19,25) and that firm hard fruit transmit high frequency energy (above 2,000 Hz) better than soft fruit (24,26,66). A number of studies have been conducted to correlate sonic response to other indices of fruit quality, such as pressure tests and sensory panel ratings (19,23,24,26). The studies show a significant correlation between the nondestructive sonic measurements and fruit texture. Instruments have been developed to sort tomatoes, blueberries, and grapes for ripeness on the basis of their responses to sonic vibrations (5,37,38).

SUMMARY

In this paper, some of the principles involved in development of nondestructive tests for agricultural products have been reviewed. I have emphasized that such tests must be based upon some type of unique interaction between the energy source and the product under test. Four test methods were discussed and are based upon the use of sonic energy, x-rays, light, and infrared radiation to characterize the product. With each method, the energy response is sensitive to certain characteristics of the product, such as mechanical resistance, mass density, pigmentation and color, or composition. Other techniques and energy sources such as microwaves (17,80), beta backscatter (47), ultrasonics (31,42,84), ultraviolet (87,90), and nuclear magnetic resonance (78,80,85) may also be applied to test agricultural products. The NDT principles described in this paper apply equally to these latter approaches. That is, the effectiveness and reliability of the measurement must be based upon established empirical relationships or correlations between a measured product-energy response and the quality factor of interest. Because of the wide differences in structure and composition, and the inherent natural variability of agricultural products, nondestructive quality evaluation instruments often must be customized for the particular commodity and quality factor of interest. Many approaches, however, are available for the engineer to consider in the design of such quality evaluation instrumentation.

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