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Correlation Analysis between Ultrasonic Parameters and Elastic Modulus of Apple

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Abstract The firmness of fruit is one of the most important quality factors and is highly correlated to the elastic modulus. In this study, the ultrasonic transmission method was applied to evaluate the elastic modulus of the apple. In order to transmit and receive the ultrasonic wave through the whole apple, the ultrasonic measurement setup consisted of ultrasonic pulser, two specially fabricated ultrasonic transducers for fruit and digital storage oscilloscope. Ultrasonic parameters such as ultrasonic wave velocity, apparent attenuation, and peak frequencies were analyzed. The elastic modulus of apple was measured by using compression test apparatus. The correlations between ultrasonic parameters and elastic modulus were analyzed. A multiple linear regression model describing the relationship between elastic modulus and ultrasonic parameters was proposed.

Keywords: Ultrasonic Parameters, Ultrasonic Wave Velocity, Attenuation Coefficient, Elastic Modulus, Apple

1. Introduction

Firmness such as elastic modulus is not only one of the major quality indicators for fruit and but also has been used as a useful guide for producer, quality inspector and consumers. Especially, in many fruits, firmness is used as an indication of the handling characteristics of the fruit, and picking and grading of fruit may be based on firmness measurement. To estimate the firmness of fruit, traditionally, as a destructive method, penetrometer or compression test have been used. Various types of penetrometers have been developed and the most common of them are Magness Taylor and Effegi varieties (Bourne, 1965; Abbott et al., 1992). The firmness tests using destructive methods have the advantage of high accurate but fruits are destroyed and wasted.

Several methods to measure the firmness of fruit nondestructively have been suggested (Finney, 1970; Yamamoto et al., 1980; Duprat et al., 1997) and most of them are acoustic methods. Even though it is fast, accurate and nondestructive, the acoustic method for assessing fruit firmness has not been widely introduced in practice. As another nondestructive method, ultrasonic technique has been used for evaluating the quality of agricultural products (Sarker et al., 1983; Mizrach et al., 1989; Kim et al., 2004). Ultrasonic technique is very useful for nondestructive measurement of the mechanical properties of materials. But most ultrasonic transducers used in previous researches were not suitable for fruit because they were made for industrial usage. Hence the fruits should be sliced uniformly to contact to the surface of the ultrasonic transducers. Recently, the ultrasonic

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transducer for fruit was successfully developed (Kim et al., 2003).

The objectives of the present study were to evaluate the ultrasonic parameters and firmness (elastic modulus) of apple and to establish relationship between the results of nondestructive ultrasonic measurements and firmness of apple.

2. Materials and Methods

2.1 Fruit Samples

Korean (*Sansa* cultivar) apples were purchased at market place. Extremely large and small apples were rejected. All apple samples were inspected to ensure that they were uniform, undamaged and not attacked by worm. After completing the inspection, the fruit samples were held room temperature (about 19-23℃) for 1 to 25 days to accelerate ripening. The experiment was conducted on random samples of 30 fruits, after allowing samples to reach room temperature.

2.2 Ultrasonic Measurement

Fig. 1 shows the overall experimental setup consisting the ultrasonic transducers, apple, ultrasonic pulse, and oscilloscope. The ultrasonic wave velocity and attenuation for the whole fruit were measured. The through-transmission mode was selected for the ultrasonic arrangement, with one transducer acting as a transmitter, and the other as a receiver. As ultrasonic transducer to transmit and receive the ultrasonic wave, the specially fabricated ultrasonic transducer having curved wear plate to direct contact to the surface of apple was used (Kim et al., 2004). The central frequency and diameter of ultrasonic transducer were 100 kHz and 40 mm, respectively. To match the acoustic impedances between ultrasonic transducers and apple, vacuum grease was used. To generate the ultrasonic wave, PUNDIT 6 (CNS Farnell Inc., US) was connected to the ultrasonic transmitter. The PUNDIT is high power and low frequency ultrasonic pulser-receiver. The transmitted ultrasonic wave signal through apple obtained by the ultrasonic receiver was connected to the digital storage oscilloscope (WaveRunner, LeCroy Co., US).

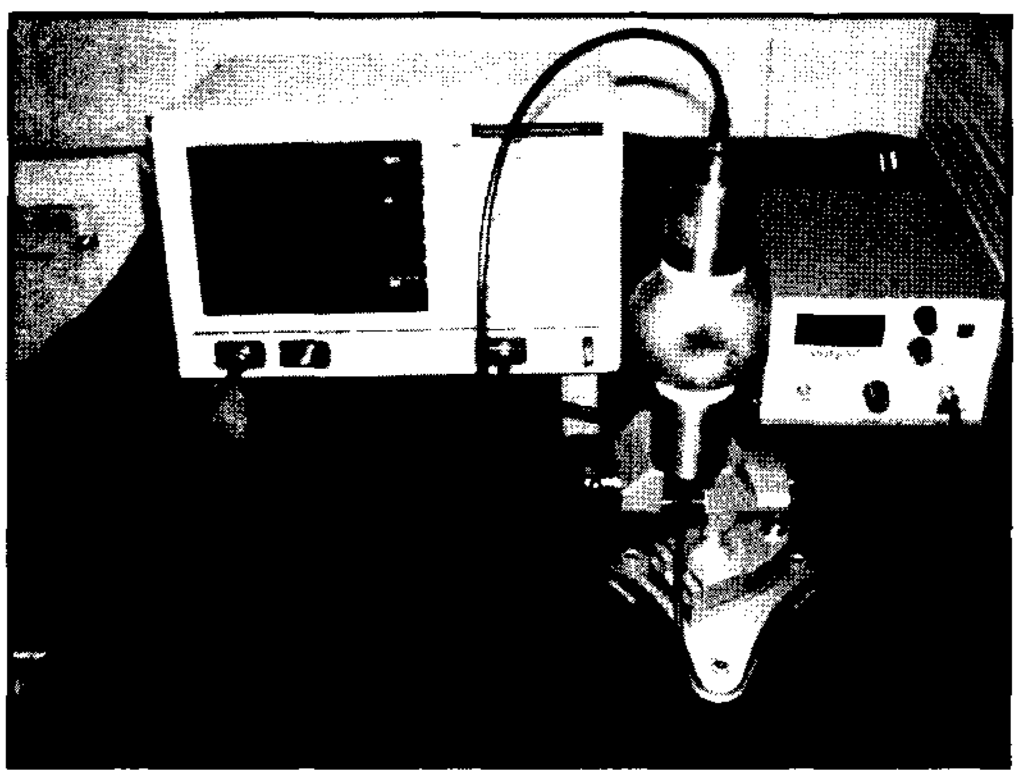

Fig. 1 Photo of experimental setup with ultrasonic transducers for fruit, apple, ultrasonic pulser and digital storage oscilloscope

For each ultrasonic measurement, 5 transmitted signals were acquired and averaged and then the time of flight was computed from the averaged signal. The ultrasonic transmission velocity was calculated from the measurements of time of flight and thickness of fruit sample. The amplitude of the received ultrasonic signal was calculated using the following equation:

$$A = A_0 \exp(-\alpha d_f) \tag{1}$$

where A and A_0 are the peak to peak ultrasonic signal amplitudes at the beginning and the end of the propagation path of the ultrasonic wave, α. the attenuation coefficient of the material in dB/mm, and d_f is the thickness of fruit sample in mm, respectively.

After calculating the ultrasonic velocity and attenuation in the time domain, the transmitted ultrasonic wave signals were analyzed by using fast Fourier transform. The frequency spectrum showed a number of peaks frequencies corresponding to the three highest magnitudes in decreasing order were labeled the first, second and third peak frequencies. The changes of these frequencies with storage time were examined.

2.3 Firmness Measurement

After the ultrasonic experiments, the firmness of each whole fruit was measured using universal testing machine. The loading rate of the crosshead was fixed at 25 mm/min, which was within the range of loading rate (2.5 to 30 mm/min) specified by the ASAE S368.3 MAR95.

As the compression began and progressed, a load-deformation curve was plotted automatically in relation to the response of each fruit sample to compression. As firmness parameters, apparent elastic modulus was obtained by taking in the equatorial region of the apple using a crosshead controlled by universal testing machine.

3. Results and Discussion

There are progressive changes in wave shape and elastic modulus during storage. The changes in wave shape of transmitted ultrasonic signals at storage times of 1, 10, 19 and 25 days were shown in Fig. 2. Fig. 2 shows the original obtained signals. From Fig. 2, the maximum amplitudes of the signal are decreasing according to storage time.

The effect of ripening (or storage time) on the elastic modulus of apples is shown in Fig. 3. It can be seen that the change in elastic modulus with storage time decreased linearly. The mean values of the measured elastic modulus of the apple, shown in Fig. 3, decreased during storage at room temperature from a very firm fruit with a firmness value of about 1150 kPa on the first day to a very soft fruit with a firmness of about 450 kPa at the end of the 25 days softening process. At this stage, the apple was too soft to measure the elastic modulus.

The relationships between ultrasonic parameters such as ultrasonic wave velocity and apparent attenuation coefficient, α and elastic modulus were analyzed as shown in Fig. 4 and 5. The measured ultrasonic velocity of apple was well agreed with the previous experimental data (Mizrach et al., 1989, Kim et al., 2004). The correlation coefficients between elastic modulus and ultrasonic wave velocity and attenuation coefficient were 0.976 and 0.930, respectively. The correlations between ultrasonic wave velocity and attenuation coefficient and elastic modulus suggest that it is possible to predict the shelf life of a batch of apples by measuring their ultrasonic parameters.

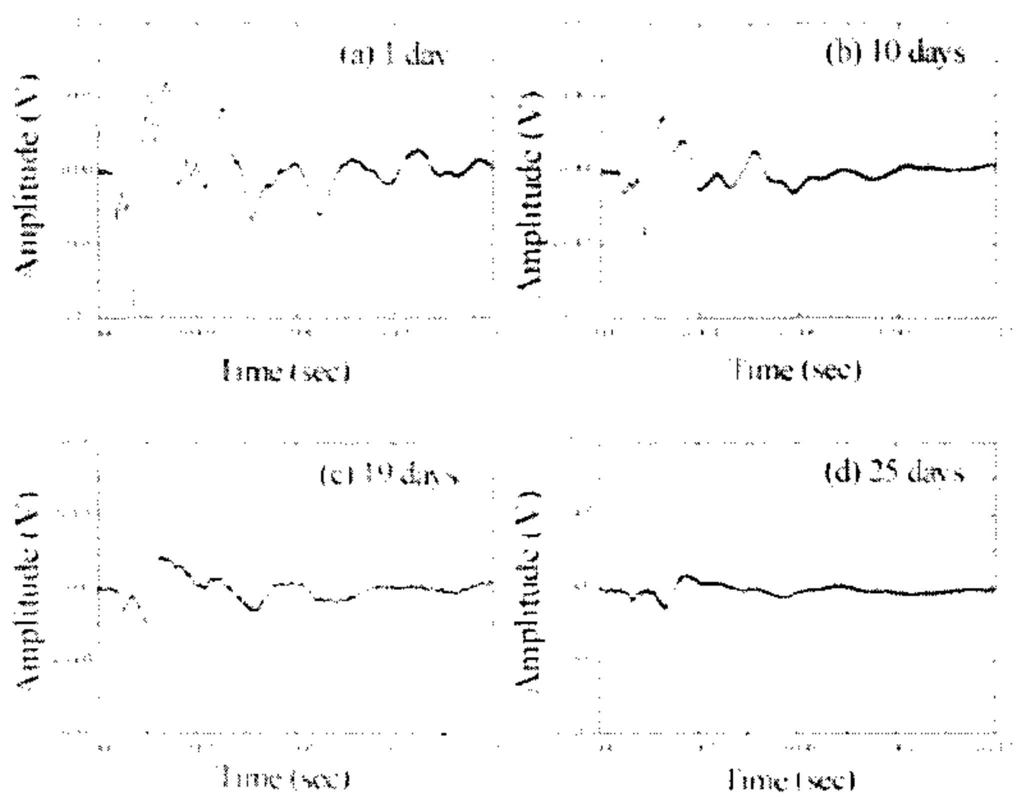

Fig. 2 Changes of ultrasonic transmitted signals of apple at several storage times

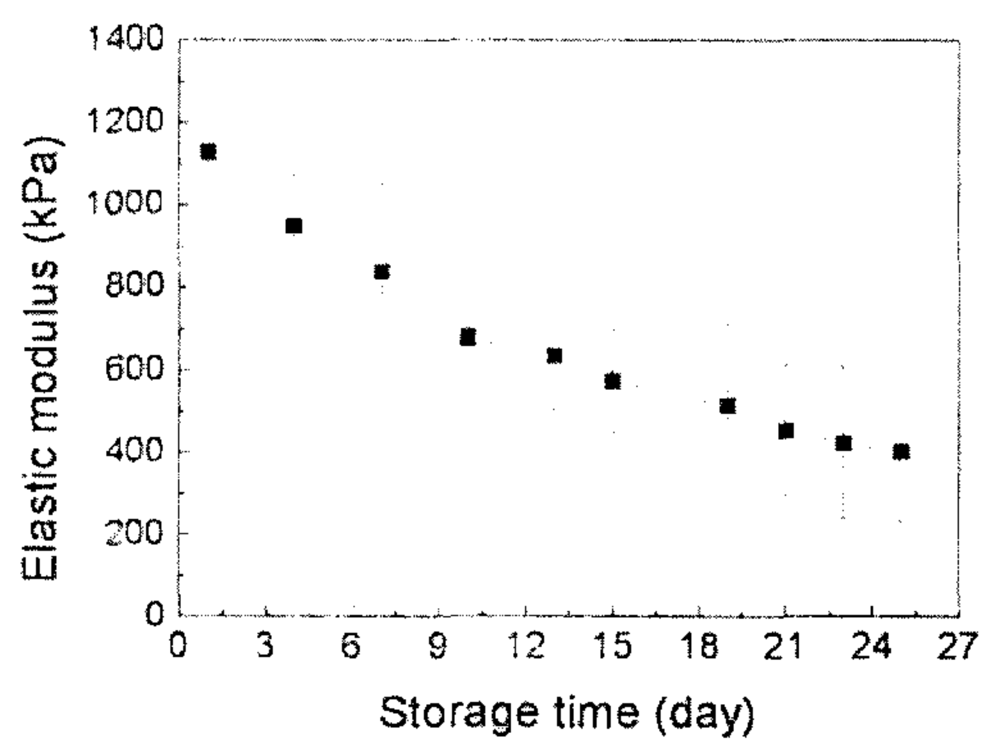

Fig. 3 The variation of the mean value of elastic modulus with the storage time for apple. Each point represents the mean value of 30 apples, Vertical lines represent confidence intervals (confidence probability is 95 percent)

Fig. 6 shows the change of the first, second and third peak frequencies (three highest magnitudes in frequency spectrum) of ultrasonic received signal according to elastic modulus. Each point represents the mean value of 30 apples in the figure. Small changes of peak frequencies were found until 15 storage days; after 15 storage days, the peak frequencies decreased rapidly. The storage time of 15 days can be a critical storage length but it is changeable due to the change of storage environment. Most of the 100 kHz frequency components (the center frequency of the ultrasonic transducer) were attenuated through passing the whole apple sample. The peak frequencies in Fig. 6 are not induced ultrasonic frequency range in our experiment and these frequencies may be thought natural frequencies of fruit (Abbott, et al., 1968). To understand and characterize the effect of firmness on frequency, as further study, additional studies such as physiological approach, analyses of fruit flesh, seed, and water content, and ultrasonic signal processing techniques for apple firmness are required.

From Figs. 4 to 5, because of the changes in the ultrasonic wave velocity and attenuation coefficient were dependent on the elastic modulus it was concluded that the determination of elastic modulus of apple using ultrasonic wave velocity and attenuation coefficient will be possible. In order to estimate the capability of determining the elastic modulus with ultrasonic wave velocity and attenuation coefficient, a multiple linear regression model was assumed as

$$E = a_0 + a_1 V + a_2 \alpha \quad (2)$$

where, E is the elastic modulus [kPa], V is ultrasonic wave velocity [m/s], a is attenuation coefficient, and a_0, a_1 and a_2 are regression coefficients.

Considering the effect of elastic modulus on the peak frequencies, we analyzed the following multiple regression models including peak frequencies;

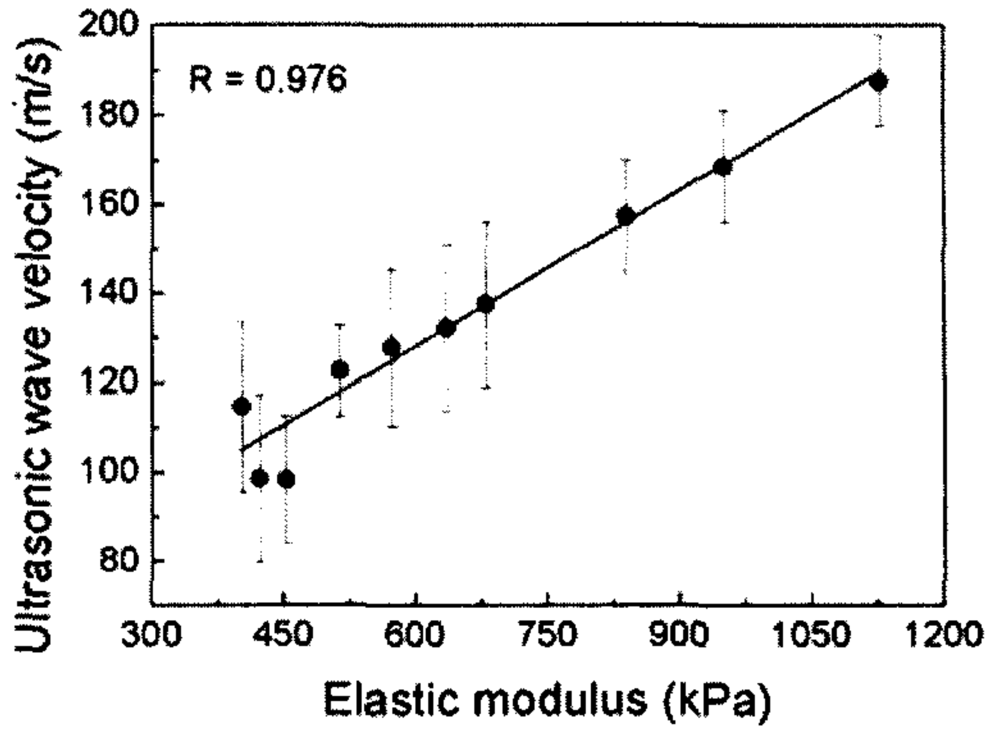

Fig. 4 The variation of the mean values of ultrasonic wave velocity with elastic modulus for apple. Each point represents the mean value of 30 apples. Vertical lines represent confidence intervals (confidence probability is 95 percent)

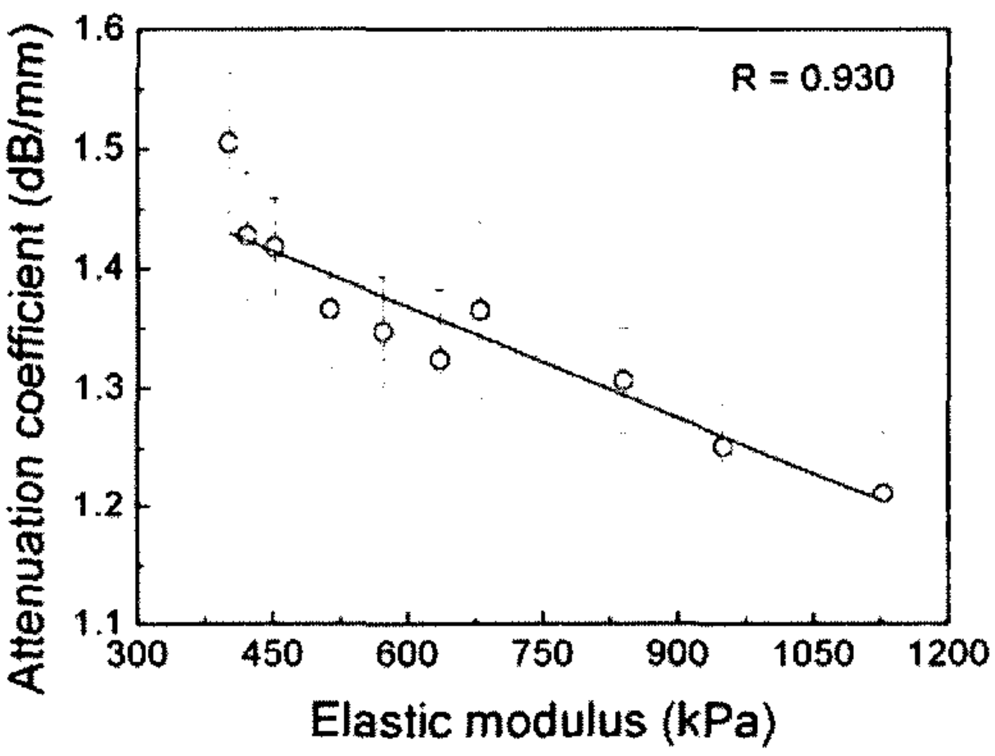

Fig. 5 The variation of the mean values attenuation coefficient with elastic modulus for apple. Each point represents the mean value of 30 apples. Vertical lines represent confidence intervals (confidence probability is 95 percent)

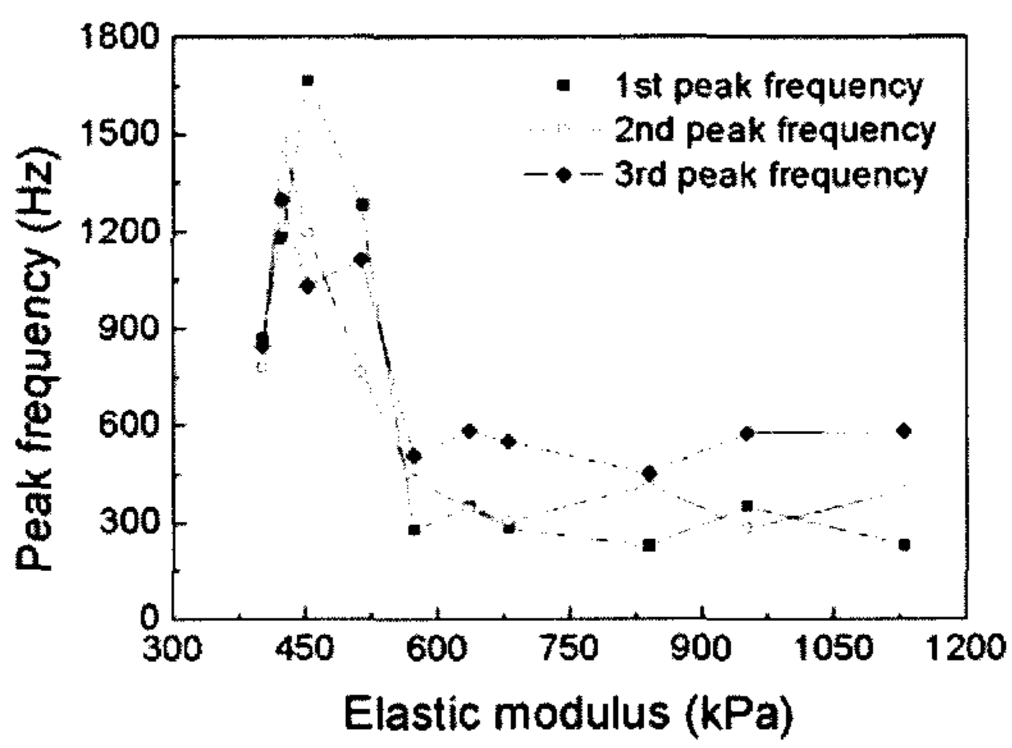

Fig. 6 The variations of the first, second, and third peak frequencies of the received signal of apple with elastic modulus

Table 1 Results of regression analysis for elastic modulus as a function of ultrasonic wave velocity, attenuation coefficient and peak frequencies

Model	Regression coefficients						R^2	RMSE
	a_0	a_1	a_2	a_3	a_4	a_5		
Eqn. (2)	1004.56	5.91	-843.39				0.972	46.01
Eqn. (3)	790.33	6.70	-785.86	0.046			0.976	45.97
Eqn. (4)	684.88	7.14	-776.06	-0.011	0.111		0.984	41.08
Eqn. (5)	741.71	7.28	-786.47	0.039	0.193	-0.195	0.990	36.13

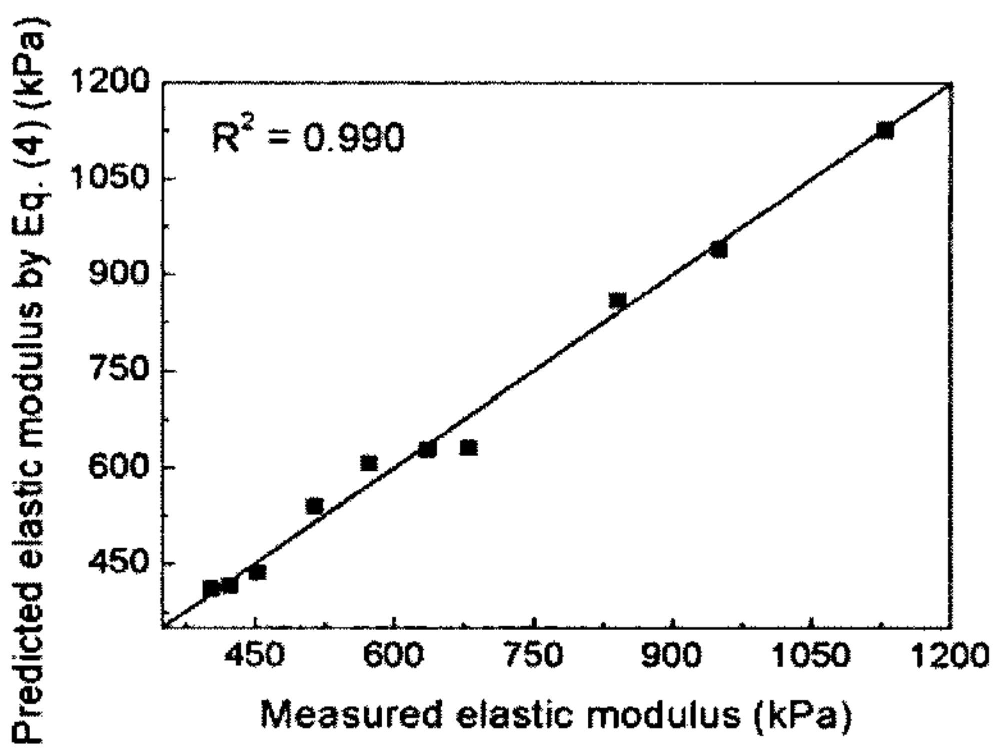

Fig. 7 Relationships between measured value and predicted value of elastic modulus of apple

$$E = a_0 + a_1 V + a_2 \alpha + a_3 f_1 \quad (3)$$

$$E = a_0 + a_1 V + a_2 \alpha + a_3 f_1 + a_4 f_2 \quad (4)$$

$$E = a_0 + a_1 V + a_2 \alpha + a_3 f_1 + a_4 f_2 + a_5 f_3 \quad (5)$$

where, f_1, f_2, and f_3 are the first, second and third frequencies.

The statistical regression analysis results are summarized in Table 1. The coefficient of determination (R^2) of all regression models are more than 0.972. From the result of regression analysis, the elastic modulus of apple will be predictable using ultrasonic measurement. Fig. 7 shows the predicted value vs. measured values of elastic modulus and this study demonstrates the feasibility of ultrasonic technique to estimate the elastic modulus of apple.

4. Conclusion

This study was performed to evaluate the potential use of ultrasonic parameters for determination of apple firmness (elastic modulus). The elastic modulus decreased with storage time of apple. The ultrasonic wave velocity increased with the increase of elastic modulus of apple but the attenuation coefficient decreased. The correlation coefficients between elastic modulus, ultrasonic wave velocity and attenuation coefficient were 0.976 and 0.930, respectively. Multiple-linear regression models describing the relationship between the elastic modulus of apple and ultrasonic parameters (ultrasonic wave velocity, attenuation coefficient and peak frequencies) were proposed and found to be a reliable method for predicting the elastic modulus of apple. The elastic modulus could be predicted with coefficient of determination of more than 0.972 for apple. The technique for elastic modulus measurement based on ultrasonic parameters may provide a promising method for development of practical instruments in measuring the firmness of fruit.

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