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Comparison of Package Cushioning Materials to Protect Post-harvest Impact Damage to Apples

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ABSTRACT

Damage to fruits and vegetables continues to be a big challenge as global markets become a reality. Worldwide distribution of sensitive produce is faced with various levels of impacts from shipping and handling. Despite a variety of packaging options available today, bruising damage is commonplace for post-harvest apples throughout the supply chain. The major sources of bruising are compression, impact or vibration forces. Understanding where these forces occur can help reduce this type of mechanical damage to apples. The purpose of this study was to investigate the impact characteristics of foam net and corrugated board when applied as wrapping for individual apples. Two grades (count numbers 80 and 100) of “Fuji” cultivar apples imported to Thailand from China were studied. A simple ballistic pendulum test device was developed to measure bruise volume to impact energy relationship. A linear relationship for both types of apples was observed. Bruise volume occurrence probability and impact energy relationship fitted by linear regression were created for cushioned and bare apples. Absorbed energy of various cushioning materials was also calculated under compressive forces.

KEY WORDS: apple; ballistic pendulum; bruise volume; cushioning; impact energy

INTRODUCTION

This study focused on developing a simple methodology to compare the performance of cushion wrapping materials that can be used for impact-sensitive fruits and vegetables. Countries such as China and India with low labor rates can use such methods to provide extreme levels of protection to fruits to compete in the global market.

Apples are a popular and nutritious horticultural product popular worldwide. Consumers insist on a high quality product that is free from any bruises, cuts, punctures, physiological disorders and pathogens.[1] Bruising, which is objectionable to fresh-market consumers, can result in a lower grade for any apple. Several studies have been conducted internationally that show that compression, vibration and impact forces cause a majority of the mechanical damage, such as bruising, to apples in the supply chain.

Apples are exposed to compressive forces via forces applied by the picker's body, tree limbs, ladder rungs or rail, bulk bin rails and bottoms. Compressive forces may also get applied to apples by other apples because of excessive bulk bin depth or carton stack height, by operators forcing the cartons shut or into a tight spot, etc.[2] Vibration forces are the second major cause of mechanical damage to apples in the supply chain and are almost impossible to avoid. If the cartons or bins that carry the apples through the distribution environment hit resonance (their natural frequency matches the forcing frequency of the conveyance), severe accumulated bruise damage is inherent. Impacts impart high forces in an extremely short duration and are often not obvious in mechanical handling systems such as those used in packing lines. The effect of impact forces usually results in bruises, permanent damage and lower perceived quality. Bruise sensitivity has also been reported to increase with storage time.[2] Effectiveness of cushioning materials in protecting impact damage of apples is the primary objective of this research.

Various packaging materials are in use today to wrap individual apples to provide cushioning so that they may survive the adverse distribution environment effects. In a study, a net made of dry banana string, an agricultural waste wrapping for apples, was shown to save the fruit from damage at the impact energy of 1.1 J.[3] This study mentioned problems of fungi attack due to the wrapping on the skin of the fruit. Another research studied paper that is typically applied to line the inner surface of plastic and bamboo fruit containers for protecting fresh fruit from bamboo cuts and moisture loss during transport.[4] Paper was found not to be a good cushioning material against impact damage. Peleg describes good interior packaging as that which treats a fruit as separate units, avoids fruit-to-fruit contact, absorbs the impact energy and is practical.[5] At present, foam nets function well as one of the commercial packaging solutions.[6] However, it is not easily degradable in a landfill.[3] Figure 1 shows the typical foam net used for apples.

Impact damage to apples usually materializes as bruising.[7] Several researchers have studied apple bruising due to impacts.[8–13] Some researches have found that an apple, when exposed to small impacts, exhibits no bruising but that noticeable bruising could be detected beyond a certain amount of impact energy.[3,8] Bruises have been evaluated as bruise volume,[12,14] and linear correlations have been found between the bruise volume and the impact or absorbed energy.[8,9,15] Schoorl and Holt define slope of bruise volume and energy as bruise resistance.[11] The threshold of apple bruising has also been studied by some researchers. Bollen *et al.* expressed the phenomenon of apple bruise threshold as a curve plotted between the probability of bruising against the drop height or energy.[16] Some experts have credited corrugated board wrapping with adequately protecting fresh fruit from impact and compression forces. [5,17] The inherent affinity of corrugated board to moisture, as with any paper-based

Figure 1. Foam net packaging.

packaging material, compromises its strength and cushioning capabilities. However, because of its expedient degradability, high recycling rate and low cost of the recycled paper, corrugated board holds good potential as a cushioning material. No comparative studies on physical properties of new and used corrugated board as cushioning material for wrapping fruit have ever been conducted.

Several testing devices for observing the effect of impact forces on fruits have been developed in recent years. These instrumented devices are generally capable of measuring acceleration, force, displacement, time and contact area during impact.[10,18–20] Some of these devices are capable of recording, processing and storing impact data during the experimentation.[21,22] By using these instrumented devices, measurements can be achieved instantly and accurately, but at a very high expense. Often times, a majority of the capabilities of such devices are not utilized, and accurate measurements of impact parameters such as impact and absorbed energy can be made using a simple and affordable device that provides sufficient repeatability and reproducibility.

The main objectives of this study were as follows:

1. Develop a simple ballistic pendulum-type test fixture operable by one person that provides a high sensitivity of energy settings and dependable energy-bruise volume measurements.
2. Compare the impact-absorbing characteristics of the bare apples to apples that are wrapped

with various cushioning materials.

3. Recommend best materials and wrapping orientation for protecting against impact forces.

MATERIALS AND METHODS

Apples

“Fuji” cultivar apples imported from China to Thailand without any physical injury were used for the testing because the bruising discoloration of this apple is easily detected, and it is available in Thailand markets. Two sizes of the apple were used: count number 80 (fruit weight = 240 ± 20g) and number 100 (fruit weight = 180 ± 20g).

Simple instrumented pendulum

An impact testing device was designed to be a ballistic pendulum featuring 3.84kg rectangular steel mass hung by four 45cm long ropes like a cradle (Figure 2). The motion of the pendulum mass was curvilinear translation. A laser pointer, mounted at the back of the mass, projects a beam to mark a 1 mm red circle on a scale (each graduation is equivalent to 7.5mm/degree of motion) 15cm under the mass. This facilitates the setting of incident angle and impact energy. Pivot points of the rope at four corners of the mass were set on the same horizontal plane, passing a fulcrum providing stable motion without excessive swinging. An apple sample was placed in the sample holder with a pin plugged into the top of the fruit. There was a small rope placed perpendicular to the pendulum motion plane that connected to the pin in order to prevent the sample from falling down after the impact, thereby avoiding any unwanted mechanical injuries. The testing device was operated by a single person and proved to give higher sensitivity of energy setting and better energy–bruise volume curve fitting compared with the pendulum without instrumentation.[23]

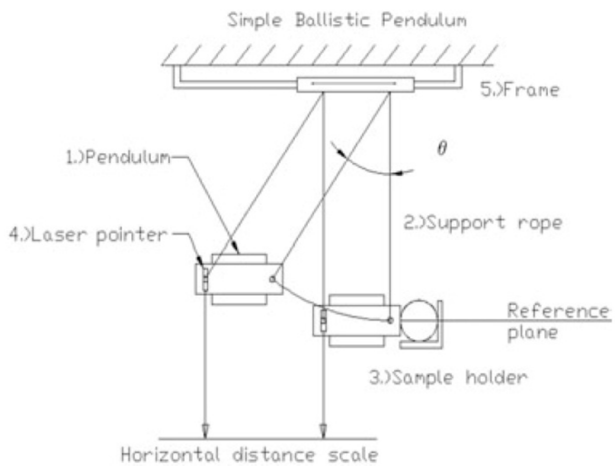

Figure 2. A schematic diagram of the simple ballistic pendulum.

Cushioning wrapping materials

Two types of cushioning material were used to comparatively test their protective performance. A 2mm thick typical apple foam net (Figure 3) and corrugated board were used as wrapping for individual apples. Four types of the corrugated board wrapping were used:

- Single face with corrugated medium outside (SFO)
- Single face with corrugated medium inside (SFI)
- New double-wall corrugated board (NDW)
- Used double-wall corrugated board (UDW)

For the NDW and UDW, 240 × 80mm each, the flutes ran parallel to the length of the wrapping. To facilitate bending when wrapping the corrugated board around the fruit, small perforations across the width giving 3mm wide strips were made (Figure 4).

To cushion an apple sample, foam net was directly put on it while the sheet of each type of the corrugated board had to be wrapped around the fruit with the sheet edges touching each other.

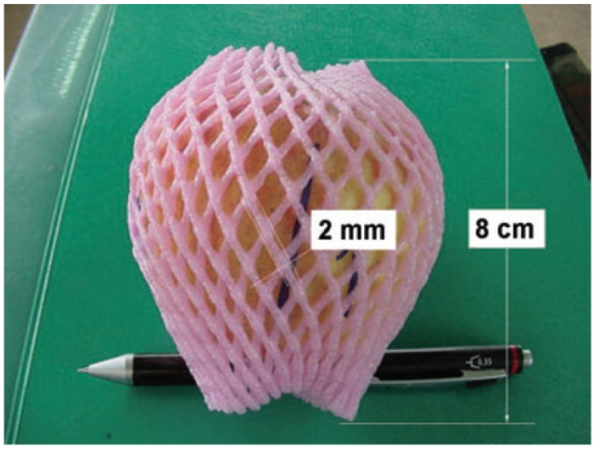

Figure 3. Foam net wrapping.

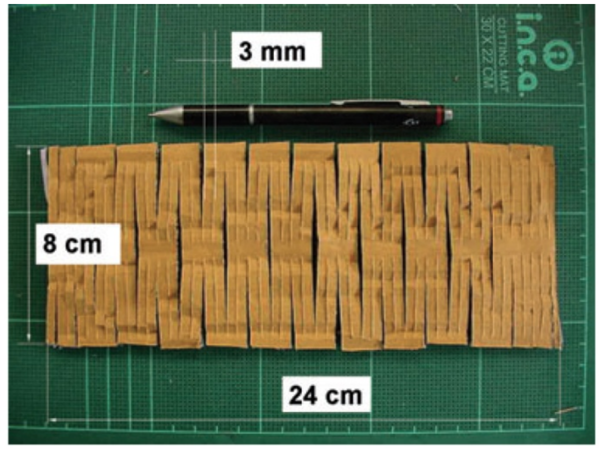

Figure 4. Corrugated board.

EXPERIMENTAL DESIGN

Impact test

The experimental design consisted of two apple sizes tested with and without the five types of cushioning materials. Mechanical behaviours of concern were bruise volume and 20 levels of impact energy (0.04–0.75J) for bruise volume and to impact energy threshold determination and 10 levels of impact energy (0.02–2.0J) for bruise volume to impact energy relationship beyond threshold.

The cushioned apple was mounted at the sample holder, and desired impact energy was located on the scale by the pointer. The pendulum was then released to impact the sample from the corresponding release angle. Bruise volume and the related impact energy were then recorded. Ten replications were conducted for each bruise volume to impact energy threshold and five replications were made for each determination of bruise volume to impact energy beyond threshold. Impact energy was calculated from the following equation:

$$E = mgR(1 - \cos\theta_i) \qquad (1)$$[8]

where E is the impact energy (J); m is the mass of the pendulum (kg); g is the gravitational constant

(9.81m/s^2); R is the length of the hanging rope (m); and θ_i is the angle of incidence (degree).

After the impact, the apples were stored for 24h at room temperature to allow the browning/discoloration to become more apparent. After this period, the apples were sectioned at the contact area. Bruise volume was calculated as follows:

$$V=(\pi/8)w^2d \qquad (2)$$[24]

where V is the bruise volume; w is the width of the bruise (mm); and d is the depth of the bruise (mm). The probability of bruising was calculated using the following equation:

$$\text{Probability of bruise volume occurrence} = \frac{\text{Number of non-zero bruises}}{\text{Number of replications of the same treatment}}$$

Compression test

Compression testing for all samples was conducted as per the TAPPI (Technical Association of Pulp and Paper Industry) T 808 standard. Ten samples of each cushioning material were cut into 32.2cm^2 circular pieces and compressed between two parallel flat platens of an Instron Universal Testing Machine (model 5569, Instron Corporation, Norwood, MA, USA) at a crosshead speed of 12.5 mm/min to determine the flat crush strengths. Forces versus deflection values were recorded. A computer program was then used to calculate the area under the curve as an absorbed energy.

RESULTS AND DISCUSSION

Bruise volume to impact energy beyond threshold relationship

Figures 5 and 6 below show the results as bruise volume to impact energy relationships for both types of apples.

The bruise volume, V, linearly increases with the energy, E, ($R^2 \geq 0.93$) for both sizes of apples. These findings agree with previous studies.[8,9,11,15]

For a certain applied energy, a smaller bruise volume was observed with the cushioned apple of lower lines. A small bruise volume for bare apples corresponds to small impact energy. This is true for the cushioned apples as well. The lower bruise volumes of the impacted cushioned apples with respect to the bare apples was a result of a very small fraction of the impact energy being transferred through the cushioning material to the apples while a large fraction of impact energy was absorbed by the cushioning material. The impact of the pendulum caused bruising on the contact face. Besides, bruising occurred on the opposite side of the fruit of the other contact because of compression resulting from

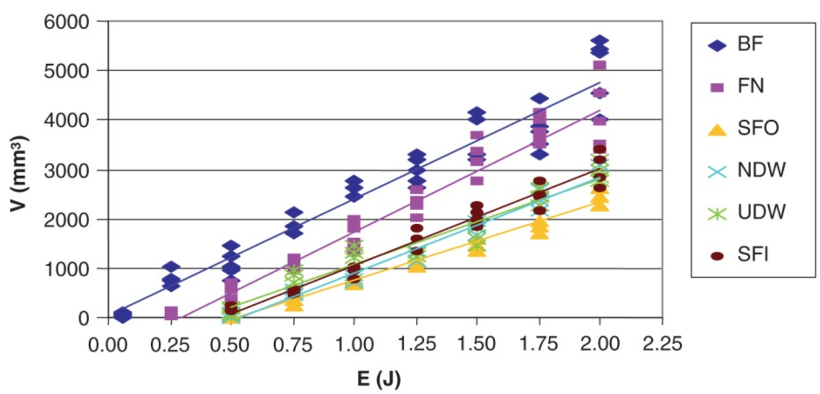

Figure 5. Bruise volume versus impact energy beyond threshold relationship for 180g apples. BF, bare fruit; FN, foam net; NDW, new double-wall corrugated board; SFI, single face corrugated board with flute on the inside; SFO, single face corrugated board with flute on the outside; UDW, used double-wall corrugated board.

the impact. The bruise volume of the backside seemed to be less than that of the front side because of less compression due to absorbed impact energy. Table 1 shows the bruise volume to impact energy

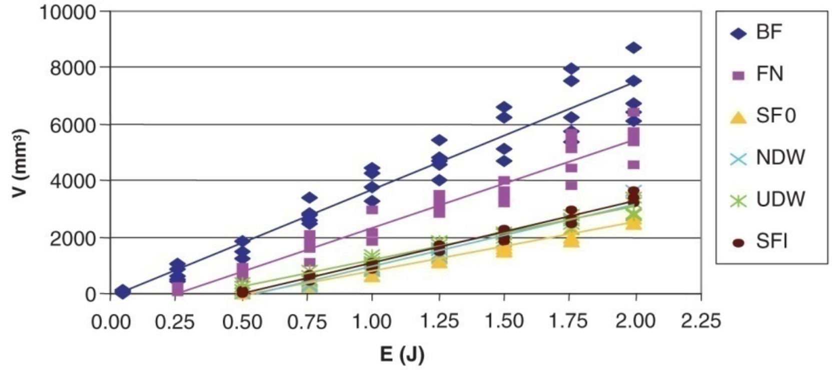

Figure 6. Bruise volume versus impact energy beyond threshold relationship for 240g apples.

Table 1. Bruise volume–impact energy relationship fitted by linear regression

Cushioning material	Equation of relationship			
	180g apples	R^2	240g apples	R^2
SF0	V = 1595.3E − 854.26	0.98	V = 1748.1E − 945.93	0.98
UDW	V = 1741.5E − 663.97	0.93	V = 1877.5E − 682.14	0.97
NDW	V = 1946.9E − 1051.1	0.97	V = 2179.4E − 1196.3	0.97
SFI	V = 1960.1E − 905.99	0.96	V = 2188.1E − 1117	0.98
FN	V = 2465.6E − 732.95	0.93	V = 3113.2E − 772.83	0.94
BF	V = 2350E + 62.415	0.94	V = 3812.5E − 145.18	0.93

BF, bare fruit; E, impact energy (J); FN, foam net; NDW, new double-wall corrugated board; SFI, single face corrugated board with flute on the inside; SFO, single face corrugated board with flute on the outside; UDW, used double-wall corrugated board; V, bruise volume (mm^3).

linear expression of the cushioned apples of both sizes. Schoorl and Holt defined the slope of bruise volume to impact energy regression lines as bruise resistance of the impacted material and apples.[11] This implies that the lower slope, derived from a small bruise volume over high impact energy, is considered to have a higher bruise resistance than those materials with high bruise volumes over small impact energy (having a high slope). The foam net for which the slope was (2466mm^3/J) steeper than that for bare apples (2350mm^3/J) exhibited a lower bruise volume than that for the bare fruit. This indicates that the bruise resistance defined by the slope is perhaps invalid. Such definition would probably be possible if the origin of all the bruise volume to impact energy fitted graphs was at the same point. But bruise volume to impact energy graphs of the cushioned apple are affected by threshold energy so that their origin (V = 0) are different. The bruise volume to impact energy relationship beyond the threshold is then insufficient to explain the bruise resistance or protective performance of the cushioning materials of apple.

Bruise volume to impact energy relationship below and at threshold

Figures 7 and 8 show the relationship between the probability of bruise volume occurrence and the associated impact energy. Bollen *et al.* used the graph of probability versus impact energy to identify the threshold of apples.[16] There are six linear regression graphs ($R^2 \geq 0.88$) corresponding to five cushioning materials and bare fruit as tested using the simple pendulum device. The bruise volume of an apple or cushioned apple can be estimated at various levels of impact energy. The greater the impact energy a cushioned apple received, the higher the bruise occurrence probability was. At the levels where probability is equal to one, the impact energy is estimated to definitely cause bruising. This is called the threshold level.

Table 2 shows threshold energy for the cushioned and bare apples. The cushioned apples could bear a higher impact energy than the bare apple. This is because of the cushioning material acting as a shield

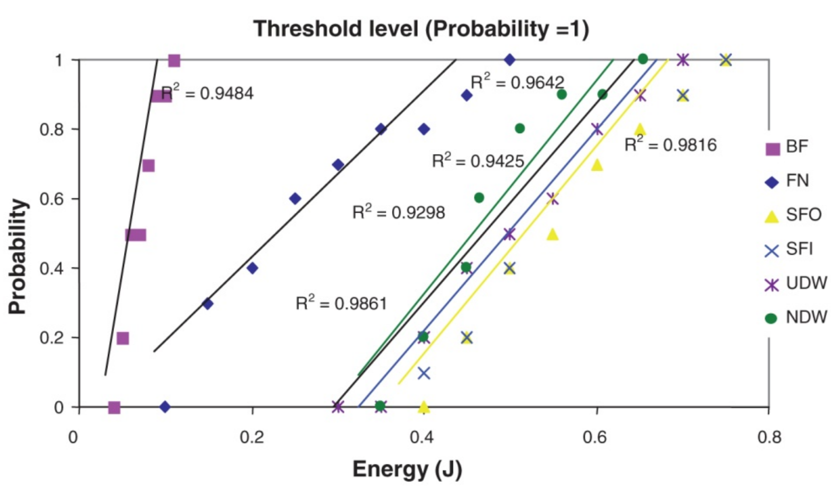

Figure 7. Bruise occurrence probability and impact energy relationship fitted by linear regression of various cushioned and bare 180g apples.

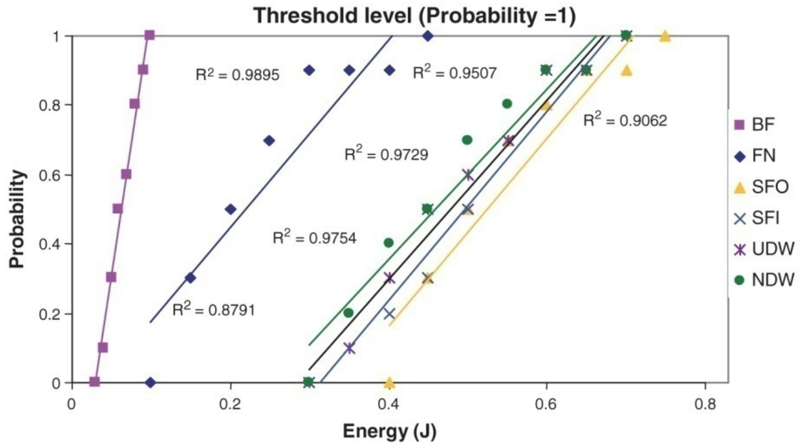

Figure 8. Bruise occurrence probability and impact energy relationship fitted by linear regression of various cushioned and bare 240g apples.

Table 2. Bruise volume and impact energy at threshold (probability = 1) of cushioned and bare apples

Cushioning material	Average bruise volume (mm^3)		Apple threshold energy* (J)
	180g apples	240g apples	
SF0	280 ± 50	307 ± 60	0.75
UDW	379 ± 70	398 ± 45	0.70
NDW	411 ± 55	424 ± 60	0.70
SFI	419 ± 25	453 ± 50	0.725 ± 0.026
FN	447 ± 50	481 ± 50	0.475 ± 0.026
BF	161 ± 30	165 ± 40	0.105 ± 0.005

*Threshold energy for a certain cushioning between the two groups of apples (180 and 240g) was insignificantly different at the confidence level of 99%. BF, bare fruit; FN, foam net; NDW, new double-wall corrugated board; SFI, single face corrugated board with flute on the inside; SFO, single face corrugated board with flute on the outside; UDW, used double-wall corrugated board.

absorbing a fraction of the impact energy and transferring the rest to the apple. If the absorbed energy, E_a, is small and the remaining fraction to impact apple, E_R, is high, the cushioning material is rendered less effective and the threshold impact energy, E_{th}, turns out to be low. On the other hand if E_a is large and E_R is low, E_{th} tends to be high and the cushioning material is fairly protective. The corresponding cushioned apples exhibited high bruise resistance. In this research, the single-face corrugated board wrapping with the flutes on the outside are concluded to be the most protective, giving the highest E_{th}

(0.75J) for both sizes of apples. The threshold energy for a certain cushioning material between the two groups of apples (180 and 240g) was insignificantly different at the confidence level of 99%.

Absorbed energy of the cushioning materials

Table 3 provides the absorbed energy from the force-deflection response of each cushioning material under quasi-static compression. The absorbed energy of the single face corrugated board with flutes on the outside is relatively high (0.11J), indicating that it could absorb higher impact energy than other cushioning materials and release the least remaining fraction to the apple, resulting in the smallest bruise to the apples (Table 2). Figure 9 shows the contact orientation of the single face corrugated board to the apples.

Table 3. Absorbed energy of cushioning materials under quasi-static compression

Cushioning material	Absorbed energy (J)
SF0	0.110 ± 0.012
UDW	0.090 ± 0.008
NDW	0.094 ± 0.008
SFI	0.110 ± 0.012
FN	0.075 ± 0.008

FN, foam net; NDW, new double-wall corrugated board; SFI, single face corrugated board with flute on the inside; SFO, single face corrugated board with flute on the outside; UDW, used double-wall corrugated board.

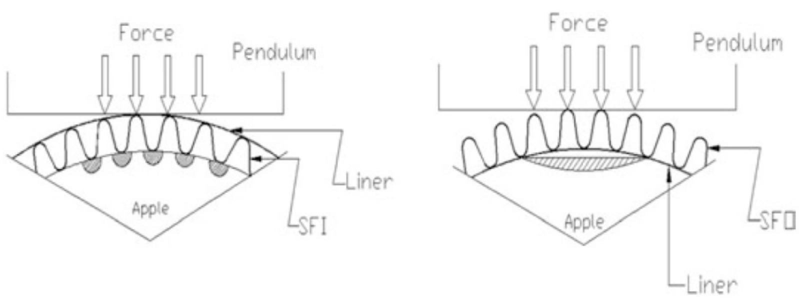

Figure 9. Contact orientation between single face corrugated board to the wrapped apple.

The single face corrugated board with flutes on the outside gave one contact point, lying in the impact line, with the apple surface, while the single face corrugated board with flutes on the inside exhibited several contact points over the contact area because of the flute contact with the apples. This created greater contact pressure over the small contact points, hence giving rise to bigger bruise volumes. Even though the absorbed energies for both the single face corrugated board orientations are the same, the difference in the contact orientation between the single face corrugated paper and wrapped apple surface differentiated the bruise volume and bruise volume pattern.

CONCLUSIONS

This study evaluated the various types of protective cushioning systems that can be used directly on fruits such as apples to reduce bruise injury resulting from post-harvest and transportation to retailers. The study developed a simplified test method that can be used to measure impact resistance strength characteristics of apples or other fruits, and evaluate cushioning materials that can provide shock protection. Both plastic and paper based protective wraps can be effective in providing against bruising from impacts. Results show that the best protection was achieved with the single face corrugated board with flutes on the outside. Threshold energy for a certain cushioning was insignificantly different between the two sizes of apples.

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