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Susceptibility of apples to bruising inside ventilated corrugated paperboard packages during simulated transport damage

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ABSTRACT

The incidence of fruit postharvest losses and waste due to mechanical damage during handling is a major problem in the fresh produce industry Among the various range of force loading conditions experienced during handling and transportation, vibration is one of the key factors which may result in fruit bruise damage and the type of package used during handling of fruit could significantly affect the physical quality of the fruit. A simulated transport study was used to assess the susceptibility of apple fruit inside two ventilated corrugated paperboard (VCP) packages (MK4 and MK6) commonly used in fresh produce industry for packing apple fruit. An electro-dynamic shaker was used to excite vibrations at three frequencies (9, 12 and 15 Hz) and 0.9 g amplitude for four hours, which is usually adopted for truck transport simulation. Packaging transmissibility and incidence of bruise damage were measured at different frequencies. Results showed that both the incidence and severity of apple bruising were affected by package design and frequency. For both package designs at the three vibration frequencies investigated, packaging transmissibility ranged from 100 to 250%, with the highest transmissibility observed on the MK6 package with a lower length–to–height ratio at 12 Hz compared to the MK4 package. Apple fruit inside the MK4 package with higher length–to–height ratio had less damage than fruit inside the MK6 package. Irrespective of the package design, apple fruit on the top layer were more susceptible to bruising and the range of the proportion of bruised apples was between 50 and 74% at all the three frequencies, which are rather extreme conditions that usually occur when loads of packed fruit damage during transport.

1. Introduction

Horticultural products, especially apples are highly susceptible to damage during transportation and postharvest handling (Sittipod et al., 2009; Eissa et al., 2012). The need to provide high quality products without blemish, cuts, bruises, physiological disorders and pathogens is important, which is emphasised and insisted on by consumers (Timm et al., 1996; Remón et al., 2003; Eissa et al., 2012). Various studies have been conducted which indicate that impact, compression and vibration forces account for the majority of the mechanical damage of horticultural products (Idah et al., 2007; Jarimopas et al., 2007; Opara et al., 2007; Van Zeebroeck et al., 2007a,b; Chonhenchob et al., 2009; Lu et al., 2010; Ahmadi, 2012; Babarinsa and Ige, 2012; Eissa et al., 2012; Lu et al., 2012; Fadiji et al., 2016). Transportation is important in the distribution process of horticultural products, however, vibration during transportation causes critical damage to packages and produce (Sittipod et al., 2009). Mechanical damage is responsible for the deterioration in the quality of fresh produce. Disposed produce due to mechanical damage is estimated to be about 40% (Barchi et al., 2002; Vursavufi and Özgüven, 2004). Cautious handling and proper packaging have shown to minimise the losses

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of fruits due to mechanical damage (Singh et al., 1992; Chonhenchob and Singh, 2003; Chonhenchob et al., 2009). Evidence of severe problems of mechanical damage is on the increase and is affecting the trade in fruits and vegetables (Okhuoya, 1995), giving a clear indication of the need to improve the handling methods, particularly optimising the packages to provide better protection.

Several studies have been reported investigating the effects of vibration during transport on different horticultural products such as peaches (O'Brien et al., 1969; Vergano et al., 1991; Oeguet et al., 1999), loquats (Barchi et al., 2002), pears (Slaughter et al., 1993; Jancsók et al., 2001; Berardinelli et al., 2005; Zhou et al., 2007), tomatoes (Olorunda and Tung, 1985; Singh and Singh, 1992; Babarinsa and Ige, 2012a, 2012b; Idah et al., 2012; Bello et al., 2013), kiwifruit (Tabatabaekoloor et al., 2013) and apples (Timm et al., 1996; Vursavufi and Özgüven, 2004; Van Zeebroeck et al., 2006; Acıcan et al., 2007; Eissa et al., 2012). Hinsch et al. (1993) studied the vibration of cherries, nectarines and pears on semi-trailers with steel spring suspension systems. The authors reported that the highest Power Spectral Density (PSD) levels occurred at the rear of the trailer at a frequency of 3.5 Hz. Also, frequencies of 3.5, 9, 18.5, and 25 Hz were the most frequent during transportation. Vertical acceleration was much higher than the horizontal acceleration with similar observations reported by Singh and Marcondes (1992). Similar to these findings, Slaughter et al. (1993) found the most severe damage at frequencies of 3.5 and 18.5 Hz in transit damage of Bartlett pears. Chonhenchob and Singh (2005) performed an actual shipment and vibration test in order to compare the packaging performance and the effects on quality of two cushioning systems; foam nets and paper-based wrap materials for exporting papaya fruit. The authors reported that although the paper-based cushions provided a similar protection as to the plastic foam nets materials, the paper-based cushions offered a better ripening response for papayas. In another study by Park et al. (2011), the authors evaluated the vibration transmissibility of corrugated paperboard with corrugation shape and equilibrium atmospheric conditions by a sinusoidal sweep vibration test. Vursavus and Ozguven, 2004 studied the effects of vibration parameters and packaging methods on mechanical damage in apples. The volume packaging method had the highest packaging transmissibility as compared to the pulp tray packaging and pattern packaging methods. For all the packaging methods used in the study, packaging transmissibility was at similar high levels at a vibration frequency interval of 8–9Hz. The authors concluded that the equivalent severe bruise index was affected significantly by vibration frequency, vibration acceleration, packaging methods and vibration time. In a recent study by Eissa et al. (2012), the authors compared the package cushioning materials for apples to vibration damage using an exciter vibration Table and a force transducer to evaluate the damage on the apple. Three types of cushioning materials (foam-net, paper-wrap and without (control)) were used. The foam-net package was concluded to be the most suitable for packaging and it reduced the percentage of fruit damage by 50–63%.

Vibration due to transportation is influenced by the road roughness, distance, traveling speed, truck suspension, load and number of axles (Berardinelli et al., 2003; Vursavus and Ozguven, 2004; Idah et al., 2012; Pathare and Opara, 2014). Although, damage caused by vibration on different species of fruits and vegetables such as apricot, tomatoes, grapes and pears etc. have been assessed by several authors as reported by Berardinelli et al. (2005), very little knowledge is available on package and fruit interaction when subjected to vibration. A clear understanding of the behaviour of package and produce under static and dynamic loads provides information in minimising the mechanical damage to packaged produce and enhancing the quality of fresh horticultural produce (Jarimopas et al., 2005; Idah et al., 2012; Eissa et al., 2012). Careful handling and proper packaging have been reported to reduce mechanical damage (Singh et al., 1992). Minimised mechanical damage would ensure that the produce gets to the ultimate users in a desirable condition.

As reported by Pathare et al. (2012), ventilated paperboard carton is commonly used for handling fresh fruit and Berry et al. (2015) also described a wide range of ventilated package designs for handling different produce in the fresh fruit industry. Previous studies have demonstrated the significant effect of package design on the cooling performance of ventilated package designs used in handling of fresh fruit, including energy use and efficiency (Zou et al., 2006a,b; Delele et al., 2013a; Delele et al., 2013b; Defraeye et al., 2013, 2014; Han et al., 2015). A recent study by Fadiji et al. (2016) reported the significant influence of package design in protecting apple fruit subjected to impact. Although, there exist a vast knowledge on the preharvest and postharvest factors contributing to fruit bruising especially when subjected to mechanical loadings (Opara, 2007; Van Zeebroeck et al., 2007a, b; Opara and Pathare, 2014). Little is known about the bruise of fruit packed inside ventilated paperboard carton during simulated transport damage. The objective of this research was to simulate the transport damage on ventilated paperboard packages and evaluate the susceptibility of packed apples inside the packages to vibration bruise damage, including the spatial variability and severity of bruise occurrence inside the package.

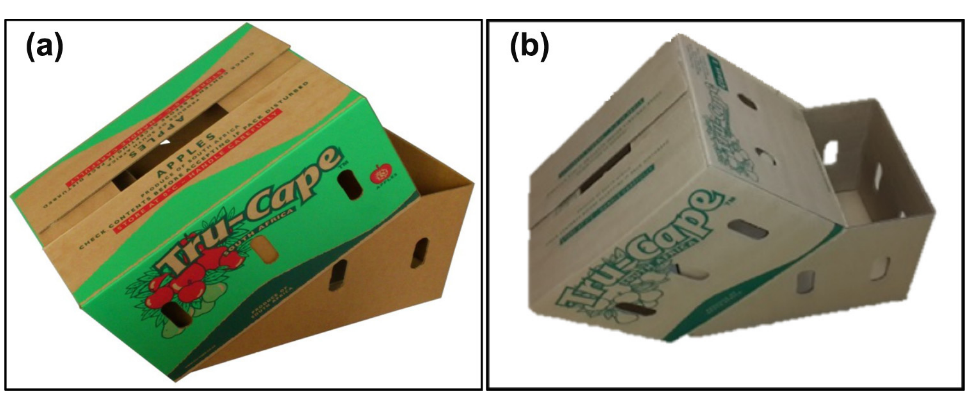

Fig. 1. (a) MK4 package and (b) MK6 package. Both MK4 and MK6 package designs have three oblong shaped vent holes oriented vertically on the long side of the package and the total area of the vent were 5007 mm^2 and 4241 mm^2, respectively. MK6 package has a lower length–to–height ratio of 1.45 and shorter trays, compared to the length–to–height ratio of 1.86 for MK4 package with longer trays.

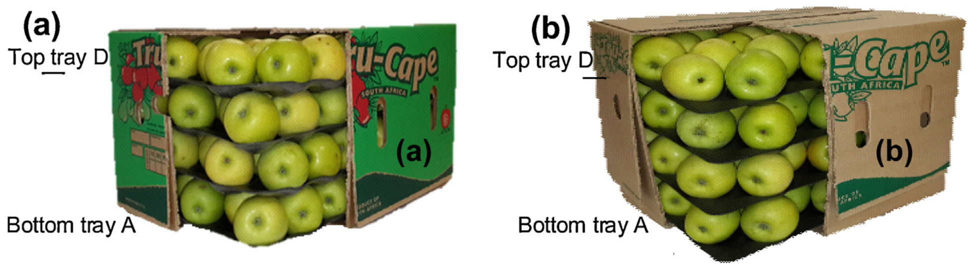

Fig. 2. (a) Tray arrangement inside MK4 package and (b) Tray arrangement inside MK6 package.

2. Materials and methods

2.1. Fruit supply

'Golden Delicious' apples were purchased during commercial harvest from a packhouse in Grabouw, Western Cape, South Africa (34°48′14″S,19°02′50″E) and transported to the Postharvest Research Laboratory, Stellenbosch University, South Africa. The duration of the transportation was about 42 min. The apple cultivar used for the experiments was selected because of its high susceptibility to bruising and bruises are easy to visually observe. Fruit of uniform size and maturity based on background colour, firmness and free from physical defects were used for the experiments. The mean diameter and mass of the apples were 65 ± 2.0 mm and 148.7 ± 7.0 g, respectively. The packed apples inside the ventilated paperboard packages were stored at 3 °C and 90% relative humidity for two days prior to the simulated transport test which was done at the ambient temperature.

2.2. Packaging materials and preparation

The experiment was conducted using two ventilated paperboard package designs which are most commonly used for handling apples in international trade in the South Africa pome fruit industry; referred to as MK4 and MK6, respectively. Both package designs consist of separate inner and outer boxes (Fig. 1). The MK4 package dimensions (length × width × height) were 495 mm × 326 mm × 266 mm externally and 488 mm × 319 mm × 266 mm internally while the MK6 package were 395 mm × 293 mm × 272 mm and 388 mm × 286 mm × 272 mm externally and internally, respectively. For both package designs, the internal packaging consists of four layers of trays. Fruit were placed on the tray layers inside each package, resulting in a gross package mass of 18 kg and 13.3 kg, respectively, for MK4 and MK6 package design. MK4 package is designed to hold 120 apples per package, with 30 apples per layer while MK6 is designed to hold 84 apples per package, with 21 apples per layer. The trays were labelled A to D, starting with the bottom tray (Fig. 2). Fruit were placed carefully inside the moulded pockets of the trays with the flower stalk in the horizontal and in the same direction for all the fruit (Fig. 2). Both MK4 and MK6 package designs have three oblong shaped vent holes oriented vertically on the long side of the package and the total area of the vent were 5007 mm^2 and 4241 mm^2, respectively. MK6 package has a lower length–to–height ratio of 1.45 and shorter trays, compared to the length–to–height ratio of 1.86 for MK4 package and longer trays.

2.3. Vibration test

An electro-dynamic shaker (Brüel and Kjær, Model L148) driven by a power amplifier was used. Three ICP 333B32 accelerometers (PCB Piezotronics, Inc., Depew, New York, USA) were used. Two of

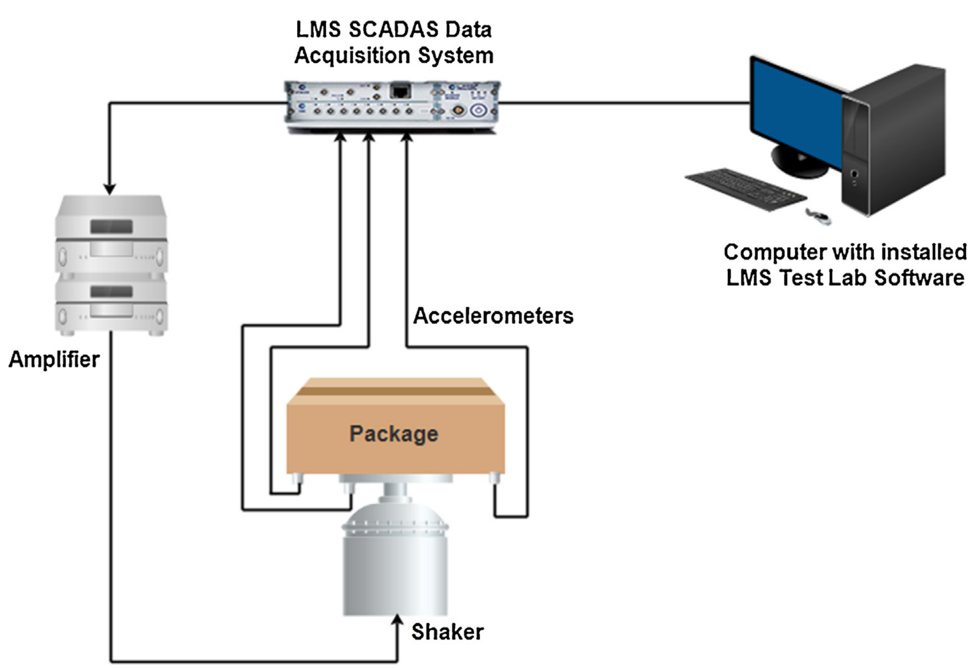

Fig. 3. Schematic layout of the system used for the vibration analysis.

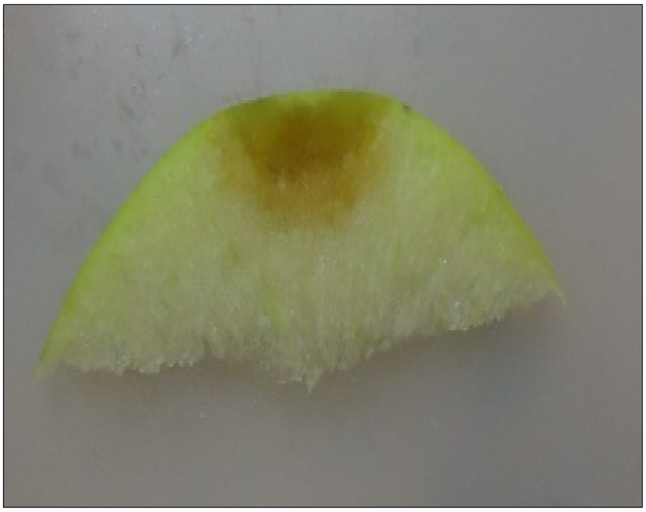

Fig. 4. Section of the apple prepared for the bruise depth measurement.

the accelerometers were fixed at two opposite corners at the bottom of the package while the third accelerometer was fixed on the shaker. The LMS SCADAS system (Model SCM01) was used for data acquisition. The schematic layout of the system used for the vibration analysis is shown in Fig. 3. Firstly, a vibration sweep test was done to determine the frequencies with the greatest responses on both MK4 and MK6 package designs, by sweeping over the frequency ranges normally encountered during road transportation and this was over the range of 0–100Hz. The ASTM D4169-09 Standard was adopted for the test. Based on the data obtained from the sweep tests and the highest frequency response obtained, the package filled with fruit was subjected to vibration at three frequencies; 9, 12 and 15 Hz at an amplitude of 0.9 g at specified duration of 4 h at the ambient temperature. Two replicates for both package designs were completed for the vibration test at each frequency.

Packaging transmissibility at each frequency was calculated using the following equation (Vursavus and Ozguven, 2004; Idah et al., 2012):

$$P_T = {}^{a_b}/_{a_t} \times 100 \quad (1)$$

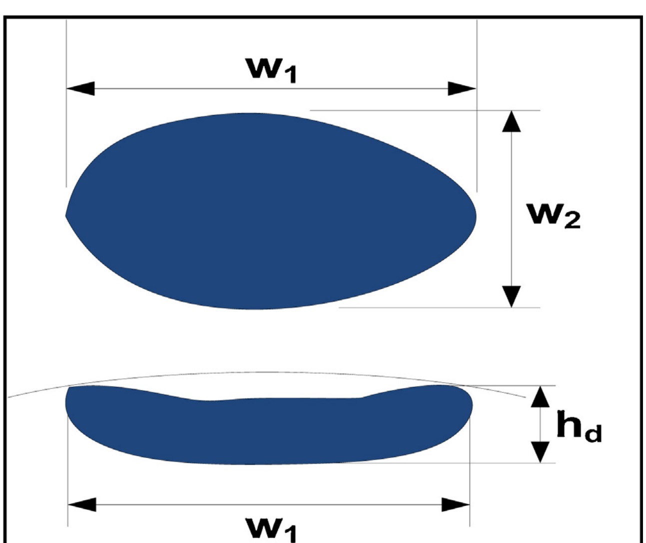

Fig. 5. Elliptical bruise thickness method for bruise size determination.

where P_T =packaging transmissibility (%),a_b = vibration acceleration on the package (g), a_t = vibration acceleration on the shaker (g).

2.4. Bruise measurement and analysis

The apples were left at room temperature for 24 h after completion of the vibration test for full development of bruises and for the bruises to become visible and easy to see. Bruise dimensions (major and minor width, and depth) were measured using digital callipers (±0.01mm). Bruise depth was measured by cutting perpendicularly along the major axis of the fruit. Bruise area (*BA*) and bruise volume (*BV*) were quantified by assuming an elliptical bruise shape (Bollen et al., 1999; Lu et al., 2010; Opara and Pathare, 2014; Fadiji et al., 2016):

$$BA = {}^{\pi}/_{4} w_1 w_2 \quad (2)$$

where w_1 and w_2 are the bruise width along the major and minor axes (mm).

$$BV = \pi^{d_b}\Big/_{24}\left(3w_1w_2 + 4d_b^2\right) \quad (3)$$

where d_b is the depth of the bruise (mm). Fig. 4 shows a typical cut section through bruised tissue while Fig. 5 shows the bruise dimensions.

2.5. Package damage

After the vibration test, a subjective pass/fail determination was made on the package. A package passed if it had no major gaps or tears, retained all products and could still be manually handled. Conversely, a package was deemed to have failed if it had major holes or gaps, the contents spilled out or was exposed, or if the package could no longer be manually handled.

2.6. Statistical analysis

The experimental data were treated with one-way analysis of variance (ANOVA) at 95% confidence level and with the differences at $p < 0.05$ considered statistically significant. The statistical tests were performed using Statistica (v. 11.0, Statsoft, USA). Graphical representations were made using GraphicPad Prism 6 software (GraphicPad Software, Inc., San Diego, USA).

3. Results and discussion

3.1. Effects of frequency and package design on packaging transmissibility

Fig. 6 shows a typical transmissibility curve for frequencies with the greatest responses for both MK4 and MK6 package designs. As shown in Fig. 7, the highest and lowest packaging transmissibility was observed at a frequency of 9 Hz and 15 Hz respectively for the MK4 package with a difference of 25%. For MK6 package, the highest packaging transmissibility was 243% at a frequency of 12 Hz while the lowest was 123% at a frequency of 9 Hz. When comparing the packaging transmissibility for both package designs at the three frequencies, there was no significant difference observed, although both package designs responded differently to increase in vibration frequency. When comparing both package designs, the highest packaging transmissibility occurred on the MK6 package design at a frequency of 12 Hz with a difference of about 98% when compared to the lowest packaging transmissibility that occurred at a frequency of 9 Hz on the MK6 package. The variability observed in the packaging transmissibility for both package designs may be attributed to the weight of the packages.

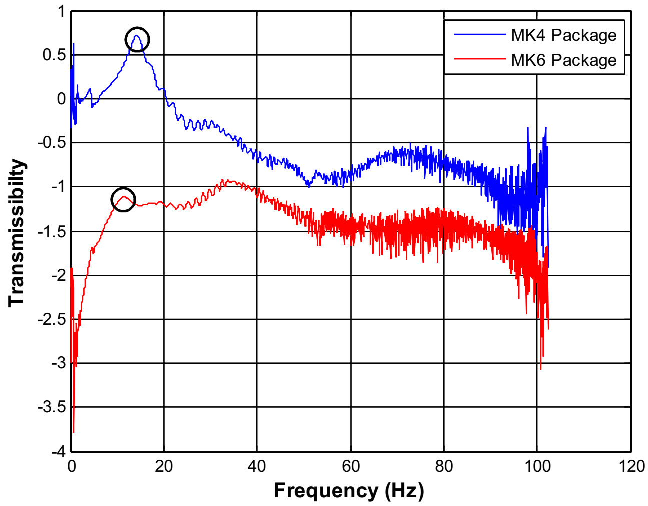

Fig. 6. Typical transmissibility curve for the ventilated paperboard packages. The vertical axis (transmissibility) was drawn with a logarithmic scale and the small black circles indicate the frequency with the greatest response.

The weight of the package causes resistance to acceleration and stores energy which must be expended to accelerate the package. As can be seen from Fig. 7, the highest packaging transmissibility for MK4 package design, with the highest weight of 18 kg occurred at a higher period (9 Hz) compared to the period (12 Hz) for which the highest packaging transmissibility occurred for MK6 package design. The packaging transmissibility obtained for both package designs (MK4 and MK6) at the three frequencies was observed to be above the green horizontal dash line at 100% (Fig. 7). This indicated that the vibration of both package designs occurred at higher acceleration levels than the shaker. Consequently, this seems to indicate that the selected frequencies are far above the critical range for both package designs. Usually, the irregular nature of vibration inputs makes it difficult to define a threshold for vibration damage and fruit will tend to vibrate when a frequency of vibration reaches a certain level (Sitkei, 1986; Shahbazi et al., 2010). When the resonance frequency of the fruit column is the same as the excitation frequency, the acceleration of the fruit can be considerably amplified as a result of the resonance which can lead to severe damage of the fruit (Sitkei, 1986; Jarimopas et al., 2005; Van Zeebroeck et al., 2007a,b; Shahbazi et al., 2010). In the report by Van Zeebroeck et al. (2007a,b), apples in bulk bin have the most movement at frequency between 7 and 15 Hz Similar results to the present study were reported by Vursavus and Ozguven (2004) who measured the packaging transmisssibilty of three apple packaging methods; paper pulp tray, pattern and volume packaging methods. The authors reported that the most critical frequencies occurred between 3 and 15 Hz for all packaging methods, with the highest packaging transmissibilty observed at a vibration interval of 8–9 Hz.

3.2. Effects of frequency and package design on bruising of apples

Fig. 8 shows the total bruise area and volume of apple fruit inside both the MK4 and MK6 package designs at frequencies of 9, 12 and 15 Hz. For MK4 package design, when comparing the bruise area of the apple fruit inside the package for the three frequencies used in this study, the largest bruise area of 588.32 mm^2 occurred at a frequency of 9 Hz while the smallest bruise area of 571.92 mm^2 occurred at a frequency of 15 Hz. The largest and smallest apple bruise area observed at these frequencies can be attributed to the packaging transmissibility of the MK4 package design at the same frequencies (9 and 15 Hz) which were observed to be the highest and lowest respectively. Due to the high packaging transmissibility, vibration forces transmitted from the shaker to the apple package are absorbed by the fruit in the package, thereby causing bruise damage (Vursavus and Ozguven, 2004). For MK6 package design, the apple fruit bruise area at 9 Hz was significantly different to the bruise area at 12 Hz. However, there was no significant difference between the apple fruit bruise area at 15 Hz to the bruise area at frequencies of 9 and 12 Hz. The largest bruise area for MK6 package

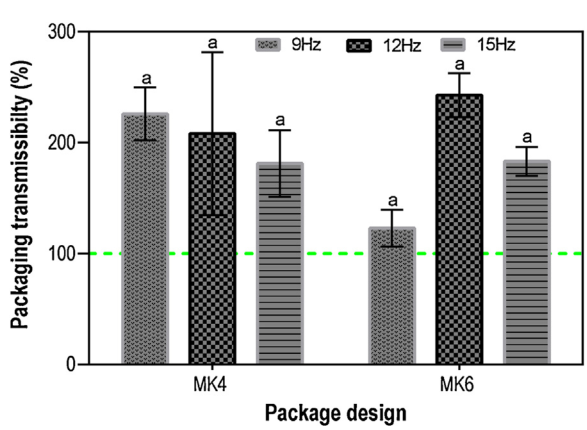

Fig. 7. Effect of vibration frequency on packaging transmissibility. Bars indicate standard error and different lower case letters indicate significant differences at $p < 0.05$.

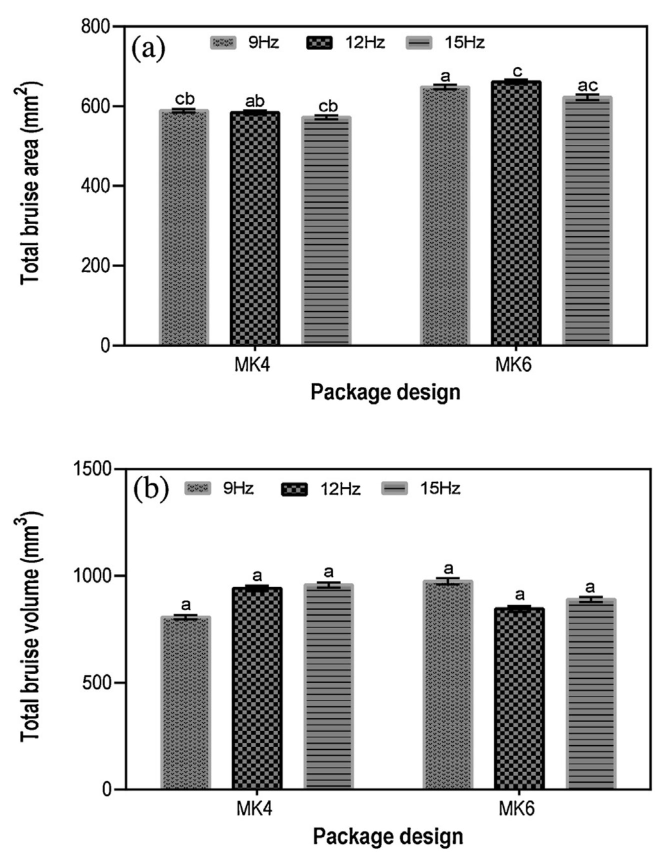

Fig. 8. Total apple bruising (a) Bruise area (b) Bruise volume inside the ventilated paperboard packages. Bars indicate standard error and different lower case letters indicate significant differences at $p < 0.05$.

was 661.10 mm^2 and it occurred at a frequency of 12 Hz which corresponded to the frequency with the highest packaging transmissibility while the lowest was 622.07 mm^2 at 15 Hz. The apple fruit bruise area at 9 Hz for the MK6 package was significantly different from the bruise area at 12 Hz for MK6 package, and at frequencies of 9 and 15 Hz for the MK4 package. For the three frequencies used in this present study, the largest apple fruit bruise area occurred was observed in MK6 package design. This indicated that the MK6 package transmitted more damage to the fruit packed inside and this may be attributed to the dimension of the package as MK6 package has a lower length–to–height ratio of 1.45, compared to the length–to–height ratio of 1.86 for MK4 package. The apple fruit inside the MK4 package have lesser apple–to–apple impact during vibration than the fruit inside the MK6 package. Bruising in fruits usually occur when the produce rub against each other, packaging containers and parts of the processing equipment (Van Zeebroeck et al., 2007a,b; Altisent, 1991). The apple fruit bruise area which was largest at a frequency of 9 Hz for MK4 package and 12 Hz for MK6 package corresponding to the highest packaging transmissibility for MK4 package and MK6 package respectively was within close proximity to the frequency reported in a similar study by Vursavus and Ozguven, (2004). The authors reported that all packaging methods (paper pulp tray, pattern and volume packaging methods) were most sensitive to a vibration frequency of 9 Hz, and this is a common vibration frequency measured on a truck-bed. In the study, the authors used frequencies between the range of 3–15 Hz. In another study, Tabatabaekoloor et al. (2013) investigated the effects of mechanical parameters such as vibration frequency (7.5 and 13 Hz), vibration acceleration (0.3 and 0.7 g), stack height (11, 23 and 34 cm) and size of kiwifruit (large or small) packed in a bin on the damage during transportation by simulating the transport vibration. The authors reported that the largest damage to the kiwifruits occurred at a vibration frequency of 13Hz, vibration acceleration of 0.7 g, stack height of 34 cm and the larger kiwifruits were more prone to damage than the smaller ones.

When comparing the bruise volume of both MK4 and MK6 package designs, there was no significant difference at the three frequencies. For MK4 package design, the largest apple fruit bruise volume was 957.10 mm^3 and it was observed at a frequency of 15 Hz while the smallest apple bruise volume was 806.46 mm^3 at 9 Hz. The largest bruise volume for apple fruit packed inside the MK6 package design was 974.75 mm^3 at 9 Hz with about 14.6% and 15.3% decrease at 15 Hz and 12 Hz, respectively. As can be seen from Fig. 9, the number of bruised apples varied between the two package designs at the three frequencies used in this present study.

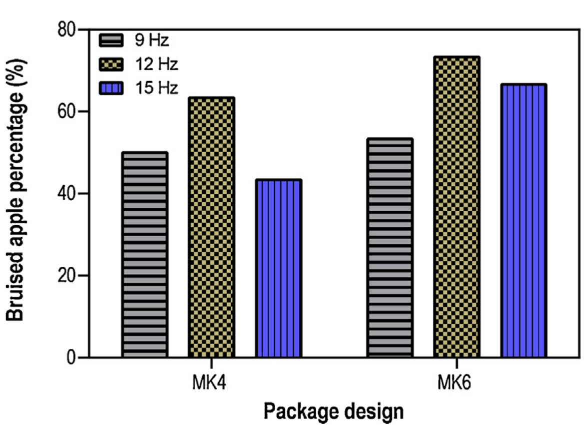

Fig. 9. The proportion of bruised apples inside the ventilated paperboard packages at different frequencies.

The range of the proportion of number of bruised apples was between 50 and 74%, which are rather extreme conditions, with the highest bruise proportion of about 73.3% observed in MK6 package design at a frequency of 12 Hz while the lowest was observed at 9 Hz in MK6 package design with a proportion of about 53.3%. For MK4 package design, the highest and lowest bruise proportion were about 63.3% and 50% observed at 12 Hz and 15 Hz, respectively. The high damage observed may be due to vibration associated with pressure which causes friction of the fruit against the wall of the package (Barchi et al., 2002). Vibration during transport was reported by Acıcan et al. (2007) and Remón et al. (2003) to be one of the major causes of mechanical damage to fresh fruits. Singh and Xu (1993) reported that as many 80% of delicate fruit such as apples can be damaged during simulated transportation by truck, depending on the type of truck, packaging methods, and the position of the container along the column. A high susceptibility of apples to vibration damage during transportation was also confirmed by Schulte Pason et al. (1990) and Timm et al. (1996).

3.3. Spatial variation of apple bruising in relation to vibration frequency and package design

Fig. 10a and b shows the bruise area and volume of apple fruit at different positions inside the package, respectively. For MK4 package at 9 Hz, tray A at the bottom of the package had the largest fruit bruise area of 159.47 mm^2 with a reduction of about 15% on the fruit in tray D, placed at the top of the package with the smallest fruit bruise area. At 12 Hz, the largest and smallest fruit bruise area occurred on tray C which is the second tray from the top of the package and tray A at the bottom of the package, respectively. The scenario was different at 15 Hz, with the topmost tray D having the largest fruit bruise area while the smallest fruit bruise area was observed on tray B; the second tray from the bottom of the package. The largest fruit bruise area observed at the topmost tray D may be attributed to increasing peak acceleration from the bottom to the top of the package due to the vibration load (O'Brien et al., 1965; Mohsenin, 1986; Van Zeebroeck et al., 2007a, b). O'Brien and Guillou (1969) reported damage to be greatest on the top layers of the fruit in the bin which may extend down two to three layers under severe transport conditions. There was no significant difference between the fruit bruise areas on tray A at the bottom of the package at 9 Hz, tray A at 12 Hz and tray C at 15 Hz. For MK6 package at 9 Hz, the largest fruit bruise area was 176.85 mm^2 while the smallest was 160.61 mm^2 observed on the topmost tray D and bottom tray A, respectively. At 12 Hz, tray B had the highest fruit bruise area compared to the apple fruit on other trays inside the MK6 package, with the lowest fruit bruise area observed on tray D. According to Slaughter et al. (1993), the fruit packed at the top in a container is prone to the greatest damage due to the higher acceleration levels in the upper containers. Similar observations were reported by Zhou et al. (2007), although these authors studied the effects of vibration levels on pears. At 15Hz, the largest fruit bruise area was 176.89 mm^2 on tray B; the second tray from the bottom and the lowest was 134.83 mm^2 on bottom tray A. The fruit bruise area on bottom trays A at 9 and 12 Hz for MK6 package was not significantly different from the fruit bruise area on trays B and C; second tray from the bottom and second tray from the top, respectively at 9 Hz. At 9 Hz for MK6 package, it was also observed that the fruit bruise area increased from the bottom tray A to the top tray Mohsenin (1986) reported that peach fruit damage due to vibration increases gradually from the bottom layer to the topmost layer in a package. Usually in stacked or palletised produce, vibration can be directed upwards through the stack thereby increasing the magnitude at higher levels and this may result in vibration damage to be severe at the top of the stack

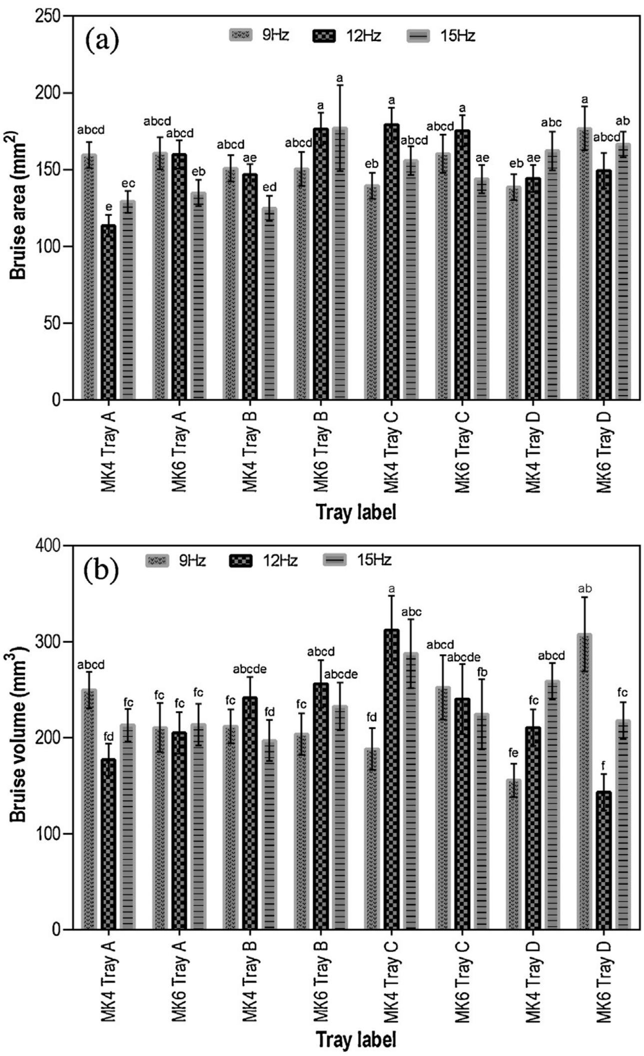

Fig. 10. Spatial variation of bruise inside the different package designs (a) Bruise area; (b) Bruise volume. Tray D is the topmost tray while tray A is the tray at the bottom of the package. Bars indicate standard error and different lower case letters indicate significant differences at $p < 0.05$.

(Sitkei, 1986; Shahbazi et al., 2010). Consequently, displaced cartons and vibration damage are most common at the top of the stack. Furthermore, vibration damage inside a package is usually localised at the top layers since fruit packed on the top layer are most capable of movement (Shahbazi et al., 2010). Similarly, the study by Vursavus and Ozguven (2004) reported that apples placed in trays at the top layer subjected to vibration are more susceptible to bruising. The fruit packed on the top layer move freely because the energy the fruit receive due to the vibration is sufficient enough to make them intermittently weightless.

Another study by Jarimopas et al. (2005) measured the vibration levels in two commercial truck types used for shipment of produce as a function of road condition and vehicle speed and the bruising of tangerine fruit packed in reusable high density polythylene (HDPE) plastic containers after vibration. The authors found that the fruit damage was largest in the topmost container for every combination of road, truck type and travelling speed which corresponded to the highest vibration level recorded. Largest damage to pears packed inside reusable plastic container in the top layer of the container was also reported by Zhou et al. (2007) with smallest damage in the bottom. This can be attributed to the higher acceleration in the topmost container (Slaughter et al., 1993). The freedom of motion of the fruit is usually high for the top layer but decreases with depth of the fruit (Van Zeebroeck et al., 2006). The study by Armstrong et al. (1991) reported, using a video camera, a peak in the motion of apples, occurred primarily in the top layers for hardwood bins and rigid metal bins at 11 and 14 Hz, respectively. In contrast, other authors reported that fruit damage subjected to vibration gradually decreases from the bottom layer to the top layer (Holt et al., 1981; Armstrong et al., 1991; Jones et al., 1991).

When comparing the apple bruise volume for MK4 and MK6 packages, the largest apple bruise volume was 312.26 mm^3 and it was observed on tray C; the second tray below the topmost tray, at 12 Hz inside the MK4 package, while the smallest apple bruise area was 143.45 mm^3 observed on topmost tray D at 12 Hz inside the MK6 package. For MK4 package at 9 Hz, the largest apple bruise volume was 249.90 mm^3 and it was measured on bottom tray A with a reduction of about 60% on the topmost tray D where the smallest apple bruise volume was observed. This finding is in agreement with the study by Armstrong et al. (1991) who using a video camera reported that the highest peak in the motion of the apple occurred in the top layers, although the apple fruit was

Fig. 11. Cracked trays after the vibration test.

packed inside hardwood bins and rigid metal bins in contrast to this present study where the apple fruit was packed inside ventilated corrugated paperboard packages. Also, it was observed that at a frequency of 9 Hz for the apples packed inside the MK6 package, apple fruit on the topmost tray D had the largest bruise volume while the apple fruit on the bottom tray A had the smallest bruise volume. This is confirmed by Fischer et al. (1992) who determined the changes in fruit quality before simulated shipping by using artificial vibrations at 2–30 Hz after harvest. The authors detected damage in the fruits at a height of 9–15 crates and reported that the greatest damage occurred on the fruits in the topmost crates at vibrations of 5–10 Hz. The reduction from the largest to the smallest apple bruise area and volume on all the trays was in the range of 10–75% at all the three frequencies for both MK4 and MK6 packages designs.

3.4. Package damage

A good package should be able to protect the fruit and reduce the amount of damage incurred by the fruit. The package being an integral and important part of the distribution system, requires an acceptable damage at a minimum cost. After the vibration test, a subjective evaluation of both package designs was done. There was no visible damage externally to either type of packaging at all the frequencies used (9, 12 and 15 Hz) in this present study, however there was a crack in the trays inside the package for both types (Fig. 11). The trays absorbed energy due to vibration, thereby minimising the bruise on the apple fruit.

4. Conclusion

This research investigated the susceptibility of apple fruit to bruising inside two ventilated corrugated paperboard package (MK4 and MK6 package designs) commonly used in fresh fruit industry during a simulated transport damage. Both MK4 and MK6 package designs have three oblong shaped vent holes oriented vertically on the long side of the package and the total area of the vent were 5007 mm^2 and 4241 mm^2, respectively. MK6 package has a lower length–to–height ratio of 1.45 and shorter trays, compared to the length–to–height ratio of 1.86 for MK4 package with longer trays. Simulated transport vibration was done at three frequencies; 9, 12 and 15 Hz. Package design had a significant influence on the bruise damage incurred by the apple fruit. Apple fruit packed inside the MK6 package had more bruise damage than the apple fruit inside the MK4 package with a difference in the range of 9–13% for all the frequencies. The largest apple fruit bruise area occurred inside the MK6 package at a frequency of 12 Hz, where the greatest packaging transmissibility of 243% was observed. The range of the proportion of number of bruised apples was between 50 and 74% at all the three frequencies for both MK4 and MK6 packages designs, which are rather extreme conditions. The apple fruit at the top tray was observed to be more susceptible to bruise damage as fruit packed on the top layer are most capable of movement due to increasing peak acceleration from the bottom to the top of the package. Therefore, the use of cushioning materials will be economical in minimising damage incurred by the fruit. Furthermore, no visible damage occurred on the package externally, however there was a crack to the trays inside both package designs at all three frequencies. This research can be of great importance to packaging designers and handlers of various fresh produce at different transportation and distribution stages. This will reduce losses due to mechanical damage especially due to vibration and will ensure that good quality fruit are delivered to the final consumers.

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