EVALUATION ALTERNATIVE METHODS OF BRUISE MEASUREMENTS IN APPLE FRUIT

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ABSTRACT

A study has been conducted to compare different methods to measure bruise susceptibility of fruit. In order to compare measured values with actual commercial bruising, an appropriate test method to simulate impact damage during handling was developed, employing a revolving tumbler.

From the analysis of bruise damage produced by the tumbler on four apple cultivars under different storage treatments, it was found that a large percentage of bruises were less than 1.5 cm^2 in area, and the number of bruises above 1.5 cm^2 did not change between treatments. It was concluded that laboratory measurements involving high impact energy levels may be insensitive as indicators of bruising levels on fruit during commercial operations. The impact loads produced by this method was very similar to those incurred by a practical grader, as indicated by Instrumented Sphere measurements. The tumbler test permitted examination of actual grader damage relationships with standard tests.

Three standard impact tests (vertical drop test, double and single pendulum test) were conducted on four cultivar apples: Splendour, Granny Smith, Pacific Rose, and Braeburn. Four different shapes of impact surface were used for each impact test. It was found that bruise susceptibility varied with different impact tests. Regression analysis was made on the data obtained from standard impact tests and tumbler test to find the correlation between the bruise susceptibility and the bruise area/apple.

Bruise susceptibility obtained from the vertical drop test using the hockey ball was closely related to the bruise area per apple produced by the tumbler test ($R^2 = 0.72$). The bruise factor obtained from the single pendulum test using the flat indenter also showed a correlation with the bruise area per apple produced by the tumbler test ($R^2 = 0.78$). However, the bruise susceptibility produced by the double pendulum test and single pendulum test was not well correlated with the bruise area/apple and bruise number /apple produced by tumbler test. The bruise susceptibility produced by using the pyramid indenters from three standard impact tests was not well correlated with the bruise area per apple and the number of bruises per apple produced by the tumbler test.

Bruise susceptibility, bruise area, and the shape of the bruise depended upon the shape of the indenter used for the experiment and the method used to conduct the impact tests. Splendour, Granny Smith and Pacific Rose all had similar bruise susceptibilities, but Braeburn was significant less susceptible to bruising. Generally, bruise susceptibility increased with storage time in all cultivars. Apples stored in a low humidity environment (65% RH) generally had lower bruise susceptibilities after 2 months storage for the flat and hockey ball indenters but not for pyramid indenters on Splendour and Braeburn apples, when compared with 90% RH storage. Bruise susceptibilities at 0.5° C were higher than at room temperature. Fruit firmness also decreased with storage time.

Bruise shape depended upon the indenter surface shape. The flatter indenters produced bruises which were less deep than the hockey ball and pyramids. The bruise shape was elliptical for the flat plate, a circle for the hockey ball, and a rhombic for the pyramid indenters. There was no cracking below the bruise region for any apples when the flat plate indenter was used in the three standard impact tests. However cracks were found below the bruise region in Splendour, Pacific Rose, and Braeburn apple (but not for Granny Smith apples) when any pyramid indenter was used. The pyramid indenters produced a more linear relationship between a 2/3 power impact energy and bruise area (without skin removal) than either a spherical or a flat indenter.

Bruise visibility depended on the impact surface shape and energy levels. Some bruise produced from standard impact tests, when the flat indenter used, were not visible unless the apple skin was removed. Braeburn required a greater impact energy to produce an initial bruise than other cultivars. Once bruising began the visibility of bruising increased with an increase in energy levels.

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CHAPTER ONE

INTRODUCTION

1.1 Statement of the problem

The postharvest handling of fruit and vegetables subjects produce to numerous impact and compressive forces. In many cases these forces exceed the elastic limit of the product and result in damage. Internationally, mechanical damage is the major cause of postharvest losses (FAO, 1989) and considerable research effort is required to increase understanding of the physical and physiological factors involved which will lead to improved handling systems.

Apple is one of New Zealand's most important horticultural export earners. In 1995-1996 season, the fresh fruit exports were valued at $991.4 million, of which apple fruit contributing to $517 million (52.2 percent). Thus apples are the most important fruit exported overseas (New Zealand Official Yearbook, 1997).

Mechanical damage is a major problem in the mechanical harvesting and handling of fruit. Contemporary systems of mechanical harvesting and handling of fruits involve many operations causing impacts or transient loading to the fruits. A fruit could be subjected to impact at different stages during the mechanical harvesting and handling system from harvesting through to the consumer. It is well known that bruising results from excessive force on the fruit surface, but it is not clear which factors determine the differences in bruising susceptibility of fruit to a given force (Topping and Luton, 1986). Bruises can be produced in a number of different ways, and especially by impact. The main types of impacts to which fruit is subjected are impact of fruit on hard or inadequately cushioned surfaces, impact of one fruit on another, and impact of fruit on a tree's limb. Each case represents a specific situation of impact in which the stresses and strains occur in different patterns. Bruising can result in poor quality, increased water loss and postharvest decay, and reduce the income of apple growers.

Bruise damage in apples and other pipfruit is a major problem in the quality fresh fruit industry. The degree of bruising damage on a fruit surface directly influences its saleability. Downgrading losses can be as high as 50%, depending on the cultivar, and how easily it bruises (Studman, 1995). According to Max and Banks (1994), each year New Zealand growers reject approximately $25M worth of apples from export grade because bruising exceeds quality standards.

A number of impact tests have been developed by many researchers who have studied the bruise susceptibility (or resistance) of fruit in. The common objective of these works was to supply data and methods to be used by the developing engineers in the design of mechanical harvesters and handling systems for fruits. The secondary objective was to obtain a better understanding of the phenomenon of fruit damage during impact. The four main of impact tests were used, drop test of a fruit, falling mass or plunger on a fruit, pendulum tests, and impact test by a ram (spring, pneumatic, or electric) striking the fruit.

In establishing a suitable test, one issue to be considered is the difference between a measurable bruise and one, which is commercially significant. While it is easy to measure brown area and volumes of apple tissue after removal of skin, industry requirements are generally based on the size of a bruise visible before the skin is removed. Bruise area is most commonly used by industry in setting acceptable quality standards due to the ono-destructive method of visual assessment. According to the worldwide standards for export fruit adopted by ENZAFRUIT, any apple with an accumulated bruise area exceeding 1 cm^2 should be rejected. In research, bruise area is often measured after peeling off the skin to avoid the influence of skin colour on the visibility of bruises. It is important to be confident that the bruising values obtained by these approaches are reliable measures of commercially important fruit bruising in practical situations (Studman, 1995).

The apple industry is particularly concerned about fruit damage during handling and transport operations. Essential information for the fruit industry should include guidance on how temperature, maturity and storage time affect bruising in practice, as well as an appreciation of bruising differences between fruit cultivars, and an understanding of seasonal differences. Although the cause of bruising is well known, *viz.* excessive force on the fruit surface, many factors, which can alter the level of bruising, have also been studied, but it is still not clear which factors determine the differences in susceptibility of fruit to a given force. Moreover, researchers have obtained conflicting results. Thus, Klein (1987) found that apple temperature had no effect on bruise susceptibility. Others indicated that bruise susceptibility increased (Saltveit, 1984), decreased (Pang, 1993), or both increased and decreased (Gil et al., 1984) with increasing fruit temperature. Conflicting research results on the effects of storage times and fruit maturity have also been reported. As a result of these problems, many commercial operators have disputed the validity of laboratory results.

Bruise area and bruise volume has been commonly used by previous researchers and quality controllers, but little work on the importance of the number of bruises has been found in the literature. Apple sales depend to a considerable extent on appearance, and several small bruises can make the apples less attractive to the consumers (Gaston and Levin, 1951). The appearance could be influenced by the number of bruises as much as the absolute bruises size. Maintaining high quality standards involves the rapid inspection and removal of bruised fruit, and the avoidance of subsequent damage to the fruit after inspection (Pang, 1993).

1.2 Objectives

The objectives of this study were:

- To examine and compare different methods of impact test.
- To determine an approach for assessing bruise damage which correlates closely with the actual damage produced by a handling operation.
- To examine and compare methods of determining fruit bruise susceptibility.
- To determine the effects of temperature, storage condition and time of storage on bruise susceptibility.
- To investigate the effects of indentor shape on bruise susceptibility.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Apple bruises detract from the market quality of fruits. Bruises, stem punctures, and other forms of mechanical damage detract from the appearance of the product and reduce storage life by allowing pathogenic organisms to enter and cause decay. Bruising and similar types of mechanical injury or damage can lead to significant economic losses during the storage, handling, and marketing. Mechanisation of apple harvesting, sorting, and packing has led to increased concern over impact damage to fruit. A reduction in damage can be achieved only if the factors governing susceptibility of fruit to bruising are well understood. The need to understand the factors has led many researchers to investigate the mechanical damage problems of fruit and develop indirect methods of bruise assessment (O'Brien et at. 1973; Holt and Schoorl, 1977, Chen and Yazdani, 1991; Horsfield et al., 1972; Brown et al., 1990) (Bilanski et al., 1984; Klein, 1987; Max and Banks, 1993; Pang, 1993). These indirect measurements are useful only if they correlate closely with actual fruit damage. In this review a range of previous research related to methods of determining fruit bruising, factors which affect bruising levels, theoretical analyses and practical studies of apple impacts is reviewed and discussed.

The quality systems which operate in most postharvest handling systems specify a damage tolerance which is not to be exceeded – for example 'the total bruise area shall not exceed 1 cm^2 in surface area'. This criteria is difficult to interpret in relation to the force/bruise size relationship. In addition the susceptibility can be influenced by numerous factors. The variability of these factors within a crop population will determine the variability of the bruise susceptibility.

2.2 Apple Bruising

2.2.1 Effects of impact on tissue structure

In recent years, several studies (Chen et al. 1986; Diehl et al. 1979; Garcia et al. 1988; Holt and Schoorl 1977a; Topping and Luton 1986) have been carried out to investigate the appearance and development of fruit bruises. Bruising develops in the fruit after a mechanical load is applied, and is evaluated by the amount of tissue softening and discoloration (Coombe 1976). Cellular softening is accomplished by polygalacturonases, pectinmethylesterases, and cellulases degrading cell wall material (Ben Arie and Naomi 1979). Generally, bruise evaluation encompasses direct visual characteristics, such as presence of discontinuities or fractures, and shape and size (Chen et al. 1986; Garcia et al. 1988; Holt and Schoorl 1977; Hyde and Ingle 1968; Topping and Luton 1986). Discontinuities and fractures of them appeared some millimetres below the skin, where the maximum stresses and/or strain is thought to occur. The stress and maximum deformation are greatest slightly beneath the epidermis located in an area that approximately equals the radius of the indentor used to damage the fruit (Horsfield et al. 1972, Miles and Rehkugler 1971).

Holt and Schoorl (1983) studied the fracture in potatoes and apples by slow compression and impact test, and reported that there are three different energy dissipative mechanisms operating when apples are loaded in quasi-static compression and impact loading. Some energy is stored elastically and recovered on the release of the load. Some energy is dissipated in hysteresis. When the stored energy reaches sufficiently high levels, apples fail continuously by bruising and energy is dissipated by this mechanism. The results showed that 30% of the input was dissipated by mechanisms other than bruising and elastic recovery. The proportion of input energy recovered in apples is 0.33 for slow loading and 0.27 for impact and the remainder is absorbed by cell bursting producing bruising. However, Pang et al, (1992) found the recovery depended on the severity of the impact.

Apple tissue is made up of liquid-filled parenchyma cells and it may be postulated that the energy absorbed as hysteresis is dissipated in the cell walls. The liquid within each cell is unlikely to absorb much energy as the cell is distorted. Elastic recovery in apples is probably due to the recovery of elastic deformation in the cell walls (Holt and Schoorl, 1983).

Rodriguez et al. (1990) found that impacted tissue showed a great number of injured cells in the central region, approximately at 9 or 10 mm beneath the skin, but no cell wall rupture. They suggested that polyphenols and polyphenoloxidase meet somewhere in the altered cytoplasm or at the interface of the cell wall causing the browning reaction. Additionally, the altered and broken membranes may leak these compounds from inside of the cell to the intercellular spaces, and thus the oxidative reaction may take place in the intercellular spaces as well. Thus, the browning reaction in fruit under applied loads can take place either outside or inside the cell. They concluded that rupture of the cell wall was not essential, at least in small bruises, for the reaction to succeed. This finding contradicted the finding of Diehl et al. (1979) and Pitt (1982) that cell wall rupture was necessary.

2.2.2 Estimation of apple bruise

There is no one standard method for assessing the severity of a bruise which is agreeable to researchers, customers and industry. Consequently researchers have often designed their own scale for detection and evaluation (Mohsenin, 1984). Research on factors influencing bruising requires techniques, which quantify bruising responses to known severity of impact. The severity of bruise damage depends on the distance the fruit falls, the impact energy, the number of impacts, the type of impact surface, and the size and maturity of the fruit (Chen and Yazdani, 1991). The bruise severity is generally measured in terms of bruise diameter, area or volume, depending on the application of analysis, and there are variations in the calculations of these parameters. Bruise area is most commonly used by industry in setting acceptable quality standards due to the non-destructive method of visual assessment.

Consumers judge bruise severity by bruise visibility, which depends on degree of discoloration and the extent to which the brown colour is masked by apple skin colour. Lighter skinned apples show bruised tissue much more clearly than red skinned cultivars (Banks, 1993).

Bruise dimensions

Grade allocation is influenced by bruise diameter, bruise depth, and number of bruises (USDA, 1978). Diameter (d) and bruise depth (h) are primary measurements that are made to evaluate bruise size. Bruise diameter both with skin on and skin removed are important variables which have been used in many studies (Sober et al., 1989; Brown et al., 1990). Surface area estimation and the number of bruises are factors used by fruit inspectors and consumers when determining the extent of bruise damage. Although bruise diameter can be easily measured with micro-callipers, but bruise depth can only be measured by cutting the apple (Siyami et al. 1988).

Bruise area

Bruise area is the measure, which is most closely related to that used by industry and consumers to determine if an apple satisfies required standards. ENZA Fruit New Zealand stipulates that an export apple should not have more than 1 cm^2 bruised area whilst consumers may differ in what they consider is acceptable (Banks, 1993).

Brown et al. (1990) reported that the present U.S. Grade standards allow one bruise less than 198mm^2 area to be ignored if it is not readily visible. To maintain the Extra Fancy Grade, based on multiple bruises, the total bruise area can not exceed 127 mm^2. They evaluated 25 commercial packing lines and found that the multiple bruises area between 32 and 127 mm^2 were often readily visible, and when accumulated could easily exceed the 127 mm^2 limit. When the apple was peeled, even bruises of 32mm^2 area resulted in brown tissue, which would be objectionable to the consumer.

Bruise Volume Calculation

Mohsenin (1970) described a simple method of bruise volume calculation based on the assumption that the bruise was spherical.

$$V_b = \frac{\pi h}{24}(3d^2 + 4h^2)$$

Where *h* is the depth of bruise at the centre and *d* is the surface diameter of the bruise (mm). Holt and Schoorl (1977) noted that the theory proposed by Mohsenin underestimated the bruise volume due to the effect of the apple deformation on the measurement of depth. They described the bruise shape as being spherical above and below the contact plane. The volumes of bruise above the contact plane, V_2 and below V_1 are shown in Figure 2.1. Total bruise volume, V_b, of the bruise was calculated by:

$$V_b = V_1 + V_2 = \frac{\pi h}{24}(3d^2 + 4h^2) + \frac{\pi x}{24}(3d^2 + 4x^2)$$

Where, the height, x, of the bruising above the contact plane can be calculated:

$$x = R - \sqrt{R^2 - \frac{d^2}{4}}$$

and Where, R is the radius of the apple.

Diener et al. (1979) defined the bruise as a partial sphere, rewriting the equation as:

$$V_b = \frac{\pi}{6} d(0.75D^2 + d^2)$$

Where, d is the depth of bruise centre and D is surface diameter of the bruise.

A more simple formula was used by Chen and Sun (1981). The degree of bruise was evaluated by cutting through the centre of the bruised region and measuring the maximum width the depth of bruise with a scale. The shape of the bruise was assumed to be a semi-oblate spheroid, and the bruise volume, V_b, was estimated by the following relation:

$$V_b = \frac{1}{6}\pi h D^2$$

Where, h and D are the depth and width of bruise, respectively (Ouyang, 1995).

While it is easy to measure brown areas and volumes of apple tissue after removal of skin, industry requirements are generally based on the size of a bruise visible before the skin is

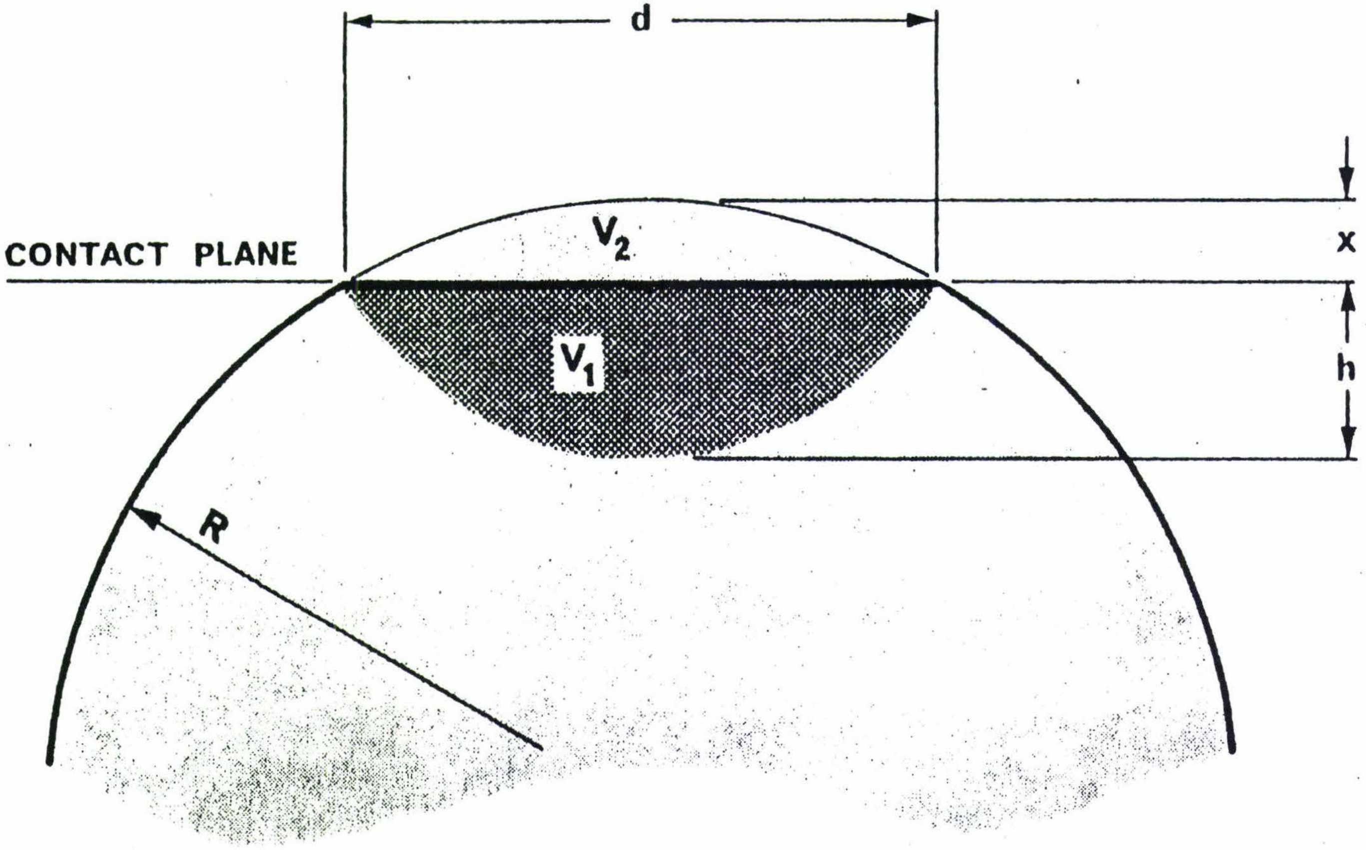


Figure 2.1 Cross-section of idealized bruise showing symbols used by Holt and Schoorl (1977)

removed. In many cultivars this is often difficult to determine, particularly if the threshold bruise area is small. In the New Zealand fruit industry, a simple way has been developed using bruise volume factors (New Zealand Apple and Pear Marketing Board, 1982). The bruise volume is calculated by multiplying bruise diameter by a bruise volume factor dependent on the range of bruise diameter. The factors were obtained experimentally from measurements of a range of bruises and were believed to provide a useful and consistent scale for indicating bruise damage (Pang, 1993).

2.2.3 Bruise colour change

Bruise colour relative to that of the surrounding skin is also important in consumer acceptability of bruised fruit. Consumers judge bruise severity by bruise visibility which depends on degree of discolouration and the extent to which the brown colour is masked by apple skin colour. Intensity of bruise colour has been shown to be associated with the level of phenolic compounds, particularly chlorogenic acid, in apple tissue (Ingle and Hyde 1962). Enzymatic oxidation by polyphenoloxidase and non-enzymatic oxidation of these compounds has been linked to the development of the intensity of brown colour observed in bruised apple tissue soon after bruising. Lighter skinned apples show bruised tissue much more clearly than red skinned cultivars (Mowatt and Banks, 1994).

CoSeting and Lee (1987) and Klein (1987) found that PPO activity was higher in 'Red Delicious' than in the cultivars 'Golden Delicious' and 'Granny Smith'. Klein proposed that high levels of total polyphenols in the peel of red coloured fruit may be because of the greater amount of anthocyanin in them. A study of changes with time in aspects of bruise colour in 'Granny Smith' apples was conducted by Samim and Banks (1993a) and they found that bruised cortical tissue became darker (decreased lightness), browner (decreased hue angle), and increased in colour intensity (increased chroma) in the first few hours following impact. Discoloration subsequently faded gradually with time. To assess bruises at their most intense degree of discoloration, they suggested that bruise should be allowed to develop for a period of 4-14 h before sectioning.

Zocca (1991) tested apple fruit of 16 cultivars to determine the impact response of apple to mechanical harvesting. The samples were bruised by a hard flat object with a 0.2 J force and they found that the lesser extent of browning in the deeply coloured fruit skin is to be ascribed to the fact that the colour in the bruised spots tends to be redder and, hence, less evident, as shown by the fact that there is no correlation between flesh and skin browning. By contrast, flesh browning appears to be correlated to polyphenol content. In the Red Delicious group, bruising was not very apparent but of extensive size, and flesh browning very marked, whereas in the Golden Delicious group, bruising was extensive and highly visible externally but less evident in the flesh.

2.3 Bruise Susceptibility

Bruise susceptibility has been defined as the change in measured bruise volume corresponding to the energy absorbed during either mechanically applied compression or resulting from free fall impacts onto a given surface (Holt and Schoorl, 1977; Brusewitz and Bartsch, 1989; Garcia et al. 1988). Most bruising occurs as a result of impacts. Several researchers have shown that bruising is linearly related to impact energy (Chen and Sun, 1981, Pang et al. 1992), but bruising varies among varieties, and the amount of bruising which occurs at a constant value of impact energy is variable (Garcia et al., 1995).

Previous research has documented differences in apple bruise susceptibility due to cultivar, maturity, and storage time (Klein, 1987; Brusewitz and Bartsch 1989; Hyde and Ingle, 1968; Timm et al., 1989). Physiological and biochemical makeup of a fruit, as well as variations in cell wall thickness, cell packing arrangement, and cell turgidity may account for these differences.

2.3.1 Cultivar

It has been well established that different cultivars exhibit variable tissue damage responses to standard impact energies (Hyde and Ingle, 1968; Topping and Luton, 1986; Klein, 1987). In general, the cultivars that are known to bruise easily are those where the damage was greatest. However, Topping and Luton (1986) found that in Bramley's Seedling apple, bruise susceptibility appeared to be high qualitatively; however, quantitatively, it appeared to be relatively resistant. The explanation for this may be that the homogeneous ground colour of the cultivar, together with the relatively translucent skin, cause blemishes to be more noticeable on Bramley than on red skinned cultivars. It is also possible that the relatively more rapid rate of browning of damaged tissue leads to more noticeable bruising in this cultivar.Vincent (1989) reported that reasons for gross variation in bruise susceptibility between cultivars is probably accounted for by cultivar variation in specific gravity and cellular air space tissue in the outer parenchyma.

2.3.2 Maturity

Klein (1987) found that early maturing cultivars such as 'Cox's Orange Pippin' had higher bruise susceptibility than late maturing cultivars such as 'Granny Smith'. Johnson and Dover (1990) reported that bruising increased as picking date is delayed in ' Bramley′ apple. Hyde and Ingle (1968) found that maturity affected bruise size resulting from a standardised impact. Bruise size increased with advancing maturity. Ruiz (1990) quantified the change in susceptibility associated with ripening: fruit changed from an elastic to a plastic state during ripening and elastic rebound energy decreased from 40% to less than 10%, clearly substantiating increased susceptibility with enhanced maturity. In contrast, Diener et al. (1979) reported that more mature fruit were less easily bruised.

2.3.3 Storage time and temperature

Storage time and temperature are important environmental factors that could govern susceptibility of fruit to bruising. Kader (1992) stated that for each increase of 10 °C above optimum, the rate of deterioration increased two to three-fold. Quality apples need to be kept in coolstore regardless of whether they are for export or local consumption. An understanding of how the apple bruise susceptibility is affected by temperature and storage time would help the apple industry greatly in adjusting operating conditions and pre-conditioning apples to minimise the bruise problem. Because the physical characteristics of the fruit change during storage and vary between varieties, the impact response and corresponding bruise susceptibility of the fruit also vary with storage time. Numerous studies have been undertaken to determine some of these changes and their effect on impact bruise susceptibility.

Hyde and Ingle (1968) reported that bruise susceptibility significantly declined with increased time in storage. This finding has subsequently been confirmed by Diener et al. (1979) and Klein (1987). On the other hand, Brusewitz and Bartsch reported that the change in bruise volume per unit change in total impact energy increased with storage time. However, Holt and Schoorl (1984) reported that bruise susceptibility (bruise volume per unit energy absorbed) remained fairly constant during 18 weeks storage at 2° C. Their explanation for this unchanging bruise resistance was that there was a change in internal mode of tissue failure.

Conflicting effects of temperature on the severity of impact bruising have also been reported in the literature. Quasistatic tests conducted by Nelson and Mohesenin (1968) showed higher values for bioyield point for apples (c.v. McIntosh) at 32° C than at 4° C. The dynamic test in which the apple was used as a pendulum striking a rigid plate showed greater resistance to bruising at 4° C than at 32° C. Apples at lower temperature were 'firmer,' and they were less resistant to internal cell rupture as manifested through their lower values of bioyield force. The higher yield force exhibited at the higher temperature could be due to the reduced turgidity which enabled the cells to undergo a greater deformation without rupturing.

Holt and Schoorl (1977) found no significant effect of temperature on bruising in 'Granny Smith' apples. In contrast, Saltveit (1984) used a drop tester to determine the temperature effects on bruise susceptibility of apple and found significant bruise volume increases with both increasing bruising temperature and holding temperature during bruise development of Starkrimson Delicious' and 'Golden Delicious' apples. Salveit's use of apples that had been stored for six months prior to testing, however, may mean that his results are not comparable to those of other researchers who used fruit that were either freshly harvested or stored for only a few weeks.

Klein (1987) determined the effect of harvest date and length of time in storage on New

Zealand 'Gala' and 'Granny Smith' apples. Apples were bruised once by dropping them on their cheek from 10 or 40 cm onto a wooden table surface. After the first impact the apple was caught by hand to avoid a second impact. Bruises were allowed to develop 12 to 24 hours at 18° C and then were cut through the bruise along the stem-calyx axis. The radius of apple and the diameter and depth of the browned area of the bruise region were measured to calculate bruise and bruise volume, after which the browned tissue was excised and weighed. The percentage of total individual fruit weight or volume was taken as a parameter to express bruise susceptibility.

The results shown that bruise susceptibility increased with lateness of harvest and decreased over storage time. Storage period appeared to be more significant than harvest date in governing susceptibility to damage. The greatest decrease in bruise susceptibility occurred during the initial storage period. Fruit temperature at impact or during subsequent bruise development had no effect on bruise susceptibility of 'Granny Smith' or 'Gala' apples. It was also found that the absolute bruise volume and weight were greater in both large sized 'Gala' and 'Granny Smith' apples than in smaller fruit.

Zhang et al.,(1992) reported that the bruise susceptibilities decreased as temperature increased for both Golden and Red Delicious apples. The results of the moisture experiment showed a general trend that bruise susceptibilities decreased as storage humidity decreased for both kinds of apples. At same time, they found that storage time (about 5 weeks) did not have a significant effect on apple bruise susceptibility. However, in the same time period, the apple firmness continually decreased with time.

Pang and Studman (1992) reported that fruit at low temperature had high bruise susceptibility. They concluded that handling fruit at low temperature may result in more bruising, so those apples should be graded at room temperature to reduce bruise damage.

Due to the different treatments and methods used, it is not easy to compare results obtained by researchers. The question of the effect of storage temperature and storage time on the bruise susceptibility of apples remains open and needs further study.

2.3.4 Methods for determining bruise susceptibility

Many researchers have established a relationship between bruise severity and impact energy (Hyde and Ingle, 1968; Holt and Schoorl. 1977; Diener et al, 1982; Saltveit, 1984; Klein, 1987; Brusewitz and Bartsch, 1989; Johnson and Dover, 1990; Chen and Yazdani, 1991). Although many methods have been developed to determining bruise susceptibility, but there is not a standard method for determining bruise severity that reflected the magnitude of bruises that would result from postharvest handling.

Nelson and Mohsenin (1968) sought to determine the maximum allowable static and dynamic loads for McIntosh apples by deriving readily used relationships for practical situations. The impact loads were expressed in terms of the total energy, energy absorbed, total momentum, and momentum absorbed. They found that there was significant correlation with bruise volume for all methods of expressing impact load (i.e., total energy, energy absorbed, total momentum and momentum absorbed). Although all these relations were significant, the energy absorbed and momentum absorbed provided better expressions of load than total energy and total momentum. This was because the total load did not account for the type of surface impacted. If the impacting surface was made up of some sort of cushioning material, the material would absorb some of the energy.

Schoorl and Holt (1980) suggested the use of a bruise resistance coefficient defined as the ratio of the bruise volume to the energy absorbed in the impact. This method is based on the strong linear correlation between bruise volume (V) and energy absorbed (E_a) in an impact. The relationship is of the form $V = AE_a + B$ where the intercept, B, is small and results from curve fitting (Holt and Schoorl, 1977). The larger the coefficient A the more prone the apple flesh is to bruising. Small values indicate a high resistance to bruising (or high shear strength). The energy absorbed during bruising can be found by dropping a single apple onto a solid surface and recording drop and rebound heights.

$$E_a = mg\,(h_1 - h_2)$$

Where E_a = energy absorbed (J); m = mass of apple (kg); g = gravitational constant (9.81

$m/s^{2)}$; h_1 = drop height (m); h_2 = rebound height (m). In this method, a series of impact tests must be carried out to obtain the correlation between the energy absorbed and the bruise volume. At least 10 tests were required to give an estimate of the bruise resistance coefficient. The main difficulty with this method is that the energy absorbed is extremely difficult to measure outside of the laboratory.

The specific bruise used by Diener et al. (1982) was simply the bruise volume divided by the mass (or weight) of the fruit. This measure is based on the assumption that there is a linear relation between the bruise volume and the mass of the dropped fruit.

The use of impact energy in the damage relationship was also studied by Brusewitz and Bartsch (1989) to quantify the change of bruise size with the change of impact parameter. Fruit was dropped by vacuum release onto a force transducer. The drop height was infinitely adjustable from 0 to 40 cm. Impact peak force, duration time, time to peak force, impulse, apple diameter and mass, and rebound height were measured during the tests. The bruise volume was computed from the bruise depth, bruise diameter and the fruit diameter assuming a spherical bruise shape (Mohsenin, 1970). The results produced a linear relationship between bruise volume and absorbed energy (R^2 = 0.93), and a linear relationship between bruise volume and approach energy (R^2 = 0.83). The (peak force / time to peak force) ratio, F/T, was highly correlated with approach energy. It was concluded that the F/T value appears to be a parameter, which was sensitive to firmness changes and less variable than other impact parameters. It also correlated with bruise volume changes during storage.

Kampp and Nissen (1990) developed a method of determining the impact damage susceptibility of apples with the use of a pendulum. All tests were performed with the use of a flat impact head; halved apples that were fastened to the holder on the pendulum were used. The volume of the bruises was determined as described by Holt and Schoorl (1977). They found that there was a clear correlation between energy absorption and the size of the resulting bruise.

Studman and Banks (1989) conducted experiments on Nashi and apples to determine the bruise susceptibility of fruit when subjected to impact loading. It was suggested that a surface measurement method would be more useful of rapid field works than measurement of bruise volume. Fruit was impacted by one of four indenters in the equatorial region of the fruit. The four metal indenters consisted of a 25.4 mm ball, a flat plate, and two cones with vertex angles of 150° and 130°. All the indenters were of the same mass. The results showed these conical indenters produced a more nearly linear relationship between impact energy and contact area than either a spherical or a flat indenter. Bruise shape and bruise susceptibility values were affected by indenter geometry.

Mowatt and Banks (1994) sought to develop a rapid and reliable field technique to determine the severity of bruising on apples. This method involved dropping a ball from a given height down a vertical held tube onto a firmly held apple. The giving impact energy was 0.3 J. Bruise area or bruise volume with this standard impact energy could be used as a measure of bruise susceptibility.

Some researchers have measured impact load-time traces, producing useful additional information about the physical properties of fruit tissue (Chen, and Yazdani, 1991; Cox, 1993; Lichtensteiger et al., 1988). The difficulty with the majority of these approaches remains the absence of a comparison with commercial grading experience. This is particularly important when it is appreciated that fruit are graded largely on surface appearance rather than bruise volume. It is important to be sure that the assessment of bruising is based on the same criteria used by the industry, and so measures such as bruise susceptibility and bruise resistance as defined above are in reality of little value to those concerned with designing handling and grading systems for high quality fruit (Pang et. al. 1996).

In order to overcome problems in relating laboratory assessments of the susceptibility of apples to bruising with field experience during handling, a new method for rapid assessment of bruise damage was proposed by Pang et al. (1996). The method involved dropping fruit from a geometrically increasing series of heights onto a flat steel surface using a pendulum, and counting the number of bruises observed with skin intact. The resulting number was termed the bruise factor, to distinguish it from other measurements of bruising. They concluded that bruise factor related reasonably well with the number of bruises produced by a mechanical fruit grader. It was also suggested that bruise initiation and threshold visibility should be used as the basis for assessment of bruising.

2.4 Different impact test methods

The measurement of impact loads is extremely difficult, especially since the load is affected by the size and shape of the fruit itself. It is often very difficult to detect exactly where fruit is being bruised in a handling system, even though the damage to fruit is evident from quality control checks. The problem is further complicated by the random nature of impact damage and by variations in bruise susceptibility of the fruit itself.

Different kinds of impact tests have been developed by researchers who have investigated the fruit impact phenomena. These different kinds of impact tests attempted to simulate the different kinds of impacts involved in handling and harvesting of fruits, i.e., free fall of fruit on cushioned surfaces or on hard surfaces, impact of fruit on fruit, and impact between fruit and a moving limb during shaking of the tree (Manor, 1978). The five common types of impact tests generally used in the past were dropping the fruit on a surface, impacting the fruit with a falling mass, two types of pendulum tests, and an impact test by a ram (spring, pneumatic, or electric) striking the fruit. Figure 2.2 shows, schematically, these different impact tests. The specimens used for these impact tests can be either intact fruits, fruit halves, or cylindrical specimens. A critical analysis of these techniques has been given by Manor (1978).

1. Simple drop tests: (either dropping the product upon a rigid surface or dropping a mass upon the product), have been widely used (Timm et al. 1989, Brusewitz and Bartsch 1989, Chen and Yazdani, 1991, Schulte et al. 1992, Mowatte and Banks, 1994). Falling masses instrumented with accelerometers have been developed by several investigators. The drop test method is more common because the apparatus is simple and it easily simulates field conditions. However there are a number of problems associated with the free fall apple method. Because apples of greater mass have greater kinetic energy at impact than apples of small mass when dropped from the same height, this does not provide a standardised impact energy. Variation in bruise size caused by variable impact energies (apples of differing mass) can be compensated for in part by expressing bruise volume as

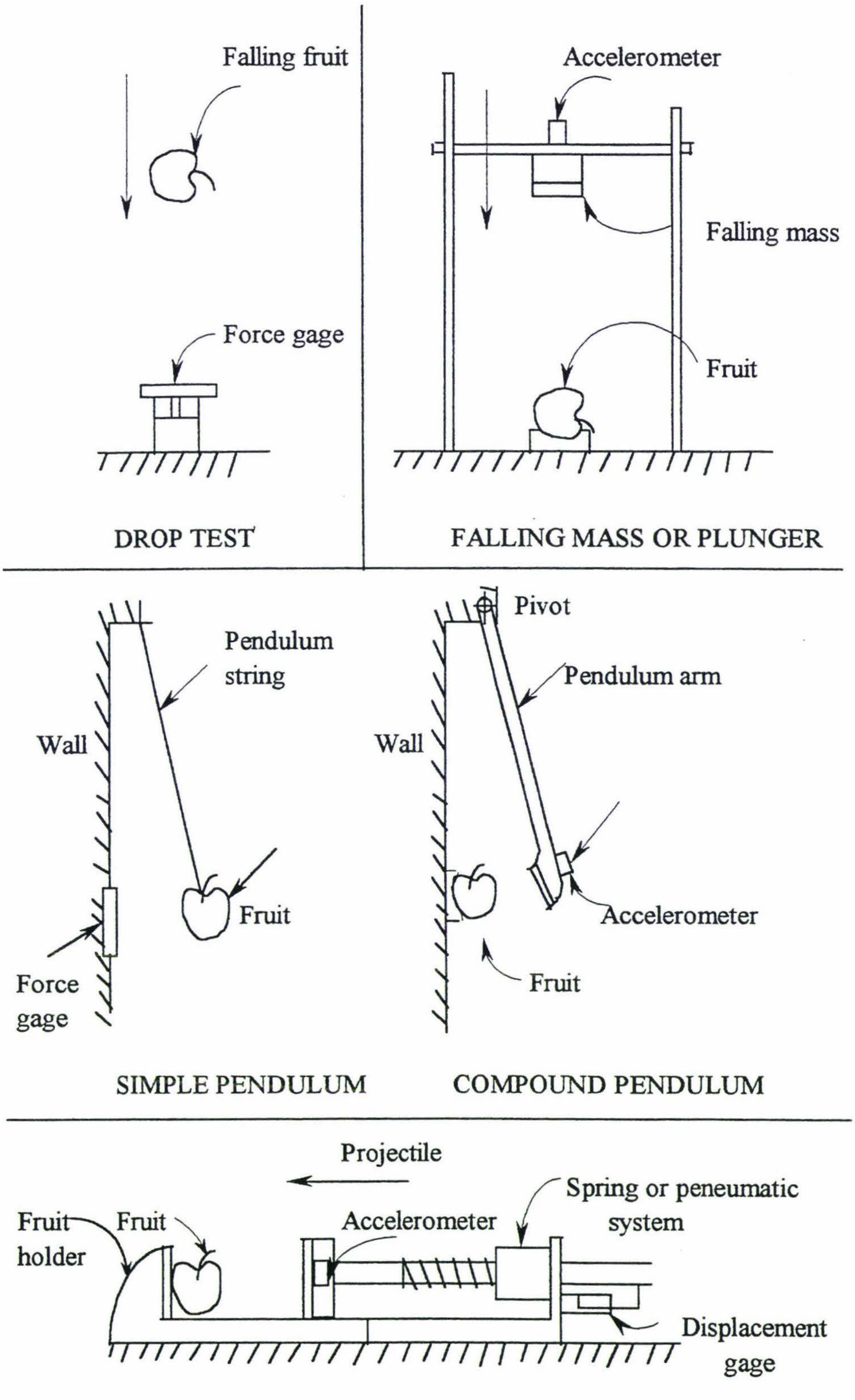


Figure 2.2 Different Methods of Impact Tests Used for Fruits (Manor, 1978)

a percentage of total apple volume. However, to test the effect of treatments applied to influence bruise susceptibility every effort must be taken to reduce sources of variability. On this basis, dropping apples of variable mass onto flat surfaces is unlikely to provide an ideal comparative test. The other problem is the fruit may rotate during the fall and the location of impact on the fruit cannot be precisely predicted (Mowatt and Bank, 1994). However the falling mass technique has the advantage of simple construction and can be instrumented easily.

2. Pendulum impact test: A popular device for apple impact loading is the pendulum (Johnson and Dover 1990, Kampp and Nissen 1990, Pang et al. 1992, Bollen and Cox, 1995, Pang et al. 1996). It can be instrumented to measure forces and product deformation during impact. Research workers have used pendulums in different ways. Some have preferred simple pendulums where samples, suspended at the end of a string or thin wire, were allowed to impact solid surfaces, whilst others have used compound pendulums to impact stationary samples held by a fixed load or freely suspended. These methods vary in sophistication, both in the range and the way impact properties (thought to be useful in assessing susceptibility to damage such as energy absorbed, deformation and time of contact) were measured. An energy balance was developed for the pendulum test in which total impact energy was equated to energy absorbed by the support, fruit bruise energy and fruit rebound energy. This method produces satisfactory results but the apparatus is not easily moved and the procedure is time consuming.

3. Other impact tests, such as a pneumatic ram or a spring loaded projectile used by Holt and Schoorl (1977), have also been used in investigating the fruit impact phenomenon, despite the fact that they are not simulating the practical impact situations. A very different approach by Le Lezec (1990) involved using a motor driven tumbler similar to a hot air clothes drier to produce a random distribution of bruising.

Obviously, there is a major difference in the rigid body motion between the free fall test and the pendulum and impacting mass tests, where the apple is supported against a surface which has a significant mass. In the free fall, only the apple velocity is reduced in the process of momentum transfer. In contrast, when an apple is subjected to impact of a falling mass or pendulum, it behaves like a medium that is used for transferring the momentum of the falling mass to the base under the product. It follows that in the free fall only one loaded area is produced, while in the impact mass or pendulum two loaded areas are generated, one against the impactor, and the other between the fruit and the surface on which it lies (Manor 1978).

Although many parameters measured during the impact have been established as a bruise indicator, it is not possible, yet, to decide what is the most significant parameter for fruit damage, and to say, for instance, that the bigger bruise volume is due to a bigger impulse. Therefore, a comparison between different test methods can be made only on the basis of one parameter. Even if only one parameter is kept identical for different tests, each kind of impact test may give different results of fruit damage (Manor, 1978).

Differences in research findings reported in previous studies may be due to differences in impact energy levels and methods of bruise assessment. This may be the reason why researchers and the industry disagree on bruising differences between cultivars.

2.5 Methods for bruise prediction

The previous attempts at predicting apple bruising may be divided into analytical and experimental techniques based on regression analysis. Analytical methods are based on the Hertz theory of contact stress or on a modified Hertz theory (Srivastava et al. 1992). Methods of predicting bruise dimensions have been studied in various ways. Siyami et al (1988) investigated four models to predict bruise size in apples incurred by impact, using data recorded on a programmable impact table. The prediction models assessed were the Hertz elastic contact theory, an adjusted Hertz theory, the Plastic theory, and a Multiple linear regression analysis. They found the Hertz elastic contact theory over-estimated the measured bruise diameter by 25%, but when adjusted by a time factor related to viscoelastic impact conditions this theory give a greatly improved bruise diameter prediction. A plastic contact theory under-estimated the bruise diameter by 20% for a 2 ms impact and both under and overestimated it for a 6 ms impact, so its predictions did not fit measured values well. A multiple linear regression model based on apple diameter, Magness -Taylor force, maximum acceleration and total velocity change was the preferred method for predicting apple bruise diameter and provided very good predictions of measured bruise diameter for both 2 and 6 ms duration impacts ranging from 305 to 3370 m/s^2 peak acceleration. This model had a coefficient of variation of 0.95, and the 99% confidence belt for a single bruise diameter was ± 4.0 mm above and below the regression line.

Timm at al. (1989) also developed multiple linear regression models for predicting the sizes of bruises. Tests were conducted with three apple varieties to determine the affect of flesh firmness and impact surface characteristics on bruise incidence and size. They found that multiple linear regression based on peak acceleration, impact duration, total velocity change, and Magness -Taylor firmness provided good predictions for bruise dimensions on both hard and padded surfaces.

Chen and Yazdani (1991) described a bruise-predicting model, which is based solely on the acceleration history of the impact and the mass of the impacting fruit. The model was used to predict bruise size based on the available information from the instrumented sphere. A total of twenty measured and calculated parameters were compared in a correlation matrix. They found that a linear model based on six impact parameters could predict bruise volume with a coefficient of multiple determination (R^2) of 0.903. A five–variable model based solely on the parameters derived from the acceleration and impacting mass data could predict bruise volume with an R^2 value of 0.862, and a four – variable model based solely on the Fourier transformed acceleration data could predict bruise volume with an R^2 of 0.883.

Bollen (1993) described a probabilistic approach that enabled the prediction of bruise occurrence of a specified size based on impact data (impact energy/drop height). The paper showed the relationship between the probability of damage (where damage is specified as a 1 cm^2 bruise area) and impact energy. The model used is a logistic function for normally distributed data. Unlike other models which use a relationship between an average value of bruise area and energy, this approach assigns a probability of a specified bruise occurring at any energy level, based on binary data representing either 'damage' or 'not damaged' results. The authors suggested that the logistic function provided a more accurate prediction of probability at low energy levels than other linear models could achieve, and that commercially tolerable levels of damage are generally at around 1% and 5%, which correspond to these low energy levels.

2.6 Bruise boundary in apple fruit

Bruise boundary based on the concept used in packaging theory is defined as the edge of a region where packaged products would not be damaged on a velocity change versus acceleration graph (Turczyn et al. 1986). The bruise boundary is normally formed by two lines which are parallel to the horizontal and vertical axes respectively. The positions of the lines are determined by experiment. Firstly, the velocity change remains unchanged and the acceleration is altered to determine the critical acceleration at which the product begins to fail, then a vertical line is drawn through the critical points. Secondly, the velocity change is altered by using a special programmed drop test machine at constant acceleration until the product fails. A horizontal line through the failure points on the graph and the vertical line then form a bruise boundary for that product.

Schulte-Pason et al. (1990) conducted impact tests to determine the minimum impact required on different surfaces to initiate apple bruising and to develop a preliminary bruise threshold curve (on a peak g's vs velocity change plot). The IS was dropped from a range of drop heights onto a series of surfaces with differing levels of padding. The surfaces were steel and different types of foam mounted to a steel substrate. Next, the variety of fruit under test was dropped from the same drop heights onto the same impact surface. After 24 hours the fruit were examined for bruising and the bruise measured by peeling the skin. The tests with the IS generated a set of points which were plotted on a velocity change versus peak acceleration graph to produce impact response lines. The points on the response line which produce 0%, 10%, 50%, and 100% bruise on fruit were taken as the threshold of bruising. When the tests were repeated for different padding surfaces, the lines joining the equal percentage of bruise on different response lines were then drawn to give a bruise envelope as shown in Figure 2.3. This meant that any combination of peak acceleration and velocity change, produced by the IS when it was run through a handling operation, which lay to the right of the selected point on the response line would produce unacceptable bruising.

A similar approach was taken by Bollen and Dela Rue (1990) for Braeburn apples where a preliminary bruise threshold was developed for the onset of a 1 cm^2 bruise (equivalent to the export standard 1 cm^2 tolerance for bruising on export fruit). Fruit were dropped, in a pendulum impactor, from various heights onto different foam surfaces, and the diameters of the resultant bruise measured. The IS was then dropped from the same heights to characterise the impacted surfaces by measuring the peak g's and velocity changes. Bruise probabilities could then be assigned to each point on the graph and an estimated threshold line drawn.

Pang et al.(1992) examined the relationship between apple-to-apple impacts and IS output for predicting damage thresholds. First, an apple was attached to two thin nylon lines and suspended as a pendulum. A second apple was also suspended on nylon lines and was initially stationary at the bottom of the arc. The suspended apple was dropped from five different drop heights onto the stationary apples. An IS was

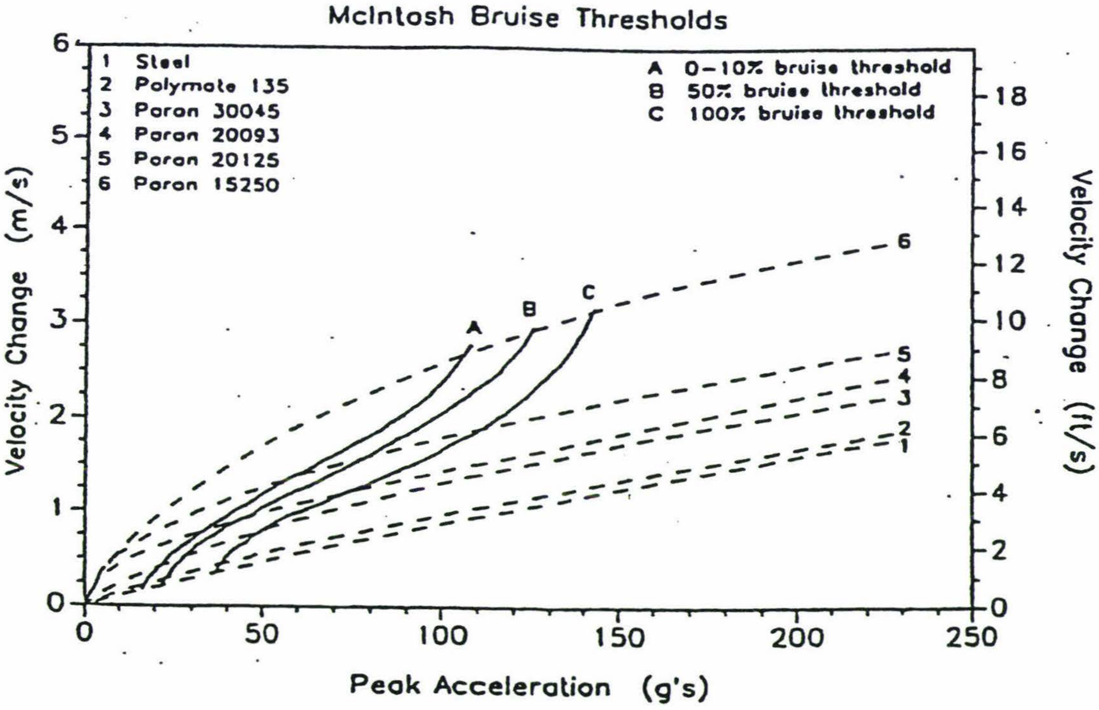


Figure 2.3 Apple bruising initiation threshold lines (0-10,50 and 100% bruising) for velocity change versus peak acceleration compared to impact surface response lines created using a 89 mm diameter IS (Schulte-Pason et al., 1990)

dropped in turn onto the stationary apples from the same series of drop heights. When the results of apple-to-apple and IS-to-apple impacts were compared, it was found that the area of the larger of the two bruises produced in fruit-to-fruit impacts was directly related to the peak acceleration recorded by the IS when it was dropped onto a fruit from the same height. Using this comparison, damage thresholds resulting from fruit-to-fruit impacts were determined by analysing IS output. The regression equations obtained were used to estimate the IS acceleration corresponding to the maximum acceptable bruise area (the bruise threshold) of 1 cm^2. The bruise threshold calculated in this way ranged from 21 g's for Granny Smith and Splendour, 22 g's for Fuji, 26 g's for Gala, and 33 g's for Braeburn apples for fruit-to-fruit impacts.

It was noted that the peak acceleration alone is not sufficient to assess the severity of an impact, since on a curved surface the sphere output may be lower than on a flat surface, while the resulting bruise may be much larger (Studman et al., 1990). It was suggested that a separate threshold be developed for fruit to fruit impacts and it was concluded that there was no general interpretation of the IS output in the fruit to fruit impact region, but rather each impact point had to be examined by video to determine the nature of the impact surfaces.

2.7 Practical Studies of Apple Packing Lines

Apples are highly susceptible to impact damage during the many stages of handling. Mechanical equipment and operations used on apple packing lines often bruise the apples. Most handling damage results in one or more bruises (which range in size from barely visible to very visible and massive) on each apple. Bruising, which is objectionable to fresh market consumers, can result in a lower grade for any apple (Brown et al., 1993). Several studies have been conducted recently to identify sources of mechanical injury to apples during typical handling procedures prior to the retail store (Burton et al., et al. 1989; Schulte Pason et al., 1990; Brown et al., 1990; Guyer et al., 1991; Studman 1990).

2.7.1 Apple damage in American packing lines

During the 1986-87 packing season, Brown et al. measured the bruise damage on apples caused by 1) the hand packing and bin hauling operations of 6 different growers for McIntosh, 2) the packing line operations of 8 different packers for Golden Delicious, and 3) the distribution operations for 2 different produce distributors of Golden Delicious.

The average number of bruises (larger than 6.35mm. dia.) caused per fruit was about 2.6 for the packing operation, 2.2 for the bin hauling operation, 5.4 for the packing line operation, 2.7 for the bagging operation, and 0.34 to 1.45 for the distribution operation, depending on the packing system and total transportation distance (up to 500 kms) in conventional spring-suspension semi-trailers. The results indicate the packingline operations caused most of the damage, the picking and hauling operation caused somewhat less, and the distribution operations caused by far the least (warehouse workers were not allowed to throw or drop any cartons). Most bruises were caused by apples impacting hard surfaces and other apples.

2.7.2 Apple Bruise damage in New Zealand Packinglines

In 1989, a survey of bruising was conducted on a number of orchards in one of the main growing regions of New Zealand known as Hawke's Bay (Banks, 1991). They found that more than half of all bruising in the post-harvest handling of Granny Smith apples occurred between the sorting table and the final size bins or tray fillers. With a 4mm diameter threshold, the average bruise area per fruit increased progressively through the postharvest handling chain. Unloading of fruit from packing containers into the field bins was a major source of medium sized bruises (i.e. greater than 10 mm diameter, which is equivalent to the present export threshold for an unacceptable bruise) but not of larger bruises (i.e. more than 12 mm diameter). Another source of large bruises (greater than 12 mm diameter) was on the grader, after the sorting table to the final size bins. Impacts during singulation, following release from the cup and during the drop into the final size bins are all potential sources of damage over this stage (Studman, 1990).

A further investigation on the incidence and severity of bruising occurring between the sorting table to the final size bins was conducted by Banks (1991). They examined bruising using Splendour apples on 11 graders in Hawke's Bay and found four points most likely to cause problems (Fig. 2.4). Most serious bruising on apples resulting from the sizing operation on grading equipment occurred at points 2 and 4. On average over all graders, points 1 and 3 resulted in a low and similar incidence of bruised fruit (3.3% and 3.0%, respectively) and severely bruised fruit (1.7% and 2.3%). Point 2 caused more fruit to be classified as bruised (12.2%) or severely bruised (9.7%) than either point 1 or point 3. Point 4 contained more bruised fruit than any of the other samples (16.0%). Fruit-fruit impacts were the principal source of damage at point 4. Point 4 was a consistent problem on most graders, whereas point 2 was a particular problem on certain graders. Point 1 typically caused a high incidence of small bruises, which would be of minor importance at quality inspection.

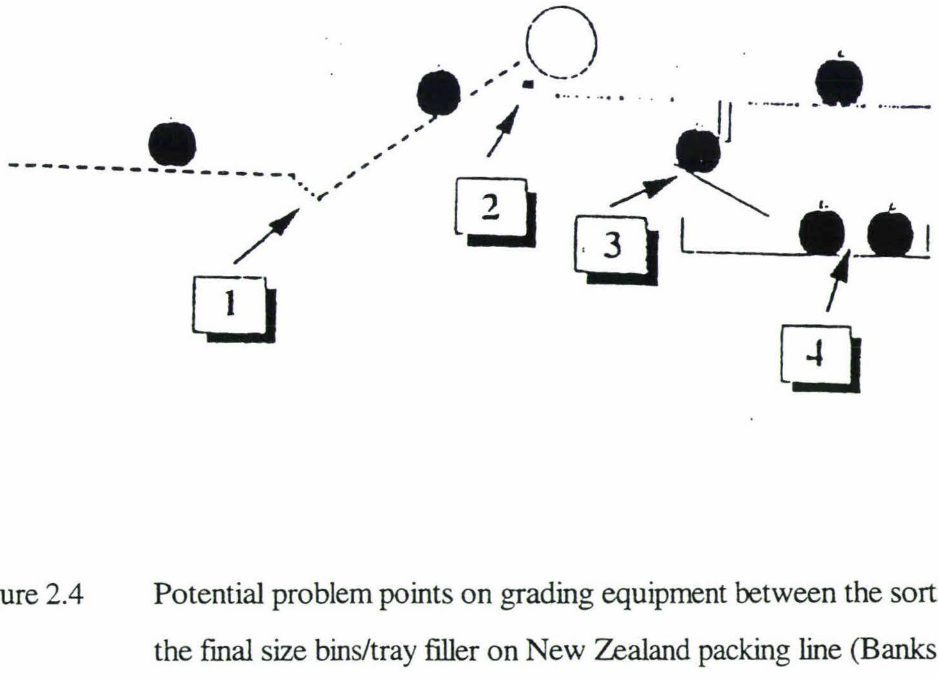


Figure 2.4 Potential problem points on grading equipment between the sorting table and the final size bins/tray filler on New Zealand packing line (Banks 1991).

1. drop from sorting table onto singulator
2. descent from singulator to cup race via the transfer wheel
3. first drop onto chute following release from cup race
4. subsequent fall from point 3 down into final size bins or tray filler.

2.8 Discussion and Conclusions

Bruises can be produced in a number of different ways, and especially by impact. The main types of impacts to which fruit are subjected are impact of fruit on hard or inadequately cushioned surfaces, impact of fruit on other fruits, and impact of fruit on a tree's limb. The degree of bruising damage on a fruit surface directly influences its saleability. Customers are reluctant to buy severely damaged fruit in which a bruise is visible through the skin.

Research on factors influencing bruising requires technique, which quantify bruising responses to different impact loads. The severity of bruise damage depends on the distance the fruit falls, the impact energy, the number of impacts, the type of impact surface, and propertres of the fruit, including maturity and cultivars. Although many methods have been developed to determine bruise susceptibility, a reliable relationship between a laboratory test method and commercial handling operations does not appear to have been established. It is important to confirm that the bruising values obtained by standardised laboratory approaches are eliable measures of commercially important fruit bruising in practical situations.

Bruise susceptibility has been defined as the change in measured bruise volume corresponding to the energy absorbed during either mechanically applied compression or resulting from free fall impacts onto a given surface. The larger this coefficient the more prone the apple flesh is to bruising. Small values indicate a high resistance to bruising.

The different methods for assessing the extent of bruising have been outlined. Differences in research findings reported in previous studies are attributed to differences in impact energy levels and methods of bruise assessment. At the current time, commercial practice continues to be to use the visible bruise area measured without removing the skin. While this is often a little more difficult to measure accurately, it is likely to remain as the commercial criterion for bruise assessment (Pang et al., 1996).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

Mechanisation of apple harvesting, sorting, and packing has led to increased concern over impact damage to fruit. In some cultivars bruising may result in downgrading of up to 50% of the total crop picked (Pang et al., 1996). A reduction in damage can be achieved only if the factors governing susceptibility of fruit to bruising are well understood. The need to understand the factors has led many researchers to investigate the damage problems of fruit and to develop indirect methods of bruise assessment (Holt and Schoorl, 1977, Chen and Yazdani, 1991; Brown et al., 1990, Banks, 1993; Pang, 1993). These measurements are useful only if they correlate closely with actual fruit damage produced by a grading system. If a suitable laboratory testing method for bruising assessment which gives results consistent with commercial experience, and which could be used in a commercial environment, were available, then a particular shipment of fruit could be tested in advance. If a shipment were found to be particularly susceptible to bruising, the damage could be reduced by adjusting the flow rate through the grading machinery, and by increasing the level of care at all stages of handling.

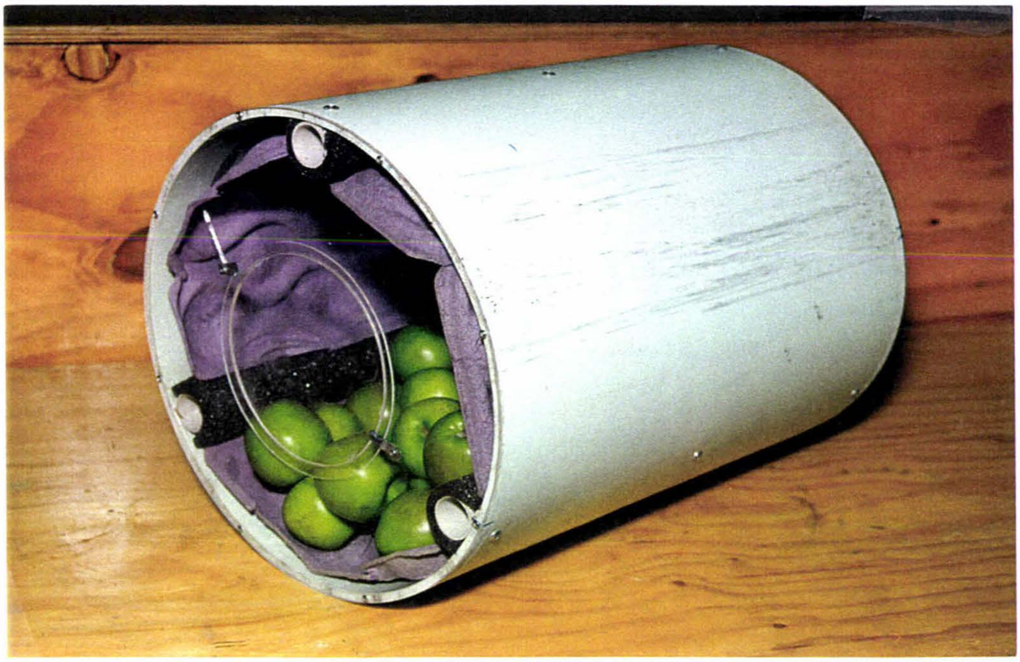
3.2 Development of reference system

Ideally experiments should be conducted using commercial grading equipment operating under standardised conditions. This was ruled out on practical grounds since such equipment was in use during the harvest period and subject to continuous unpredictable system modification. In order to overcome problems in relating laboratory assessments of the susceptibility of apples to bruising, with actual field experience during handling (and to compare measured values produced by standard impacts test with actual commercial bruising), a reference system to simulate fruit-fruit impacts damage during handling was developed. This method involved a revolving tumbler. The bruising produced by this method was used as a criterion, and a series of experiments was conducted to compare different methods of bruise susceptibility determination.

After a review of the literature, a tumbler system following the principles described by Le Lezac (1990) was selected as a laboratory reference system to produce impact loads similar to that experienced by fruit in commercial handling systems. Apples were bruised by a tumbler (50 cm long, and 40 cm diameter) to produce a random distribution of bruises (Fig. 3.1). The two ends of the cylinder were made of Plexiglas. Attached to the inside wall of the cylinder were three vanes (diameter of 3.5 cm). Initial tests were conducted with the inside wall of the cylinder padded with and without paper pulp trays.

In order to simulate commercial conditions, the design of the tumbler was established by experiments in which 40 apples were carefully put into the tumbler, and then the tumbler was rolled on the ground by hand through four complete revolutions. During the tumbler test, an 89 mm diameter Instrumented Sphere (IS) was used to study the impacts produced by the tumbler. The IS is a self contained, spherical, logger with integrally mounted accelerometer. It moves with the apples in the tumbler and measures all impacts the product is subjected to. Accelerometer output was downloaded onto a PC for analysis. The software calculated the acceleration and the "velocity change" (the area under the acceleration-time curve).

The results from the IS were compared with IS data obtained from commercial grading sheds. The design was then adjusted by altering the vane size and padding materials used until the impact distribution was similar to that obtained in commercial trials. The impact loads for the tumbler without paper pulp trays was not representative of commercial handling systems. Some high impact loads occurred because the IS struck the inside wall (without padding) of the tumbler. Lining the wall with paper pulp trays produced much closer IS results. A sample of typical IS impacts measured in the tumbler with paper pulp trays has been extracted and is shown in Figure 3.2a. The results of IS output generally showed a range of peak acceleration from 15 g's to 68 g's (1 g= 9.81 m/s^{-2}) and velocity change as shown in Figure 3.2a for a tumbler test. Typically around 80 impacts were recorded while rolling the tumbler 4 times. Figure 3.2b was adopted from Pang (1993).



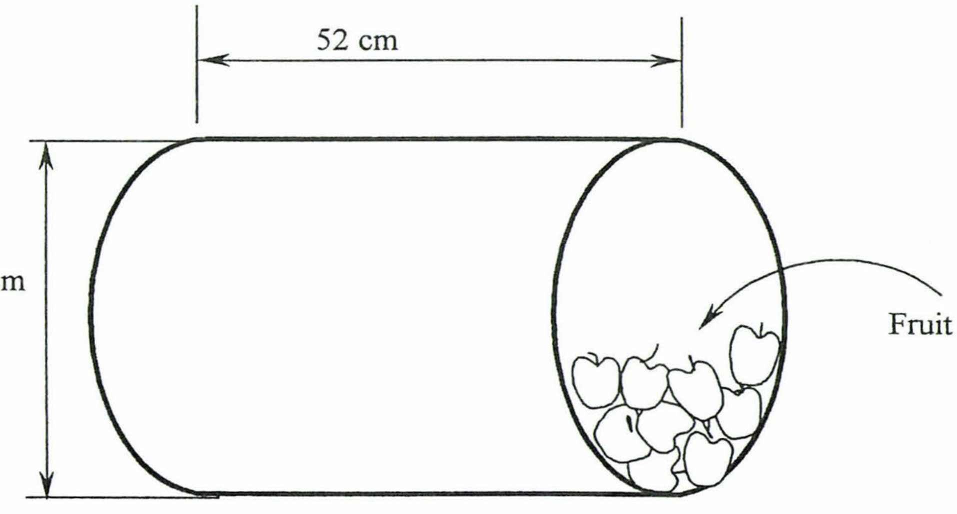


Figure 3.1 Tumbler test device

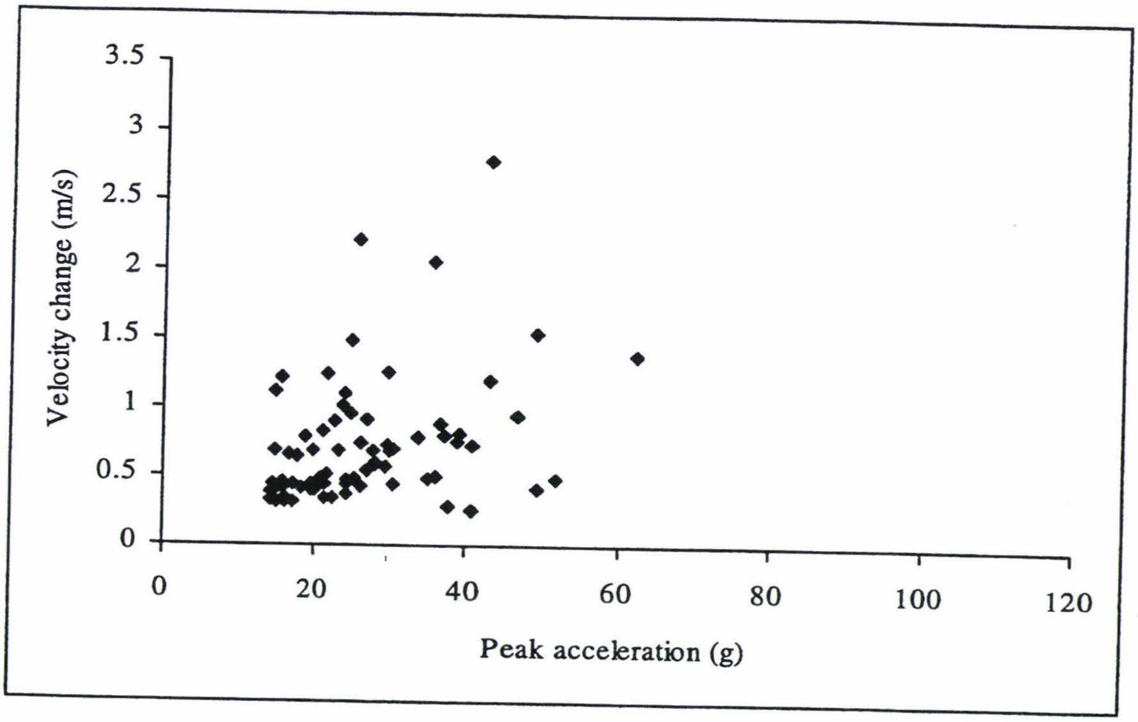


Figure 3.2a The impacts recorded by IS from a tumbler padded with paper pulp trays after rolled on the ground four revolutions.

(Note: cut off threshold set at 13g)

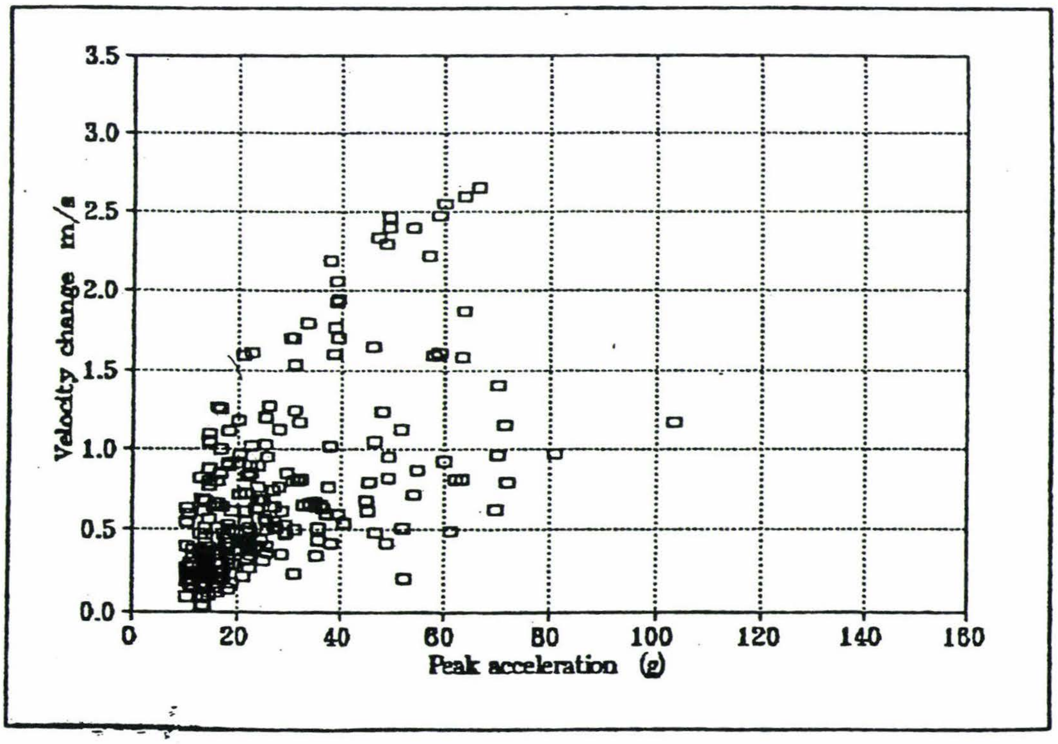


Figure 3.2b the impacts recorded by IS from a New Zealand typical fruit packing line (Pang, 1993).

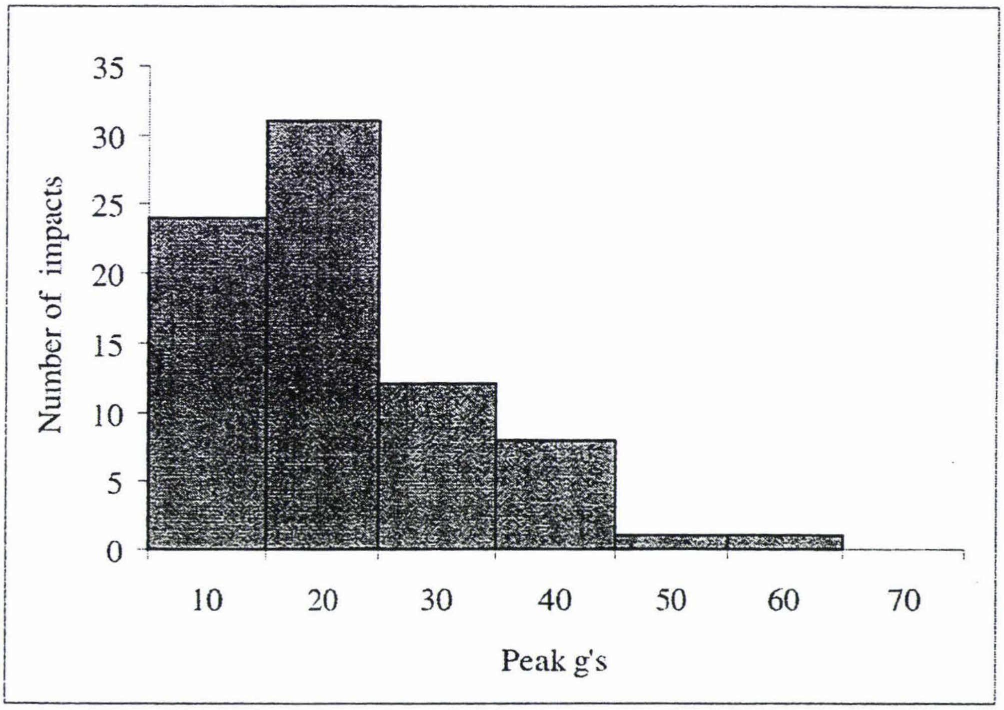


Figure 3.3a Peak g distribution of a tumbler padded with paper pulp trays after rolled on the ground four revolutions.

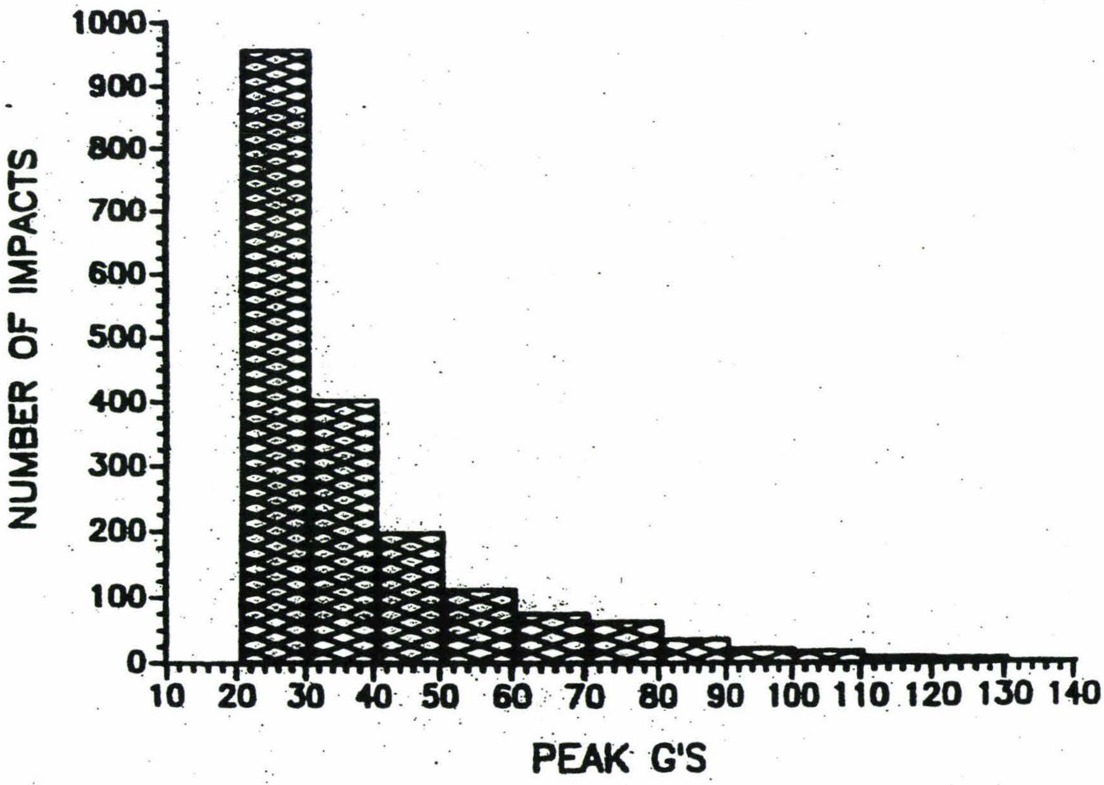


Figure 3.3b Peak G Distribution of Apple Packing Line Impacts (Sober, et.al,1989)

A histogram of the peak g distribution, Fig 3.3a, shows that most impacts occurred between 10 and 40 g's. Approximately 85% of the impacts experienced in normal packing operations are accounted for in this range (Sober et al., 1989; Pang, 1992; Bollen and Dela Rue, 1994). Figure 3.3a shows the distribution of velocity change corresponding to the impacts. Velocity changes ranged for 0.2 m/s to 2.8 m/s. However, only 3 impacts were recorded with velocity change greater than 2 m/s. Figure 3.3b was adopted from Sober et al. (1989). Most impacts were caused by apple-to-apple impacts. Hence the tumbler padded with paper pulp trays was adapted to simulate the real situation, and was therefore used as the standard in these studies. The validity of this approach is discussed in Chapter 4.

3.3 Fruit Preparation

In the 1997 harvesting season 'Splendour', 'Pacific Rose', 'Granny Smith', and 'Braeburn' were hand picked from trees in the Fruit Crops Unit, Massey University. They were then taken to Massey University laboratory. One hundred and sixty apples for each variety were selected randomly from fruit collected and tested at room temperature immediately. There were designated as fresh (F). The remainder were stored. Fruit of each variety were divided at random into two groups; one of them was stored at high humidity (90%), and other at low humidity (65%) for two months (see below for details). The temperature of the cool- storage was kept at 0.5 °C. In order to determine the temperature effect on bruising, after storage some Splendour and Granny Smith apples at 90% RH were divided into two groups. One group (HW) was taken out of the cool-store and allowed to reach room temperature before testing. The other group (HC) was tested at the cool-store temperature of the apples. In order to determine the humidity effect on bruising, some Splendour and Braeburn apples at 65% RH was taken out of the cool-store and allowed to reach room temperature before testing. Some Pacific Rose and Braeburn apples at (90%) RH) was taken out of the cool-store and allowed to reach room temperature before testing. In all, 480 'Splendour' apples, 160 'Pacific Rose' apples, 320 'Granny Smith' and 'Braeburn' apples were randomly selected from fruit collected for the impact tests. Details are given in Table 3.1.

3.3.1 Relative Humidity

The two storage humidity conditions were obtained by placing apples in polyethylene bags with 16 holes to allow a limited airflow through. Each bag contained 3 layers of apples placed in paper pulp trays; each tray held about twenty apples. For 65% RH only, silica gel was placed in the bags to absorb water (Macguire, 1998). The silica gel was packed into small 4 layer paper bags, 25g in each bag, and placed into the bags with six packages for one layer, and 18 packages for one plastic bag. In order to keeping the RH value constant, the silica gel bags were changed at regular intervals.

Table 3.1 The apple samples were used for the tumbler tests and three standard impact tests

Cultivar	Treatment		Number of sample	Average weight (g)
Splendour	Fresh (F)		160	188.97
	Stored (RH 65%) Warmed(LW)		160	182.25
	Stored (RH 90%)	Warmed(HW)	160	183.19
		Cold (HC)	160	181.36
Pacific Rose	Fresh (F)		160	209.27
	Stored (RH 90%) Warmed(HW)		160	220.05
Granny Smith	Fresh (F)		160	195.75
	Stored (RH 90%)	Warmed (HW)	160	189.34
		Cold (HC)	160	198.50
Braeburn	Fresh (F)		160	150.29
	Stored (RH 65%) Warmed(LW)		160	152.17
	Stored (RH 90%) Warmed(HW)		160	148.77

During the store time, the two levels of humidity were measured at regular intervals inside polyethylene containers by a Dew point meter (Michel model 3000 Hygrometer) and humidity probe (Vaisala Model HMI-33). The high RH environment remained between 85-90% and the low RH was between 60-65%.

3.4 Bruising methods

Bruises were produced in four ways: (1) by tumbler; (2) by dropping four different indenters onto the apples; (3) by impacting different indenters onto a freely supported apple using a double pendulum device; (4) by impacting apples onto different indenters surface using a simple pendulum device.

3.4.1 Tumbler test (T)

Four apple cultivar with different treatments: Granny Smith, Splendour, Pacific Rose, and Braeburn were used for the tumbler tests. A sample of 40 apples of each cultivar was carefully put into the tumbler, and then the tumbler was rolled on the ground four times by hand. Bruises were allowed to develop for 4-6 hours after rolling. The apples were then inspected and any bruises were measured without removing the skin of the apple. Each fruit was closely inspected and each bruise was outlined carefully using a waterproof marker. Using the method adopted by Schultz et al (1989), 11 circles of increasing diameter (8 to 15mm) were drawn on a transparent A4 sheet, and the appropriate circles were matched with the outlined bruises on the apples (Appendix 1). The number of bruises within each diameter range was determined, and from this the total bruise area was estimated using the mean diameter for the range. Bruise area was totalled for each apple and the bruise area/apple and bruise number/apple were used in the subsequent statistical analysis (Appendix 2).

This approach provided a simple and speedy non-destructive method to determine bruise areas. Non-circular bruises could be fitted by eye into the appropriate band. The degree of sensitivity of this method is related to the graduation between areas on the transparent sheet.

3.4.2 Vertical drop tests (V)

Apples were bruised by dropping a hockey ball (mass of 157.5g), a flat surface, and three metal pyramid indenters (with vertex angles of 150°, 120° and 100°) (Fig. 3.4). To reduce puncturing the skin the tips of the pyramids were rounded. All the indenters were of the same mass (157.5g). The hockey ball was allowed to fall down a vertical tube from a stationary position 20 cm onto an apple (this was a typical height apples were observed to drop during commercial handling (Mowatt and Banks, 1994))(Fig. 3.5). Apples were supported on a cushion to avoid bruising opposite the impact spot. The radius of the hockey ball was similar to apples (diameter of 7cm). Flat plate and three

Figure 3.4 The different impact indenters selected for impact tests.

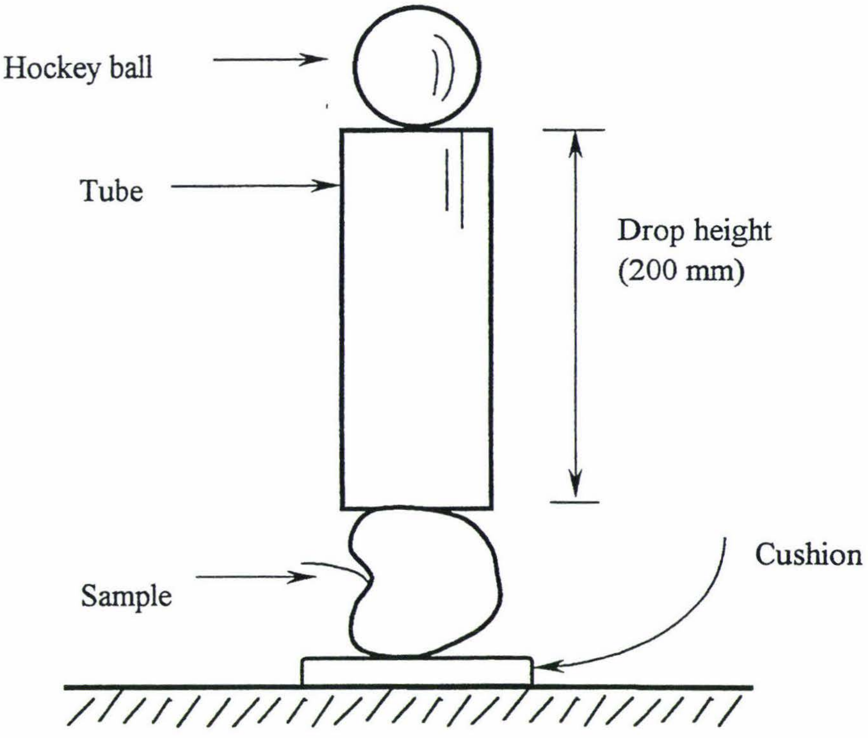
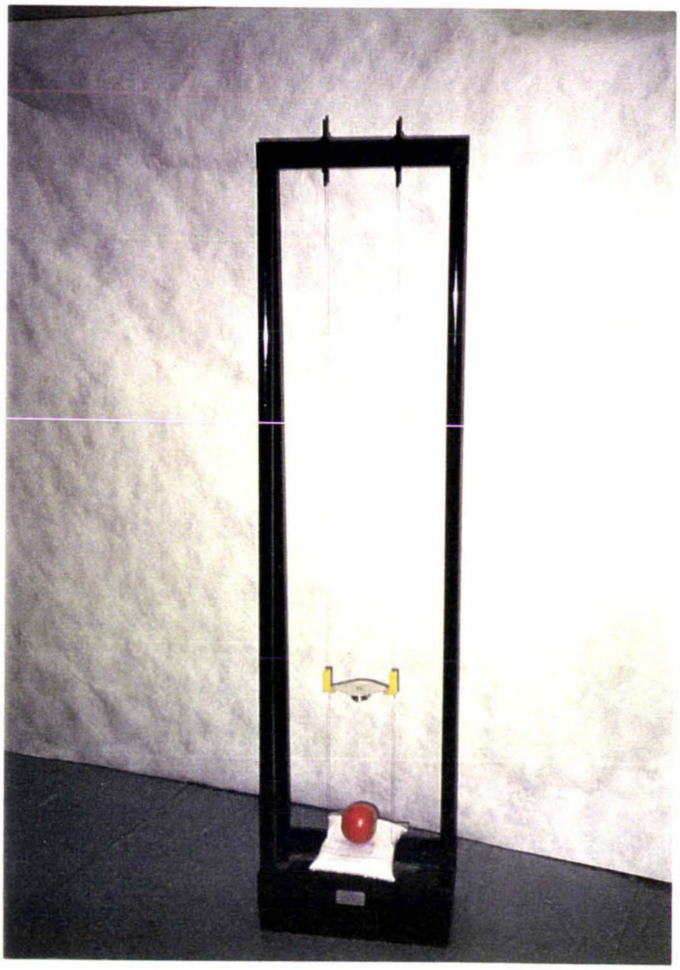


Figure 3.5 Hockey ball impact device



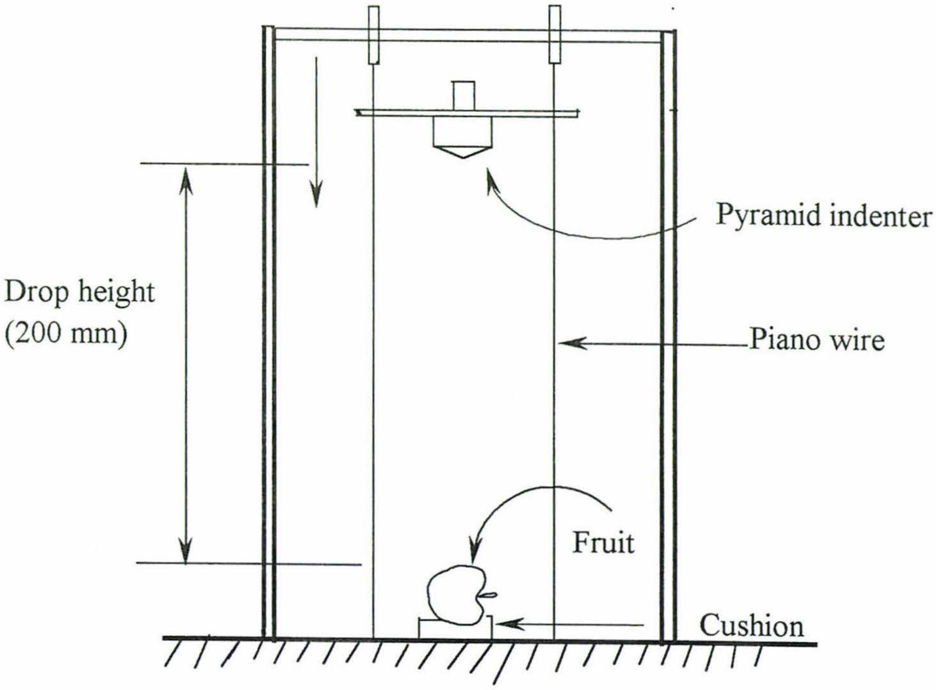


Figure 3.6 Pyramid indenter drop device

pyramid indenters were dropped by a bruise machine (Figure 3.6). This comprised a 1.6m high frame constructed using 2cm steel pipe welded to the corners of a 0.4 x 0.2m heavy steel base. Piano wires were secured running parallel from the base to the top 14 cm apart. Two frictionless plastic holders were drilled and threaded onto each wire before tensioning. These were then joined by an aluminium plate. At the middle of the plate, a hole was drilled, and then the indenter was fixed on the aluminium plate by a screw. The indenter could then be easily dropped from 20cm height guided by the wires onto an apple firmly held at the base.

Each apple was subject to one impact from the hockey ball and three indenters at four different points around its cheek area. The 100° pyramid indenter was used only on fresh fruit, and the flat plate on stored fruit. The impact energy from the four types of indenters was identical (0.31J).

3.4.3 Double pendulum tests (D)

A double stringed pendulum was used to swing each of four different shape indenters onto a suspended stationary apple from a constant impact angle. The impact energies from the four types of indenters were 0.31J (the indenters were same as the drop test). The pendulum device is shown in Figure 3.7. The two pendulums were mounted on a roller bearing, and able to swing freely in a vertical plane. The diameter and mass of the apples were recorded by a micro-caliper and a two decimal place balance before test. Each apple had a hole through the centre along the calyx to stalk axis, which was produced by a cork borer 3 mm in diameter. This allowed the apple to be slipped onto the pendulum arm, 500 mm from the axis of rotation. The indenter was slipped onto the other pendulum arm, 500 mm from the axis of rotation, and fixed by a screw. The distance between the indenter and apple was adjusted so the indenter and apple just touched on a horizontal line between their centres.

The indenter was swung back and released from the given impact angle, and allowed to strike the stationary apple, which was free to move after impact. After the first impact, the indenter was caught by hand in order to avoid a second impact. The apple was then

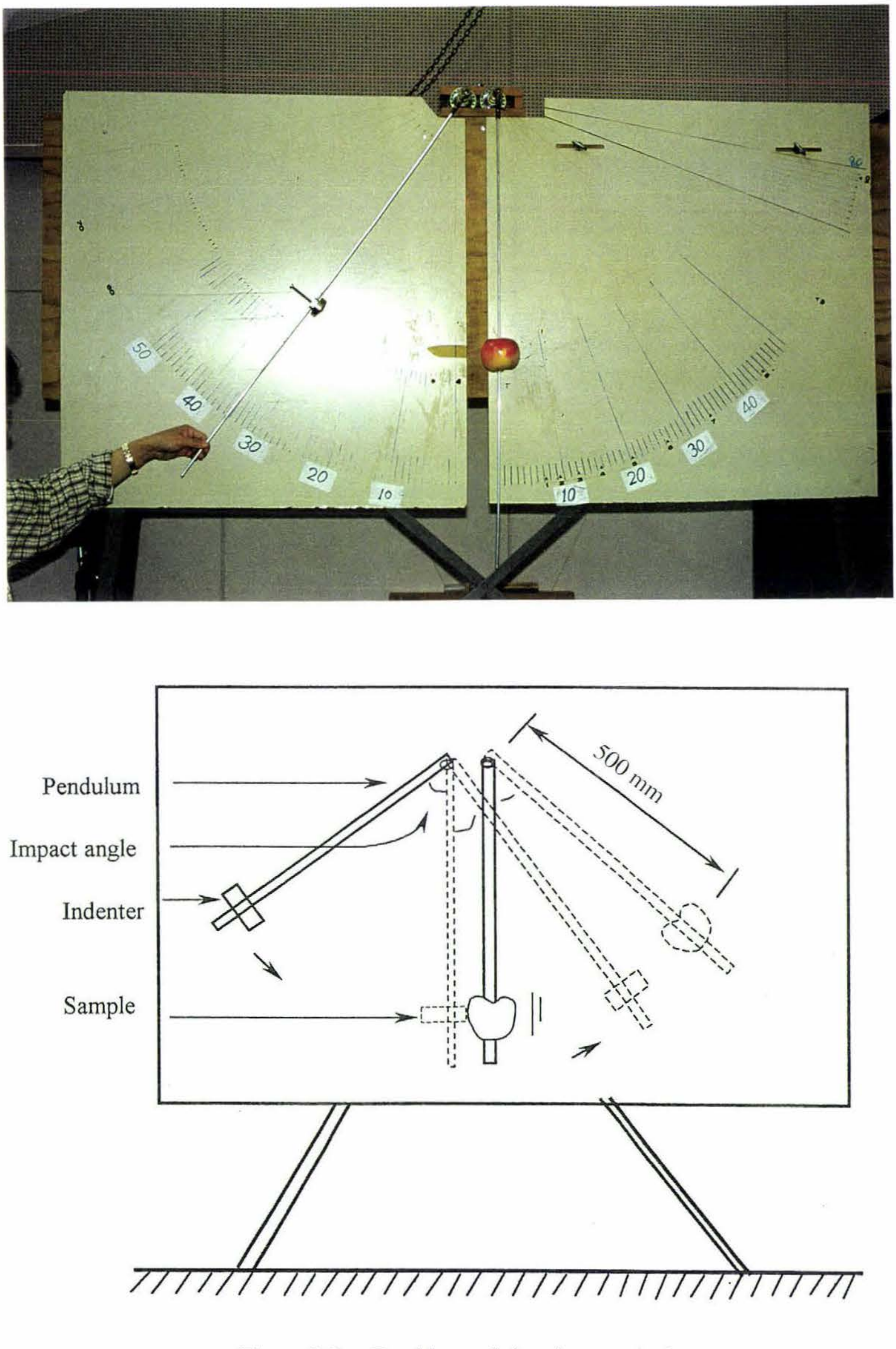


Figure 3.7 Double pendulum impact device
Note: dotted lines show position of pendulum after impact

rotated 90° around the pendulum arm to another target position. Each apple was subjected to one impact from each of four indenters at four different points around its cheek area. After each impact, the impact positions were marked by a marker pen. The movements of the indenter and apple were recorded with a video camera, and the recording was played back in slow motion in order to measure rebound angles. A sample of 20 apples for each of four cultivars was used. The masses were recorded.

3.4.4 Single pendulum tests (S)

The apple to be tested was mounted on a pendulum. This was single aluminium pendulum 750 mm long with a mass of 0.101 kg. The pendulum was supported on a roller bearing. Fruit were located at the centre of percussion of the rod, 500 mm from the axis of rotation. Four different indenters (as described above) were used as the impact surface. These were rigidly fixed in the apparatus. A pendulum system was used since this improved the control over the experiment. Although the apple was constrained to move in a circular path, the impact velocity and energy were the same as if the apple fell through the same vertical drop height. The pendulum device is shown in Figure 3.8.

The range of drop heights was chosen to represent the range of impact levels in a handling system. A geometrical progression was used to determine the drop heights (H, mm) given by

$$H=k_q q_p^{\,n-1}$$

Where, $n=1$ to 10, and k_p and q_p were 4.00 mm and 1.668 respectively. The initial drop height, k_p, was chosen so that it was unlikely to cause bruising in fresh apples. The factor of 1.668 produced a range of ten-drop heights, which represented impact energy levels on a fruit grader (up to 400mm vertical drop height)(Pang et al, 1995).

This test was carried out on 80 apples of each of four cultivars, twenty for each indenter test. The diameters and weights of the apples were recorded by a microcaliper and a two decimal place balance before test. Each apple had a hole through the centre along the

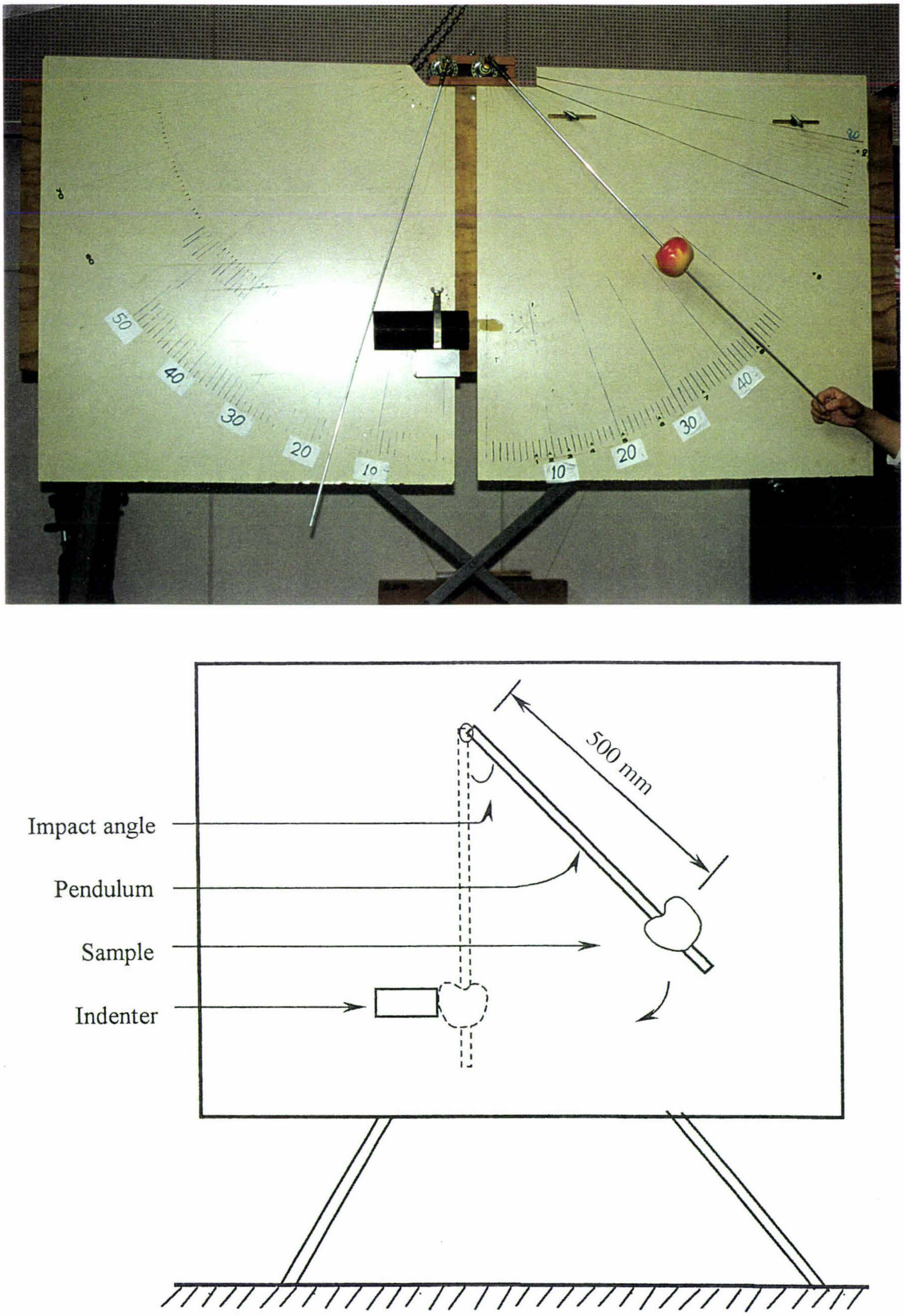


Figure 3.8 Single pendulum impact device
Note: Dotted lines show position of pendulum after impact

calyx to stalk axis, which was produced by a cork borer 3 mm in diameter. This allowed the apple to be slipped onto the pendulum arm, 500 mm from the axis of rotation. The indenter was fixed onto the pendulum board, 500 mm from the axis of rotation. The position of the pendulum was adjusted so that the apple would strike the impact block at the bottom of its swing. The pendulum was raised by hand and released from the lowest drop angles. It was caught after the first impact in order to avoid a second impact. After each impact, the fruit was then rotated around the pendulum arm to another target position and released from the next drop angle. There were ten impact points on each apple from ten dropping heights.

3.4.5 Other tests

Twenty fruit from each treatment were selected at random for firmness test. Firmness (the force required to penetrate the cortical tissue without skin in kg) was measured using a penetrometer, with an 11 mm diameter cylindrical probe. The penetrometer was mounted in a drill press and the force to penetrate the apple tissue to a depth of 10 mm was recorded. Two tests in the cheek area on opposite sides were taken for each fruit.

3.5 Bruise measurement

After the apples were impacted, the bruises created by the vertical drop test, double and single pendulum were allowed to discolour for 24 hours at room temperature before measurements were taken. For the single pendulum test, the bruising area (with skin on and skin removed), and bruising depth produced only by the eighth drop angle (corresponding to a vertical drop height of 20mm) was measured for calculating the bruise susceptibility. For other impact angles, only the bruise area with skin on was measured. Bruise diameter was measured, with micro-callipers, twice (the major and minor diameters) at right angles within the plane of the bruise. The surface shape of bruise produced by 120° and 150° indenters was assumed to be a rhombus, so the two diagonals of the bruise were measured. The mean of these two measurements was then used in subsequent calculations. The depth of bruising was evaluated by making a longitudinal cut through the centre of the bruised region and measuring the depth of bruise.

Bruising area produced by flat and ball indenter was calculated by the following formula:

$$A = \frac{1}{4}\pi d_1 d_2$$

Bruise volumes were calculated using the equation of Chen and Sun (1981):

$$V = \frac{1}{6}\pi d_1 d_2 h$$

Where, d_1 and d_2 were the major and minor diameters (cm); and h was the depth of the bruise (cm).

Bruise area produced by the pyramid indenter was calculated by the following formula for a rhombus:

$$A = \frac{1}{2} d_1 d_2$$

Where, d_1 and d_2 were the diagonals of bruise (cm).

Bruise volume was calculated by assuming a pyramid shape, using the following equation:

$$V = \frac{1}{3} Ah$$

Where, A was the bruise area (cm^2); and h (cm) was the bruise depth.

Bruise susceptibility was defined as the ratio of bruise volume to impact energy for the vertical drop test, and as the ratio of bruise volume to absorbed energy for the other two pendulum tests. For the single pendulum test, the number of bruises was added and divided by 20 to give a bruise number, which was defined as a Bruise Factor ranging from 0 to 10 (Pang et al., 1996). The larger the number the more sensitive was the fruit to bruise damage.

3.6 Statistical Analysis

The statistical package **SAS** (Statistic Analysis System) was used to assist with the analysis of all experimental data. An analysis of variance and coefficient of variation and other computations were completed with **SAS** programme (SAS Institute Inc., 1989).

CHAPTER FOUR

RESULTS

In this chapter the results obtained from different impact tests outlined in the preceding chapter are presented and discussed. In the graphs mean values are presented with error bars representing the standard error.

4.1 Description of bruises

4.1.1 Bruise shapes

The bruise shape depended upon the indenter surface shape. In apples the flatter indenters produced bruises which were less deep than the hockey ball and pyramids. The flat plate indenters frequently caused a bruise, which appeared to surround an unbruised area just below the surface. In this case, the bruises often could not be seen until the skin was removed. This region was not present when the hockey ball and the pyramid indenters were used. The bruise shape was elliptical for the flat plate, a circle for the hockey ball, and a rhombic for the pyramid indenters.

The skin of fruits was often split when the 100° pyramid indenter was used. It was found that all apples were punctured by the 100° indenter on Splendour and Braeburn apples, 90% of Pacific Rose, and only 5% of Granny Smith apples. In these cases the bruising underneath the region of splitting was severe. When light pressure was applied to the bruise, juice was released. The bruise colour produced using the pyramid indenters was darker than bruises caused by the flat and hockey ball indenters. The 100° pyramid indenter was not used after the fresh fruit trial.

4.1.2 Cracking

There was no cracking below the bruise region for any apples when the flat plate indenter was used in the three standard impact tests. When the hockey ball was used on stored fruit, it was found that only Pacific Rose apples had cracks in the tissue. However cracks were found (5-20mm long) below the bruise region in Splendour, Pacific Rose, and Braeburn apples when any pyramid indenter was used (Fig. 4.1). In Granny Smith apples, the cracks were found only when the 120° and 100° pyramid indenter were used (cracking ranged from 6-18mm). It was also found that sometimes the skin was punctured by the edge of the 120° pyramid indenters for Splendour, Pacific Rose, and Braeburn apples but not for Granny Smith apples.

Nearly all bruises were identifiable on the skin surface as a slight flattening of the curvature of the fruit and/or were softer to the touch than the surrounding tissue.

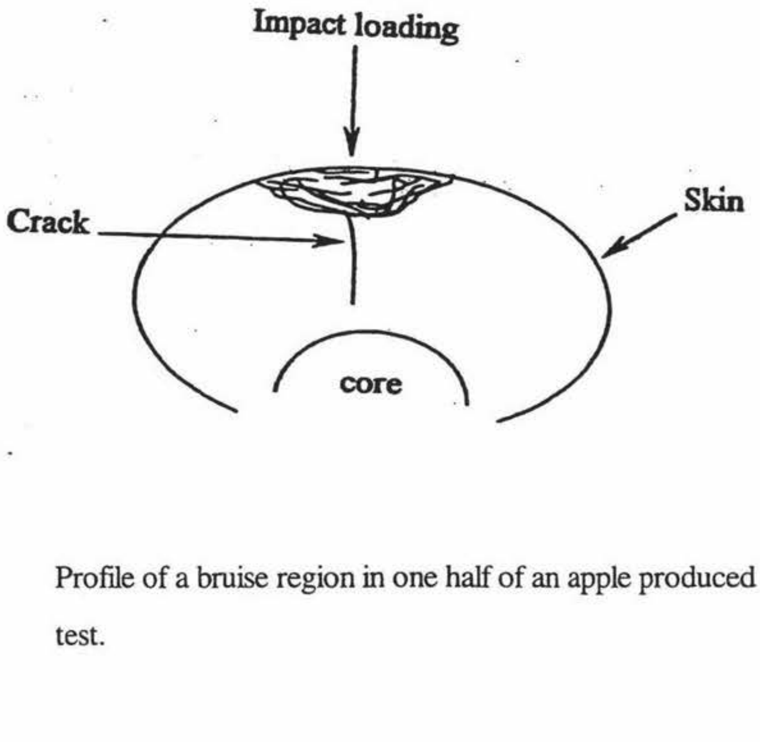


Figure 4.1 Profile of a bruise region in one half of an apple produced by an impact test.

4.2 Bruises produced by tumbler (T)

All bruises visible on the surface of the apples were counted and the sizes measured. Figure 4.2 shows a frequency distribution of apple bruise size found after the tumbler test for different treatments of 'Splendour' apples. The greatest numbers of bruises for fresh apples

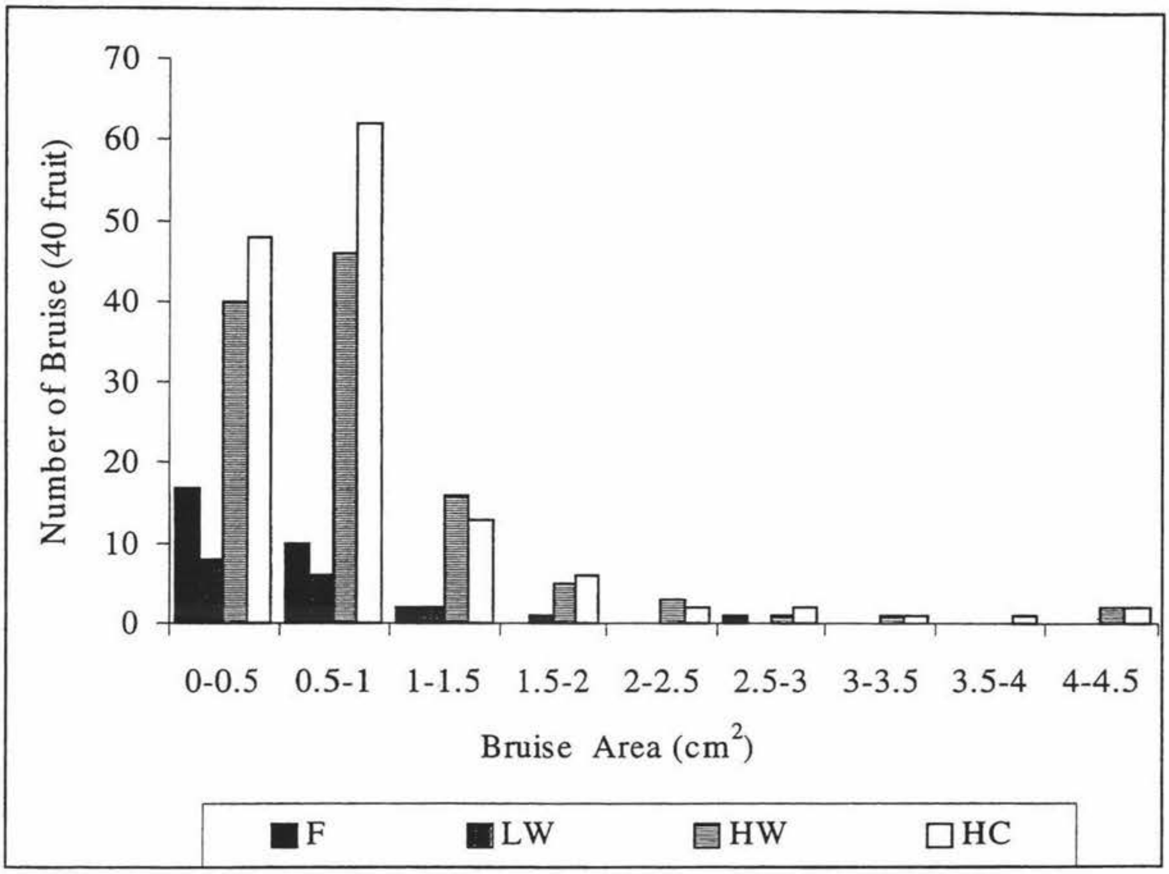


Figure 4.2 Frequency distribution of bruise ares (cm^2) produced by a tumbler on Splendour apple for different treatments.

F: Fresh fruit tested within 24 hours of harvest.

LW: Fruit stored for 2 months at 65% RH, and allowed to reach room temperature before testing.

HW: Fruit stored for 2 months at 90% RH, and allowed to reach room temperature before testing.

HC: Fruit stored for 2 months at 90% RH, and tested at cool-stored temperature.

(F) were recorded in the 0 to 0.5 cm^2 band, and then numbers decreased sharply. After 2 months storage at 90% RH (HW and HC), the greatest number of bruises was in the range from 0.5 to 1 cm^2. For the fruit stored at 65% RH (LW), the greatest number of bruises were recorded in the 0-0.5 cm^2 band. Very few bruises above 2 cm^2 were observed for all treatments.

Figure 4.3 shows a frequency distribution of apple bruise size for (a) fresh (F) and (b) stored at 90% RH (HW) fruit for all cultivars. In Splendour and Granny Smith apples there were more bruises in the 0.5-1 cm^2 band. In Pacific Rose there were more bruises in the 0.5-1.0 cm^2 range in both tests. The total numbers of visible bruises without skin removal on different varieties of apples counted after rolling the tumbler two revolutions are given in Figure 4.4. The numbers of bruises on fresh Splendour and Pacific Rose apples were much higher than on Braeburn apples but slightly less than those on Granny Smith apples. After two months storage at 0.5 °C (RH 90%), the numbers of bruises on HW fruit were increased by 263% for Splendour, 65% for Granny Smith, 27% for Pacific Rose and 50% for Braeburn apples compared with fresh (F) fruit. Splendour had more bruises than other cultivars, especially in the 0-0.5 cm^2 band.

Figure 4.6 and Figure 4.7 show the bruising temperature and storage humidity effect on the total number of bruises for different cultivars. There were many more bruises on fruit stored at high humidity compared with fresh and stored at 65%RH (LW).

The average bruise area per apple and bruise number per apple for each variety are shown in Table 4.1. A linear regression test was conducted. The result (Fig.4.8) showed there was a highly linear correlation between the bruise number per fruit and the bruise area per fruit.

4.2.1 Observations of impacts during Instrumented Sphere experiments

The impacts took several forms during tumbler rolling; the IS was dropped onto the apple which rolled away, or the apple itself was dropped onto the IS, or IS impacted a fixed fruit and bounced backwards, or may have bounced over the top, or IS landed in a gap between several fruit and stopped, or some combination of these. These impacts were very similar to events on a commercial handling and grading system, although in a postharvest handling system the impact situations are considerably more complex, as fruit may bounce over several fruit, impacts are often at oblique angles, and multiple impacts are the norm (Bollen, 1993). Most of these fruit-fruit impacts occur in the orchard, or in the field bin or fruit down into the final size bins. Apples tended to absorb energy as they rolled, especially when they are not rolling about their stem-calyx axis. As an apple 'tumbled' in the tumbler, multiple small impacts were occurring.

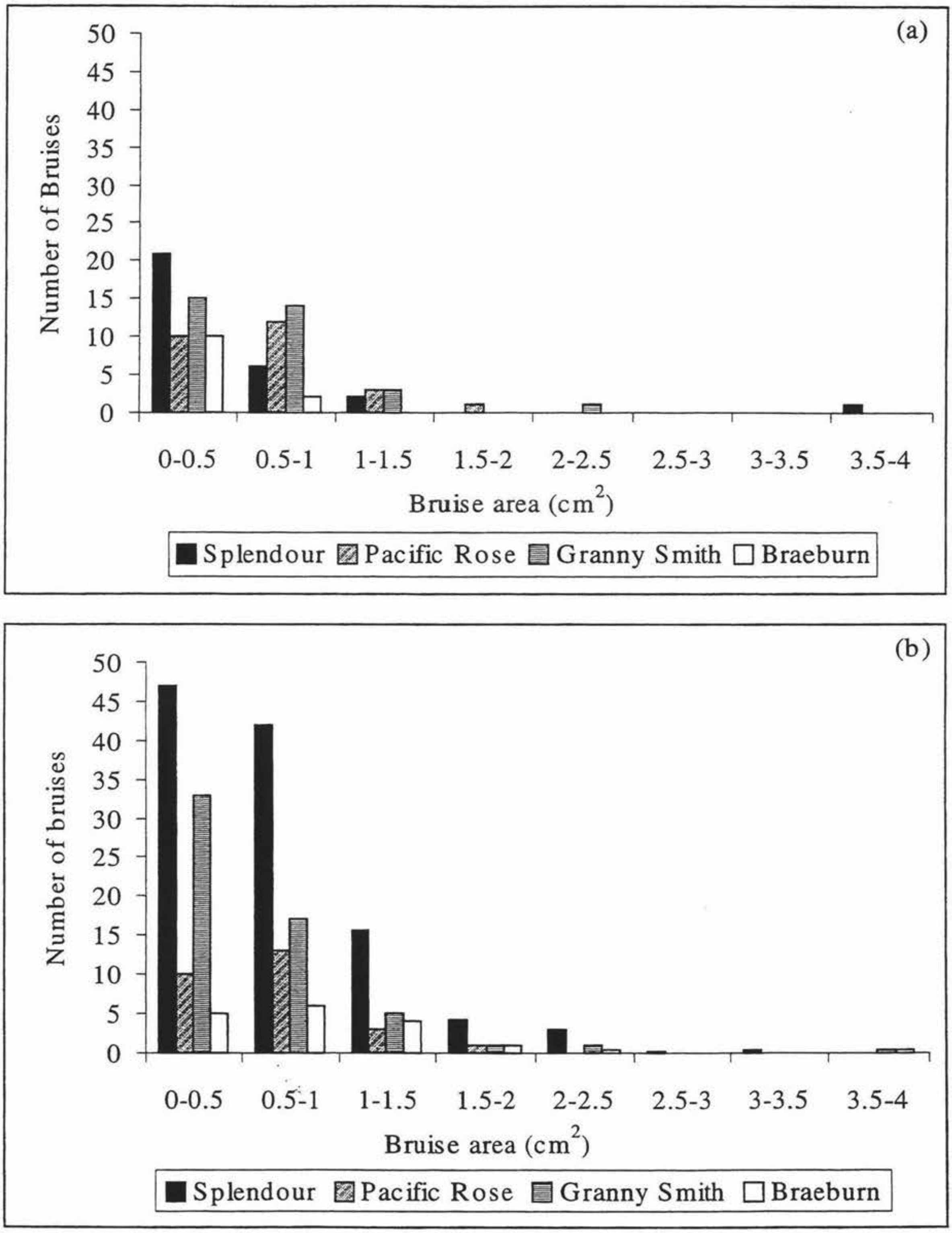


Figure 4.3 Frequency distribution of bruise areas (cm^2) produced by the tumbler test on (a) fresh (F) and (b) stored (HW) of four apple cultivars.

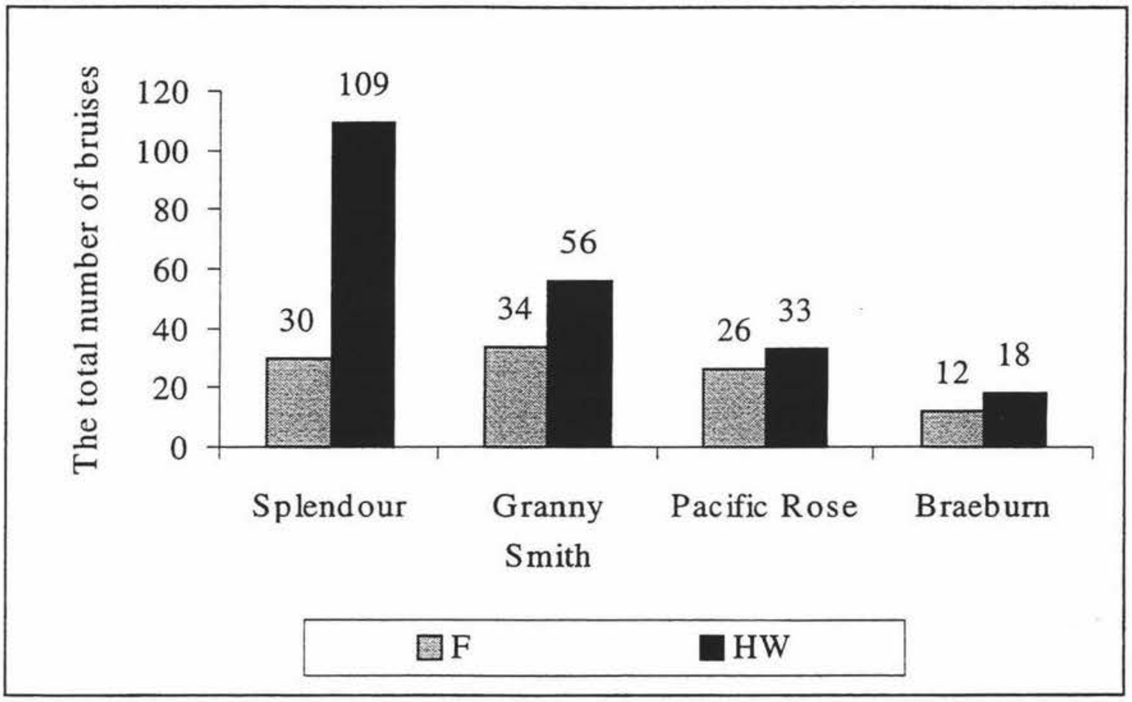


Figure 4.4 The total number of visible bruises produced by the tumbler on four apple varieties (40 fruit per variety).

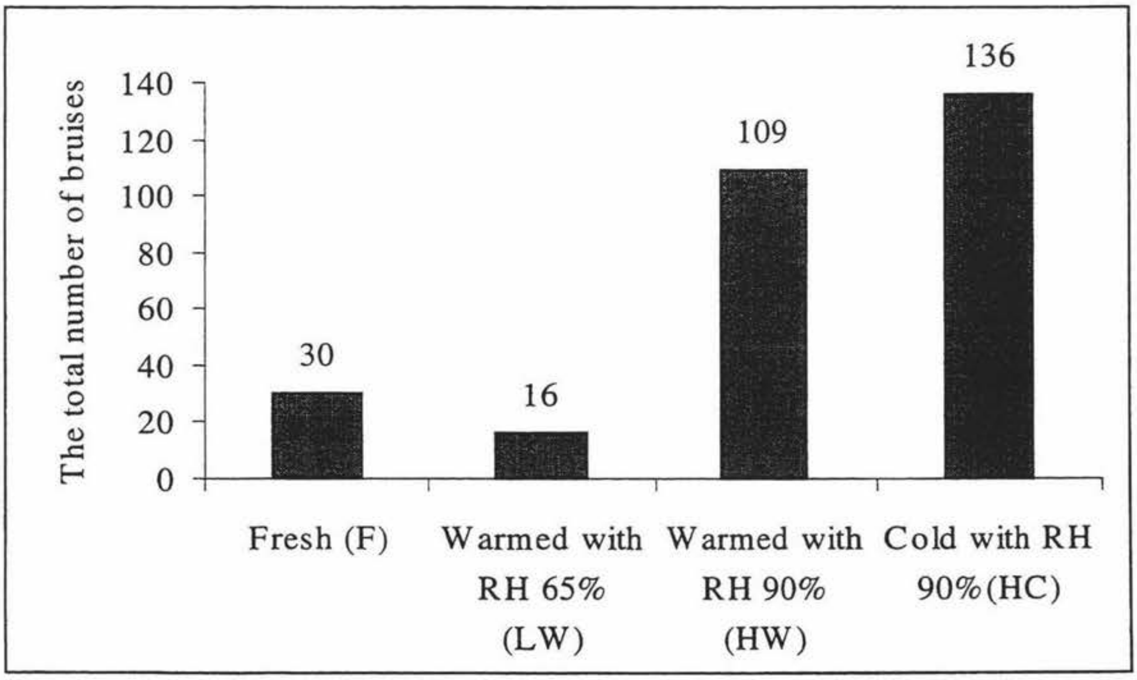


Figure 4.5 The total number of visible bruises produced by the tumbler on 'Splendour' apples for different treatments (40 fruits per treatment).

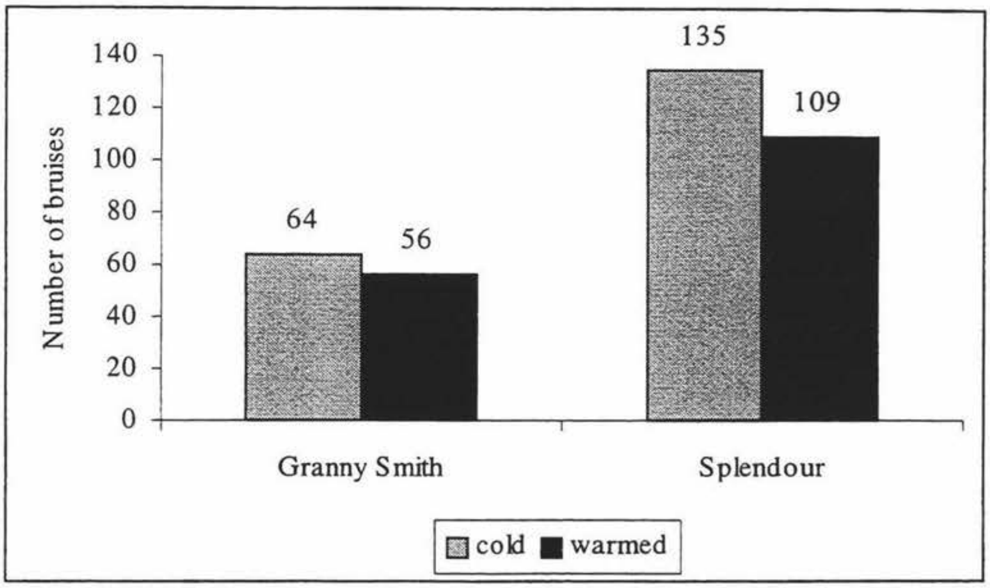


Figure 4.6 The number of bruises produced by the tumbler test on cold (HC) and warmed (HW) Splendour and Granny Smith apples.

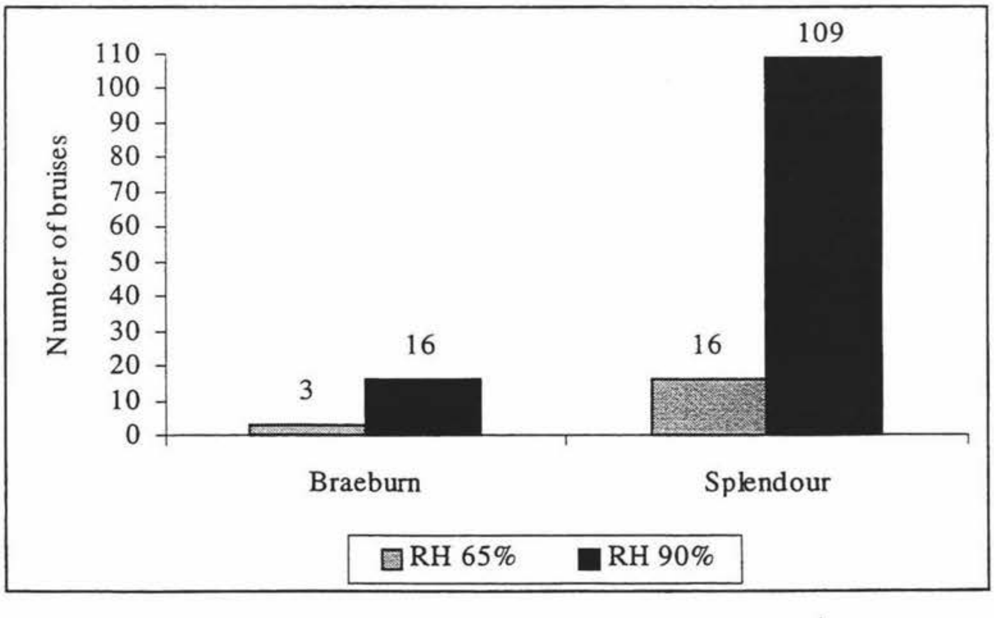


Figure 4.7 The number of bruises produced from the tumbler test on stored Splendour and Braeburn apples with two RH levels.

Table 4.1 Bruise area per apple and bruise number per apple produced from tumbler test on different apple varieties.

Cultivar	Treatment	Bruise area per apple (cm^2)	Average number of bruises per apple
Splendour	F	0.76	0.75
	LW	0.32	0.75
	HW	2.45	2.73
	HC	3.31	3.38
Pacific Rose	F	0.57	0.65
	HW	0.65	0.68
Granny Smith	F	0.72	0.85
	HW	1.11	1.4
	HC	1.33	1.59
Braeburn	F	0.17	0.3
	LW	0.04	0.075
	HW	0.44	0.40

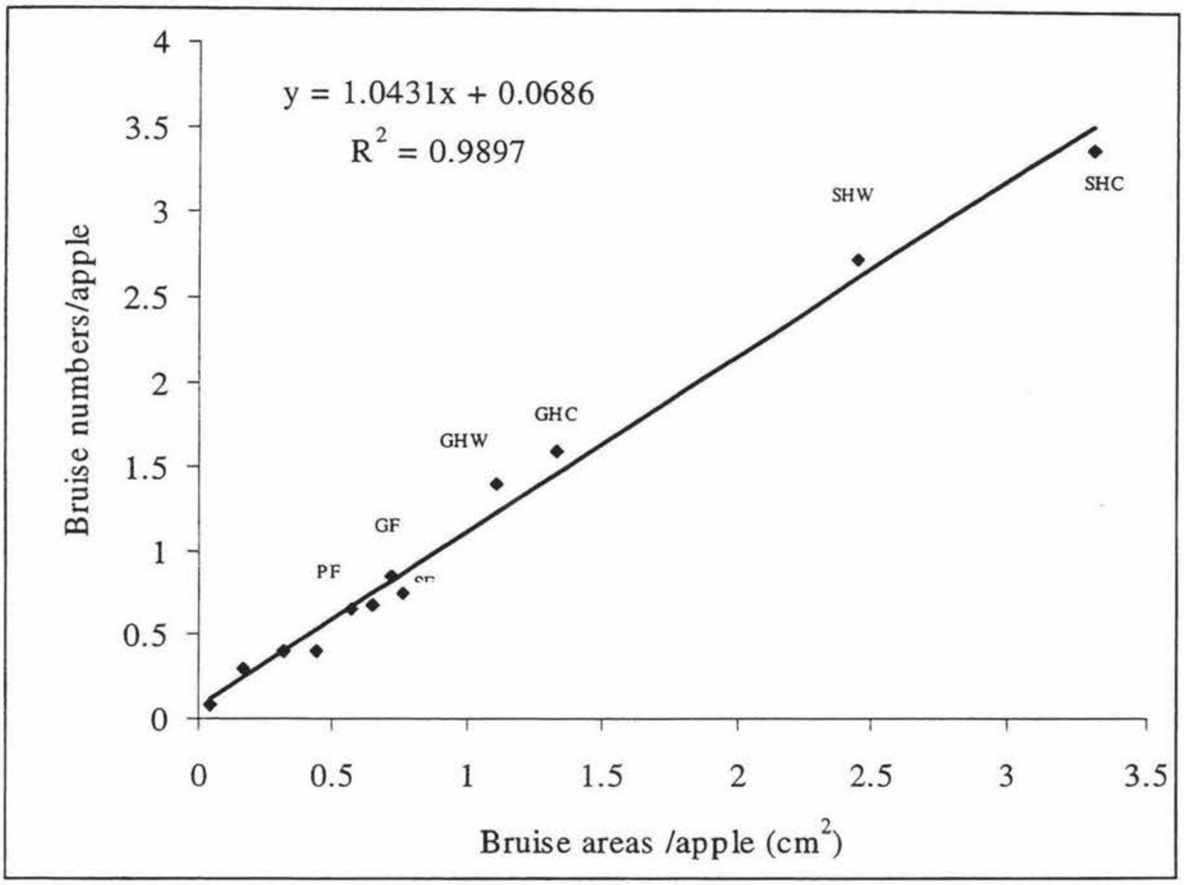


Figure 4.8 The bruise areas/apple and bruise numbers/apple produced by the tumbler test

S= Splendour

G= Granny Smith

P= Pacific Rose

B= Braeburn

4.3 Bruising produced from standard impact tests

4.3.1 Bruise susceptibility produced by the vertical drop test (V) on different varieties of apples

Different values for the bruise susceptibility were obtained using different indenters on all varieties, with lower values being obtained for greater angles of penetration at the edge of the contact area. The results of the bruise susceptibility, the bruise area, and the bruise depths produced from test V on different treatments fruits for all five indenters are summarised in Table 4.2-4.3. The means and standard deviations of the bruise susceptibility, area, and depth are shown in Figure 4.9-4.11.

Bruise susceptibility produced by using the flat and hockey ball was much higher than those produced by using the pyramid indenters. For fresh (F) fruit, the least differences in the bruise susceptibility between the hockey ball and other pyramid indenters were 66% for Granny Smith, 57% for Pacific Rose, 54% for Splendour, and 70% for Braeburn apples (Table 4.2). For HW fruit, the least differences in the bruise susceptibility between the hockey ball and Pyramid indenters were 67% for Granny Smith, 80% for Pacific Rose, 73% for Splendour, and 70% for Braeburn apples. Splendour had the largest bruise susceptibility, and Braeburn had the smallest bruise susceptibility in all cases determined with the hockey ball (Table 4.2).

The bruise susceptibility for HW fruit using the flat plate and the hockey ball differed considerably between cultivars. The bruise susceptibility for the flat plate was only slightly different compared to the hockey ball on Splendour and Granny Smith apples, but the bruise susceptibility value from the flat plate was much less than the hockey ball for Pacific Rose and Braeburn apples.

The bruise susceptibility obtained by using the hockey ball was significantly higher on HW fruit for all cultivars compared to F fruit, but the trend was not consistent across all indenters. There were few differences between F and HW fruits for the pyramid indenters

Table 4.2 Bruise susceptibility (ml/J) produced from the vertical drop test (V) (input energy=0.31J).

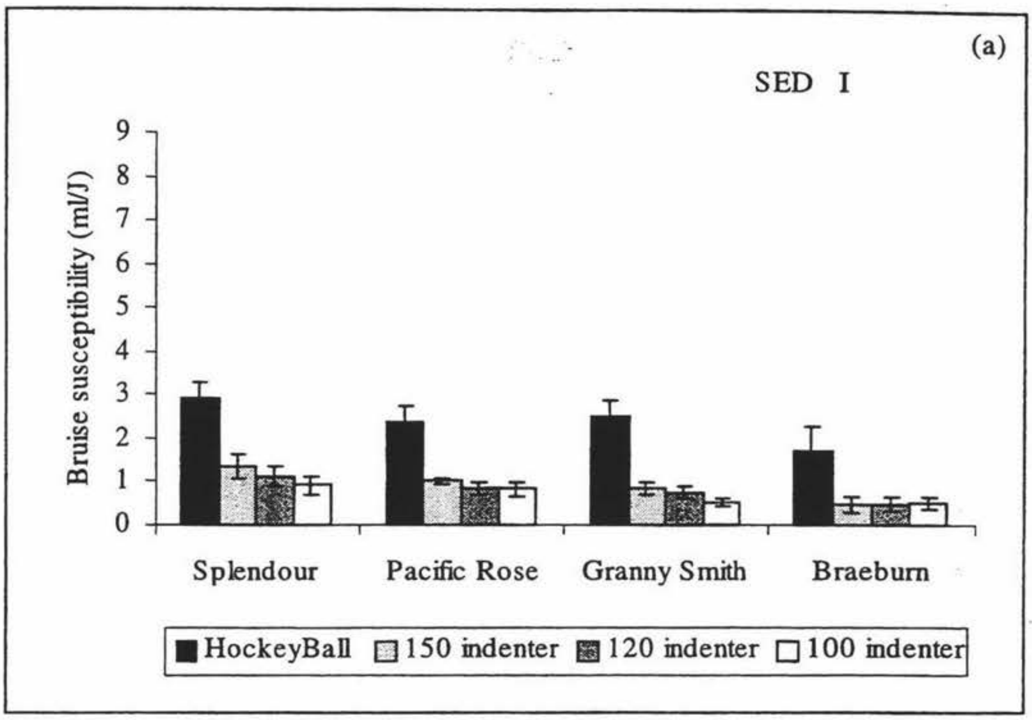
Cultivar	Treatment	Flat Plate		Hockey ball		150 Pyramid Pyramid		120 Pyramid Pyramid		100 Pyramid Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F			2.910	0.082	1.333	0.063	1.120	0.049	0.911	0.050
	LW	1.998	0.169	2.188	0.070	0.831	0.067	0.816	0.047		
	HW	3.335	0.119	3.281	0.101	0.873	0.037	0.696	0.035		
	HC	3.795	0.155	3.514	0.131	0.799	0.037	0.823	0.047		
Pacific Rose	F			2.351	0.088	0.998	0.017	0.828	0.031	0.825	0.039
	HW	1.908	0.209	2.681	0.102	0.545	0.055	0.542	0.046		
Granny Smith	F			2.513	0.083	0.857	0.032	0.735	0.033	0.523	0.02
	HW	3.058	0.159	2.869	0.087	0.956	0.051	0.870	0.031		
	HC	3.572	0.174	3.343	0.055	1.035	0.064	0.920	0050		
Braeburn	F			1.724	0.123	0.464	0.040	0.483	0.035	0.515	0.033
	LW	0.778	0.120	1.625	0.101	0.527	0.040	0.457	0.025		
	HW	1.014	0.13	2.047	0.059	0.607	0.031	0.397	0.026		

Table 4.3 Bruise area (cm^2) (skin removed) produced from the vertical drop tests (V)

Cultivar	Treatment	Flat indenter		Hockey ball		150 Pyramid		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F			2.25	0.04	1.81	0.046	1.57	0.040	1.42	0.044
	LW	2.33	0.120	1.90	0.044	1.44	0.048	1.35	0.042		
	HW	2.79	0.070	2.47	0.053	1.38	0.029	1.18	0.040		
	HC	3.20	0.087	2.60	0.043	1.33	0.06	1.29	0.050		
Pacific Rose	Fresh			1.97	0.035	1.62	0.039	1.32	0.029	1.17	0.025
	HW	2.09	0.110	2.13	0.049	0.99	0.072	0.95	0.054		
Granny Smith	F			2.03	0.048	1.38	0.038	1.18	0.027	0.99	0.027
	HW	2.85	0.133	1.99	0.04	1.46	0.062	1.11	0.044		
	HC	2.96	0.073	2.30	0.030	1.47	0.060	1.23	0.051		
Braeburn	F			1.38	0.046	0.92	0.039	0.87	0.039	0.89	0.038
	LW	1.06	0.099	1.37	0.040	0.94	0.037	0.86	0.032		
	HW	1.18	0.062	1.56	0.045	0.99	0.032	0.75	0.029		

Table 4.4 Bruise depth (mm) produced from the vertical drop tests (V)

Cultivar	Treatment	Flat indenter		Hockey ball		150 Pyramid ° Pyramid		120 Pyramid Pyramid		100 Pyramid pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F			5.45	0.09	6.25	0.21	5.67	0.22	6.23	0.22
	LW	3.99	0.25	5.35	0.16	5.27	0.23	5.57	0.17		
	HW	5.57	0.20	7.1	0.12	5.85	0.19	5.47	0.21		
	HC	5.50	0.14	6.85	0.20	5.42	0.28	5.87	0.19		
Pacific Rose	Fresh			5.17	0.16	5.47	0.16	5.25	0.17	6.60	0.27
	HW	4.10	0.31	5.85	0.17	5.05	0.24	5.15	0.23		
Granny Smith	F			5.75	0.12	5.57	0.15	6.02	0.19	5.55	0.11
	HW	5.05	0.21	6.65	0.11	6.10	0.21	6.65	0.15		
	HC	5.75	0.16	6.76	0.08	6.45	0.19	6.86	0.18		
Braeburn	F			5.27	0.16	4.75	0.22	4.85	0.21	4.70	0.21
	LW	3.20	0.22	5.45	0.21	5.20	0.18	4.90	0.17		
	HW	3.87	0.20	6.15	0.15	5.65	0.17	4.87	0.21		



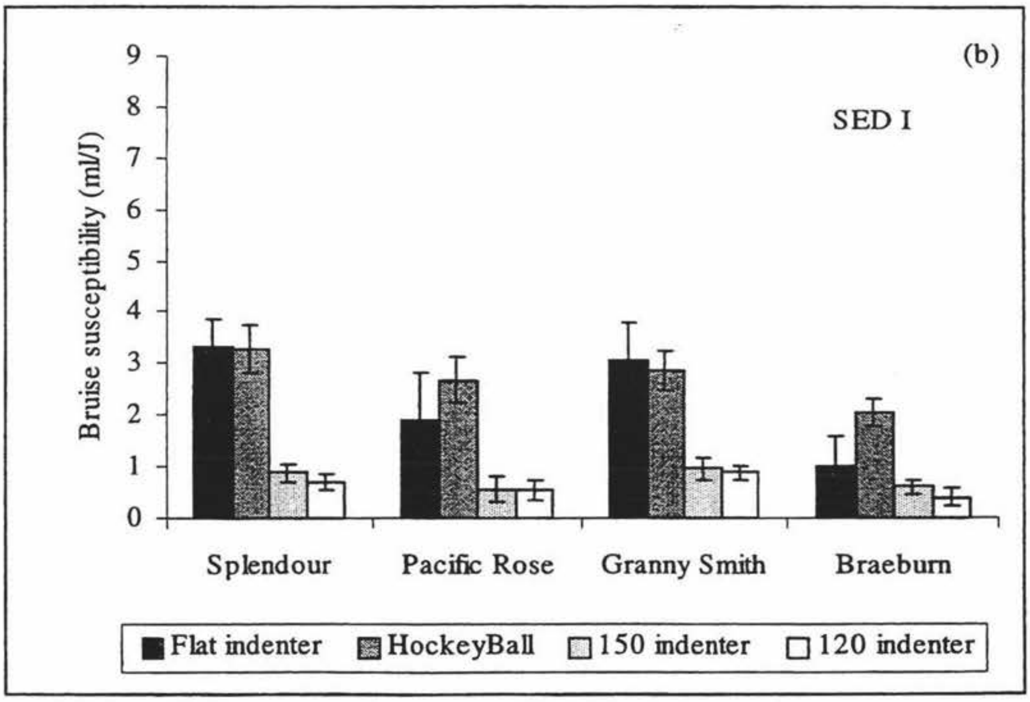
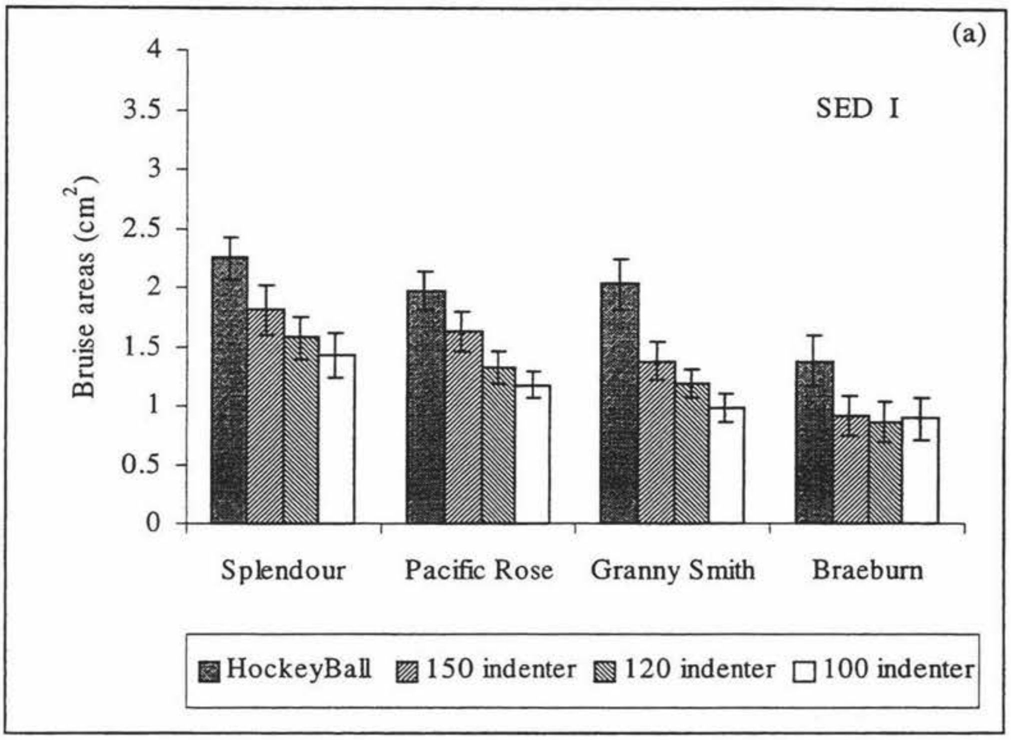


Figure 4.9 Bruise susceptibility (ml/J) from test V using different indenters on (a) F and (b) HW fruit.



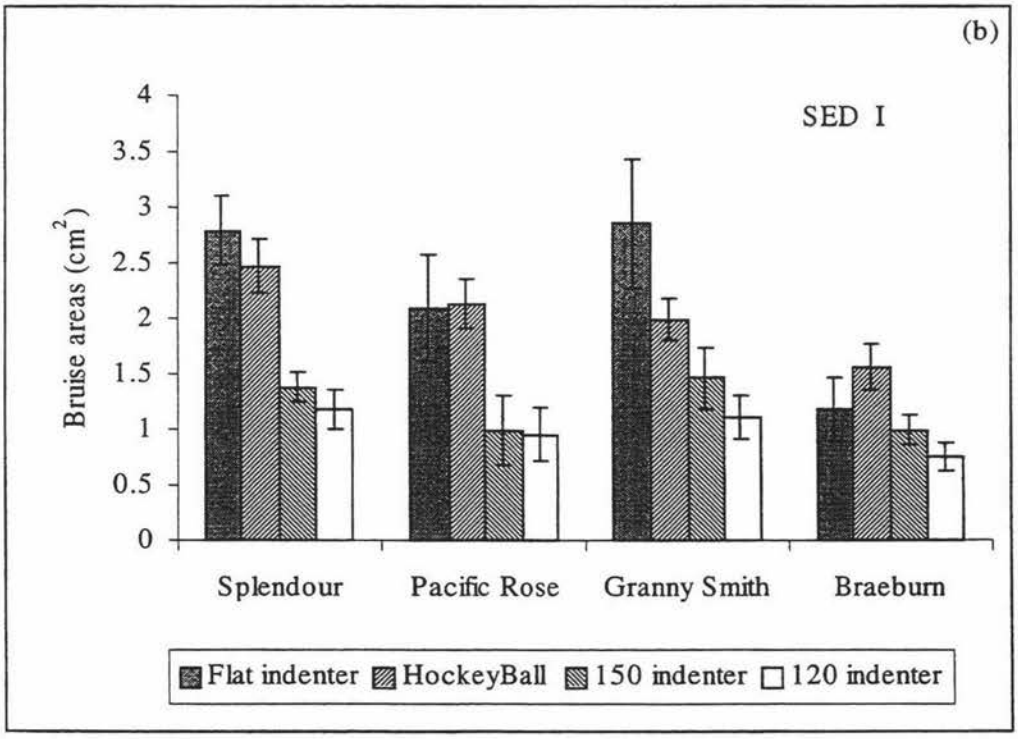
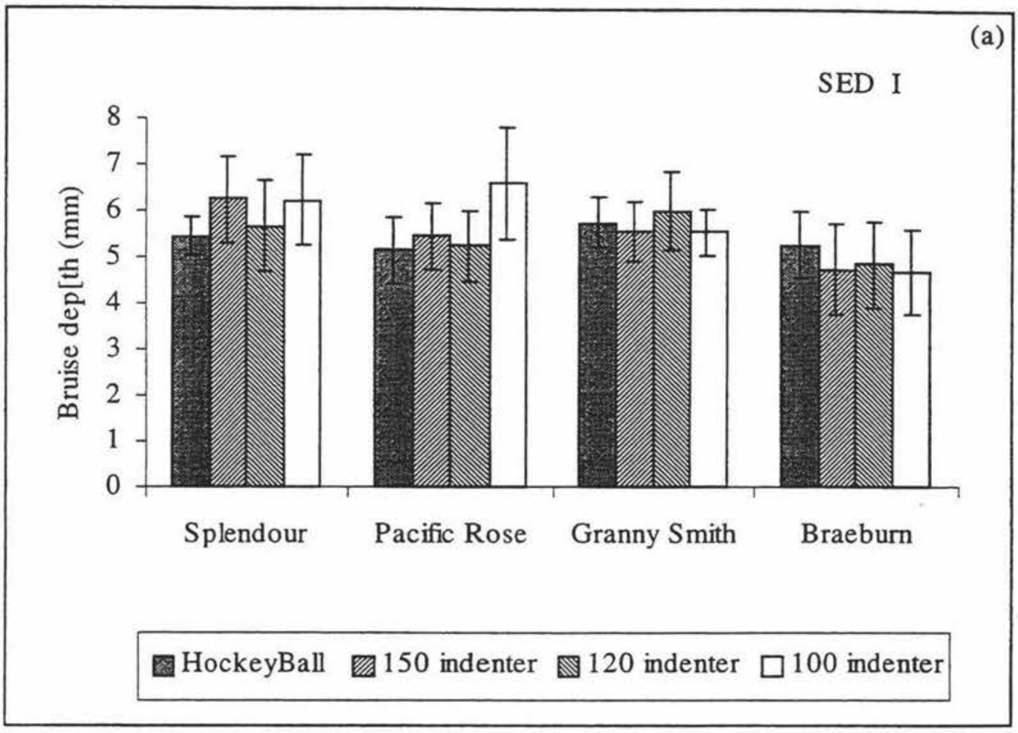


Figure 4.10 Bruise areas (cm^2) from test V using different indenters on (a) F and (b) HW fruit.



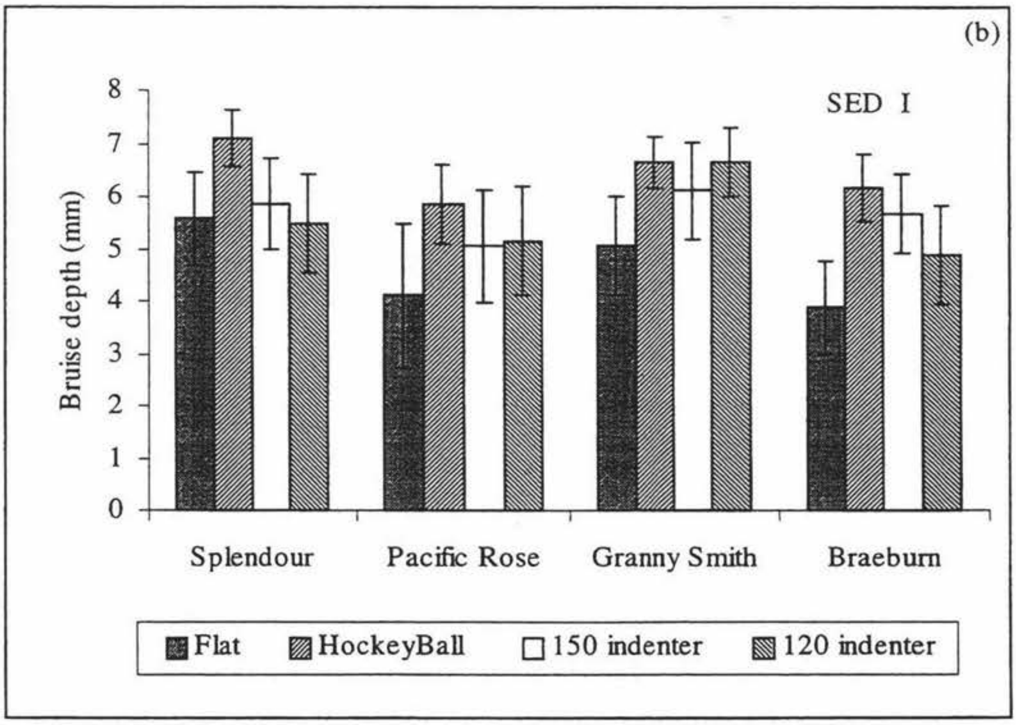


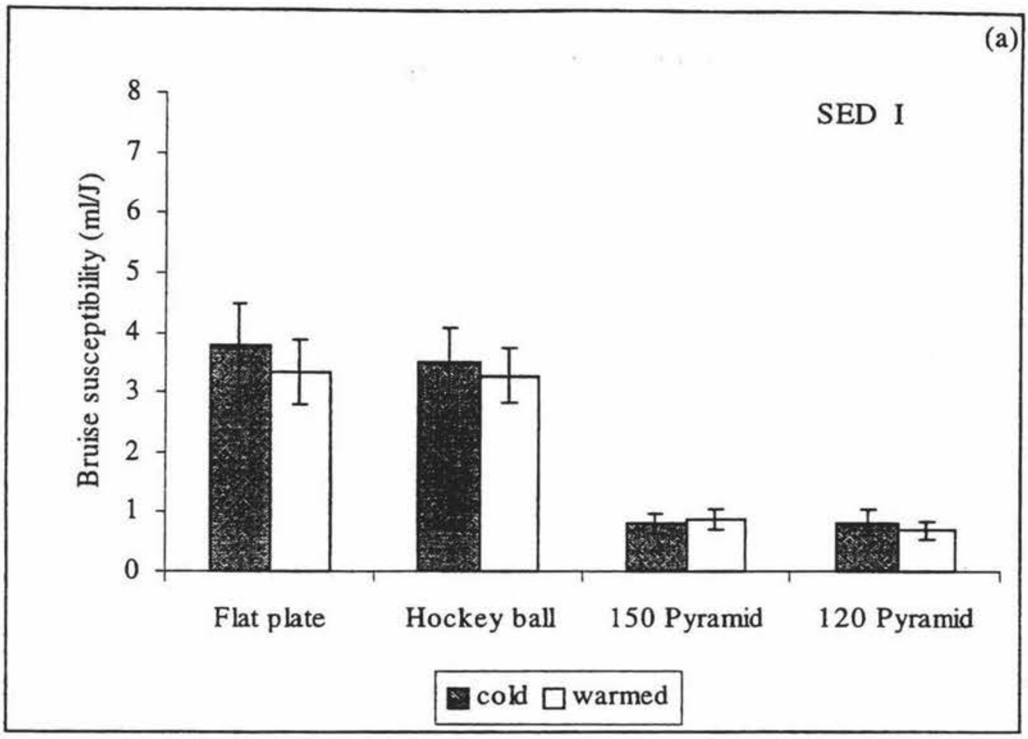
Figure 4.11 Bruise depth (mm) from test V on (a) F and (b) HW fruit.

on all cultivars. Apples sustained about 14% more for Granny Smith and Pacific Rose13% for Splendour and 19% for Braeburn apple damage if they were impacted using the hockey ball following 2 months storage at RH (90%) than if they were impacted after harvest. This shows that there was a direct effect of store time on bruise susceptibility.

Figure 4.10 and 4.11 show the bruise area and bruise depth changed corresponding to the bruise susceptibility in Fig. 4.9. Bruise area showed a similar trend compared with the bruise susceptibility. The flat indenter and hockey ball have larger bruise area than the pyramid indenters. After 2 months stored at 90% RH, fruits sustained more bruise area than fresh fruits. Braeburn had the smallest areas in all cases (Table 4.3). The standard errors of the bruise area were smaller than the bruise susceptibility. But there were no consistent trends in bruise depth between fresh and stored fruits, and among the different indenters (Table 4.3 and Fig 4.10).

The results of bruise susceptibility by test V for cooled and warmed (HW and HC) Splendour and Granny Smith apples area shown in Figure 4.12. Splendour and Granny Smith apples when subjected to impact damage using the flat and the hockey ball indenters at room temperature incurred bruise susceptibility that were 7% to 14% less than if they were bruised at 0°C. For the pyramid indenters, there were no significant differences between HW and HC fruits.

As discussed in the methods section, the storage humidity was controlled for 2 months at two levels (65% and 90%). Water loss was measured by weighing a carton fresh apple samples (80 apples) for each humidity level and then weighing it again after 2 months storage for both Splendour and Braeburn apples. The humidity level in the cool storage room affected weight loss. The water loss was 4.31% for Splendour, and 5.02% for Braeburn apples for 65% humidity level, and 1.20% and 1.16% respectively for 90% humidity. Apples stored in 0.5°C/65% RH area had weight losses 3.6 times greater for Splendour, and 4.3 times greater for Braeburn than those stored in the high humidity environment for 2 months. This agrees with other results (Samim, 1992) reporting 'Gala' and 'Granny Smith' apples at low RH (66%) lost weight approximately twice as fast as those at high RH (95%).



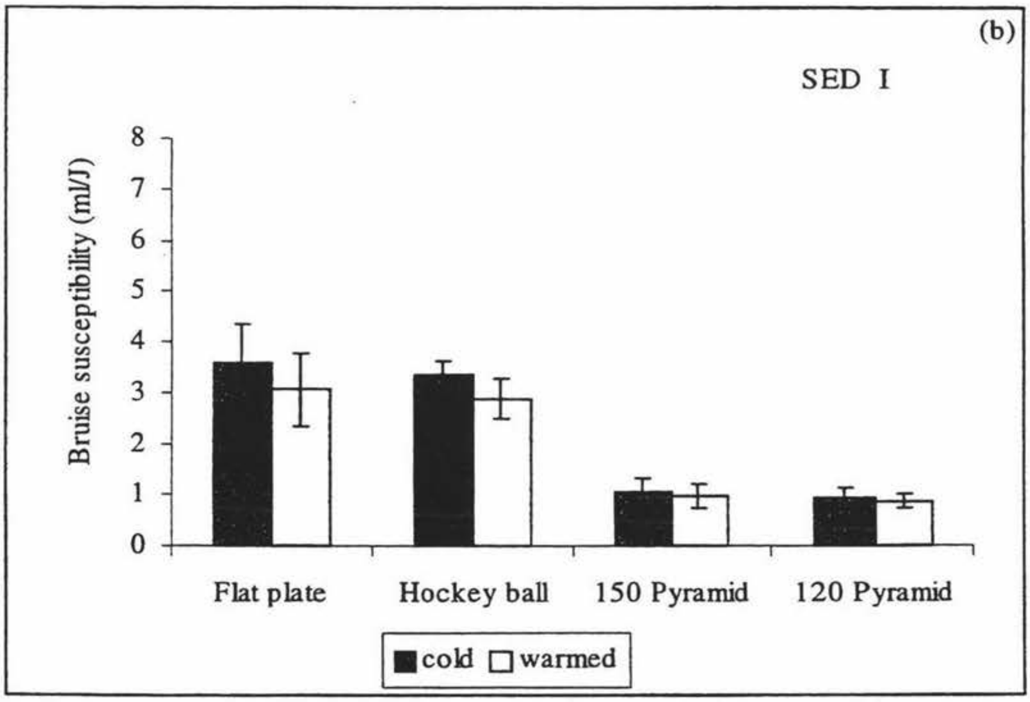
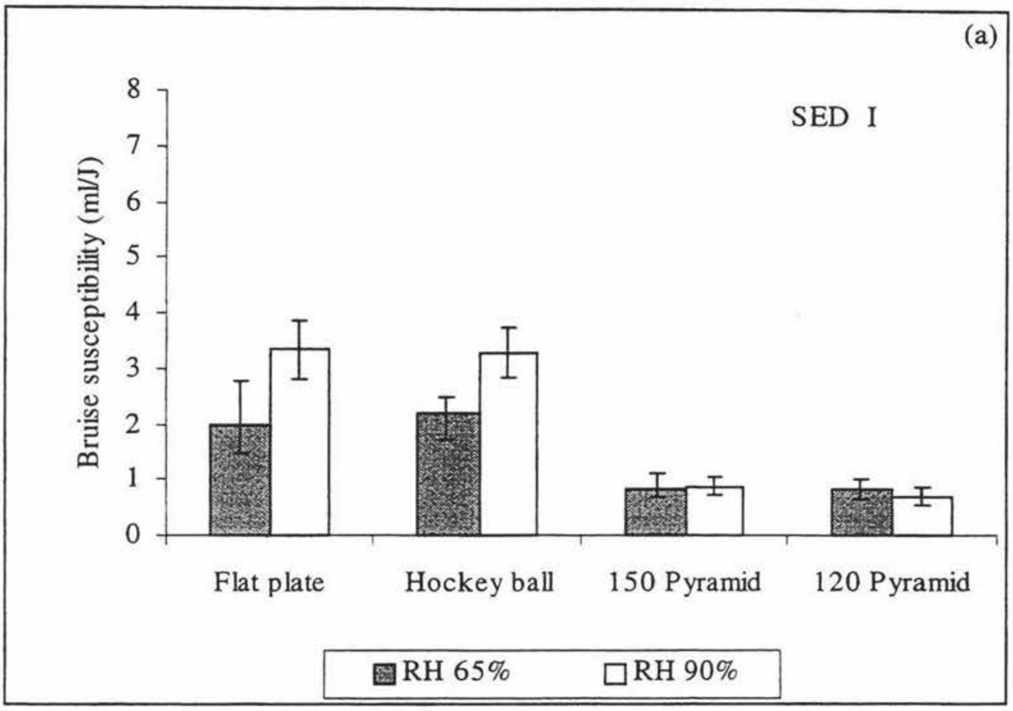


Figure 4.12 Bruise susceptibility (ml/J) on HC and HW (a) Splendour and (b) Granny Smith apples from test V.



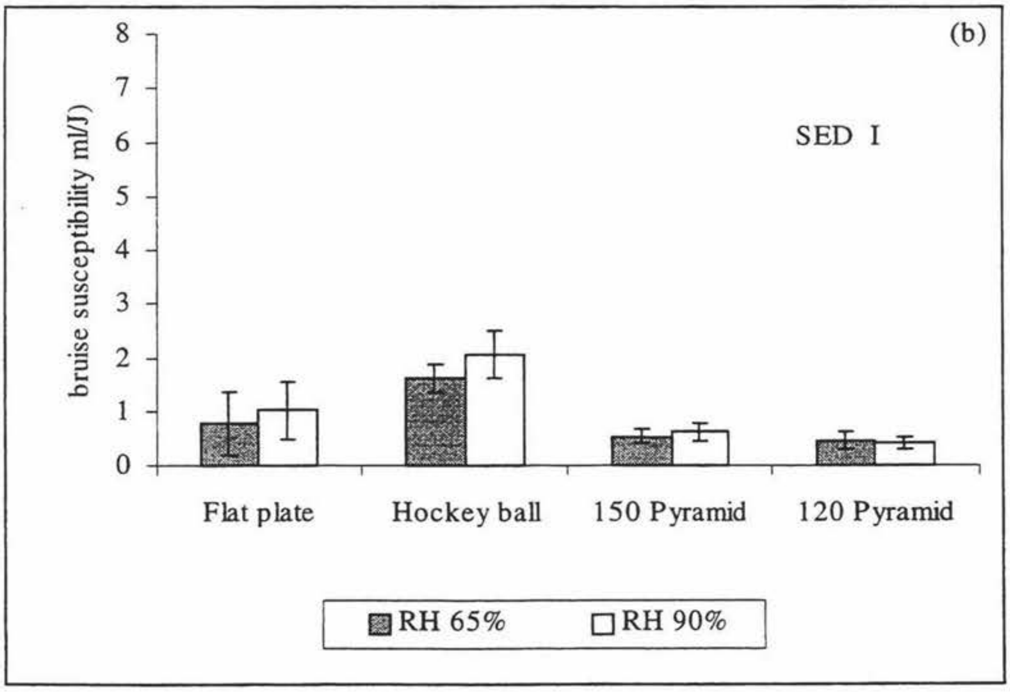


Figure 4.13 Bruise susceptibility (ml/J) on LW and HW fruit for (a) Splendour and (b) Braeburn from test V.

The results of bruise susceptibility produced using different indenters for low and high relative humidity storage on Splendour and Braeburn apples are shown in Figure 4.13. There were significant differences in the bruise susceptibility between LW and HW fruits for Splendour and Braeburn measured by dropping the flat and hockey ball indenters ($p<0.05$). There were no significant differences in bruise susceptibility obtained by dropping the 150° and 120° pyramid indenters ($p>0.05$) on HW and HC fruits.

It was noticed that the standard deviations of the bruise susceptibility were smaller for the pyramid indenters, compared with the flat and the hockey ball indenter.

4.3.2 Bruise susceptibility produced from the double pendulum tests (D)

The bruise susceptibility, bruise area and depth values produced from the double pendulum test (D) for different treatments fruits was quite different to the vertical (V) drop tests (Table 4.5-4.7). The tables give means and standard errors of the bruise susceptibility from individual experiment. For fresh fruits, there were much difference among four cultivars. 'Granny Smith' apple had the largest bruise susceptibility value in all cases, 'Pacific Rose' apple had the lowest bruise susceptibility value for all indenters (Fig. 4.14 (a)). After 2 months storage, Braeburn apple became the most resistant to bruise again for both HW and LW fruits. For HW fruit, there were few differences in bruise susceptibility values among Splendour, Pacific Rose and Granny Smith apples for each indenter (Fig. 4.14 (b)).

Between the pyramid indenters, there were also no significant differences in the bruise susceptibility ($p>0.05$) on fresh and stored fruits for any cultivar. The bruise susceptibility produced by dropping the flat plate was much higher than those produced by dropping the pyramid indenters. The least differences in the bruise susceptibility between the flat plate and other pyramid indenters were 71% for Granny Smith, 58% for Pacific Rose, 51% for Splendour, and 70% for Braeburn apples. For HW fruit, the least differences in the bruise susceptibility between the flat plate and other pyramid indenters were 72% for Granny Smith, 69% for Pacific Rose, 71% for Splendour, and 72% for Braeburn apples.

Bruise susceptibility produced by using the flat plate increased for HW Splendour and Pacific Rose fruit (81% for Splendour, 124% for Pacific Rose). Bruise susceptibility decreased 16% for HW Granny Smith apples. For Braeburn, there were few differences between F and HW fruit, but LW fruit had much lower bruise susceptibilities. The bruise susceptibility on stored fruit between the flat and the hockey ball were not different for all cultivars.

Figure 4.15-4.16 show the means and standard deviation of the bruise susceptibility, area and depth from test D. Changes in bruise area were similar to the bruise susceptibility changes as in Figure 4.14. For HW fruit, the bruise area decreased as the vertex angles of indenters decreased. The bruise depth varied slightly in value for each indenter and each cultivar, but there were no consistent trends. In particular Braeburn bruise depths were similar to bruise depths for the other three cultivars.

The bruise susceptibility increased as the testing temperature decreased ranged from 26-32% for all indenters for HW and HC Splendour apples. For Granny Smith apples, there were no statistical differences between HW and HC fruits in all indenters (Fig. 4.17).

Figure 4.18 shows the bruise susceptibility for Splendour and Braeburn apples produced by test D on LW and HW fruits. There were significant differences ($P<0.05$) in bruise susceptibility in all cases for both cultivar apples. The apples stored at high humidity had larger bruise susceptibility than those stored at low humidity.

The standard deviations of the bruise susceptibilities were smaller for the pyramid indenters, compared with the flat plate, and larger for bruise depth. An energy balance calculation showed that only about 50-60% energy was lost during the double pendulum test.

Table 4.5 Bruise susceptibility (ml/J) produced from the double pendulum test (D) (input energy=0.31J).

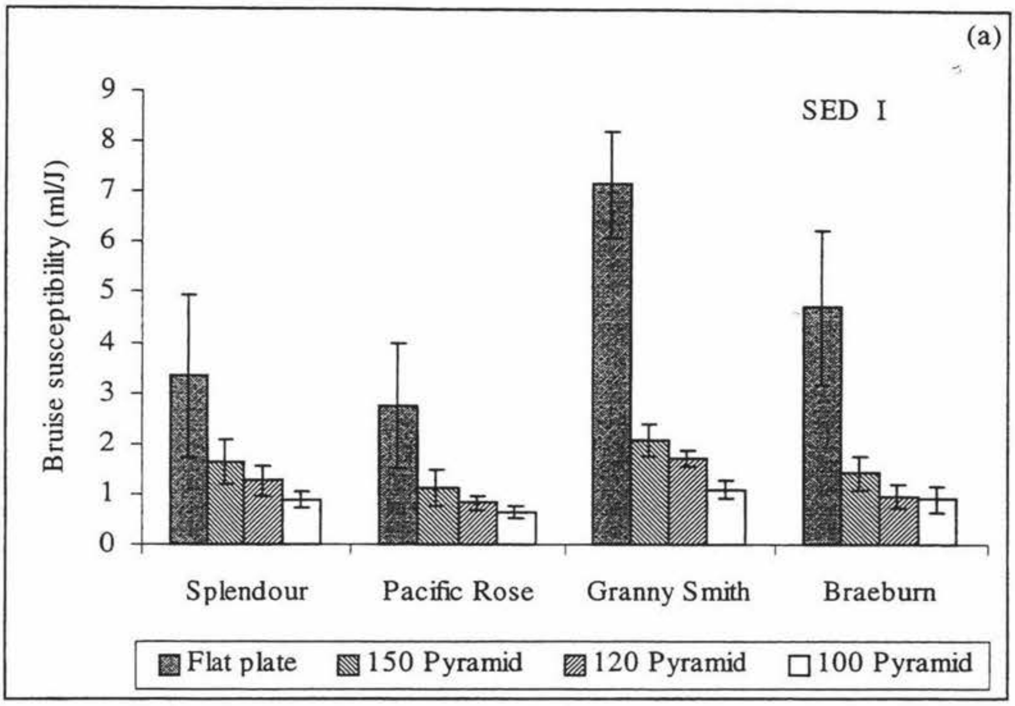
Cultivar	Treatment	Flat Plate		Hockey ball		150 Pyramid		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F	3.330	0.360			1.634	0.101	1.255	0.063	0.861	0.035
	LW	3.036	0.230	4.33	0.18	0.682	0.035	0.549	0.015		
	HW	6.038	0.326	6.224	0.234	1.742	0.102	1.270	0.081		
	HC	8.002	0.260	8.034	0.28	2.261	0.086	1.606	0.070		
Pacific Rose	F	2.752	0.280			1.126	0.080	0.821	0.030	0.630	0.03
	HW	6.020	0.370	6.414	0.270	1.845	0.085	1.28	0.045		
Granny Smith	F	7.152	0.240			2.060	0.070	1.721	0.039	1.087	0.038
	HW	6.123	0.209	6.074	0.122	1.702	0.042	1.291	0.040		
	HC	6.225	0.176	6.128	0.157	1.749	0.046	1.332	0.043		
Braeburn	F	4.723	0.341			1.416	0.076	0.972	0.054	0.914	0.058
	LW	2.203	0.217	3.595	0.172	0.837	0.043	0.632	0.027		
	HW	4.893	0.280	5.195	0.23	1.366	0.054	0.965	0.047		

Table 4.6 Bruise area (cm^2) (skin removed) produced from the double pendulum tests (D) (input energy = 0.31J)

Cultivar	Treatment	Flat indenter		Hockey ball		150 Pyramid °		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F	2.060	0.074			1.39	0.047	1.13	0.025	0.95	0.025
	LW	1.72	0.085	1.73	0.048	1.15	0.029	1.01	0.051		
	HW	2.92	0.092	2.39	0.054	1.50	0.043	1.19	0.027		
	HC	3.26	0.057	2.59	0.04	1.76	0.03	1.37	0.025		
Pacific Rose	F	1.66	0.078			1.12	0.036	0.91	0.028	0.70	0.018
	HW	3.01	0.110	2.45	0.041	1.65	0.037	1.28	0.023		
Granny Smith	F	3.13	0.047			1.54	0.033	1.22	0.040	0.93	0.023
	HW	2.77	0.057	2.24	0.036	1.39	0.026	1.07	0.019		
	HC	2.86	0.041	2.31	0.035	1.50	0.031	1.17	0.019		
Braeburn	F	1.76	0.075			1.08	0.040	0.86	0.020	0.77	0.025
	LW	1.30	0.078	1.44	0.033	0.85	0.033	0.73	0.017		
	HW	2.04	0.079	1.78	0.049	1.18	0.033	0.92	0.022		

Table 4.7 Bruise depth (mm) produced from the double pendulum tests (D) (input energy = 0.31J).

Cultivar	Treatment	Flat indenter		Hockey ball		150 Pyramid		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F	3.47	0.27			5.52	0.18	5.22	0.16	4.57	0.12
	LW	3.63	0.16	5.15	0.16	5.00	0.18	4.87	0.10		
	HW	5.23	0.19	6.40	0.15	6.32	0.23	5.80	0.27		
	HC	6.03	0.17	7.53	0.16	6.75	0.17	6.20	0.17		
Pacific Rose	F	3.74	0.27			5.01	0.22	4.70	0.22	4.53	0.13
	HW	5.65	0.22	6.33	0.20	6.12	0.22	5.50	0.12		
Granny Smith	F	5.21	0.17			6.77	0.09	7.10	0.16	6.72	0.14
	HW	5.45	0.11	6.82	0.12	6.77	0.085	6.73	0.13		
	HC	5.53	0.11	6.54	0.09	6.43	0.12	6.25	0.17		
Braeburn	F	5.90	0.27			6.12	0.19	5.30	0.19	5.33	0.25
	LW	3.730	0.37	6.125	0.25	5.40	0.21	4.77	0.15		
	HW	5.83	0.21	7.15	0.20	6.32	0.16	5.77	0.17		



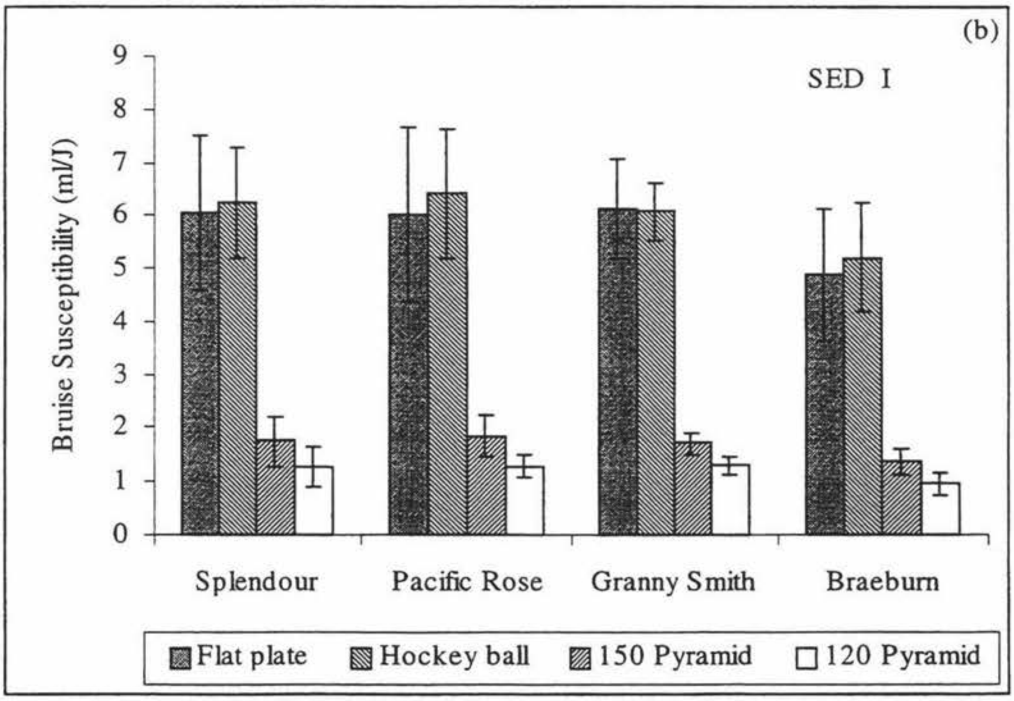


Figure 4.14 Bruise susceptibility (ml/J) from test D on (a) F and (b) HW fruit.

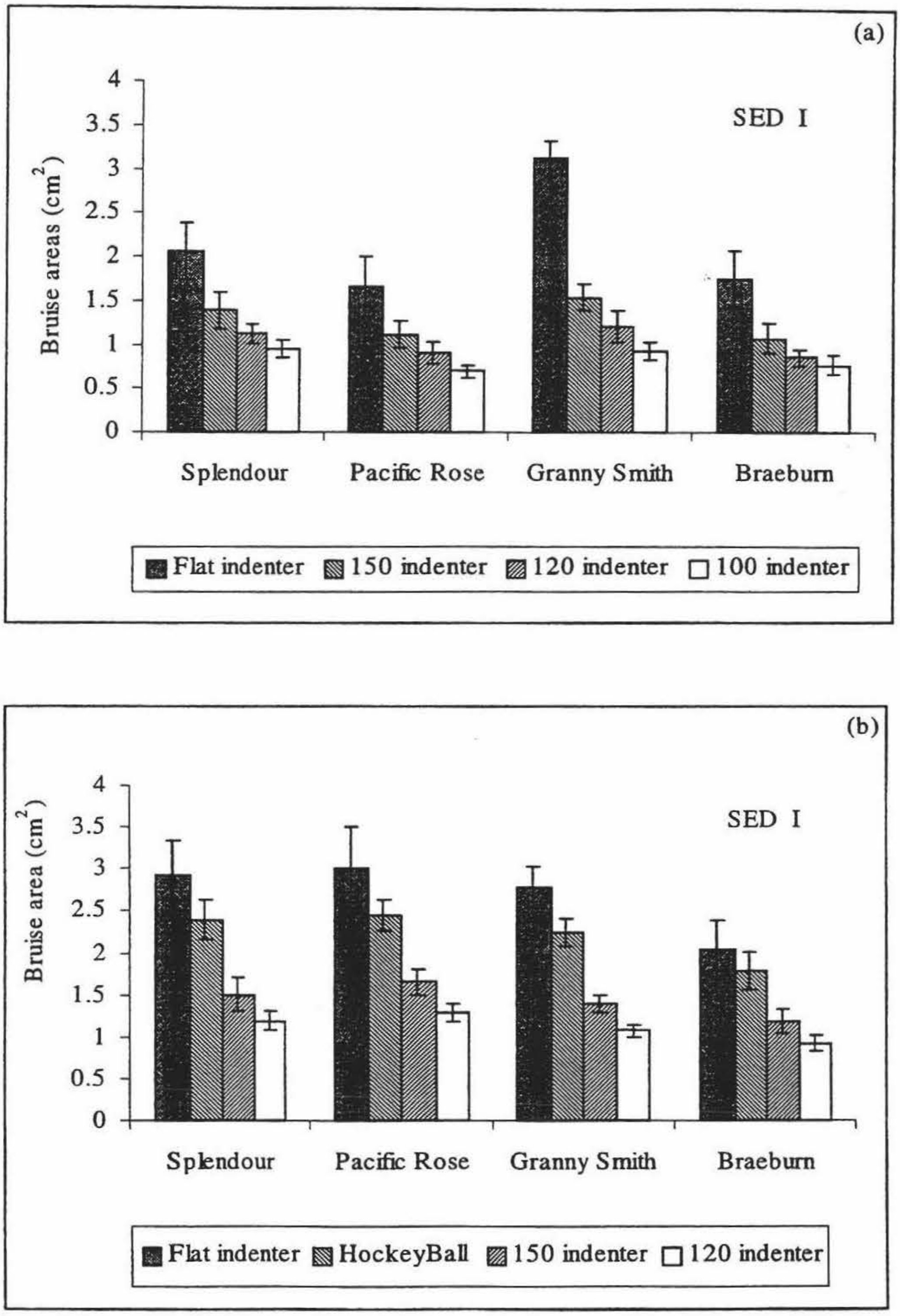
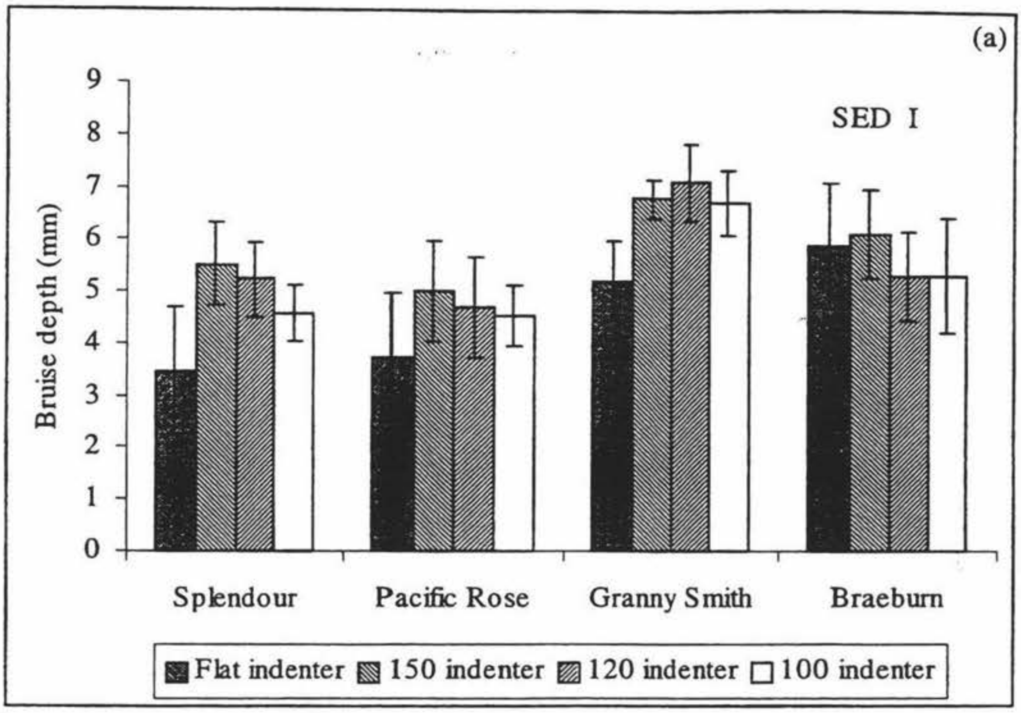


Figure 4.15 Bruise areas (cm^2) from test D on (a) F and (b) HW fruit.



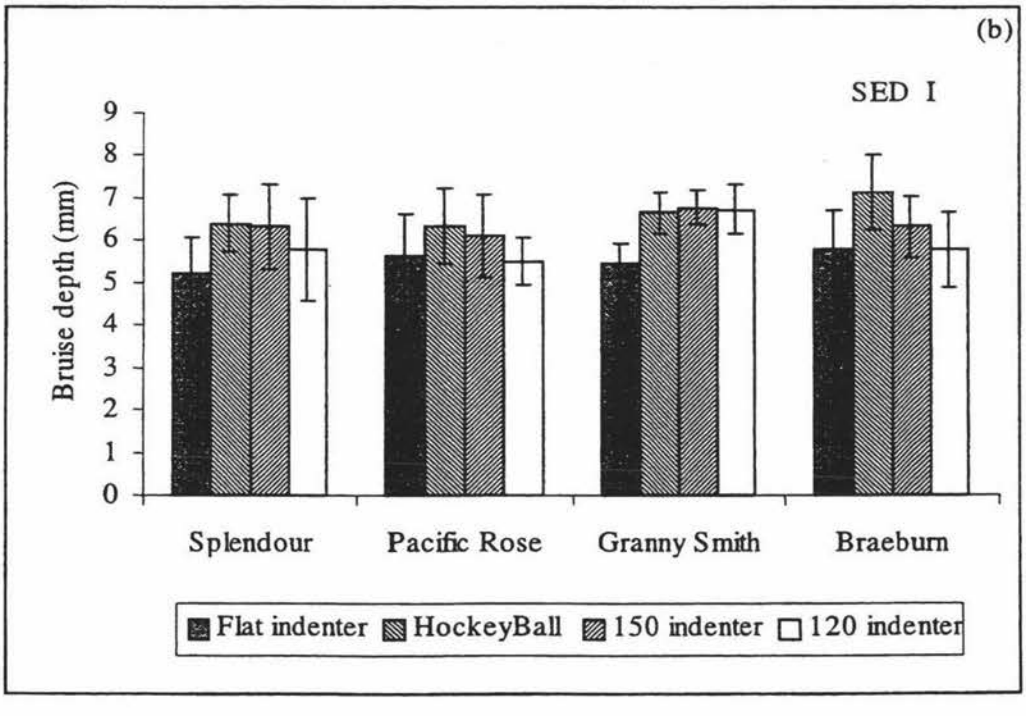
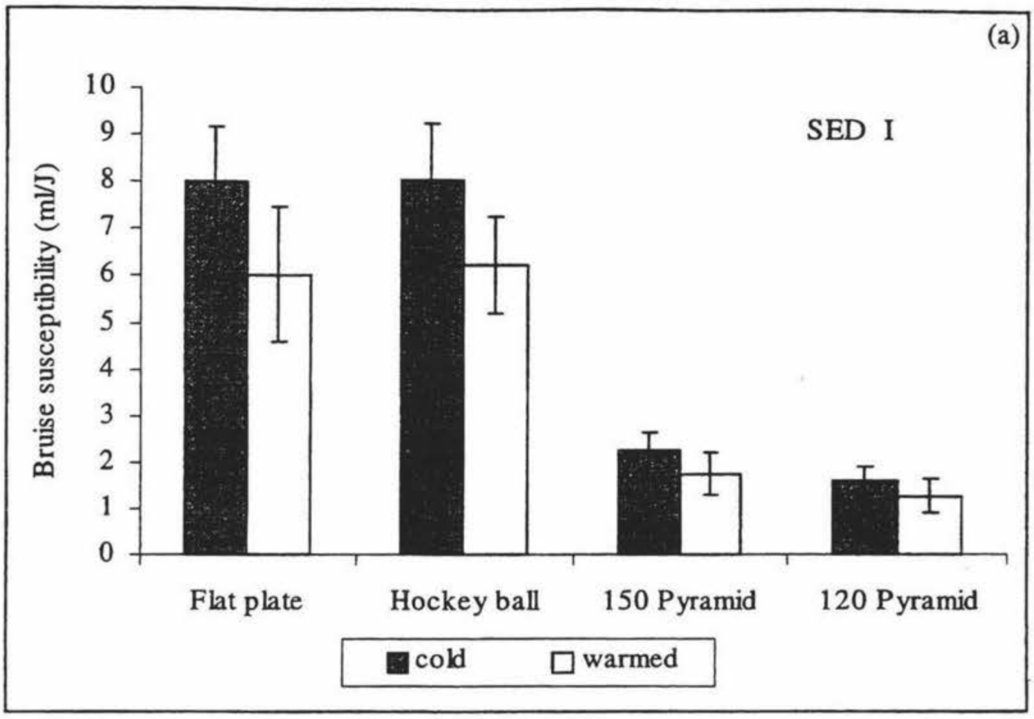


Figure 4.16 Bruise depth (mm) from test D on (a) F and (b) HW fruit.



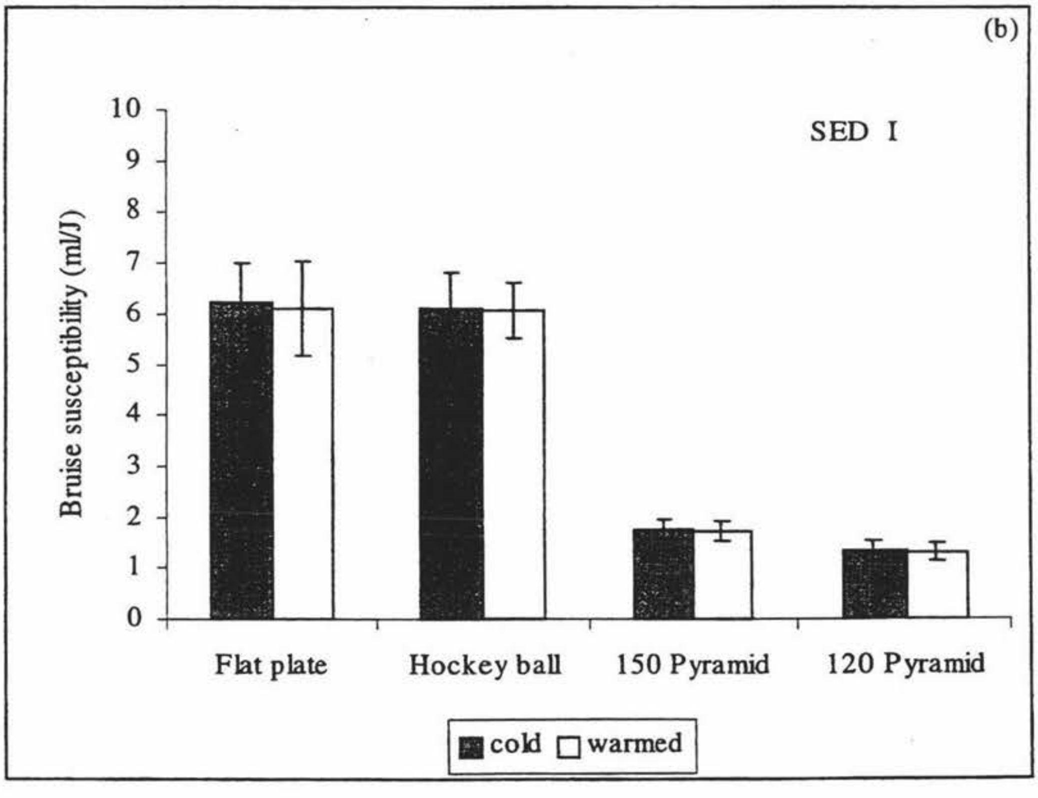


Figure 4.17 Bruise susceptibility (ml/J) on cold (HC) and warmed(HW) (a) Splendour and (b) Granny Smith apples from test D.

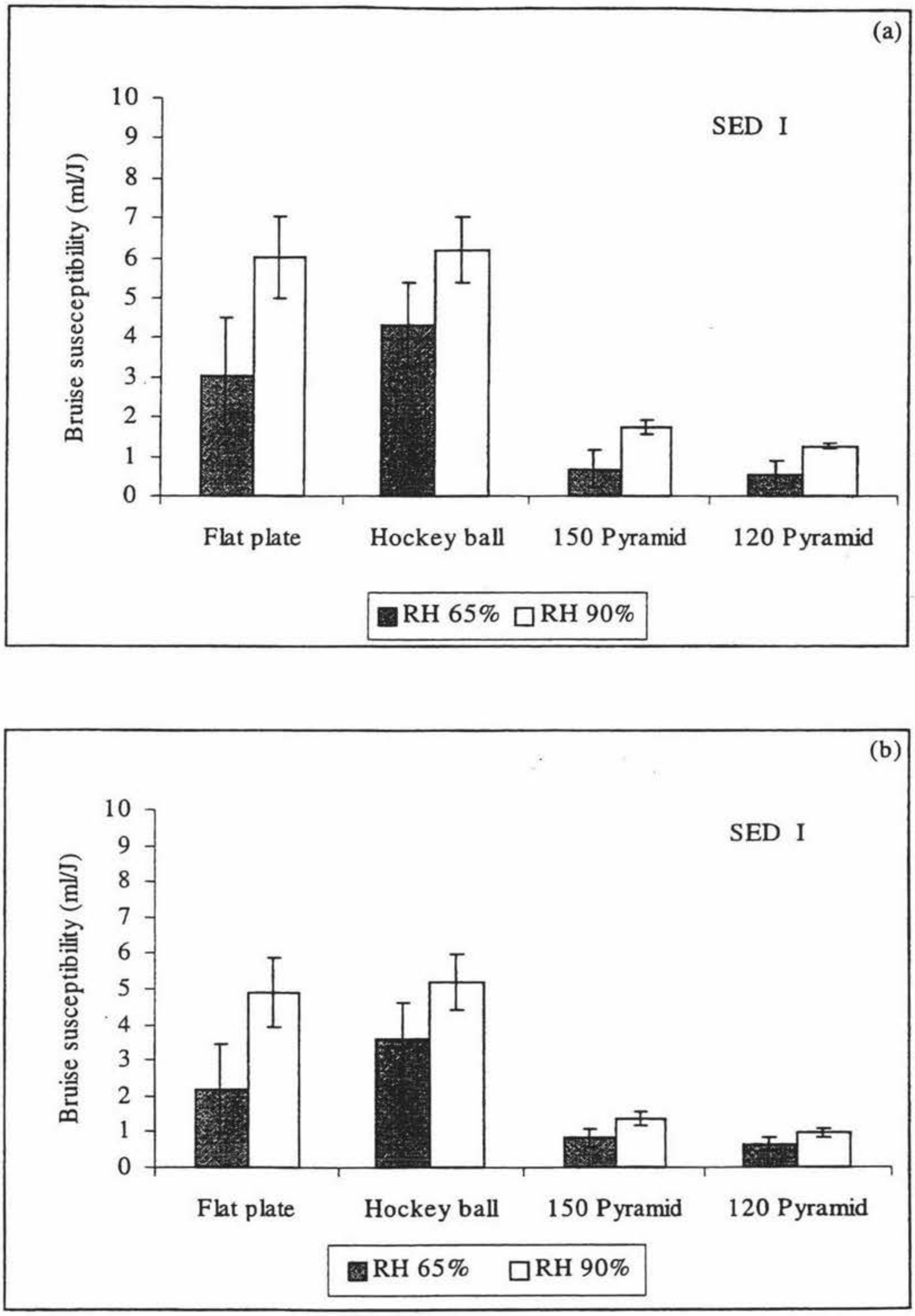


Figure 4.18 Bruise susceptibility (ml/J) on LW and HW fruit for(a) Splendour and (b) Braeburn from test D.

4.3.3 Bruises produced by the single pendulum test (S)

During the single pendulum test, the bruise area (skin removed) and bruise depth produced by the eighth drop angle (corresponding to a vertical drop height of 20 cm) were measured. The bruise susceptibility, bruise area, and bruise depth obtained are summarised in Table 4.8-4.10. The impact energy was not identical because of the different mass of apples. The bruise susceptibility increased in all HW cultivars after 2 months storage at 90% RH compared to fresh. The bruise susceptibility obtained by using the flat plate indenter was much high than those produced by the pyramid indenters.

When the flat plate indenter was used, the bruise susceptibility of Splendour bruised at room temperature incurred bruise that were 13% less than if they were bruised at 0°C. (the impact energy was 0.28J for cold fruits, 0.29J for warmed fruits). However, there was a 9% reduction in bruise susceptibility on fruits bruised at 0°C as opposed to bruised at room temperature for Granny Smith apples (the energy was 0.27J for cold fruits and 0.30J for warmed fruits) (Table 4.8 and Fig 4.18).

Bruise susceptibilities from S test were significantly higher on HW fruits compared to the LW fruit for Splendour for all indenters (Fig.4.19). There was a 23% to 43% difference in bruise susceptibility for all indenters. However there were few differences between HW and LW on Braeburn apples for all indenters.

Table 4.11 shows the total numbers of visible bruises and Table 4.12 shows the total number of bruises area with bruise above 1 cm^2 in each separate experiment. It can be seen that the number of visible bruises increased as the vertex angles of indenters decreased, and the number of bruises with bruise area above 1 cm^2 decreased as the vertex angles of indenters decreased.

Table 4.8 Bruise susceptibility (ml/J) produced from the single pendulum tests (S) (the eighth drop angle).

Cultivar	Treatment	Flat Plate		Hockey ball		150 Pyramid		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F	4.65	0.19			1.518	0.07	0.853	0.024	0.865	0.044
	LW	4.269	0.11	3.60	0.13	3.00	0.17	2.319	0.076		
	HW	7.749	0.22	4.667	0.08	1.91	0.06	1.322	0.054		
	HC	8.881	0.29	5.561	0.18	2.00	0.09	1.535	0.065		
Pacific Rose	F	5.308	0.29			1.371	0.078	0.994	0.042	1.259	0.081
	HW	8.890	0.30	5.093	0.22	1.366	0.047	1.091	0.040		
Granny Smith	F	5.945	0.13			1.439	0.042	1.195	0.038	0.814	0.072
	HW	7.914	0.21	4.187	0.15	1.938	0.064	1.513	0.053		
	HC	7.238	0.22	4.519	0.18	2.00	0.058	1.514	0.043		
Braeburn	F	3.062	0.335			0.973	0.071	0.653	0.039	0.528	0.038
	LW	4.201	0.22	2.771	0.13	1.168	0.075	0.949	0.084		
	HW	4.541	0.20	3.281	0.17	1.419	0.07	1.048	0.051		

Table 4.9 Bruise area (cm^2) (skin removed) produced from the single pendulum tests (S) (the eighth drop angle)

Cultivar	Treatment	Flat indenter		Hockey ball		150 Pyramid		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F	3.40	0.086			1.92	0.052	1.31	0.02	1.39	0.031
	LW	2.87	0.073	2.33	0.053	1.89	0.033	1.63	0.033		
	HW	4.27	0.088	3.09	0.057	1.97	0.037	1.57	0.028		
	HC	4.64	0.11	3.39	0.057	2.41	0.056	2.01	0.035		
Pacific Rose	F	3.60	0.13			1.96	0.100	1.46	0.048	1.56	0.042
	HW	5.07	0.12	2.87	0.052	1.99	0.045	1.58	0.037		
Granny Smith	F	3.45	0.084			1.67	0.034	1.57	0.037	1.16	0.045
	HW	4.70	0.092	2.44	0.069	1.90	0.044	1.59	0.033		
	HC	3.93	0.098	2.48	0.050	2.02	0.039	1.74	0.036		
Braeburn	F	2.02	0.13			1.19	0.048	0.96	0.038	0.80	0.026
	LW	2.11	0.075	1.42	0.054	1.16	0.030	0.99	0.025		
	HW	2.75	0.077	1.68	0.052	1.38	0.034	1.14	0.025		

Table 4.10 Bruise depth (mm) produced from the single pendulum tests (S) (the eighth drop angle)

Cultivar	Treatment	Flat indenter		Hockey ball		150 Pyramid		120 Pyramid		100 Pyramid	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Splendour	F	5.72	0.11			7.10	0.16	5.75	0.14	5.60	0.21
	LW	5.72	0.16	6.32	0.15	5.72	0.28	5.72	0.12		
	HW	6.95	0.12	6.93	0.097	7.15	0.17	6.47	0.25		
	HC	7.3	0.14	7.8	0.12	7.52	0.24	7.26	0.26		
Pacific Rose	F	5.85	0.25			5.90	0.19	5.75	0.15	7.03	0.37
	HW	7.50	0.23	7.4	0.30	6.15	0.18	6.00	0.15		
Granny Smith	F	6.25	0.12			7.12	0.11	7.22	0.12	5.92	0.24
	HW	7.21	0.14	7.15	0.17	7.90	0.13	7.80	0.19		
	HC	6.69	0.14	7.06	0.18	7.65	0.16	7.51	0.14		
Braeburn	F	6.20	0.32			7.02	0.33	5.95	0.27	5.92	0.28
	LW	5.75	0.17	6.12	0.17	6.32	0.34	6.17	0.44		
	HW	6.79	0.22	6.25	0.19	6.97	0.23	6.15	0.21		

Table 4.11 Total number of visible bruises from the single pendulum test using different indenters.

Cultivar	Treatment	Flat Plate	Hockey ball	150 Pyramid	120 Pyramid	100 Pyramid
Splendour	F	105		169	194	195
	LW	63	102	133	190	
	HW	140	177	187	192	
	HC	175	196	200	200	
Pacific Rose	F	78		158	178	200
	HW	124	185	187	197	
Granny Smith	F	112		171	183	197
	HW	119	161	199	200	
	HC	109	153	200	200	
Braeburn	F	53		158	182	193
	LW	35	77	100	128	
	HW	73	93	132	151	

Table 4.12 Number of bruises with area above 1 cm^2 from the single pendulum test

Cultivar	Treatment	Flat Plate	Hockey ball	150 Pyramid	120 Pyramid	100 Pyramid
Splendour	F	103		99	83	86
	LW	62	102	75	68	
	HW	132	130	88	70	
	HC	157	136	111	49	
Pacific Rose	F	78		117	89	66
	HW	118	117	86	69	
Granny Smith	F	107		92	90	67
	HW	115	125	91	71	
	HC	105	122	96	79	
Braeburn	F	53		74	70	58
	LW	35	63	67	60	
	HW	73	77	82	69	

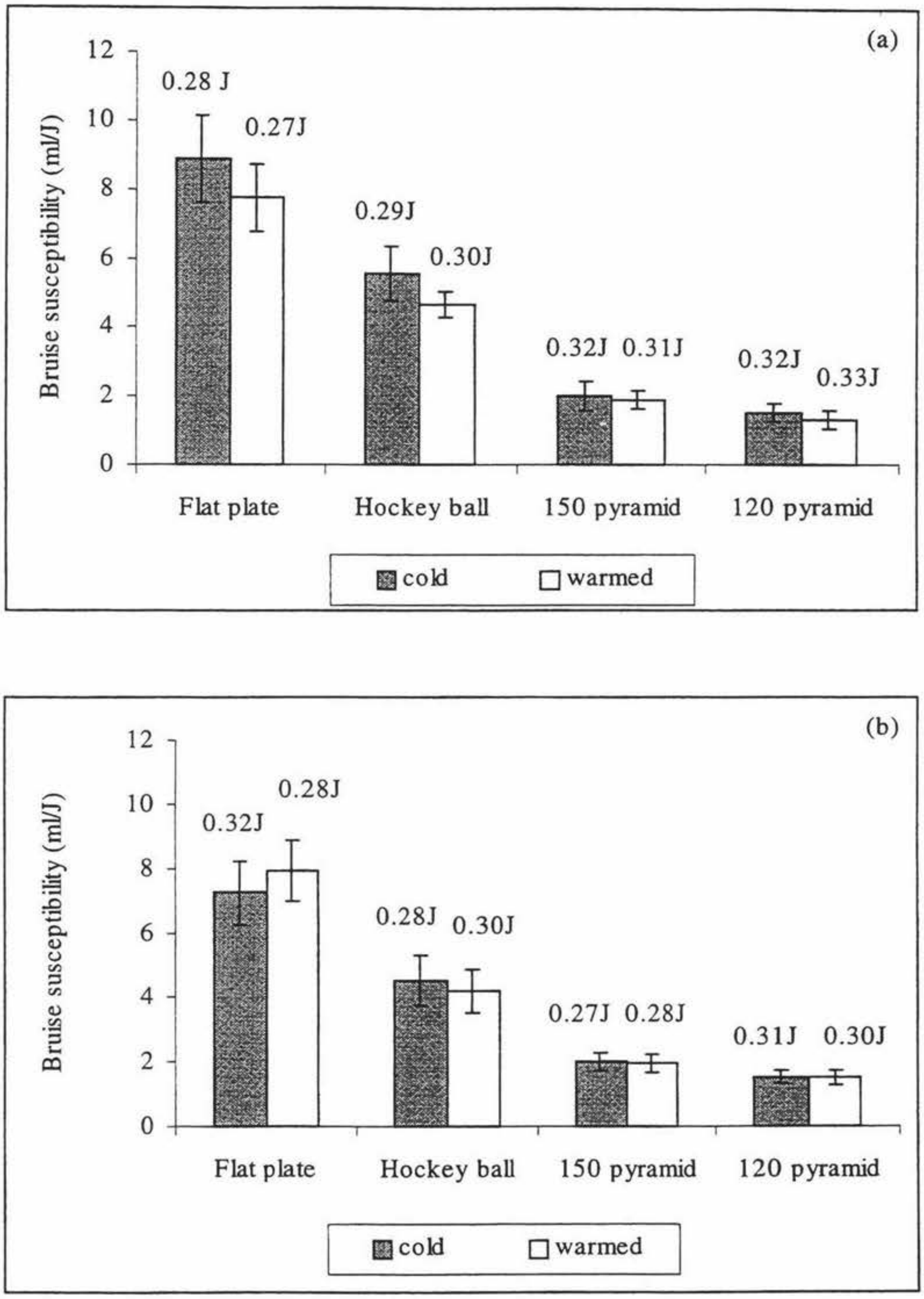


Figure 4.19 Bruise susceptibility (ml/J) on HC and HW (a) Splendour and (b) Granny Smith apples from test S.

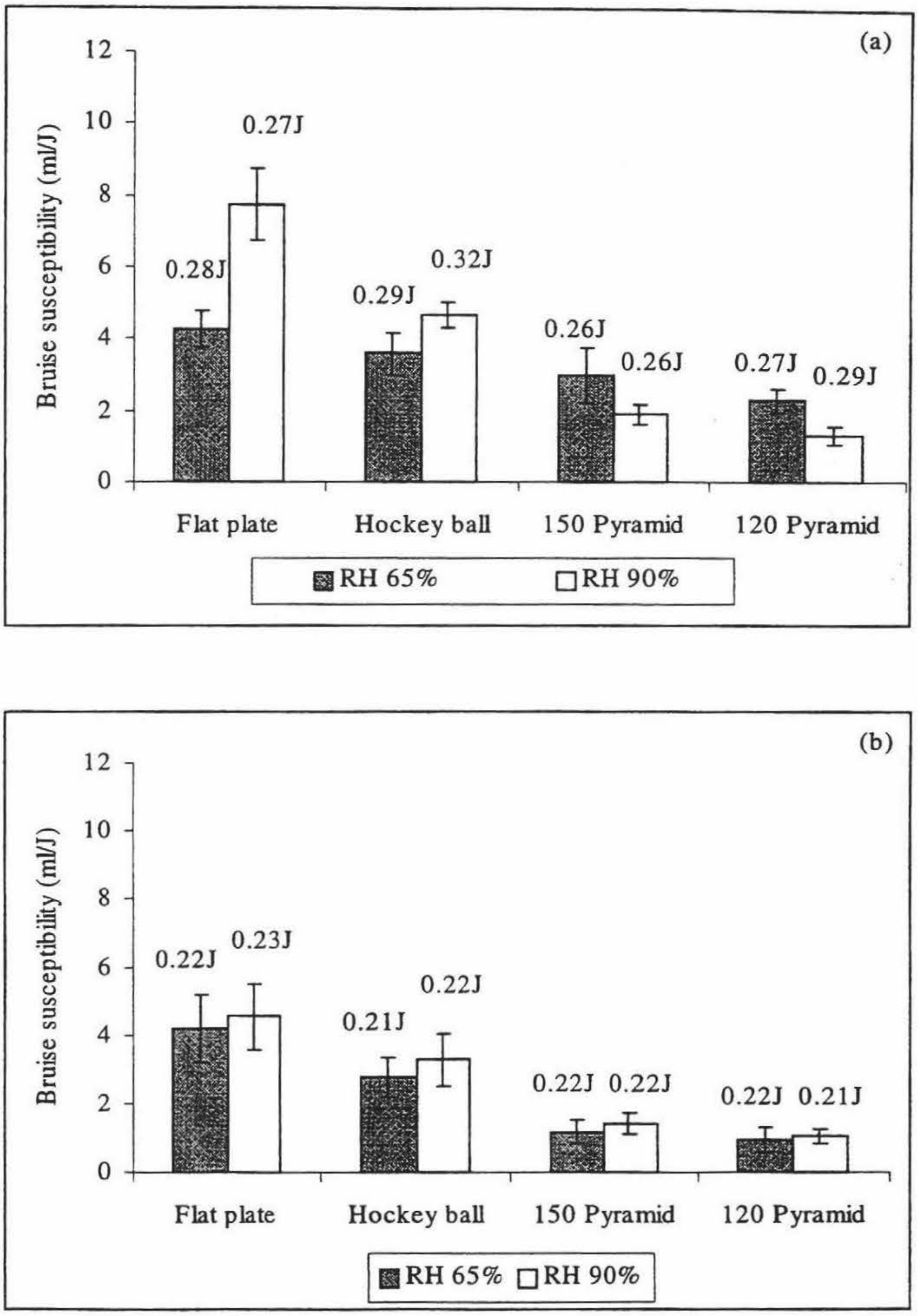


Figure 4.20 Bruise susceptibility (ml/J) on LW and HW (a) Splendour and (b) Braeburn apples from test S.

4.3.4 Bruise factor test

Table 4.13 shows the bruise factors for four cultivars of apples measured by the bruise factor test from the single pendulum tests. The bruise factor increased with decreasing vertex angle of indenters in all cases. From table 4.13, it can be seen that at low fruit temperature the bruise factor increased, and then dropped again when the fruit was returned to room temperature. There were considerable differences between cultivars, with Braeburn having the lowest bruise factor, and Splendour the greatest.

Table 4.13 Bruise Factor measured from the single pendulum test on four cultivar apples

Cultivar	Treatment	Flat Plate	Hockey ball	150 Pyramid	120 Pyramid	100 Pyramid
Splendour	F	5.25		8.45	9.7	9.75
	LW	3.15	5.1	6.65	9.5	
	HW	7	8.85	9.35	9.6	
	HC	8.75	9.8	10	10	
Pacific Rose	F	3.9		7.9	8.90	10
	HW	6.2	9.25	9.35	9.85	
Granny Smith	F	5.65		8.55	9.15	9.85
	HW	5.95	8.05	9.95	10	
	HC	5.45	7.65	10	10	
Braeburn	F	2.65		7.9	9.1	9.58
	LW	1.75	3.85	5	6.4	
	HW	3.65	4.65	6.6	7.55	

4.4. Firmness tests

The average measurements of fruit firmness by a penetrometer are shown in Table 4.14. Each value in the table represents the average of 20 measurements respectively. Firmness was found to decrease with increased storage time. The average value for stored fruit was less than fresh fruit for Granny Smith, Pacific Rose, and Braeburn apples (a reduction of 2.2%, 2.4% and 15% respectively), but there was no significant difference on Splendour apples (Table 4.14).

Table 4.14 Fruit firmness of four variety apples for both fresh and stored measured by penetromenter (N)

Treatment	Granny Smith	Splendour	Pacific Rose	Braeburn
LW		$79.07^{a}\pm0.093$		$80.96^{b}\pm0.074$
F	$80.26^{a}\pm0.090$	$77.91^{a}\pm0.099$	$80.07^{a}\pm0.073$	$88.49^{a}\pm0.082$
HW	$65.56^{b}\pm0.084$	$78.30^{a}\pm0.104$	$78.11^{b}\pm0.092$	$75.07^{c}\pm0.095$
HC	$66.78^{b}\pm0.091$	$78.32^{a}\pm0.102$		

Values followed by a different letter in each column are significantly different ($P<0.05$).

4.5 Bruise visibility

In the vertical drop tests and the double pendulum tests using the flat indenter impacts, the bruises often could not be seen until the skin was removed. During the vertical drop tests on stored fruit, it was found that 45% of bruises were visible on Pacific Rose apples without peeling the skin. All bruises were visible on Splendour and Granny Smith apples, but no visible bruises were observed on Braeburn apples prior to peeling. In the double pendulum tests for fresh fruit where bruising was produced, it was found that only 85% on Pacific Rose, 65% on Splendour, and 15% on Braeburn apples were visible without peeling the skin. For

Granny Smith, all bruises were visible prior to peeling. However, after the skin was removed, bruises were clearly visible in all cultivars. The bruise dimensions measured after peeling were used in this study.

The bruise visibility results from the single pendulum test are presented in Figure 4.20-4.23. It can be seen that bruising damage occurs at very low energies. In generally, the bruising visibility increased with an increase in energy levels. No bruising (with skin on) was found on fresh when fruit dropped from a 0.02J energy level onto a flat impact surface, even though the other indenters did cause clear damage at the same impact energy levels. In these cases the bruising underneath the region of flesh splitting was severe. Generally the bruises were more clearly visible as the edges were more sharply defined. The 100% bruise visibility occurred at lower energy levels using pyramid indenters although the bruise area was very small. The energy for producing 100% visible bruises was much lower using the Hockey ball compared with the flat indenter. There seemed to be a trend that the percent of fruit with visible damage increased with storage time.

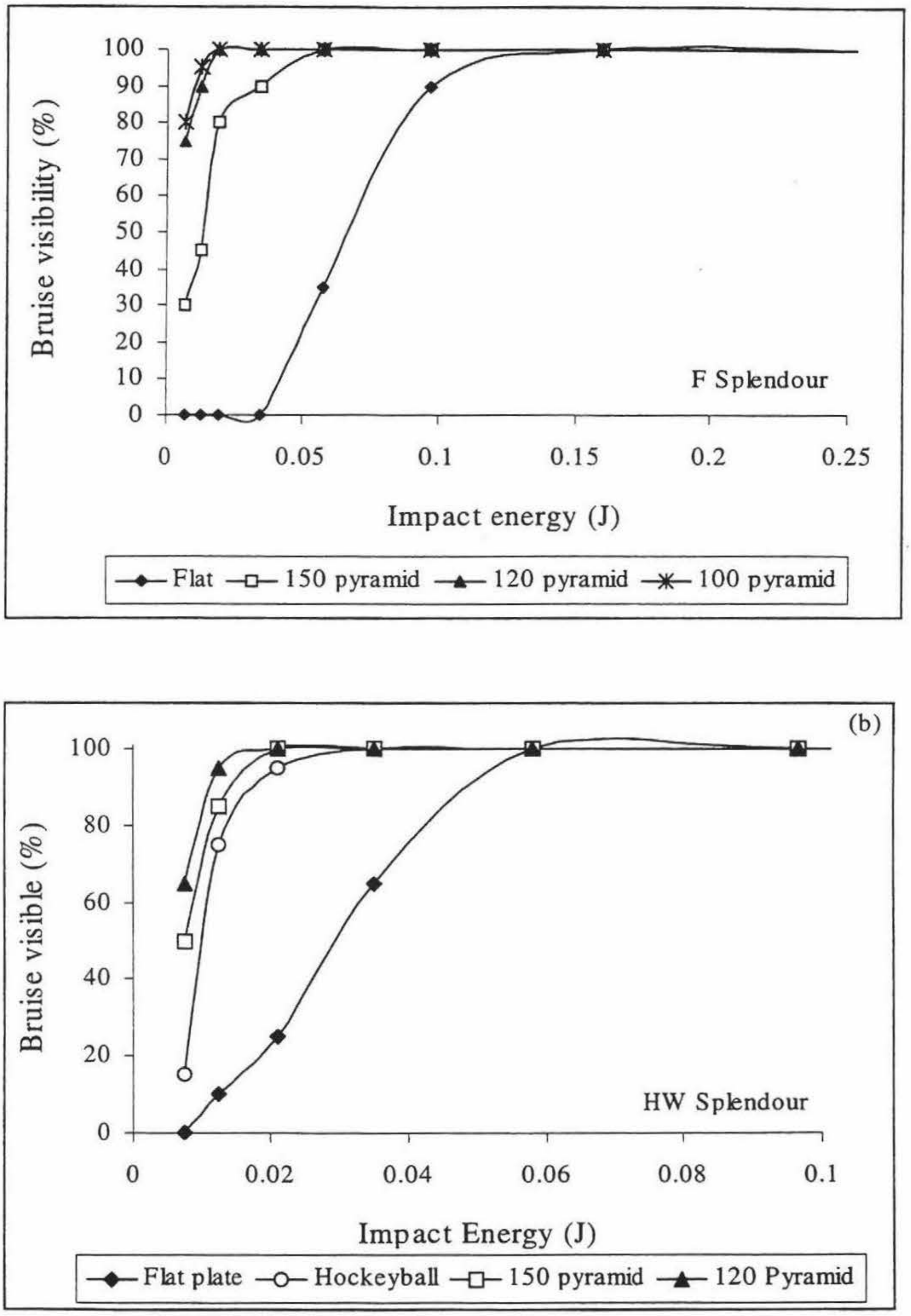
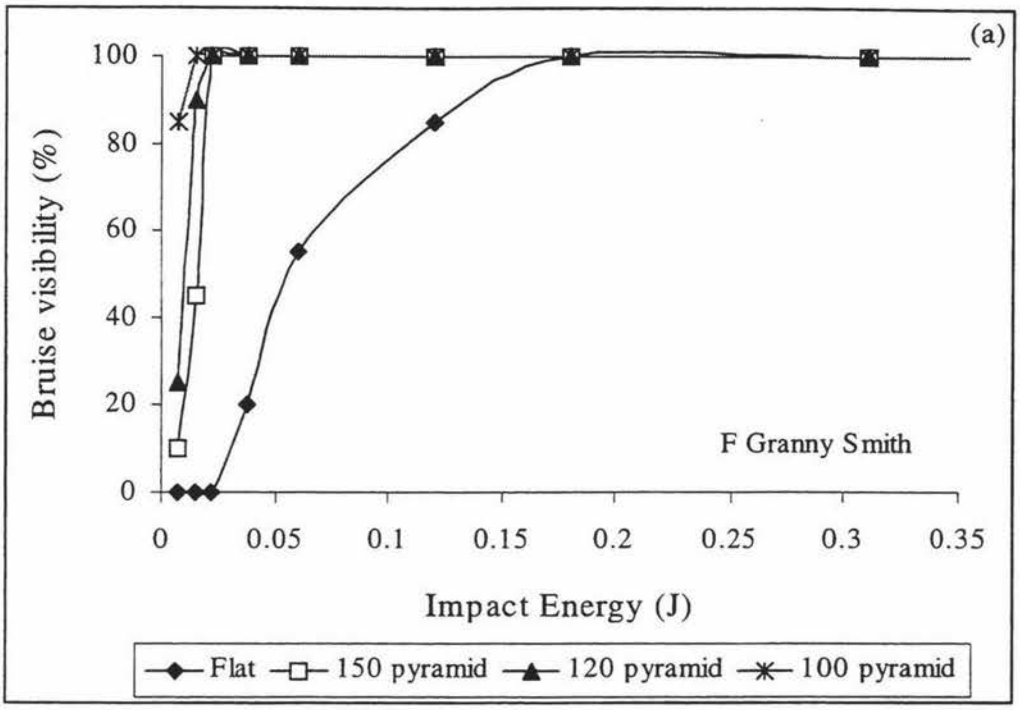


Figure 4.21 Bruise visibility (%) produced from the single pendulum test on (a) F and (b) HW Splendour apples.



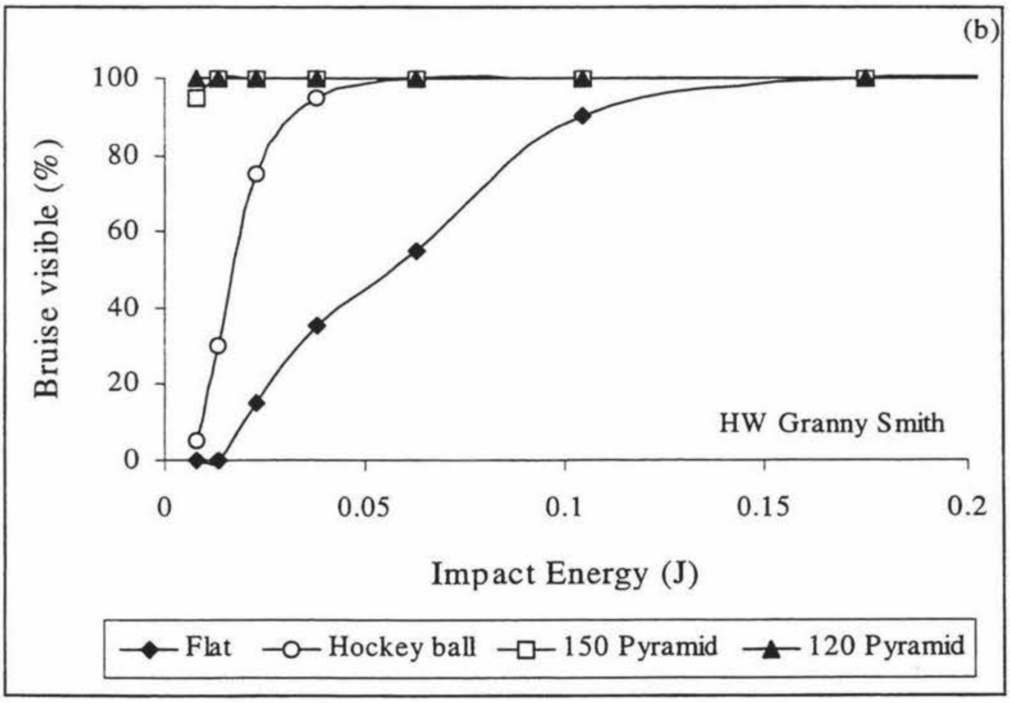
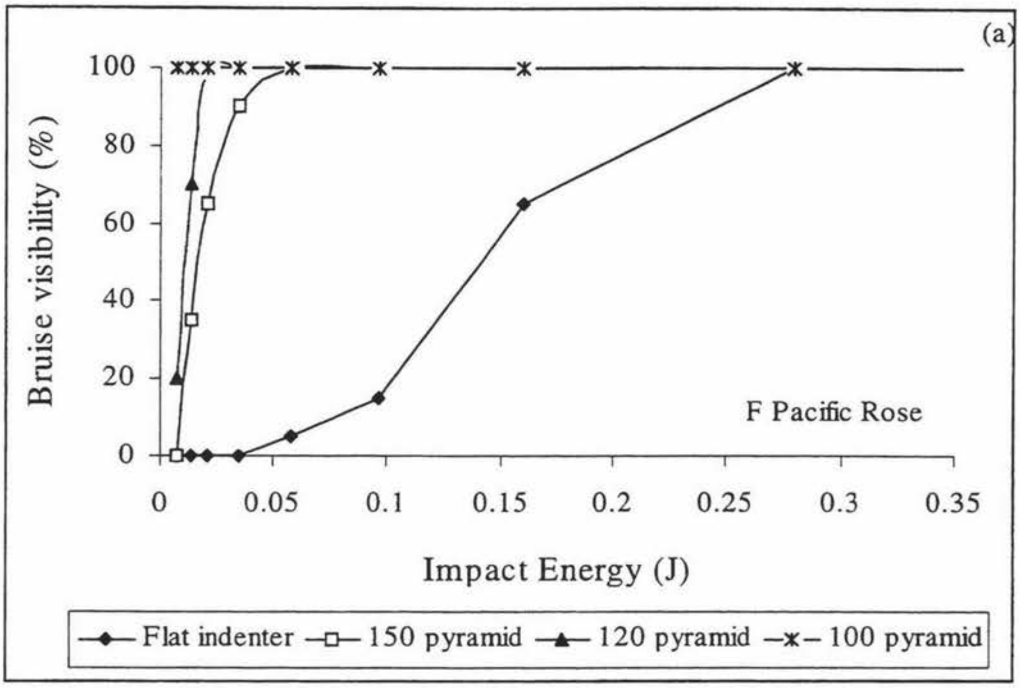


Figure 4.22 Bruise visibility (%) produced from the single pendulum test on (a) F and (b) HW Granny Smith apples.



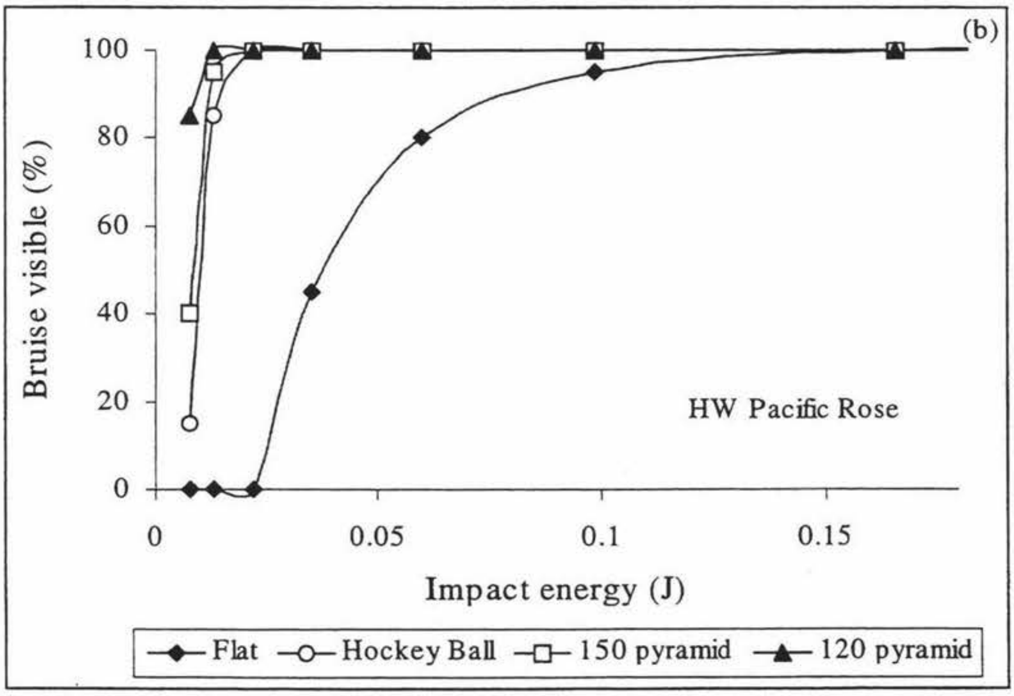


Figure 4.23 Bruise visibility (%) produced from the single pendulum tests on (a) F and (b) HW Pacific Rose apples.

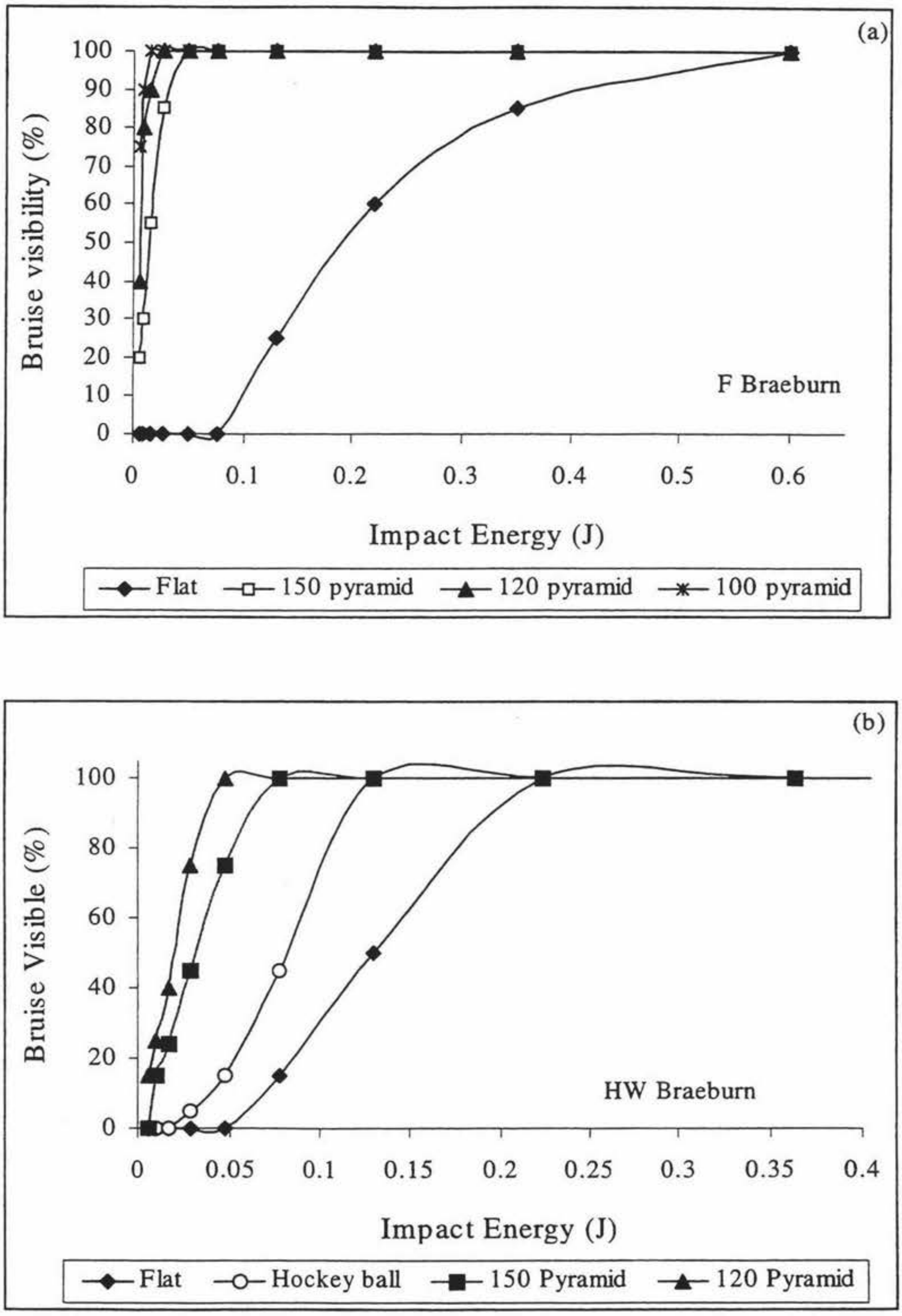


Figure 4.24 Bruise visibility (%) produced from the single pendulum test on (a) F and (b) HW Braeburn apples.

4.6 Relationship between bruising area (skin on) and impact energy

Bruising area and impact energy were related by a two-thirds power relationship for F and HW fruit as shown in Figure 4.24-4.27. The relationship between bruise area and 2/3 power impact energy level was more linear for the pyramid indenters than the flat plate indenters as indicated by the R^2 values obtained by linear regression of bruise area on impact energy (Table 4.15 and 4.16). From the Figures 4.24-4.27, it can be seen that at low impact levels, the bruise area (skin on) was not well linearly related to the impact energy. Each data point in the graph is the mean value of 20 samples. Data includes tests where there was no bruising visible.

The error bars were smaller for pyramid indenters, compared with the flat indenter. This is to be expected since the contact area for the flat indenter will depend to a greater extent upon the curvature of the fruit in the contact area. For spherical indenters the error bars were also small due to this effect. Between variety, Braeburn had the smallest bruising area for a given impact energy.

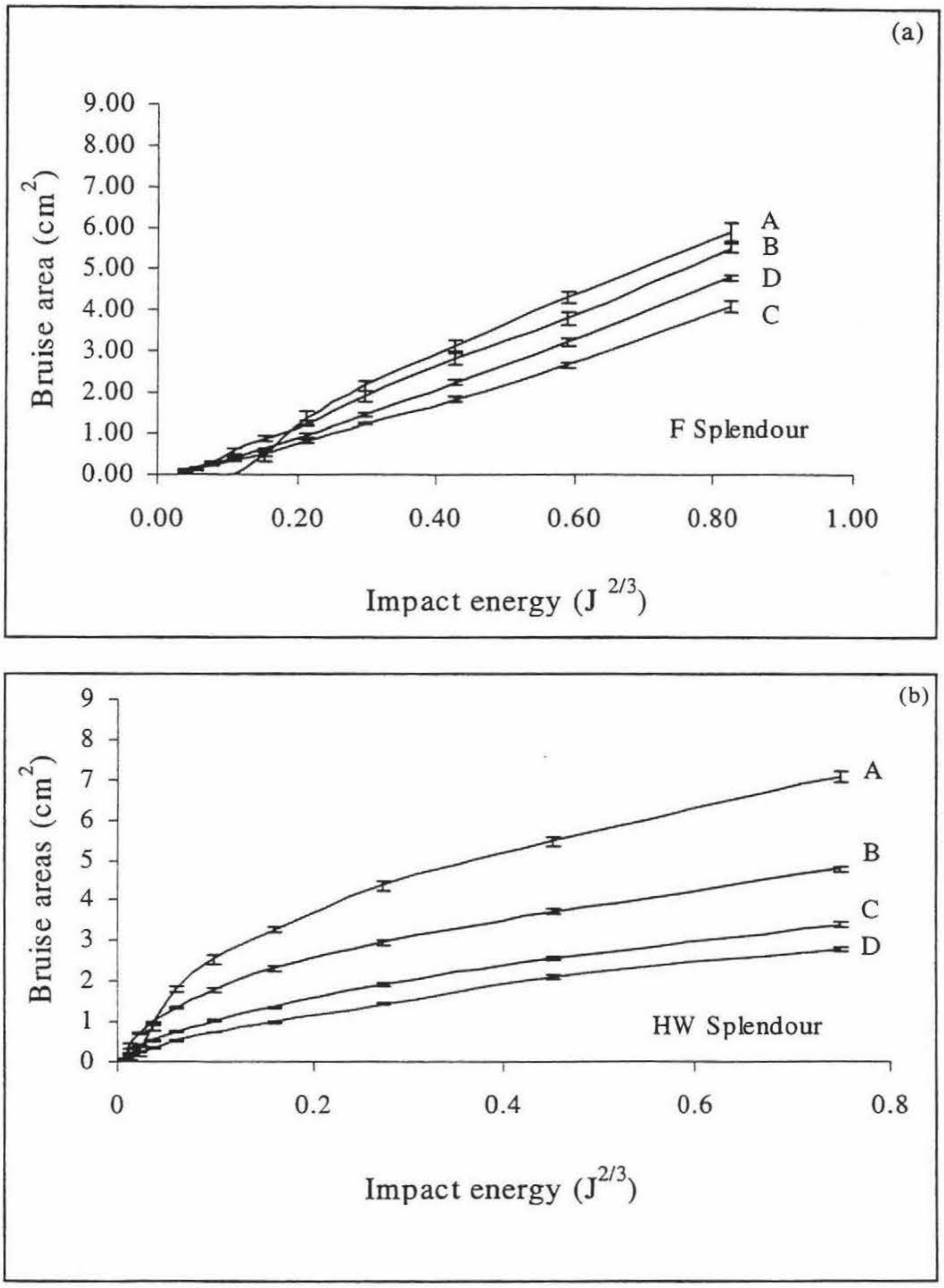


Figure 4.25 Bruise areas plotted against impact energy for (a) F and (b) HW Splendour apples (Standard error bars for each mean).

A: Flat indenter B: 150° pyramid indenter

C: 120° pyramid indenter D: 100° indenter for F fruit, Hockey ball for HW fruit.

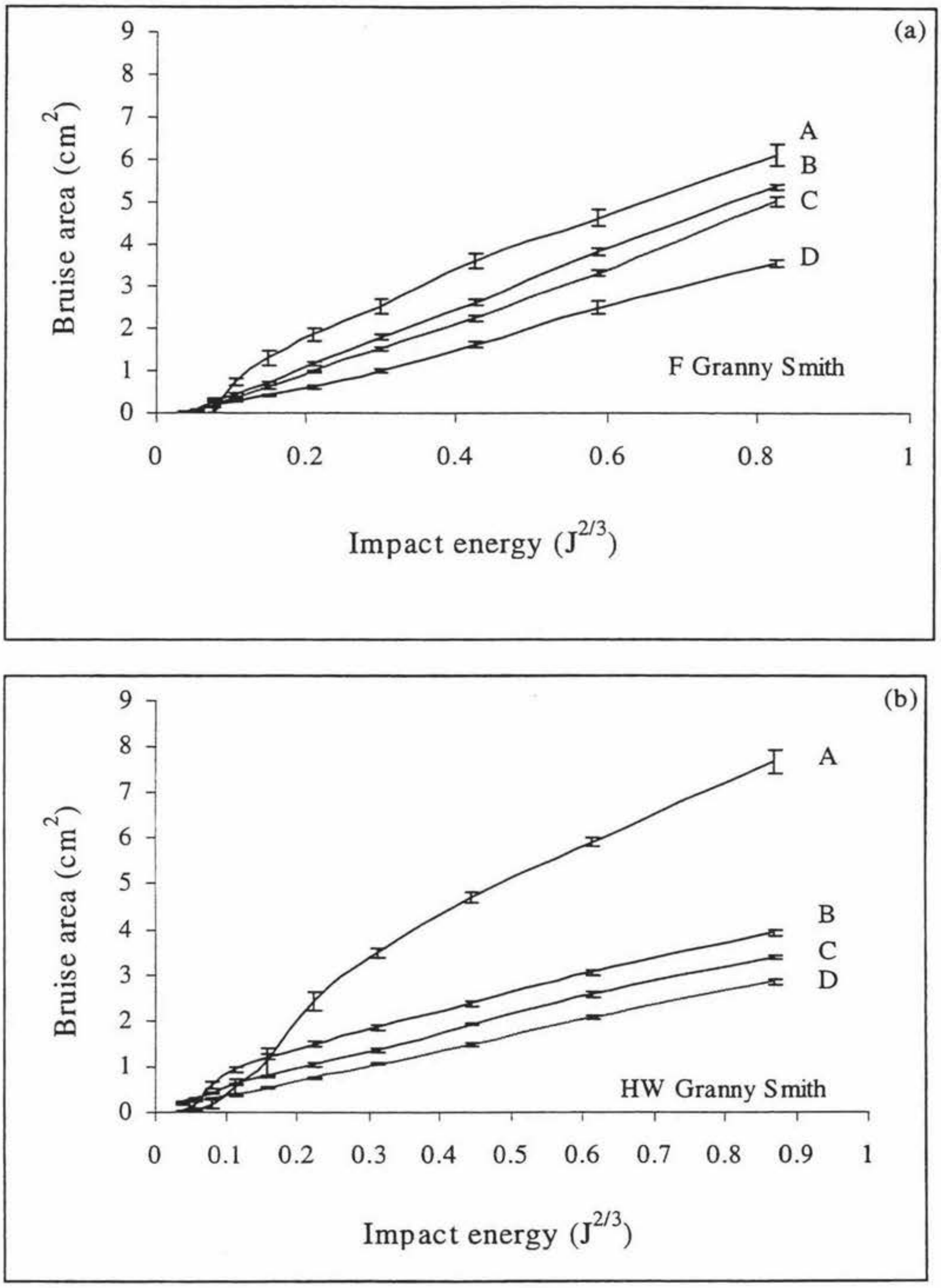


Figure 4.26 Bruise areas plotted against impact energy for (a) F and (b) HW Granny Smith apples (Standard error bars for each mean).

A: Flat indenter B: 150° pyramid indenter

C: 120° pyramid indenter D: 100° indenter for F fruit

Hockey ball for HW fruit.

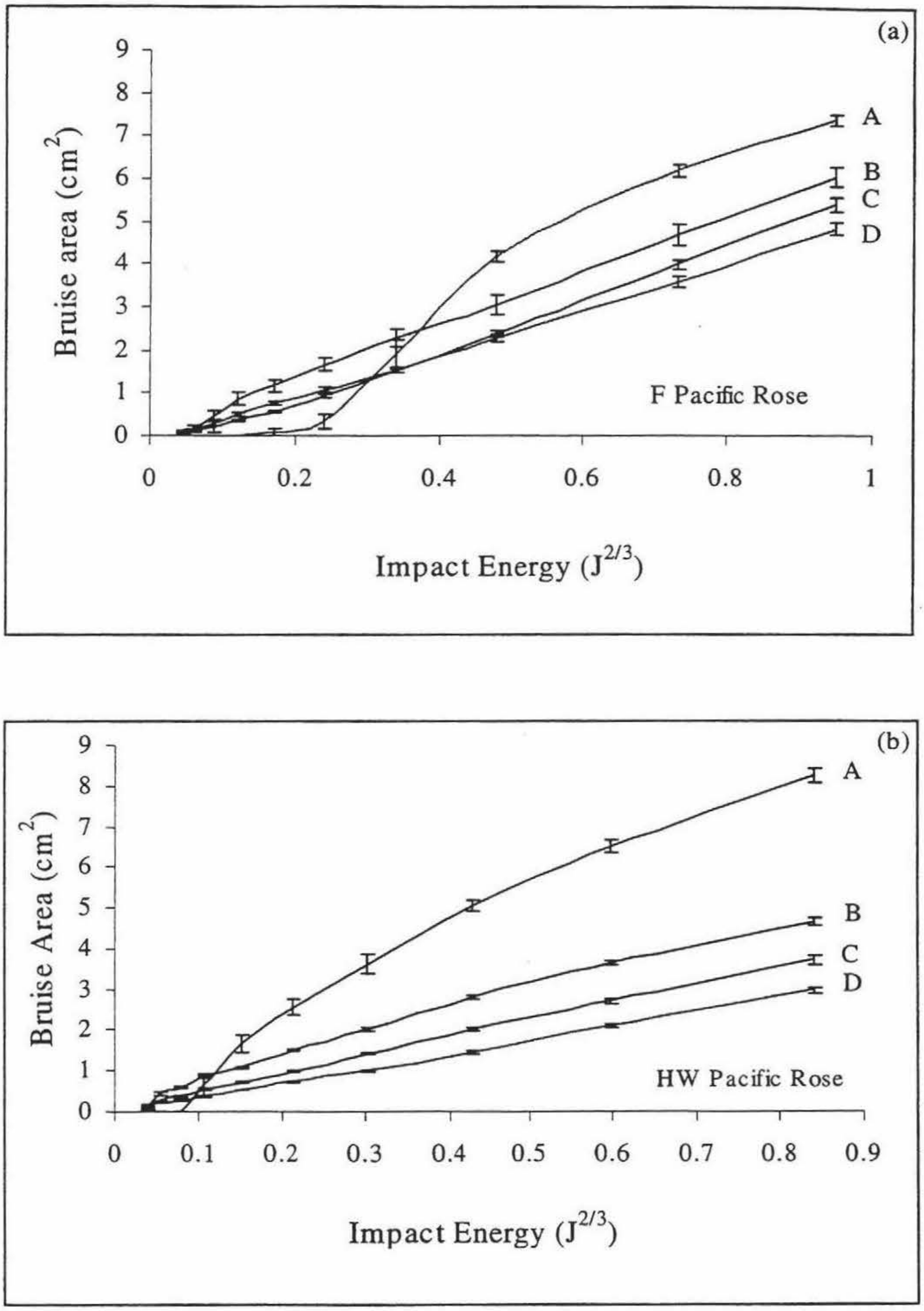


Figure 4.27 Bruise areas plotted against impact energy for (a) F and (b) HW Pacific Rose apples (Standard error bars for each mean).

A: Flat indenter B: 150° pyramid indenter

C: 120° pyramid indenter D: 100° indenter for F fruit

Hockey ball for HW fruit.

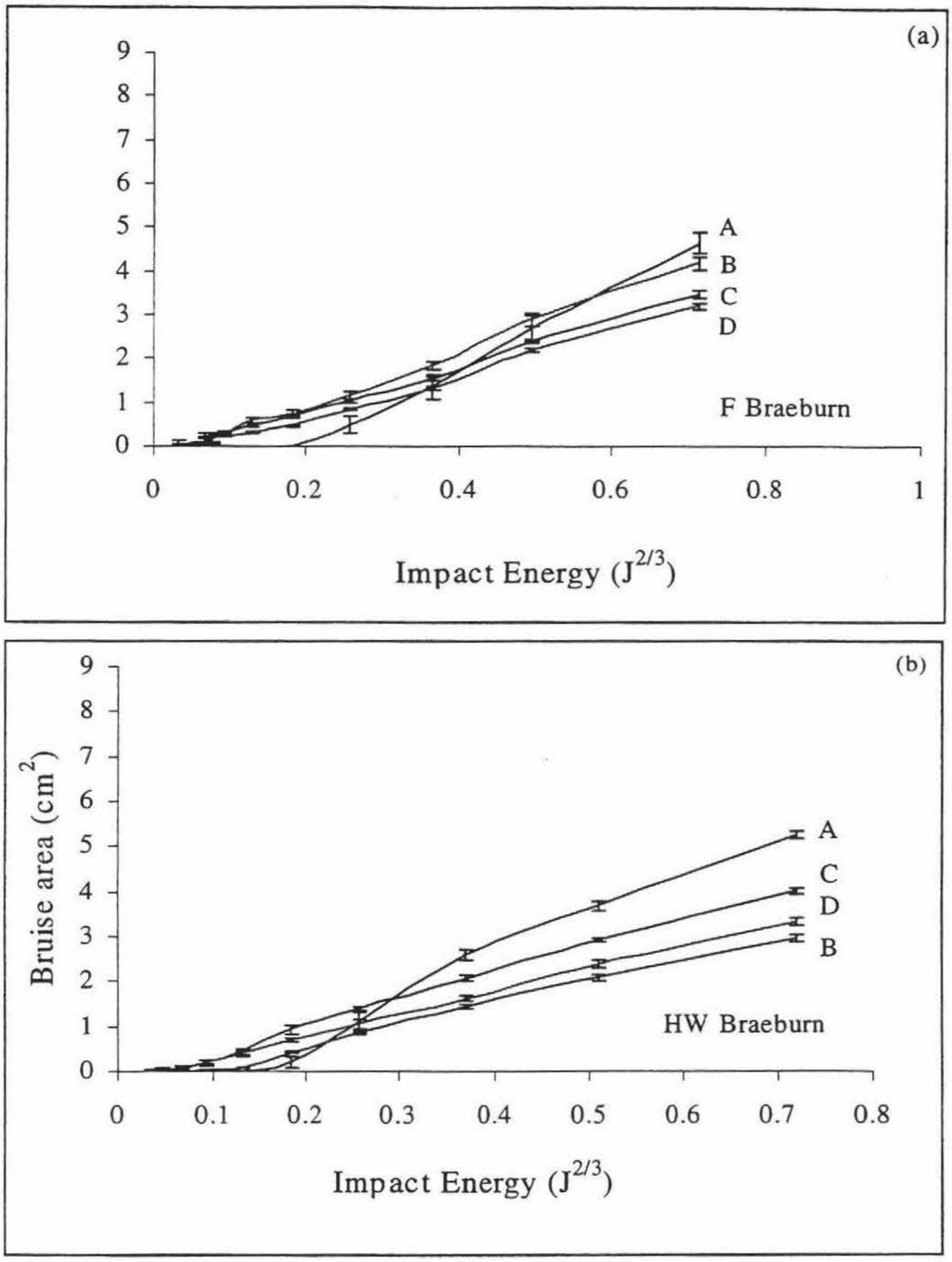


Figure 4.28 Bruise areas plotted against impact energy for (a) F and (b) HW Braeburn apples (Standard error bars for each mean).

A: Flat indenter B: 150° pyramid indenter

C: 120° pyramid indenter D: 100° indenter for F fruit

Hockey ball for HW fruit.

Table 4.15 Relationship between bruise area (cm^2) and impact energy (J$^{2/3}$) on F fruit.

Cultivar	Indenter	Regression Equation	R^2
Splendour	Flat plate	$A_b = 7.997E - 0.4760$	R^2=0.98
	150 Pyramid°	$A_b = 6.9199E - 0.1997$	R^2=0.99
	120 Pyramid°	$A_b = 5.0092E - 0.1865$	R^2=0.99
	100 Pyramid°	$A_b = 5.9401E - 0.2213$	R^2=0.99
Pacific Rose	Flat plate	$A_b = 8.8538E - 0.4877$	R^2=0.97
	150 Pyramid°	$A_b = 6.5171E - 0.0608$	R^2=0.99
	120 Pyramid°	$A_b = 5.1909E - 0.1631$	R^2=0.99
	100 Pyramid°	$A_b = 5.9082E - 0.3376$	R^2=0.99
Granny Smith	Flat plate	$A^b = 8.0606E - 0.1530$	R^2=0.97
	150 Pyramid°	$A_b = 6.8769E - 0.2763$	R^2=0.99
	120 Pyramid°	$A_b = 6.3411E - 0.3264$	R^2=0.99
	100 Pyramid°	$A_b = 4.5328E - 0.2210$	R^2=0.99
Braeburn	Flat plate	$A_b = 6.9114E - 0.7429$	R^2=0.93
	150 Pyramid°	$A_b = 6.2616E - 0.3169$	R^2=0.99
	120 Pyramid°	$A_b = 5.0868E - 0.2017$	R^2=0.99
	100 Pyramid°	$A_b = 4.7298E - 0.2540$	R^2=0.98

A_b = Bruise area (cm^2); E = 2/3 power impact energy (J)

Table 4.16 Relationship between bruise area (cm^2) and impact energy ($J^{2/3}$) on HW fruits.

Cultivar	Indenter	Regression Equation	R^2
Splendour	Flat plate	$A_b = 9.2293E + 0.0177$	R^2=0.96
	Hockey Ball	$A_b = 5.7748E + 0.3064$	R^2=0.97
	150 Pyramid°	$A_b = 4.1289E + 0.0899$	R^2=0.99
	120 Pyramid°	$A_b = 3.4727E - 0.0186$	R^2=0.99
Pacific Rose	Flat plate	$A_b = 1954E - 0.2565$	R^2=0.97
	Hockey Ball	$A_b = 5.6079E + 0.1876$	R^2=0.98
	150 Pyramid°	$A_b = 4.4795E + 0.0179$	R^2=0.99
	120 Pyramid°	$A_b = 3.4982E - 0.0064$	R^2=0.99
Granny Smith	Flat plate	$A_b = 9.8472E - 0.2633$	R^2=0.97
	Hockey Ball	$A_b = 4.5082E - 0.2763$	R^2=0.96
	150 Pyramid°	$A_b = 3.8469E + 0.1410$	R^2=0.99
	120 Pyramid°	$A_b = 3.2793E + 0.0262$	R^2=0.99
Braeburn	Flat plate	$A_b = 8.2381E - 0.6972$	R^2=0.96
	Hockey Ball	$A_b = 4.5742E - 0.3139$	R^2=0.98
	150 Pyramid°	$A_b = 6.0874E - 0.2597$	R^2=0.99
	120 Pyramid°	$A_b = 4.9545E - 0.2094$	R^2=0.99

A_b = Bruise area (cm^2); E = 2/3 power impact energy (J)

CHAPTER FIVE

ANALYSIS AND DISCUSSION

5.1 Bruise produced by tumbler

From the analysis of bruise damage on four cultivar apples for different treatments produced by the tumbler, it was found that the bruise produced from the tumbler was very similar to those found by Pang et al., (1996) who studied on bruising produced by a typical commercial grading machine. A large percentage of bruises were less than 1.5 cm^2 in area, and the number of bruises above 1.5 cm^2 did not change between treatments (Fig. 4.2-4.3). It is not sufficient to say there was no change at all in bruise area, but the change was not enough to show a difference in fruit bruise levels. This implied that while bruising tests based on impacts causing bruise areas above 1.5 cm^2 may result in a solution which is not related to the real bruise susceptibility of fruit in mechanical handling operations because of the excessive range of impact energy.

There were more small bruises on HW and HC fruit than on F fruit. It is likely that fruit with more small bruises would give the impression that the fruit were more susceptible to bruising. This is quite reasonable since, according to international standards for export used by ENZAFRUIT, any apple with an accumulated bruise area exceeding 1 cm^2 should be rejected. A large percentage of bruises produced by the tumbler were less than 1.5 cm^2 in area and it was rare to have any bruises above 3 cm^2. Four cultivar apples after 2 months storage at 90% RH were found to bruise more easily.

There is no way to exactly quantify and explain the energy absorbed by a rolling apple, as each fruit is unique in shape. Any given fruit will also roll eratically, which in turn creates a variation in the amount of energy absorbed. Fridley and Adrian (1966), Horsfield et al (1972) and Studman (1997) found that multiple impacts with less energy per impact cause the same injury, as do fewer impacts with more energy per impact. Thus energy, at least when some minimum stress is exceeded, is a direct cause of injury.

5.2 Relationship between the bruise produced from standard impact tests and the tumbler test

A regression analysis was made on the data obtained from standard impact tests and the tumbler test to find the correlation between the bruise susceptibility and the bruise area/apple.

(a) **Test V**: Figure 5.1 shows the correlation between the bruise susceptibility obtained by the test V using the different indenters and the bruise area/apple produced by the tumbler tests on four cultivars. The regression coefficient (R^2) was 0.72 for the hockey ball; 0.70 for the flat plate; 0.07 and 0.11 for 150° and 120° pyramid indenters. The bruise susceptibility only produced by the hockey ball was better correlated to the bruise produced by the tumbler compared with other indenters.

(b) **Test D:** The agreement between the bruise susceptibility obtained by test D using different indenters on four cultivars and the bruise area/apple produced by test T was poor (Figure 5.2). The regression coefficient (R^2) was 0.73 for the hockey ball; 0.47 for the flat plate; 0.45 and 0.38 for 150° and 120° pyramid indenters.

(c) **Test S:** The results of test S (Fig.5.3) did not show any clear relationship between bruise susceptibility and bruise area/apple. Figure 5.4 shows there were some correlation between the bruise factor and the bruise area/apple. The regression coefficient (R^2) for the flat indenter was 0.78. Bruise from other indenters was weakly correlated with the bruise area/apple (R^2_{ball}=0.62; R^2_{150} = 0.46;and R^2_{120} = 0.30).

(d) **Firmness test:** There was no correlation between the bruise area/apple and the mean firmness of the different cultivars as measured by the penetrometer (R^2=0.061) (Fig.5.5).

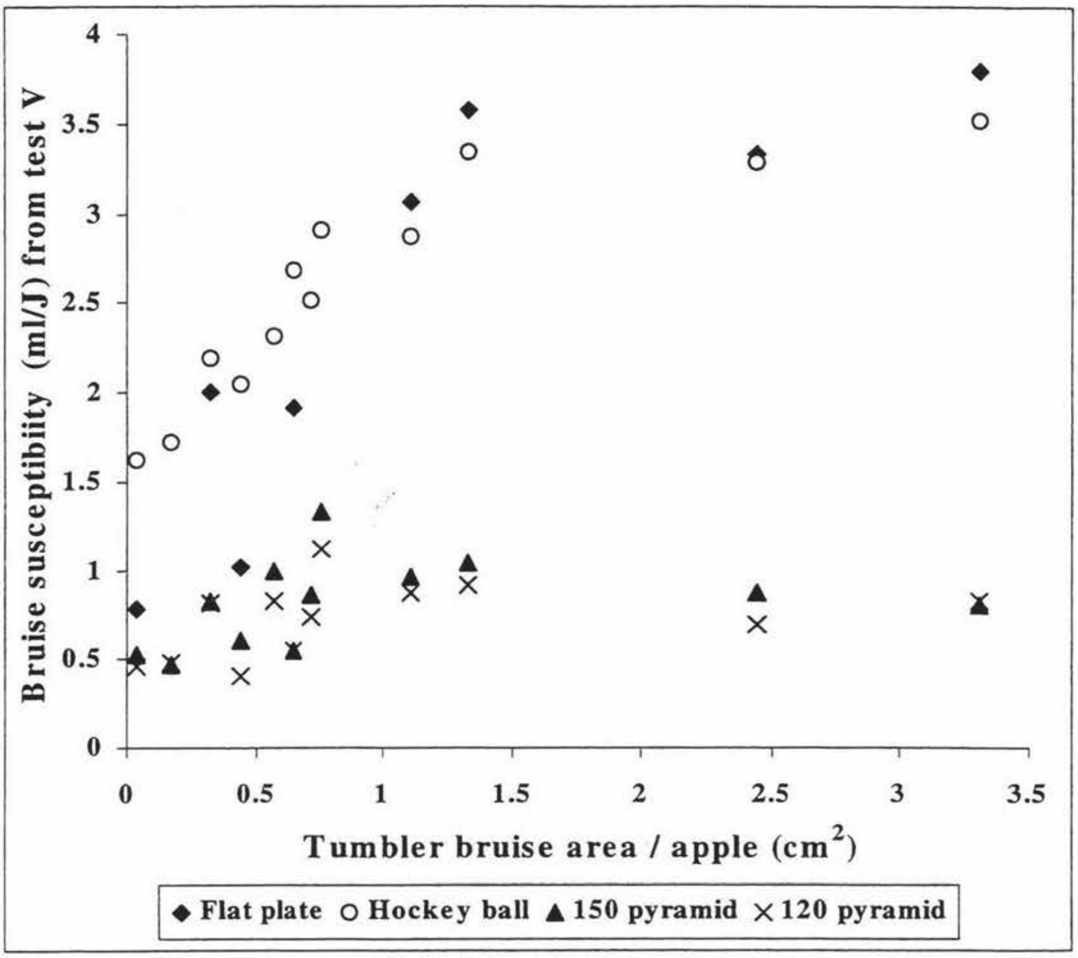


Figure 5.1 Bruise susceptibility produced from test V and the bruise area/apple from the tumbler test

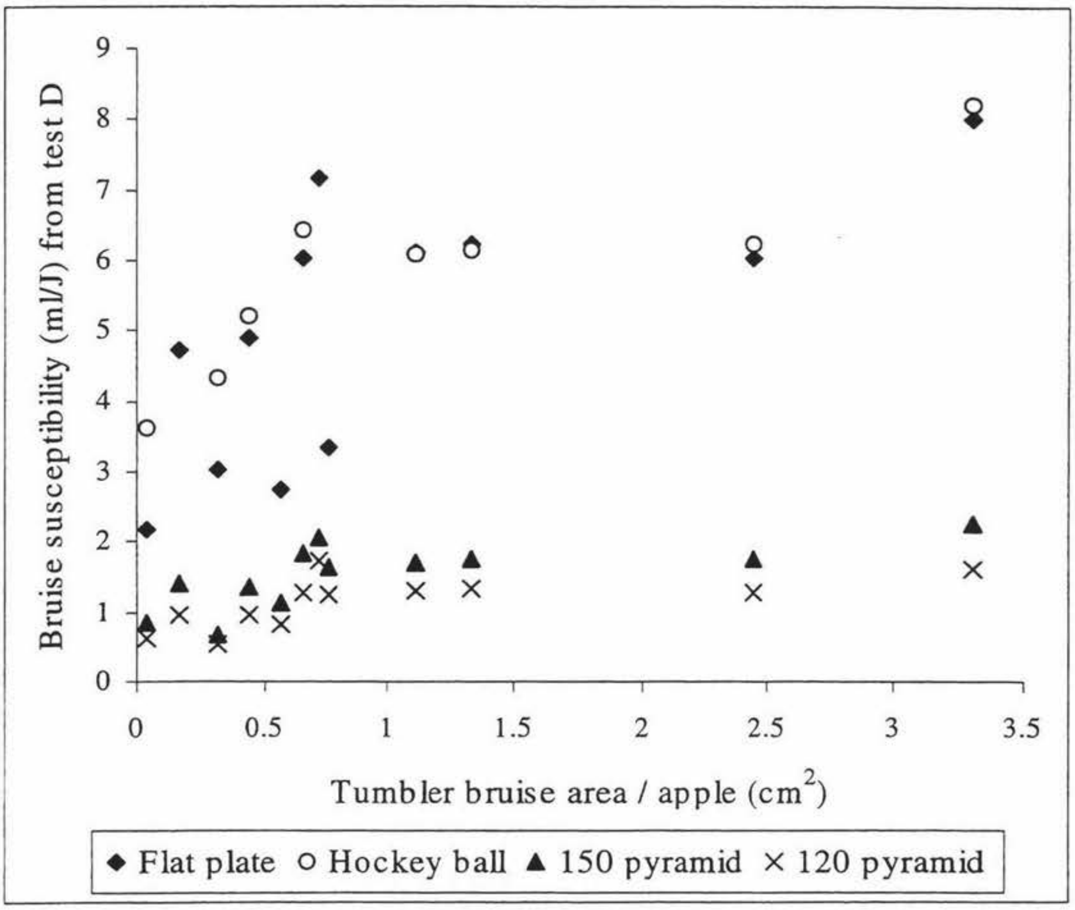


Figure 5.2 Bruise susceptibility from test D and the bruise area/apple from test T.

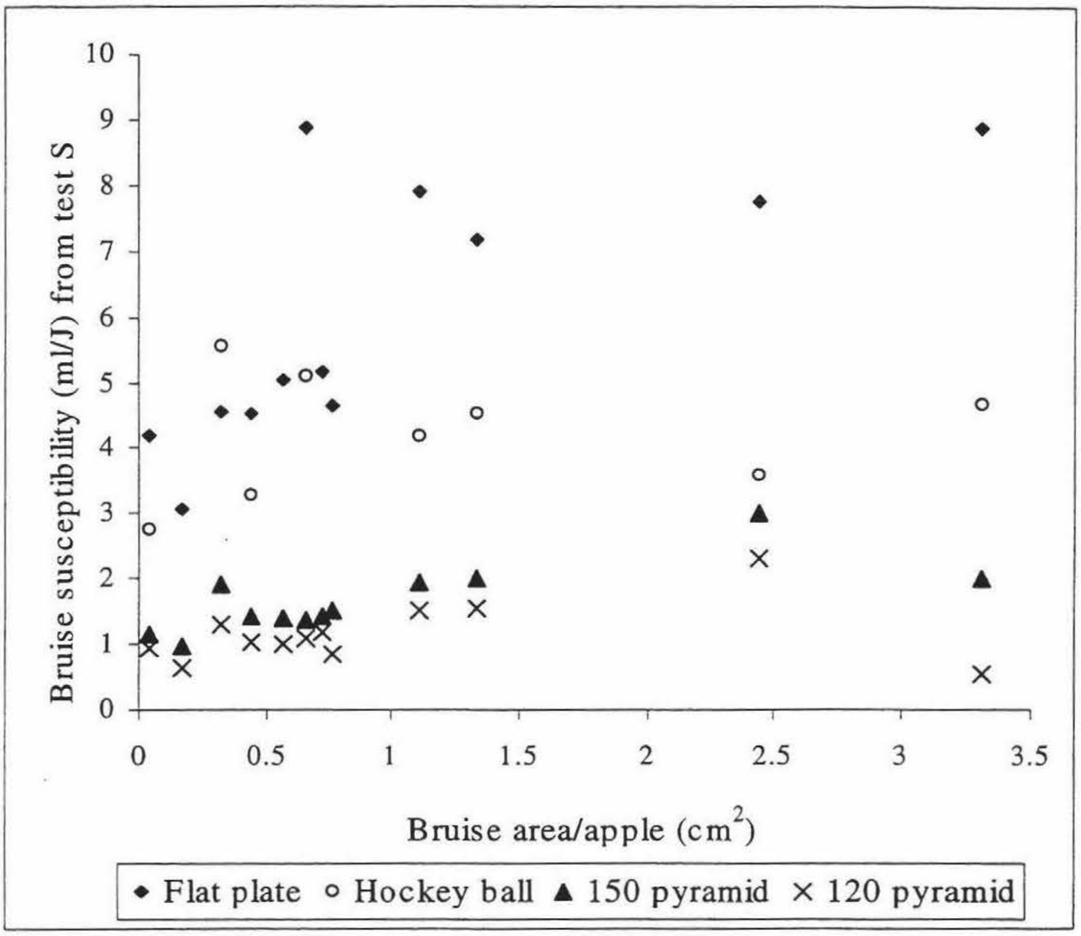


Figure 5.3 Bruise susceptibility from test S and the bruise area/apple from test T.

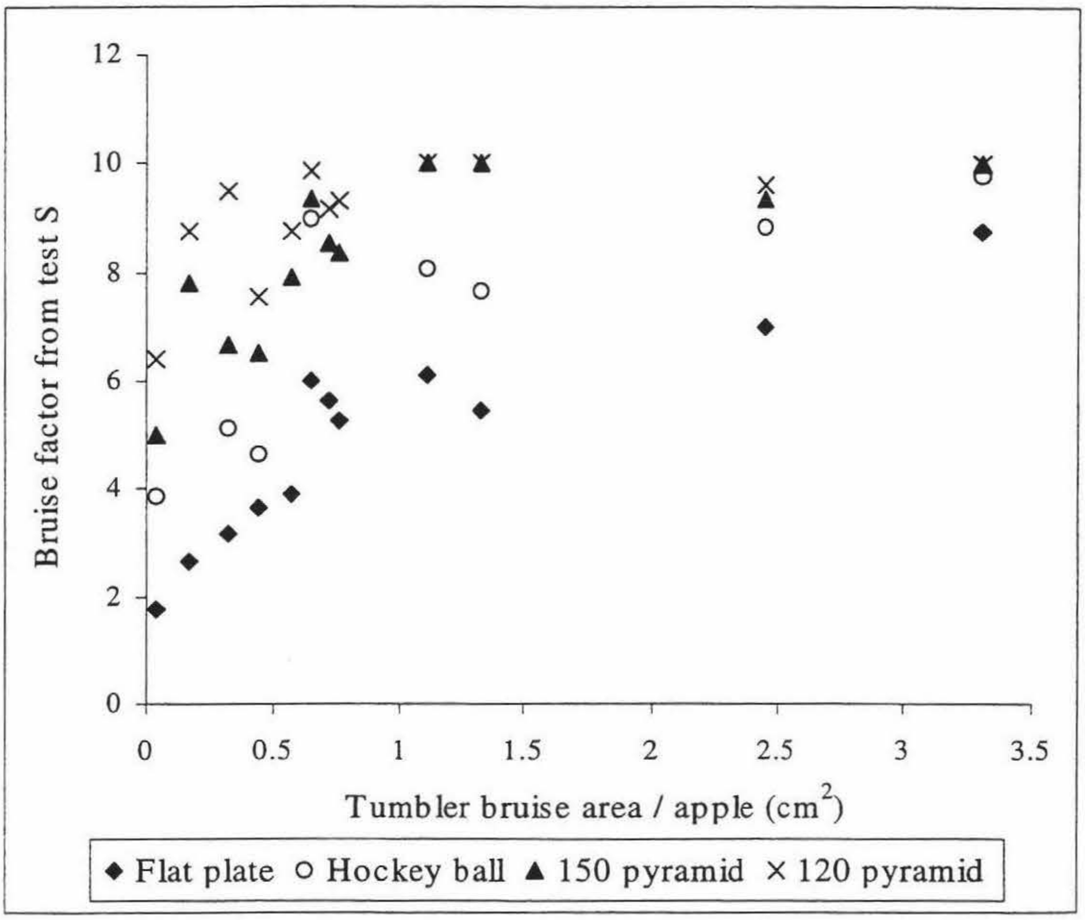


Figure 5.4 Bruise factor from test S and the bruise area/apple from test T.

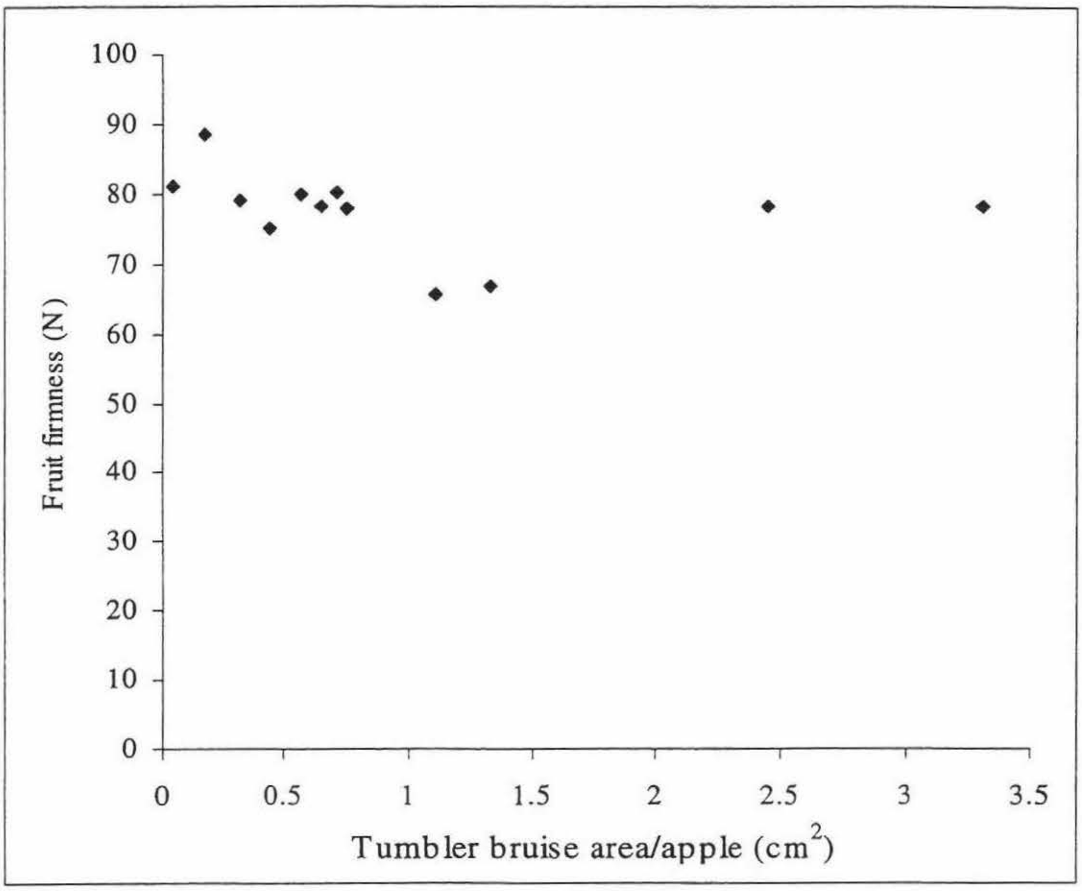


Figure 5.5 Fruit firmness (N) and the bruise area/apple from test T.

From Fig. 5.1-5.3, it can be seen that small changes in bruise susceptibility between these four cultivars resulted in large variations in tumbler damage. Results from the standard bruise drop test show that on the average, Splendour apple was the most susceptible to bruising, while Braeburn was the most resistance to bruising. Bruise susceptible fruit had a larger bruise area. These results agree with the common belief of the apple packing industry. These findings also confirm that testing for bruise susceptibility with the standard bruise test provides valuable data that relates fruit attributes at harvest to its tendency to incur bruises during the grading on different variety apples.

The relationship between the hockey ball bruise test and tumbler test is influenced by a number of factors (Banks, 1994):

- Tumbler bruise is largely a result of apple to apple collisions, the impact characteristics of which differ considerably to those resulting from the hockey ball bruise. Two colliding apples (both considered to have elastic properties) each have some ability to absorb the resultant impact energy and may also be able to move at the moment of impact. Therefore, tumbler bruise dimensions are likely to be different to those produced by the ball.

- The hockey ball test is applied to the equator of each apple. Tumbler bruises occur all over the apple surface where differing responses to impact may result from variation in cortex cell size. With tumbler test the opportunity for each apple to experience a similar number of impacts of similar energy was increased by rolling the tumbler 4 times. With tumbler test however the consistency of impacts experienced by each individual fruit varies widely.

5.3 Bruise factor test

The bruise factor method for assessment of bruise damage was developed by Pang and Studman (1993). The bruise factor method attempted to simulate the range of impacts on fruit experienced through a handling operation, and to reflect the methods of assessing bruising used commercially. It is a measure of bruise initiation rather than bruise size above a threshold. It should therefore relate more closely to bruising sustained during handling operations, allowing for the variation in fruit size, shape and mass.

The bruise factor correlated well with the bruises area/apple produced by the tumbler on four cultivars (R^2=0.78) (Fig.5.4). Pang (1993) found that the bruise factors related reasonably closely to the number of bruises produced by the fruit grader for different varieties. The storage time and conditions, and the apple temperature at impact significantly affected the bruise factor (Table 4.13), as would be expected for the tumbler test. Increased bruising with storage times and a decrease in damage with increased temperature at impact have been noted by other investigators as well (Schoorl and Holt, 1977, Mowatt and Bands, 1994). On the other hand, there were some conflict findings reported by Klein (1987) and Saltveit (1984). The data from this study showed that the bruise factor of Splendour apples at room temperature was less than that at cool-stored temperature, which agrees with the results of previous researchers (e.g. Mowatt and Banks, 1992; Pang, 1993) and agree with the results from fruit handling systems. But for Granny Smith, the bruise factor by using the flat and hockey ball indenters at room temperature was higher than that at cool-stored temperature. The data also showed that the bruise factor of F apples was less than that HW fruits but higher than LW fruits. It can therefore be concluded that handling Splendour, Pacific Rose and Braeburn after two months stored at 0.5°C with 90% RH is likely to result in more bruises.

When the number of bruises with area greater than 1 cm^2 (produced from test S using flat plate indenter) was removed from the data set, there was a better linear correlation between the remaining data and the bruise areas/apple produced by the tumbler (R^2=0.86) (Fig 5.6). This implied that bruising tests based on impacts causing bruise areas above 1 cm^2 would predict that little difference in bruising would be expected during handling fruit. Some high-energy impacts during the simple pendulum test were about 1J, and this was too high. In practice, typical drop heights of 20 cm are found in commercial packing lines, and the results of the grader test (Mowatt and Bank, 1994; Pang, 1993) and a tumbler test from this study suggest that most bruises occurred at a smaller range of impact levels. By its nature, bruise factor is related to the bruise area/apple likely to occur during handling, rather than to the absolute size of bruise volume. By choosing a pendulum loading method, it was possible

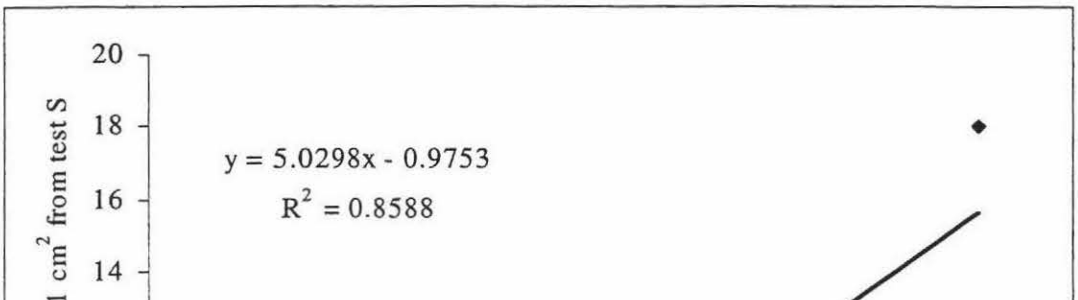


Figure 5.6 The number of bruise with areas less than 1 cm^2 from test S and the bruise area/apple from test T.

to conduct impacts corresponding to very small drop heights, so that the bruise factor test could be conducted in the range where small bruises were produced. In this context, it should be noted that commercial criteria are related to cumulative bruise area (i.e. its sum of all bruise areas on the apple).

5.4 Bruise susceptibility produced from three standard impact tests

The results showed that bruise susceptibility, bruise area, and the shape of the bruise depended upon the shape of the indenter used for the experiment and the method used to conduct the impact tests.

Different values for the bruise susceptibility were obtained using different indenters, with lower values being obtained for greater angles of penetration at the edge of the contact area (Table 4.2, 4.5, and 4.8). Although there were some differences in the bruise susceptibility produced from the three standard impact tests using the pyramid indenters, the differences were not significant. In a comparison between the bruise susceptibility obtained using the flat and hockey ball indenters, it was found that there were many differences among the three standard impact tests. In test V, there were significant differences in bruise susceptibility between the flat and the hockey ball indenters for 'Pacific Rose' and 'Braeburn' apples, but not for 'Splendour' and 'Granny Smith' apples (Fig. 4.9) at 0.31J energy level. There were no significant differences in bruise susceptibility between the flat and hockey ball indenters in the test D on all cultivars (Fig 4.14). Bruise susceptibility differences were significant between the flat and the hockey ball indenters in test S for all four cultivars. Bruise susceptibility was much higher for the flat plate than hockey ball indenter, even in some cases the input energy was lower for the flat indenter than hockey ball indenter (Table 4.8). Clearly cultivars of apples differ in their impact bruise response. The largest varietal difference in damage susceptibility observed was that between Braeburn and the other cultivars, but the bruise depth between cultivars doesn't show much difference between cultivars. This may imply that Braeburn tended to incur internal bruises rather than external injuries. The data from this experiment also implied that Granny Smith apples had a relatively weak flesh and relatively strong skin.

From the data obtained in this study, the effect of storage time on bruise susceptibility was also different among cultivars, impact methods, and impact surfaces. There is evidence that the mechanical strength of apple tissue deteriorates with storage time (Holt and Schoorl, 1984), and it may be expected that fruit bruise susceptibility for different cultivars should be different. Data from the tumbler test showed that there were significant differences between cultivars in their susceptibilities to bruising on F and HW fruit. For example, the bruise area/apple increased by 166% on Splendour, 60% on Granny Smith, 50% on Braeburn, and 27% on Pacific Rose. In the standard impact tests, the bruise susceptibility increase ranged from 13-19% for test V using the hockey ball, 33-67% for test S using the flat plate on four cultivars on HW fruit in comparison with F fruit. For test D using the flat plate, the bruise susceptibility increased by 81% on Splendour, 119% on Pacific Rose, and 4% on Braeburn. The bruise susceptibility decreased in HW fruit in comparison with F fruit for Granny Smith. However, the bruise susceptibility produced from the pyramid indenters was little different between cultivars and tests.

5.5 Physiological causes of variation in bruise susceptibility

Apple bruise susceptibility is affected by cultivar, maturity, and storage time. Physiological and biochemical makeup of a fruit, as well as variations in cell wall thickness, cell packing arrangement, and cell turgidity may account for these differences. The impact conditions that cause bruising depend on each fruit's tissue structure (Garcia and Ruiz, 1988). Kunze, et al., (1975) stated that dense tissue, with a low volume of air-filled space (i.e., peach), is susceptible to deep bruises that are typically not visible at the skin surface and will often develop internal cone-shaped and radial fractures when impacted. Tissue with a high volume of air-filled interstitial space (i.e., apple) appears to distort in an elastic manner at the contact surface until cell breakage occurs. The elastic region is continuously re-established further into the fruit until all of the impact energy is either dissipated by cell breakage or stored by elastic membrane distension (Holt et al., 1981). It may be assumed that different cultivars of apple have differences in volume of air-filled interstitial space between tissue. This difference may have a direct effect on bruise susceptibility of apples (Garcia et al., 1994). For Braeburn, the bruise susceptibility, and bruise area (skin removed) from three impact tests were much different from the other three cultivars, but the bruise depth did not show much difference between Braeburn and the other three cultivars. It was also found that there were relatively few differences in the bruising produced from test V and Test D between F and HW fruit. This could imply that studies conducted on cool stored 'Braeburn' apple will also apply to fresh apples. For Splendour, Pacific Rose, and Granny Smith, there were little difference in the bruise susceptibility, bruises area, and bruise depth among these three cultivars. It was noted that the bruise susceptibility decreased in HW fruit in comparison with F fruit in test D using different indenters for Granny Smith. Increased bruising with storage times and decrease in damage with storage times have been noted by previous investigators by using difference impact tests and difference varieties for different storage periods (Schoorl and Holt, 1977; Hyde and Ingle, 1968; Klein, 1987; Pang, 1993).

The shape of the surface impacted by the fruit can affect the extent and visibility of bruising. The radius of curvature of pyramid indenters was small when compared to impact objects, and created bruises that were deep for their width. Bruises incurred on handling systems tend to be shallower and of greater width. The elastic properties of the skin and the cell packing arrangement, especially in the hypodermal layer, may be important in imparting bruise resistance (Klein, 1987). By impacting with relatively high energy on to a small surface area the effect of the skin and outer cells on bruise severity may not be adequately taken into account. The difference between the maximum and minimum bruise dimensions from a sample of apples bruised given this type of standard test was usually small. Thus, differences in bruise dimensions between experimental treatments may be difficult to detect.

According to the models bruise susceptibility is affected by fruit turgidity and firmness changes during ripening; bruise damage would decrease with decreasing fruit turgidity, or would increase with decreasing fruit firmness, depending on which is the main factor in the ripening process (Garcia et al 1994). The results from this study showed that the bruise susceptibility for all four cultivars increased after 2 months storage at 0.5°C with 90% RH. Fruit firmness decreased after two months storage either LW and HW fruit except for Splendour; which had little change in firmness after two months storage either for LW and HW fruit. A combination of factors probably accounted for the enhanced fruit firmness of 'Splendour' apples stored at 0.5 °C with 90% RH for 2 months. From Table 14, it can be seen that temperature had no significant effect on flesh firmness of

Splendour and Granny Smith cultivars tested. Firmer fruit were shown to be less susceptibile to bruising (i.e. Braeburn).

5.6 Temperature and storage humidity effects on fruit bruising

5.6.1 Temperature effects

Increasing bruise susceptibility at low bruising temperatures is consistent with the popular notion that apples are crisp and more prone to bruising at low temperature. Pang (1993) tested 'Granny Smith' apples and Mowatt and Banks (1994) tested 'Royal Gala' apples and both of them reported that the bruise susceptibility increased with decreased fruit temperature. But Schoorl and Holt (1977) and Klein (1987) tested 'Granny Smith' apples and found that the effect of apple temperature on impact bruising was not significant.

The results from this study showed some differences between cultivar and impact methods. The results generally showed that there was a general trend that the bruise susceptibilities increased as temperature decreased for both Splendour and Granny Smith apples but the increase was different for both cultivars. For the tumbler test, the bruise area/apple (cm^2) increased 35% for Splendour and 20% for Granny Smith apples (Table 4.1). The results from test V using the flat and hockey ball indenters showed the bruise susceptibility at 0.5°C was significantly different from the bruise susceptibility at room temperature for both Splendour and Granny Smith apples ($P<0.05$). But there were no significant differences between the bruise susceptibility using the pyramid indenters (Fig. 4.12), but the results from test D showed some differences from test V. For Splendour, the bruise susceptibilities at 0.5°C were significantly different in bruise susceptibilities at room temperature for all indenters ($P<0.05$). But for Granny Smith apples, the bruise susceptibilities at 0.5°C were higher than those for warmed fruit, but the difference was not significant for all indenters ($P>0.05$) (Fig. 4.17). In comparison Schoorl and Holt (1977) found that the effect of apple temperature on impact bruising was not significant for Jonathan, Delicious and Granny Smith apples. In this study apples impacted at low temperature sustained more damage than at high temperature. This finding contrasted with the study reported by Saltveit, (1984).

Although bruise susceptibility for cold fruit measured by three standard impact tests using pyramid indenters was higher than warmed fruit, there were no statistical differences in the bruise susceptibility between 150° and 120° pyramid indenters for both Splendour and Granny Smith apples.

In general, HC fruit sustained more bruises than HW fruit in test S, in some cases were slightly heavier than HW fruit. The difference in fruit mass would presumably have led to a greater impact energy for HC fruit dropped from a given height in test S, however, the magnitude of the difference in mass of fruit in these two groups was not large enough to explain the large difference in bruise susceptibility resulting from test S for HC and HW fruit.

5.6.2 Effect of storage humidity

Fruit under different relative humidity conditions showed differences in their physical properties and bruise susceptibility. The results of the standard impact tests show a general trend that bruise susceptibilities decreased as storage humidity decreased for Splendour and Braeburn apples (Fig 4.13, 4.18, and 4.20). But the trend was not consistent across all indenters and cultivars.

Increased cell turgor pressure has been associated with a reduction in the strength of Cox apple tissue as indicated by lower shear press values (Hatfield and Knee, 1988) and an increase in sensitivity to bruising of model tissue (Pitt and Davis, 1984). It is obvious that greater bruising will occur in handling highly turgid products. Increasing weight loss of apples after two months in low RH storage condition reduced bruise susceptibility. Whilst there may be some potential to reduce bruising during commercial grading by allowing fruit to dehydrate it would be necessary to avoid detrimentally influencing long-term storage potential or other essential quality attributes. It might be more appropriate to consider the regulation of water loss during the storage period, in which case the most effective period for increasing evaporation needs to be identified (Johnson and Dover 1990).

Some physical change of the apples was observed during the experiment. The apples skin often appeared to shrivel and become soft in the low humidity level storage. These phenomena showed that apples in the low moisture storage did lose some water content. Apples stored at lower humidity environment generally gave lower bruise susceptibilities.

5.7 Bruise visibility

Bruise area with skin on plays an important role in bruise measurement. Experimentally; it is a visible and easily measured parameter in practical situations. The measured bruise area with skin on was very similar to the area measured when the skin was removed from standard impact tests using the Hockey ball and pyramid indenters . This was mainly because of the curved edge of the impact surface, which produced a clear edge to the bruised area. Bruises were clearly visible in all varieties with skin removed.

The flatter indenters (i.e. the flat plate and the ball) produced larger bruise susceptibility values than the others. The bruise shape depended upon indenter shape. The bruise shape was elliptical for flat and ball indenters, rhombi for pyramid indenters.

The visibility of bruises prior to skin removal forms an important aspect of the practical assessment of fruit quality. It was found that the shape of the surface impacted by the fruit could affect the extent and visibility of bruising. These studies have indicated that many bruises cannot be seen until the skin is removed. Although the previous studies indicated some test conditions where 100% bruising was avoided, they did not identify the impact conditions (energy levels and surfaces) for which bruise initiation and threshold visibility was avoided. During this study it was found that the bruising visibility depended on the impact surface shape and energy levels. Once bruising began the visibility of bruising increased with an increase in energy levels.

Commercially, there is little importance in the size of a bruise once it exceeds the level which makes it unacceptable for the fresh fruit market. In practice the percentage of fruit rejected is more important than the size of bruises on rejected fruit. Although unlikely, if a handling system produced larger bruises on fewer apples, it could be argued that this would be preferable commercially.

The Impact energy above which bruising was initiated on a flat plate surface decreased with storage time for all four cultivars. The range of the energy for fruit impacted on a flat plate surface that resulted in 0-100% bruising were 20-75% lower for the stored fruits than the fresh fruits. 'Splendour' apples had 60% lower allowable impact energy to initiate bruising than 'Braeburn' apples. The range of drop heights chosen for the simple tests did not allow the energy level where bruising initiated for all cultivars on the ball and pyramid indenters to be determined, since the energy limits appeared to be low. Braeburn apples had an allowable impact energy to initiate bruising which was more than two times higher than the other three cultivars.

The energy of standard impact used to bruise fruit in this study closely relates to the energies of impact that apples incur in the postharvest handling system and which cause bruises that lead to rejection of fruit for export. Such bruises are common in the postharvest handling system and the relationship established has therefore considerable commercial significance (Mowatt and Banks, 1994).

CHAPTER SIX

CONCLUSIONS

A study was conducted to compare different methods to measure bruise susceptibility of fruit. Particular emphasis was given to relating bruising measurements obtained from different impact methods to practical situations. In order to compare measured values with actual commercial bruising, an appropriate test method to simulate impact damage during handling was developed, employing a revolving tumbler. The nature of the impact loads produced by this method was very similar to those incurred by a practical grader, as indicated by Instrumented Sphere measurements.

Fruit–fruit impacts were a major cause of damage in the tumbler test. Bruise damage produced by the tumbler test related closely to bruising sustained during handling operations, allowing for the variation in fruit size, shape and mass. Bruise sizes were mostly small, resulting from low energy impacts, and the number of small bruises was affected by storage and temperature of testing, while the numbers of large bruises did not change with these factors. Apple damage was summarised in terms of the average number of bruises per fruit and the average accumulated bruise area per fruit. A large percentage of bruises were less than 1.5 cm^2 in area and it was rare to have any bruises above 3 cm^2. After 2 months cool stored at 90% RH all four apple cultivars were found to bruise more easily. Braeburn apples had the smallest bruising area per apple and number of bruises per apple than the other cultivars. There were smaller differences between the other cultivars.

The tumbler could be used to simulate an actual grader's damage and permitted a controlled comparison of simulated grader damage with laboratory impact methods. Differences in bruise susceptibility between fruit from different cultivars can be clearly indicated by the amount of bruising produced by the tumbler.

It was found that bruise susceptibility varied with different impact tests, and treatments. Bruise susceptibility from test V using the hockey ball was related to the bruise area per apple produced by the tumbler test ($R^2 = 0.72$). But the bruise factor obtained from test S had the best correlation with the bruise area per apple produced by the tumbler test ($R^2 = 0.78$).

Fruit stored at high humidity (HW) had a higher bruise factor than fresh (F) fruit. Splendour apples at low temperature had a higher bruise factor than at room temperature, indicating that they would be more likely to be bruised at low temperature during commercial handling. Braeburn apple had the lowest bruise factor in all cases.

The bruise susceptibility produced by the pyramid indenters was not correlated with the bruise area/apple from the tumbler test. Test D, Test S and the penetrometer test did not indicate any significant difference between treatments, showing that they were not reliable indicators of bruising levels in this experiment. It was concluded that Bruise factor provided a more reliable indicator of assessment of bruising than the other methods.

Bruise susceptibility measurement was affected by the indenter geometries and the methods conducted. The bruise susceptibility produced by using the flat and hockey ball indenters was shown to increase with storage time for Splendour, Pacific Rose and Braeburn apples in tests V, D, and S, but the extent of the increase was cultivar-dependent. Apples impacted using the flat and hockey ball at low temperature sustained more damage than at high temperature. Storage time and impact temperature had no significant effect on the bruise susceptibility measured using pyramid indenters.

The impact energy required to produce an initial visible bruise (as measured without the skin removed) depended on the cultivar. It was found that the bruising visibility increased with energy levels. The energy at which bruising was initiated on a flat plate surface decreased with storage time. The pyramid indenters produced 100% bruise visibility at very lower energy levels for all cultivars although the bruise area was very small.

Pyramid indenters produced a more linear relationship between 2/3 power impact energy and bruise area than either a spherical or a flat indenter. Bruise shape and bruise susceptibility values were affected by indenter geometries.

Differences in research findings reported in previous studies are attributed to differences in impact energy levels and methods of bruise assessment. It is suggested that bruise initiation and threshold visibility should be used as the basis for assessment of bruising. Finally it is argued that experimental studies which focus on smaller bruises close to commercial thresholds (i.e. less than 1 cm^2) are a more reliable indicator of commercial bruising than studies involving larger bruises.

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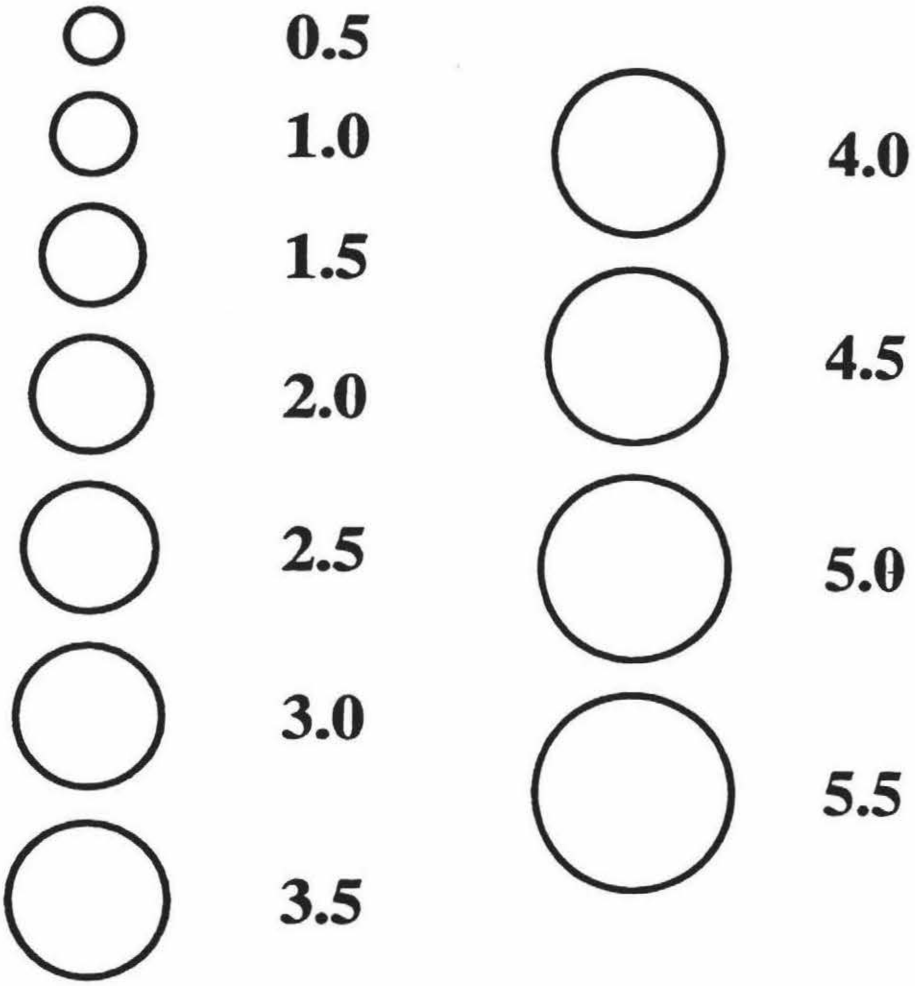
APPENDIX 1

Circles of increasing diameter (normally on a transparent sheet) used to estimate the size of individual bruise on apples for tumbler test. Calculation of bruise area and bruise number/apple is given in Appendix 2.



APPENDIX 2

Data sheet used for tumbler test on which bruise area and bruise number/apple are entered and calculated. For each apple the bruised areas are matched to the respective circle on a transparent sheet and an entry is made in the column under that particular bruise area. The total number of bruises in each column for each fruit are then multiplied by their respective bruise area and summed to give bruise area/apple. Bruise number is the sum of the number of bruises/apple. An example for apple 1 is given.

Apple number	0.5 cm^2	1.0 cm^2	1.5 cm^2	2 0 cm^2	2.5 cm^2	3.0 cm^2	3.5 cm^2	4.0 cm^2	4.5 cm^2	Bruise area/ apple	Bruise number/ apple
1	√√	√	√		√					6.0	5