Effects of Temperature and Loading Characteristics on Mechanical and Stress-Relaxation Properties of Sea Buckthorn Berries. Part 1. Compression Tests.

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ABSTRACT

Force and energy required to rupture the sea buckthorn berry were measured using the plate test at loading velocities ranging from 0.1 to 4.0 mm/s and ambient temperatures of 4.5, 16.5, 25, and 34.5°C. As berry temperature increased from 4.5 to 34.5°C, the rupture force decreased 20.7%. There were no significant differences in rupture energy at temperatures of 16.5, 25, or 34.5°C; but the rupture energy was significantly higher at 4.5°C. Average berry deformation was 1.5 mm and did not vary with temperature. Consequently, berry firmness decreased as temperature increased. The rupture force and energy for large berries was significantly higher than that for small berries at 16.5°C, however, the small berries were firmer. Loading velocity had a significant effect on rupture force, rupture energy, deformation, and firmness of berries of the Sinensis cultivar, but there was no effect on berries of the Indian Summer cultivar. For these two cultivars, berry masses and geometric mean diameters ranged from 0.14 to 0.38 g and from 6.2 to 8.8 mm, respectively; with the Sinensis berries being more spherical.

Keywords: Sea buckthorn, Critical Impact Velocity, Compression Energy, Firmness, Berry Size, Flat Plate Test

INTRODUCTION

Sea buckthorn (*Hippophae rhamnoides L*) is a hardy shrub native to Europe and Asia that produces orange or yellow berries. This fruit has been used for centuries for its environmental, nutritional, and medicinal values (Mann et al. 2001). Knowledge of the physical and mechanical properties of sea buckthorn berries is considered to be necessary to design harvesting and processing machines.

Mechanical properties of agricultural products are most conveniently measured with the force-deformation curve. From this curve, a number of mechanical properties can be determined such as maximum force, energy, stiffness, and deformation. Three methods have been used to obtain such force-deformation curves (Fischer et al. 1969): i) the compression of fruit by a large flat plate (plate test), ii) the compression of the product by a small flat cylindrical die (plunger test), and iii) the compression of a sample of product cut to uniform size.

Measuring the force and energy to compress the whole fruit between two flat plates (i.e., the plate test) up to both the bioyield and rupture points is an important test. Although researchers have used many different methods for quantifying fruit firmness (Slaughter and Rohrbach 1985), some researchers use this procedure to estimate the firmness of fruit by measuring the force-deformation ratio (Mohsenin 1986; Patten and Patterson 1985; Holt 1970; Shafshak 1964). The results of the plate test will depend on such factors as the strength of the skin, the firmness of the flesh, the viscosity of the juice (Holt 1970), the turgid pressure of the fruit (Lustig and Bernstein 1987), and the size of the fruit. Blahovec et al. (1995) determined the compression force and strain corresponding to the maximum point of the compression curve for Leikora and Hergo cultivars of sea buckthorn berries. These berries were compressed between two steel plates at a constant strain rate of approximately 0.1 mm/s. The maximum compression force of the sea buckthorn berries ranged from 1.39 to 2.78 N. They have also found that the sea buckthorn berry masses ranged from 0.21 to 0.35 g and berry diameters ranged from 5.8 to 7.6 mm.

To date, there is limited data in the scientific literature describing the mechanical properties of sea buckthorn berries. The objectives of this study were to determine (using the plate test) the effect of temperature and loading velocity on the ultimate compression (or rupture) force, compression (or rupture) energy, berry deformation, and berry firmness for sea buckthorn berries.

MATERIALS and METHODS

Sea buckthorn berries of the cultivars Indian Summer and Sinensis, picked from a government orchard near Indian Head, SK and from a producer orchard near St. Claude, MB, respectively, were selected for testing. Whole branches were harvested on 27 September 2002 and 9 October 2002. The branches were transported directly to the laboratory and stored in a refrigerator at 6.5°C. Berries were manually detached from branches using sharp scissors. The experiment consisted of two tests: i) characterization of the berries (i.e., diameter and mass), and ii) compression of the berries between two flat surfaces.

Characterization of the berries

To determine the diameter and mass of the sea buckthorn berries, 110 and 50 berries were randomly selected of the Indian Summer and Sinensis cultivars, respectively. Three linear dimensions; major diameter (a), intermediate diameter (b), and minor diameter (c), were measured using a micrometer reading to 0.05 mm. Each berry was weighed on an electronic balance reading to 0.01 g.

The geometric mean diameter, D_p, of the berries was calculated using the relationship given by Mohsenin (1986), $D_p = \sqrt[3]{a \cdot b \cdot c}$. The degree of sphericity was calculated using the following equation:

$$\text{Sphericity} = \frac{\sqrt[3]{a \cdot b \cdot c}}{a} \tag{1}$$

Statistical analyses (SAS) were used to determine maximum, minimum, mean, standard deviation, and correlation dimensions and mass of the berries (Table1). The geometric mean diameter for the Indian Summer and Sinensis cultivars ranged from 6.44 to 8.83 mm and from 6.22 to 8.42 mm, respectively. The following general expression can be used to describe the relationship between the dimensions of the Indian Summer and Sinensis cultivars, respectively:

Indian Summer cultivar $a = 1.162\ b = 1.197\ c = 33.389\ m = 1.116\ D_p$
Sinensis cultivar $a = 1.016\ b = 1.149\ c = 33.380\ m = 1.053\ D_p$

Table 1. Physical characteristics of sea buckthorn berries.

Cultivar		Major diameter (mm)	Minor diameter (mm)	Intermediate diameter (mm)	Mass (g)	Sphericity (%)	Geometric mean diameter (mm)
Indian Summer+	Mean	8.82	7.37	7.59	0.260	89.6	7.90
	Minimum	7.00	5.86	6.00	0.160	84.7	6.44
	Maximum	9.90	8.20	8.50	0.380	96.9	8.83
	S.D.	0.52	0.37	0.39	0.040	2.7	0.39
Sinensis ×	Mean	7.49	6.52	7.39	0.258	95.1	7.12
	Minimum	6.45	5.60	6.45	0.140	91.7	6.22
	Maximum	8.85	7.80	8.85	0.370	98.2	8.42
	S.D.	0.74	0.62	0.65	0.035	1.6	0.66

+ Based on 110 measurements × Based on 50 measurements

The Sinensis cultivar had a higher sphericity than the Indian Summer cultivar. Berries of the Indian Summer cultivar had an oblate ellipsoid shape, while the Sinensis berries had an oblate spheroid shape.

The correlation coefficients of the berry dimensions and mass were significant at the 1% level (Table 2). Using the Indian Summer cultivar as an example, the mass of the berry was closely related to geometric mean diameter, but less associated with major diameter. Thus, the best dimension to estimate the mass of the berry is geometric mean diameter (Fig. 1).

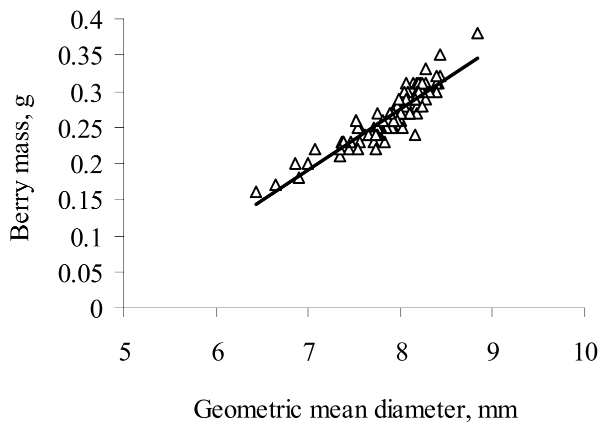

Fig. 1. Relationship between geometric mean diameter and berry mass for the Indian Summer sea buckthorn berry.

Table 2. Correlation coefficients between berry dimensions and mass for sea buckthorn berries of the Indian Summer and Sinensis cultivars.

Cultivar		Minor diameter (mm)	Intermediate diameter (mm)	Mass (g)	Geometric mean diameter (mm)
Indian Summer +					
	Major diameter, (mm)	0.648**	0.714**	0.803**	0.878**
	Minor diameter, (mm)	1	0.883**	0.824**	0.914**
	Intermediate diameter, (mm)		1	0.875**	0.942**
	Mass, (g)			1	0.915**
Sinensis ×					
	Major diameter, (mm)	0.910**	0.983**	0.968**	0.986**
	Minor diameter, (mm)	1	0.908**	0.945**	0.961**
	Intermediate diameter, (mm)		1	0.962**	0.985**
	Mass, (g)			1	0.975**

+ and × based on 109 and 49 degrees of freedom, respectively.
** Significant at 1% level.

For the Indian Summer cultivar, the best correlation among three diameters of the berries was related to the intermediate and minor diameter (Fig. 2). With the exception of a few outliers, the intermediate diameter data were clustered between 7 and 8 mm indicating sample uniformity. In subsequent testing, berries with an intermediate diameter between 7.6 and 8.1 mm were selected. For the Sinensis cultivar, the best correlation was related to the intermediate and major diameter (Fig. 3). Unlike the intermediate diameter data for

Indian Summer berries, the intermediate diameter data for Sinensis berries were not clustered. Due to the uniform distribution of intermediate diameters over the range from 6.5 to 9 mm, the Sinensis berries were sorted into two categories according to intermediate diameter for subsequent testing (i.e., 6.8 to 7.2 mm were classified as 'small' and 7.9 to 8.4 mm were classified as 'large'). This difference between the two cultivars was due to the shape of the berries (Fig. 4).

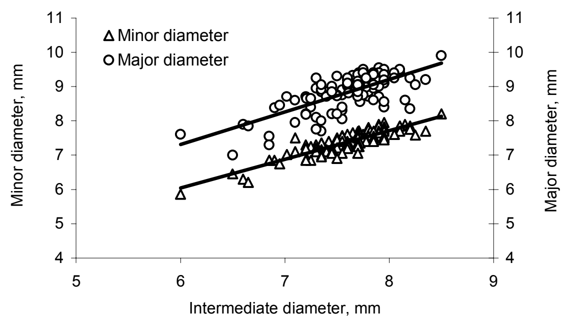

Fig. 2. Relationship among three dimensions of sea buckthorn berries of the Indian Summer cultivar (n=110).

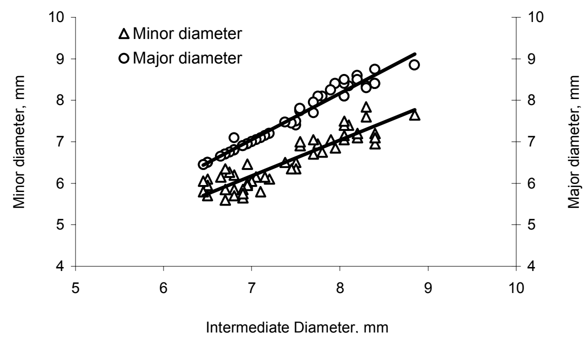

Fig. 3. Relationship among three dimensions of sea buckthorn berries of the Sinensis cultivar (n=50).

Sinensis cultivar   Indian Summer cultivar

Fig. 4. Photographs showing the oblate spheroid shape of the Sinensis berries (left) and the oblate ellipsoid shape of the Indian Summer berries (right).

Compression (Plate) Test

The compression (plate) test was used to evaluate the force and energy required to rupture the sea buckthorn berry under quasi-static loading. For each test, a single berry was placed on its cheek on a flat steel washer and then compressed with a 20 mm-diameter probe. A force-deformation curve was obtained for each berry. The initial maximum force, berry deformation to the rupture point, and rupture energy were obtained from this curve.

Two sets of compression tests were completed. In the first set, the effect of berry temperature on maximum force and energy required to rupture the small Sinensis berries was studied. Based on the maximum force and deformation at the rupture point, the ratio of force to deformation (N/mm), defined as the firmness, was calculated. Loading velocity was constant at 0.7 mm/s. Four berry temperatures were tested: 4.5, 16.5, 25, and 34.5°C. Each test was replicated 20 times. Berry temperature was modified by immersing the berries in water baths of 4.5, 16.5, 25, and 34.5°C for 15-20 min. Individual berries were removed, drained, and immediately compressed.

In the second set of compression tests, the effect of loading velocity on both firmness and the force and energy required to rupture large Sinensis berries was studied. Berry temperature was constant at 16.5°C. Four loading velocities were tested: 0.1, 0.7, 2.0, and 4.0 mm/s. Each test was replicated 25 times. Additional tests were performed using the Indian Summer cultivar at a temperature of 4.5°C. Three loading velocities were tested: 0.1, 0.2, and 0.3 mm/s. Each test was replicated 20 times.

RESULTS and DISCUSSION

Effect of temperature on rupture force and rupture energy

Figure 5 shows two kinds of force-deformation curves obtained during the compression tests. The shape of the force-deformation curve was influenced by the berry temperature, berry diameter, cultivar, and loading velocity. Peleg et al. (1976) have also discussed the effect of similar factors on force-deformation curves for some juicy fruits. The most important point of the compression curve was the first local maximum point, which was selected as the rupture force.

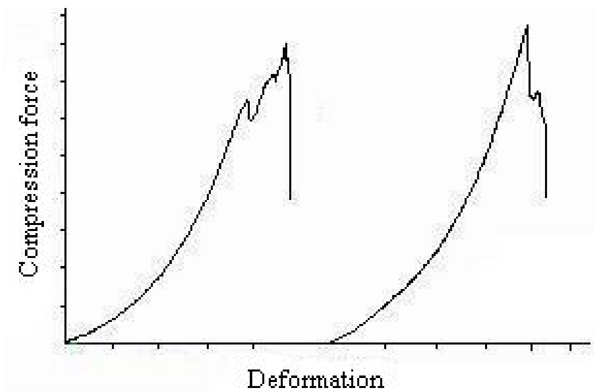

Fig. 5. Two types of force-deformation curves observed during compression tests of sea buckthorn berries.

Temperature showed a significant effect on rupture force, rupture energy, and berry firmness, but was not significant for berry deformation. With an increase in berry temperature from 4.5 to 34.5°C, the rupture force decreased 20.7% (Table 3). Duncan's test showed that the mean rupture force at 4.5°C had a significant difference with three other levels, but the difference among rupture force at 16.5, 25 and 34.5°C was not significant ($p=0.05$).

Rupture energy decreased 29.1% as berry temperature increased from 4.5 to 16.5°C. With further increase in temperature, an insignificant increasing trend was observed. These variations of rupture energy depend on variations of force and deformation of the berry to the rupture point. With an increase in the temperature from 4.5 to 34.5°C, the firmness decreased 14.2%. The differences between the mean value of firmness at 4.5 and 16.5°C, 16.5 and 34.5°C, and between 25 and 34.5°C were not significant at the 1% level.

Table 3. Effect of berry temperature on compression of small sea buckthorn berries (Sinensis cultivar) at a loading velocity of 0.7 mm/s.

Berry temperature (°C)	Force* (N)	Energy (mJ)	Deformation (mm)	Firmness (N/mm)
4.5	3.03 a	1.82 a	1.47 a	1.97 a
16.5	2.55 b	1.29 b	1.36 a	1.92 ab
25	2.39 b	1.32 b	1.48 a	1.64 c
34.5	2.40 b	1.36 b	1.51 a	1.69 bc
Average	2.59	1.45	1.46	1.80

* In each column, the data with a similar letter have no significant difference at 1%.

Effect of loading velocity on rupture force and rupture energy

The tests conducted using the large Sinensis berries showed that loading velocity had a significant effect on rupture force, rupture energy, deformation, and firmness; however, there was no significant effect on rupture force, rupture energy, deformation, and firmness for the Indian Summer cultivar at 4.5°C (Table 4).

Table. 4. Effect of loading velocity on compression force, compression energy, deformation, and firmness of sea buckthorn berry.

Cultivar	Loading velocity (mm/s)	Berry temperature (°C)	Force* (N)	Energy (mJ)	Deformation (mm)	Firmness (N/mm)
Indian Summer	0.1	4.5	1.32 a	1.26 a	2.16 a	0.58 a
	0.2	4.5	1.32 a	1.12 a	1.97 a	0.67 a
	0.3	4.5	1.46 a	1.58 a	2.20 a	0.66 a
		Average	1.36	1.32	2.09	0.64
Sinensis (large)	0.1	16.5	2.44 d	2.19 d	2.71 b	0.89 d
	0.7	16.5	3.30 c	3.00 c	2.93 a	1.13 c
	2.0	16.5	4.10 b	3.70 b	3.02 a	1.35 b
	4.0	16.5	4.63 a	4.31 a	3.06 a	1.53 a
		Average	3.62	3.3	2.93	1.23

* In each column, the data for each cultivar that have a similar letter have no significant difference at 1%.

For large Sinensis berries, increasing the loading velocity from 0.1 to 4.0 mm/s increased the mean rupture force and energy 1.9 and 2.0 times, respectively. The difference among the mean values of rupture force and energy at four levels of loading velocity was significant at the 1% level (Duncan's test) (Table 4). The firmness also increased with increasing loading velocity, with berry firmness at a loading velocity of 4 mm/s being 1.7 times higher than that for the 0.1 mm/s loading velocity. Duncan's test showed that the difference between the mean values of firmness at four levels of loading velocity was significant at the 1% level.

Comparison of the large and small Sinensis berries at 16.5°C (Tables 3 and 4) showed that the rupture force and energy for the large berries was higher than that for the small berries. Due to greater deformation, the large berries were less firm than the small berries.

CONCLUSIONS

In the compression test, the rupture force, rupture energy, and firmness were significantly affected by both temperature and loading velocity. With an increase in the berry temperature, the rupture force and energy decreased significantly. The rupture force and energy for large berries was significantly higher than that for small berries, but the large berries were less firm than the small berries. Loading velocity showed a significant effect on rupture force, rupture energy, and firmness. For the large Sinensis berries, an increase in loading velocity from 0.1 to 4 mm/s increased the rupture force, rupture energy, and firmness 89%, 97%, and 42%, respectively. The sea buckthorn berry masses and geometric mean diameters ranged from 0.14 to 0.38 g and from 6.22 to 8.83 mm, respectively.

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