Impact force of melon seeds during shelling

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Abstract: Melon seeds are shelled in a rotating impeller – a type of machine to obtain the cotyledons. The seeds exit the impeller and impact a cylindrical ring shelling the seeds. Because of the impact force, some of the seeds are broken, which would deteriorate in storage and make lower market value. An analytical method was used to determine the factors affecting the impact force on the ring. Experimental compression tests were carried out to determine the static force for breaking melon seeds. Some seeds were also shelled with an experimental shelling machine and the number of broken seeds was counted. Analysis results showed that the factors affecting the impact force were impeller speed, seed cross-section area at impact and mass ratio. The mean forces for breaking melon seeds were 13.14×10^{-3} N, 19.62×10^{-3} N and 19.55×10^{-3} N for orientations of breadthwise, lengthwise with tip up and lengthwise with tip down respectively.

Keywords: impact force, melon seeds, shelling, analysis

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1 Introduction

Melon seeds (*Citrulus vulgaris*) are small, flat and partly oval in shape containing cotyledons. The seed is covered with a thin shell having a thick ring around the edges with a tip (Figure 1). The cotyledons contain 60% protein and 50% edible oil. The seeds are shelled to obtain the cotyledons by mechanical method where the seeds move between vanes on a rotating impeller and impact on a fixed cylindrical ring. Makanjuola (1972) studied the bending properties of melon seeds when compressed between two parallel plates under static loading. During loading, the seeds deflected and the shell broke due to bending. On further application of loading, the cotyledon broke. Depending on the breadthwise and lengthwise orientations under the load, seeds broke longitudinally and transversely respectively.

During tests on the shelling of melon seeds, Odigboh (1979) found that the percentages of broken seeds were 14.24%–24.93% for unwetted seeds and 8.64%–17.05% for wetted seeds. The percentage of breakage was considered too high since any mechanical damage to shelled melon seeds would predispose them to deterioration especially acidification, and the broken seeds were highly susceptible to mould deterioration in storage. The broken seeds also lead to lower market value. Egbuta and Uyah (2003) in a 2^3 factorial experiment found that with a high speed and small diameter impeller, the number of broken shelled seeds was five times greater than that with a low speed and large impeller diameter.

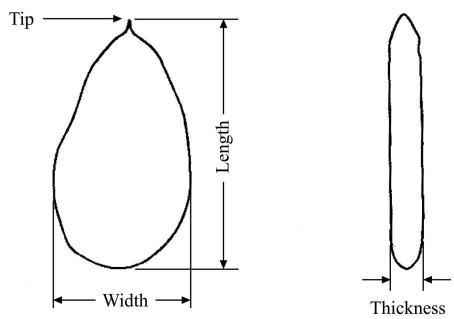

Figure 1 Principal dimensions of melon seed

Akpan (2004) found that the average forces required to crack melon seed shell of 8.3% wet basis moisture

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content (mc w.b.) between two parallel plates were 9.9×10^{-3} N, 11.6×10^{-3} N and 11.3×10^{-3} N according to the orientations of breadthwise, lengthwise with tip up and lengthwise with tip down respectively. The corresponding forces were 9.4×10^{-3} N, 17.2×10^{-3} N and 13.7×10^{-3} N at 17.8% (mc w.b.) and 8.31×10^{-3} N, 15.9×10^{-3} N and 13.7×10^{-3} N at 20.4% (mc w.b.) respectively. There was no significant effect of moisture content at 95% confidence level while significant differences were observed in the force at different orientations. Obot (2005) found that the forces to break whole melon seeds 8.2% (mc w.b) between parallel plates were 12.54×10^{-3} N, 18.92×10^{-3} N and 19.58×10^{-3} N at breadthwise, lengthwise with tip up and lengthwise with tip down orientations respectively.

This paper presents an analytical study to determine the factors affecting impact force between melon seeds and the cylindrical ring of impeller type shelling machine. Experimental data were obtained to verify the analysis result.

2 Theory

2.1 Propagation of waves in solid media

A bar of length ℓ is considered with a fixed end struck by a rigid mass M at the other end. The velocity of the body at the instant of impact is V_0. A uniformly distributed compressive stress is suddenly applied to the free end of the bar. It will produce, in the first instant, a uniform compression of an infinitely thin layer at the end of the bar. This compression will be transmitted to the adjacent layer and so on. A wave of compression begins to travel along the bar with a wave-front velocity c (Timoshenko and Goodier, 1970). The instantaneous compressive stress (σ_0) at the free end of the bar is (Juvinall, 1967):

$$\sigma_0 = V_0\sqrt{E\rho} \tag{1}$$

Where: E is the Young's Modulus of Elasticity of the bar (N/m^2) and ρ is the density (kg/m^3) of the bar. Owing to the resistance of the bar, the compressive stress diminishes as it travels along the length of the bar. Denoting by σ the variable compressive stress of the free end of the bar, υ the variable velocity of the body and A the cross-section area of the bar, the equation of motion is in the form:

$$\frac{Mdv}{dt} + A\sigma = 0 \tag{2}$$

It is found that the variable velocity of the particles is proportional to the variable compressive stress (Timoshenko and Goodier, 1970), hence,

$$V = \frac{\sigma}{\sqrt{E\rho}} \tag{3}$$

Substituting for V in equation (2)

$$\frac{M}{\sqrt{E\rho}}\frac{d\sigma}{dt} + A\sigma = 0 \tag{4}$$

The solution for which is

$$\sigma = \sigma_0 \exp(-At\sqrt{E\rho}/M) \tag{5}$$

This equation is valid for 0 < $0 < t < \frac{2\ell}{c}$, as the compression stress wave reaches the fixed end of the bar where there is no motion, it is reflected as a second wave entirely unchanged. Hence the time for the wave to travel back to the free end of the bar is t = 2 ℓ /c .

At yield point of the bar (Juvinall, 1967):

$$F = \sigma A \tag{6}$$

where F is the equivalent static force to break the bar.

Substituting equations (1) and (6) into (5):

$$F = V_0\sqrt{E\rho}\ A\exp(-At\sqrt{E\rho}/M) \tag{7}$$

Assuming that the time t for the wave to travel the length of the bar is

$$t = \frac{\ell}{c} \tag{8}$$

where ℓ is the length of the bar in meter, c is the wave-front velocity in the bar ($\sqrt{E/\rho}$)

But $\ell\rho A$ = mass of the bar, m kg

$$\therefore F = V_0\sqrt{E\rho}\ A\exp\left(-\frac{m}{M}\right) \tag{9}$$

Hence the equivalent static force (F) to break the bar is found to be proportional to the product of the initial velocity of the body at impact (V_0) and the cross-section area of the bar (A), since E, ρ, m are properties of the bar and are deemed constant. M is the mass of the body and is constant.

2.2 Dynamics of the mechanical shelling of melon seeds

Melon seeds were fed into a rotating impeller with vanes and were confined to move between the vanes predictably flat-down. It is difficult to predict the path of the seeds within the vanes and the orientation of the seeds during impact. A schematic diagram of the motion of a seed in a rotating impeller with vanes is shown in Figure 2 (see Appendix). The seeds emerged from the impeller with a velocity impacting a fixed cylindrical ring, breaking the melon seed shell to release the cotyledon.

The exit velocity of the seeds from the impeller (see Appendix for details) is∴

$$V = \omega\sqrt{r^2 - b^2} \text{ m/s} \quad (10)$$

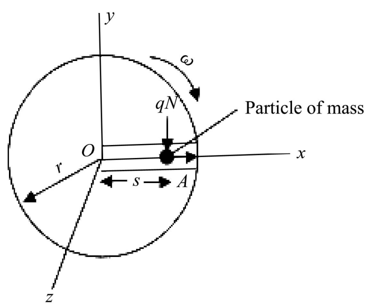

Figure 2 Schematic diagram of the motion of a particle on a slotted disc

Assume a particle of mass m moving along the slot OA in a rotating disc of radius r at ω radians/sec (Figure 2). The only force acting on the particle by the walls of the slot is q N. Let the particle be a distance s from the center of the disc. The acceleration $\vec{a}$ of the particle is:

$$\vec{a} = \vec{a}_0 + \vec{\omega} \times (\vec{\omega} \times \vec{s}) + \dot{\vec{\omega}} \times \vec{s} + \ddot{\vec{s}} + 2\vec{\omega} \times \dot{\vec{s}} \quad (1)$$

Since the disc is fixed,

$$\vec{a}_0 = \dot{\vec{\omega}} = 0$$

And expressing in unit vectors, $\vec{i}, \vec{j}, \vec{k}$

$$\vec{\omega} = -\omega\vec{k};\ \ddot{\vec{s}} = \ddot{s}\vec{i} \text{ and } \dot{\vec{s}} = \dot{s}\vec{i}$$

And noting that,

$$\vec{\omega} \times (\vec{\omega} \times \vec{s}) = -\omega\vec{k} \times (-\omega\vec{k} \times s\vec{i}) = -s\omega^2\vec{i}$$

And

$$2\vec{\omega} \times \dot{\vec{s}} = -2\omega\vec{k} \times \dot{s}\vec{i} = -2\omega\dot{s}\vec{j}$$

Then Equation (A.(1)) becomes

$$\vec{a} = -s\omega^2\vec{i} + \ddot{s}\vec{i} - 2\omega\dot{s}\vec{j} \quad (2)$$

Since force = m × $\vec{a}$

$$-q\,\vec{j} = m\left[\left(\ddot{s} - s\omega^2\right)\vec{i} - 2\omega\,\dot{s}\,\vec{j}\right] \quad (3)$$

Equating forces on the system

$$\ddot{s} - s\omega^2 = 0 \quad (4)$$

But $\ddot{s} = \dot{s}\dfrac{d\dot{s}}{ds}$

$$\therefore \dot{s}\frac{d\dot{s}}{ds} = s\omega^2 \quad (5)$$

Integrating Equation (A.(5)) and assuming that the seeds are released at a distance b from the center with negligible initial velocity,

$$\int \dot{s}\,d\dot{s} = \omega^2 \int_b^r s\,ds$$

$$\frac{1}{2}\dot{s}^2 = \frac{\omega^2}{2}(r^2 - b^2)$$

$$\dot{s} = \omega\sqrt{r^2 - b^2} \quad (6)$$

From Equation (A.(6)), the exit velocity of the seed from the impeller is

$$V = \omega\sqrt{r^2 - b^2} \quad (7)$$

2.3 Momentum and impact of melon seeds

The total momentum is unchanged (Bull, 1966) and destroyed during impact. The total momentum of the system before impact can be expressed by the mass of the seed (m) and the exit velocity (*V*).

Let *V** represent the equivalent velocity of the ring that would give a momentum equal to the momentum of the system in which the seed is fixed and the cylinder is in motion. Therefore

$$MV^* = mV \quad (11)$$

Where *M* is the mass of the ring impacting the seed.

$$\therefore V^* = Vm / M \quad (12)$$

Hence the velocity of the ring is proportional to the mass ratio (m/M)

2.4 Model equation

Combination of Equation (9), (10) and (12), from Equation (9) where *V** is substituted for V_0 gives

$$\therefore F = \sqrt{E\rho}\, V^* A \exp\left(-\frac{m}{M}\right) \quad (13)$$

Substituting Equation (10) and (12) and b = 0

$$F = \sqrt{E\rho}\,\frac{m}{M}\,\omega\, rA \exp\left(-\frac{m}{M}\right) \quad (14)$$

Since the mass ratio m/M is very small, exp (-m/M) ≈ 1

$$\therefore F = \sqrt{E\rho}\,\frac{m}{M}\,\omega rA \quad (15)$$

The equivalent static force to break whole melon seeds in an impeller-type shelling machine is proportional to the product of the impeller rotational speed (*ω*), impeller radius (*r*), seed cross-section area (A) at impact and the mass ratio m/M. The Young's modulus of elasticity (E) and density (ρ) of the seed are constant and show similar characteristics as other agricultural materials (Lewis, 1987).

3 Materials and methods

3.1 Materials

Melon seeds were sorted to obtain clean seeds. The moisture content of the sample was determined using the oven drying method as recommended by ASAE, 1982. Fifty seeds were randomly selected and weighted to obtain the average mass of each seed.

3.2 Procedure

3.2.1 Compression test

Forty seeds were randomly selected and the length, width and thickness of each seed were measured. Each seed was compressed between two parallel plates in a rig until the seed broke after bending. The force exerted when the seed broke was measured with a sensitive spring gauge (Type, Manufacturer). The seeds were placed breadthwise, lengthwise with tip up and lengthwise with the tip down between the plates.

3.2.2 Experimental shelling tests

Two hundred seeds were randomly chosen and fed into an experimental shelling machine to determine the effects of four combinations of the radius and the speed of impeller on the number of broken seeds. The machine consisted of a rotating impeller with vanes centrally positioned on a drive shaft within a cylindrical ring of Ø314 mm internal diameter, 4 mm thickness, 127 mm height and 2.44 kg weight formed from mild steel plate. The shaft was driven by a V belt from a 0.55 kW motor. The parameters were adjusted to 115 mm radius and 1,425 min^{-1} speed; 135 mm radius and 1,425 min^{-1} speed, 115 mm radius and 2,850 min^{-1} speed; and 135 mm radius and 2,850 min^{-1} speed. The number of broken seeds was counted and output was classified into groups of shelled but broken and unshelled and broken seeds. The tests were run in three repetitions.

4 Results

The moisture content of the melon seeds during the experiment was 8.7% (w.b.) and the average mass of the seeds was 0.11 g with standard deviation of 0.012 g.

4.1 Factors affecting the impact force

Equation 15 shows the relationship between the static breaking force F, modulus of elasticity of the melon seed E, density of melon seed ρ, mass of the melon seed m, mass of the cylindrical ring M, impeller rotational speed ω, impeller radius r and the seed cross-section area A.

4.2 Equivalent static breaking force

Values of the equivalent static force and the seed cross-sectional areas at three orientations are shown in Table 1.

Table 1 Static breaking forces of melon seeds at three orientations

Orientation	Cross section area/ 10^{-6} m^2			Force/10^{-3} N		
	Range	Mean	SD	Range	Mean	SD
Breadthwise	19.5-32.0	26.61	2.90	11.30-15.00	13.14	1.10
Lengthwise, tip up	13.4-23.0	16.35	2.56	16.75-22.30	19.62	1.45
Lengthwise, tip down	11.5-20.9	16.41	2.20	17.80-21.50	19.55	1.10

The static breaking force was in the range of 11.30×10^{-3} N –15.00×10^{-3} N with the mean of 13.14×10^{-3} N for breadthwise orientation. In the lengthwise orientation with the tip up, the breaking force was in the range 16.75×10^{-3} N – 22.30×10^{-3} N with the mean of 19.62×10^{-3} N. The breaking force for the lengthwise orientations with the tip down were in the range of 17.8×10^{-3} N – 21.5×10^{-3} N with mean of 19.55×10^{-3} N. The force required to break seeds at both lengthwise orientations were found to be about one and a half times greater than at the breadthwise orientation.

4.3 Quality of broken melon seeds

The amount of shelled but broken seeds and unshelled and broken seeds at different impeller radii and speeds are shown in Table 2. Results for three repetitions and mean values are presented.

Table 2 Quantity of broken melon seeds

Impeller Radius, Speed,		Shelled but broken seeds/%				Unshelled and broken seeds/%			
Mm	r • min^{-1}	No. 1	No. 2	No. 3	Mean	No. 1	No. 2	No. 3	Mean
115	1,425	6.0	6.0	7.5	6.5	2.0	2.0	2.0	2.0
135	1,425	43.0	49.0	46.5	46.2	2.5	4.5	4.5	3.8
115	2,850	49.5	51.0	51.0	50.0	7.5	9.0	9.5	8.0
135	2,850	82.8	83.5	84.0	83.3	5.5	5.0	4.5	5.0

At the radius of 115 mm and speed of 1,425 r/min the mean percentages of shelled but broken seed was 6.5%, unshelled and broken seed was 2.0%. At 135 mm radius and 1,425 r/min, speed, the mean percentages of shelled but broken seed was 46.2%, unshelled and broken seed was 3.8%. At radius 115 mm and speed 2,850 r/min, the values are 50.0% and 8% respectively. At radius 135 mm and speed 2,850 r/min, the mean percentages of shelled but broken seed was 83.3%, unshelled and broken seed was 5.0%.

5 Discussion

The impact force between the seed and the cylindrical ring was affected by the impeller radius, the impeller rotational speed, the seed cross-section area and the mass ratio. Increasing the impeller radius from 115 mm to 135 mm at the impeller speed of 1,425 r/min, the observed quantity of shelled but broken seeds and unshelled and broken seeds also increased from 6.5% to 46.2% and from 2.0% to 3.8%. The amount of shelled but broken seeds increased to seven times higher value while the quantity of unshelled and broken seeds was doubled.

When the speed is doubled to 2,850 r/min and the radius at 115 mm, the amount of shelled but broken seeds increased to eight times higher value while unshelled and broken seeds increased to four times higher value. With an impeller radius of 135 mm and speed 2,850 mm^{-1} the quantity of shelled but broken seeds increased by 13 times higher value while unshelled and broken seeds increased to two and a half times higher value. The cross-section area depends on the orientation of the seed during impact. If the seeds impact the ring at breadthwise orientation, the cross-section area during impact will be higher than during the lengthwise orientations. The orientation of the seeds cannot be determined since it is difficult to predict accurately the path of the seeds within the slot as their motion is bound to be random considering the possibility of multiple impacts (Odigboh, 1979).

The results show that the mean force required to break seeds at both lengthwise orientations are equal but the values are one and a half times greater than that at breadthwise orientation. Hence melon seeds impacting the cylindrical ring with the edge or side are more likely to be broken. The mass ratio, which is the ratio of the mass of the seed to the mass of the cylindrical ring in a machine, was assumed constant. The average mass of the two varieties of melon seed at storage moisture content range is from 0.056 g to 0.16 g (Makanjuola, 1972; Odigboh, 1979; Isiaka et al., 2006). The variation in the average mass of melon seeds is negligible when compared to the mass of the cylindrical ring. Hence the findings show that the main factor affecting the impact force is the product of the impeller radius and rotational speed.

In an impeller – type shelling machine, seeds are broken when the impact force between the seed and the cylindrical ring is greater than the range of force obtained by static loading at a particular orientation. This implies that the percentage of broken seeds during shelling is affected by the product of the impeller radius and speed, while depending on the orientations of the seed during impact.

6 Conclusions

The model equation obtained through analysis has identified four factors that could affect the quality of broken melon seeds during shelling in an impeller – a type shelling machine:

1) the impeller radius
2) the impeller rotational speed

3) the seed cross-sectional area
4) the mass ratio of the seed mass and cylindrical ring mass

However the product of the impeller radius and the rotational speed was found to be the main factor affecting the percentage of broken seeds.

The analysis was based on the assumption that the stress throughout the seeds was uniform, although whenever an actual impact occurred, the stress was seldom uniform across the cross-section area (Juvinall, 1967). The full amount of energy was never transmitted because of friction between striking surfaces. Melon seeds were viscoelastic in behavior, exhibiting both elastic and viscous effects under stress. Hence the actual developed stress could differ from the analytically developed stress.

Nomenclature

ℓ length of bar, m

ρ density of the bar, kg/m^3

A Cross section area of the bar, m^2

M Rigid mass, kg

σ_0 instant comprehensive stress, N/m^2

σ Variable compressive stress N/m^2

E Young's modulus of elasticity, N/m^2

c wave-front velocity, m/s

v variable velocity of the body, m/s

V_0 initial velocity of rigid mass, m/s

V^* equivalent velocity of the ring, m/s

V exit velocity of the seed, m/s

a acceleration of the particle, m/s^2

a_0 acceleration of the disc, m/s^2

ω angular velocity of the disc, rad/s

S distant of the seed, m

r radius of the disc, m

q force acting on the particle, N

F equivalent static force, N

m mass of the seed, kg

t compressive wave travel time, s

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