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DETERMINING THE COEFFICIENT OF RESTITUTION OF APPLES AT DIFFERENT IMPACT VELOCITIES

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Summary. In the article nonlinearly decreasing relationship between the coefficient of restitution and impact velocity for three apple varieties was determined. In addition there was performed an attempt connecting the coefficient of restitution as well as other parameters characterizing impact course such as: impact velocity, rebound velocity, impact energy, rebound energy and absorbed energy during impact with bruise quantity of apples. The bruise quantity was established through measurement of apple contact surface area as a result of impact on rigid, flat and fixed plane.

Key words: coefficient of restitution, apple, bruise, impact, velocity, energy

INTRODUCTION

The coefficient of restitution *e* is defined most often as the quotient of rebound velocity to impact velocity or the quotient of square root of kinetic energy body after and before a collision. It is usually a measure of kinetic energy losses during an impact and found application in many impact studies as a parameter describing the extent of elasticity or plasticity of a given body. McGlone [McGlone *et al.* 1997a], on the basis of impact force course measurements during two consecutive rebounds, determined the coefficient of restitution which he next used to determine kiwi fruit mass. This method served to assess impact centrality and increase firmness assessment accuracy determined on the basis of impact force course measurements using alteration including mass influence. Meredith [Meredith *et al.* 1990] correlated the coefficient of restitution with maximum value of impact response force being a measure of peach firmness. Next, he tried to use this relationship to create a method which in a direct, fast and non-destructive way would enable to assess the state of fruit on sort lines. LoCourto [LoCourto *et al.* 1997] studied soya beans coefficient of restitution impacting them on three materials: aluminium, glass and acrylic at three drop heights and at two moisture content levels. He stated the decrease of the coefficient of restitution with the growth of moisture content and its constancy depending on impact velocity in the subjected range of drop height corresponding to impact velocities from 1,7 to 3,2 $m \cdot s^{-1}$. The measured coefficient of restitution values were next used as input data to algorithms describing the behaviour of a single soya bean during the rebound. Rataj [Rataj *et al.* 1999] determined the variability of the coefficient of restitution of chickpea seeds defined as the square root of quotient of rebound height and drop height depending on their moisture content. Gan-Mor [Gan-Mor & Galili 2000] took up the development of a model describing the collision of viscoelastic product with an elastic plate. The studies were aimed at separating stones from potatoes during a mechanical harvest. The impact energy of stones was absorbed by elastic plate and as a result the coefficient of restitution decreased. The decrease of stones coefficient of restitution was sufficient to enable their separating from potatoes. The final effect was the design of a machine for separating stones and ground from potatoes. Van linden [Van linden *et al.* 2006] determined the parameters influencing the bruising of tomatoes as a result of mechanical impact. One of them was the coefficient of restitution. He obtained the negative correlation r= -0,36 between bruise susceptibility and the coefficient of restitution. Dintwa [Dintwa *et al.* 2008], in order to assess the absorbed energy value during apple impact, determined the coefficient of restitution at different impact velocities. Next he defined three various forms of the coefficient of restitution so as to establish energy losses developed as a result of action of elastic oscillation and losses caused by the influence of viscous properties. That allowed the determination of viscoelastic properties of apples and quality assessment of fruit bruise through the measurement of absorbed energy during the impact.

Often a simplifying assumption was made, that the coefficient of restitution is constant and depends only on material kind of colliding bodies. However, more insightful studies showed, that it is dependant on elastic properties, dimensions and velocity values of the investigated bodies participating in the collision. You can distinguish three mechanisms of body energy loss during the collision, which cause that the coefficient of restitution is less than 1:

1) Bodies oscillations initiated by the impact. Also vibrations of surrounding air contribute (to a small extent) to losses.
2) Energy losses because of plastic deformations or bodies cracking in the case when the maximum stress created in bodies during the impact exceeds the yield point.
3) Dispersion energy connected with viscoelastic properties of colliding bodies, which occurs below plastic deformations. This mechanism of energy dispersion is often modelled through parallel connection of a spring and a dashpot.

The aim of the researches was the determination of the coefficient of restitution depending on impact velocity in apples. In addition, there was performed an attempt to connect the coefficient of restitution and other parameters characterizing impact course such as: impact velocity, rebound velocity, impact energy, rebound energy as well as the energy absorbed during impact with bruise quantity of apples. The bruise quantity was established through measurement of apple contact surface area, which develops as a result of the impact on the rigid, flat and fixed plane.

MEASURING STAND

The pendulum principle was used at the measuring stand for impact tests and an apple was the striking element. The pendulum consisted of a pair of supported fishing line each 1m long to which a plastic plate with two tangs was fixed. An apple was fixed to the pendulum by the tangs. A titanium plate of a small mass and high stiffness was screwed into a sliding case, which next, by means of a clamp connection, made one whole with a thick steel plate fixed permanently to a concrete wall. The sliding case and the clamp-joint made it possible to arrange the fruit (fixed to the pendulum) in a vertical position to the plate at the impact moment, thereby the perpendicular direction of the impact force to the impact surface was obtained. The stand was also equipped with control screws which allowed to arrange a girder (the pendulum rotation axis) in a position in which the impact force went through the center of the fruit mass. In that way the central collision conditions in the force sensor axis were met. An apple was placed at a requested drop height and remained there by means of a suction pump. When the pump was turned off the fruit was released.

MATERIAL AND RESEARCH METHOD

The subject of the studies were Rubin, Jester and Freedom apples varieties. The measurements were carried out in October 2008. After the harvest the fruit was stored in a cold room and carried to the room with the temperature of 20°C a day before the research. To eliminate the influence of fruit size (curvature radius) only the apples of mass from 185g to 190 g were chosen for researches. An additional selection was carried out through testing the maximum apple diameter on calibrator. It could not be smaller than 80 mm and larger than 85 mm. On the basis of the preliminary studies it was stated that the changes of the coefficient of restitution values are the highest for small impact velocities. Hence the measurements were performed at velocities which created the decreasing geometrical progression with the quotient 2/3. The maximum impact velocity obtained at the measurement stand amounted to 1,5 $m \cdot s^{-1}$ and it was at the same time the first term of geometrical progression. Thus the measurements were carried out at the following velocities: 1,5; 1; 0,66; 0,44; 0,3; 0,2 $m \cdot s^{-1}$. Thereby, a higher variability of the coefficient of restitution course was achieved for small velocities, which enabled to determine more accurately the coefficient of restitution course. The drop height was determined by means of a scale with plotted quantities corresponding to the specified impact velocities.

For each variety 20 apples were tested. Each apple was hit 6 times, which corresponded to the assumed number of different impact velocities. After each impact, the fruit was turned 30° around the vertical axis going through the calyx and the floral bottom. Thereby, an apple at each drop struck its unbruised part on the flat surface.

The velocity measurement took place owing to two pairs of diodes placed opposite each other and positioned at a distance of 15 mm from each other. The diodes emitted two light beams which were hidden at drop and revealed at rebound. As a result, the diodes connected to the TDS 1002B Tektronik company digital oscilloscope released a vertically increasing and decreasing signal, appropriately. Using additionally Open Choice communication program it could be determined what time was covered by an apple in the investigated distance of 15 mm during the drop and the rebound. While determining the velocity value, simplifying assumptions were made, namely that an apple moved along the straight-line at a constant velocity. The length of the pendulum arm was 1m and was much larger than the distance between the diodes amounting to 15 mm. Hence, it could be assumed, that the arc length at such a short distance was a straight line. The diodes were placed so as the second diodes pair occurred just before the impact plane, which caused that at the moment of the impact the pendulum arm had a vertical position. At small angles of the pendulum arm deviation from the vertical position, the changes of tangent acceleration were small and at the very vertical position the tangent acceleration was 0. Therefore, it was also assumed that an apple in the investigated segment of 15 mm moved at a constant velocity.

The measurements aimed at the determination of apple bruise size at different velocities were also carried out. The studies were performed on Rubin apples variety doing 10 repetitions for each recorded velocity values. Before the impact on the area of an expected apple bruise, the diluted water latex paint was applied to determine the surface area of the impact contact. The contact surface was calculated by means of the formula for the ellipse surface area:

$$P = \pi ab, \qquad (1)$$

where: a, b – are the radiuses of the major and minor of the ellipse axes.

RESULTS AND DISCUSSION

On the basis of the carried out impact tests nonlinear decreasing relationship between the coefficient of restitution and the impact velocity was obtained (Fig. 1.). The highest increase of the coefficient of restitution values occurred for lower impact velocity values. Soft apples (Jester and Rubin varieties) had a higher value of the coefficient of restitution than hard apples (Freedom variety), amounting to 0,6 for the highest impact velocity 1,5 $m \cdot s^{-1}$. For the hard apples, the coefficient of restitution for the same impact velocity amounted to 0,55.

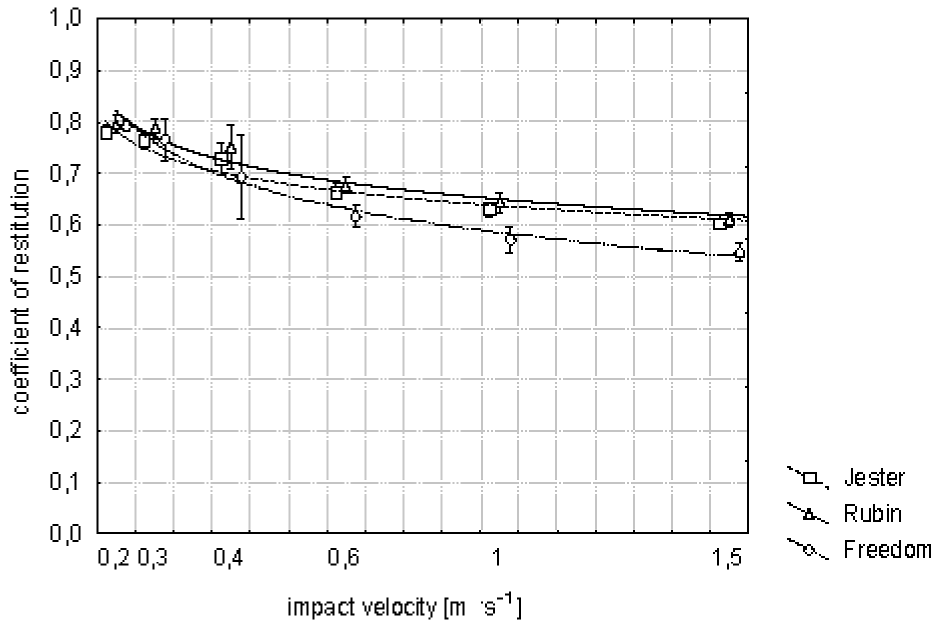

Fig. 1. The relationship between the coefficient of restitution and impact velocity for three apple varieties

It can be seen, that at higher impact velocities apples with harder flesh are more susceptible to bruises. Additionally, it was noticed, that for each variety for the impact velocity amounting to 0,4 $m \cdot s^{-1}$ occurs a large value of standard deviation of the coefficient of restitution. It confirms the supposition, that for the impact velocity being close to 0,4 $m \cdot s^{-1}$, there exists the value of an apple yield point. A wide range of the coefficient of restitution values results from the fact that one part of the apples during the impact deforms elastically which corresponds to the high coefficient of restitution values and another part of the apples obtain irreversible deformations causing the lower coefficient of restitution values. Certainly, this is an approximate way of the yield point determination, because it requires an increase of measurement point numbers in an expected velocity range as well as including the impacted fruit mass [McGlone *et al.* 1997b; Stropek & Gołacki 2007].

In the case of Rubin variety during the impact tests there was also measured an apple contact surface area with the flat, rigid surface being the measure of fruit bruise size. Next, bruise surface area values were correlated with different parameters characterizing the impact such as: impact velocity, rebound velocity, impact energy, rebound energy, absorbed energy during impact and the coefficient of restitution.

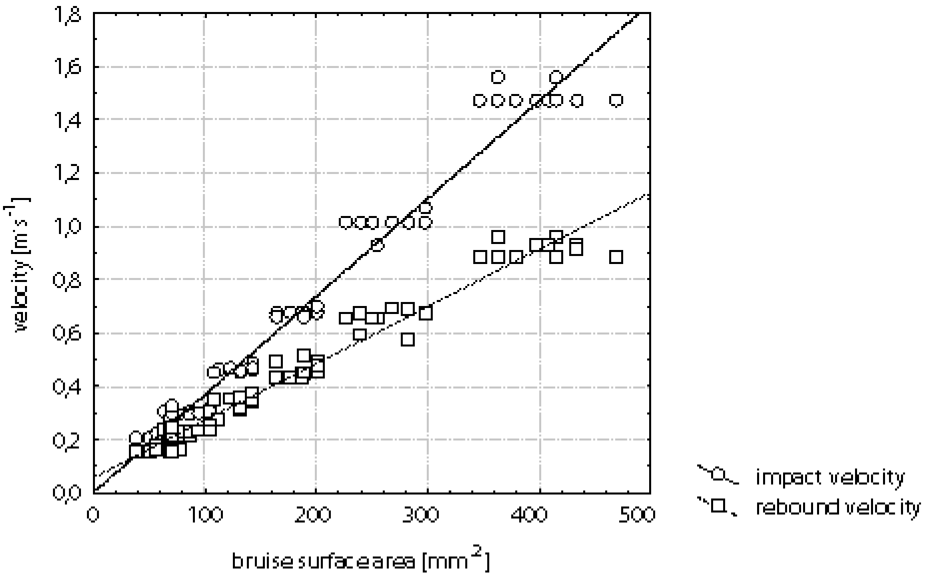

Fig. 2. The relationship between impact velocity, rebound velocity and bruise surface area for Rubin variety apples

Table 1. The correlation coefficients between apples' bruise surface area and quantities characterizing impact

	Impact velocity	Rebound velocity	Impact energy	Rebound energy	Absorbed energy	Coefficient of restitution
Bruise surface area	0,98	0,98	0,96	0,97	0,95	-0,80

High correlation coefficient values at the significance level lower than 0,05 were obtained. The correlation coefficient values between the individual quantities were showed in Table 1.

Even though the highest correlation coefficient values for impact velocity and rebound velocity were obtained, it seems that better parameters characterizing apple bruise during the impact will be: impact energy, rebound energy and absorbed energy during impact because these values additionally include the influence of impacted fruit mass [Brusewitz & Bartsch 1989]. During those studies apple mass was nearly the same on account of the established experimental assumptions, which was explained at the beginning of the article.

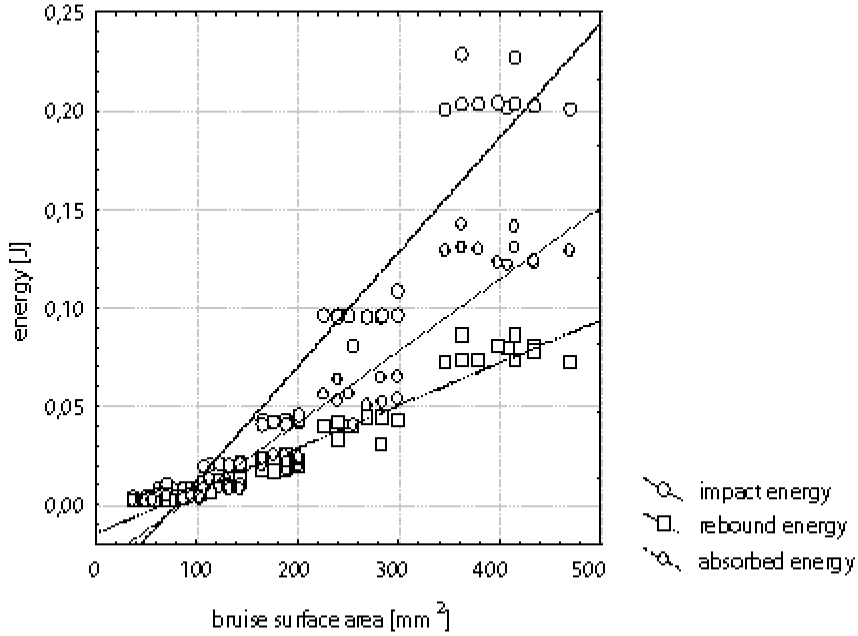

Fig. 3. The relationship between impact energy, rebound energy as well as energy absorbed during impact and bruise surface area for Rubin variety apples

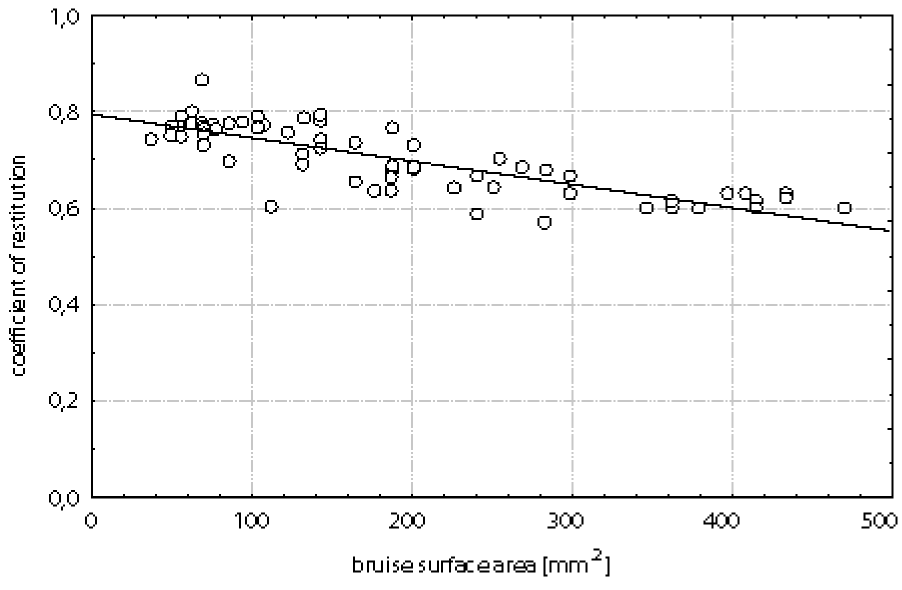

Fig. 4. The relationship between coefficient of restitution and bruise surface area for Rubin variety apples

CONCLUSIONS

The coefficient of restitution of apple decreased in a nonlinear way depending on impact velocity, moreover the highest increase of the coefficient of restitution values occurred for lower impact velocity values. The coefficient of restitution had values from 0,55 to 0,8 for specific apples varieties in the studied velocity range.

Depending on apple variety there were stated differences of the coefficient of restitution value for apples with hard and soft flesh at the highest impact velocity amounting to 1,5 $m \cdot s^{-1}$. It shows larger bruise susceptibility of apples with harder flesh at higher impact velocity.

The determination of the coefficient of restitution course depending on impact velocity enables to approximately establish the yield point area

High correlation coefficients were obtained describing the relationship between bruise surface area and impact parameters such as: impact velocity, rebound velocity, impact energy, rebound energy, absorbed energy during impact and the coefficient of restitution.

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WYZNACZANIE WSPÓŁCZYNNIKA RESTYTUCJI JABŁEK PRZY RÓŻNYCH PRĘDKOŚCIACH UDARU

Streszczenie. W artykule wyznaczono nieliniowo malejącą zależność współczynnika restytucji od prędkości uderzenia dla trzech odmian jabłek. Dodatkowo dokonano próby powiązania współczynnika restytucji oraz innych parametrów charakteryzujących przebieg uderzenia takich jak: prędkość uderzenia, prędkość odbicia, energia uderzenia, energia odbicia oraz energia pochłonięta podczas uderzenia z wielkością obicia jabłek określaną poprzez pomiar pola powierzchni styku jabłka w wyniku uderzenia o sztywną, płaską, nieruchomą płaszczyznę.

Słowa kluczowe: współczynnik restytucji, jabłko, obicie, uderzenie, prędkość, energia