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INFLUENCE OF IMPACT VELOCITY AND MOISTURE CONTENT ON MECHANICAL DAMAGES OF WHITE KIDNEY BEANS UNDER LOADINGS

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ABSTRACT - Kidney beans are more susceptible to breakage under impact loading during harvesting and processing. This problem limited the mechanical harvesting. Mechanical damage decreased the commercial values of seeds. It also decreased the biological values of seeds. Improper harvesting of beans during harvesting may also result in severe seed vigour loss. The objective of this study was to study the effect of impact velocity (at 5, 7.5, 10, and 12 m/s) and beans moisture content (at 5, 10, 15 and 20% wet basis) on percentage of physically damaged beans. The device of assessing the impact damage was used to conduct the tests. All the tests were conducted in laboratory conditions at about 25 ^{o}C and 50% relative humidity. The results showed that impact velocity and moisture content significantly influenced the physical damages of kidney beans at 1% and 5% significant level, respectively. Increasing the impact velocity from 5 to 12 m/s caused an increase in the mean percent of physical damages from 3.25 to 37.5%. The corresponding data for beans at the moisture content of 5% were from 3.7% to 45.7%. With increasing the moisture content from 5 to 15%, the mean values of percentage of damaged beans decreased by 1.4 times. However, with higher increase in the moisture content from 15 to 20%, the mean values of physically damaged beans showed a non-significant increasing trend. The relationship between the percent of physical damage with impact velocity and beans moisture content was expressed mathematically. It was found that the model has provided satisfactory results over the whole set of values for the dependent variable.

Key words: modelling, kidney bean, mechanical damage, impact, harvesting

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REZUMAT – Influența vitezei de impact şi a umidității asupra deteriorării boabelor de fasole, în condițiile recoltării şi procesării. Boabele de fasole sunt mai sensibile la spargere, în condițiile recoltării şi procesării. Această problemă a dus la utilizarea limitată a recoltării mecanice a boabelor de fasole. Deteriorarea mecanică a scăzut valoarea comercială a boabelor, precum şi valoarea lor biologică. Recoltarea în condiții necorespunzătoare a boabelor de fasole poate duce la pierderi semnificative ale vigorii seminței. Scopul acestei cercetări a fost studiul efectului vitezei de impact (la 5, 7.5, 10 şi 12 m/s) şi a umidității din boabe (la 5, 10, 15 şi 20% umiditate) asupra procentului de boabe de fasole deteriorate. Pentru realizarea experiențelor, s-a folosit o metodă de evaluare a daunelor. Toate experiențele au fost realizate, în condiții de laborator, la temperatura de 25 grade şi umiditatea relativă de 50%. Rezultatele au arătat că viteza de impact şi umiditatea au influențat semnificativ (1% şi, respectiv, 5%) deteriorarea boabelor de fasole. Creşterea vitezei de impact de la 5 la 12 m/s a dus la o creştere medie a deteriorării boabelor, de la 3.25 la 37.5%. Datele corespunzătoare boabelor de fasole, la umiditatea de 5%, au fost de 3.7% - 45.7%. O dată cu creşterea umidității de la 5 la 15%, valoarea medie a procentului de boabe deteriorate a scăzut de 1,4 ori. Totuşi, datorită creşterii umidității de la 15 la 20%, s-a observat o tendință de creştere nesemnificativă a valorilor medii ale deteriorării boabelor. S-a stabilit matematic valoarea corelației dintre procentul de boabe deteriorate, datorită vitezei de impact, şi umiditatea din boabe. Modelul a oferit rezultate satisfăcătoare asupra întregului set de valori ale variabilei dependente.

Cuvinte cheie: modelare, boabe de fasole, deteriorare mecanică, impact, recoltare

INTRODUCTION

Legumes, such as common bean (*Phasaeolus vulgaris*), widely grown and consumed throughout the world, are excellent sources of proteins (20-25%) and carbohydrates (50-60%) and good sources of minerals and vitamins (Aykroyd and Doughty, 1977). Legumes are a major food source for both human and animals, due to their nutritional benefits, such as high content in fibres and low content in fats, as well as being a cheap source of high protein content (Muzquiz et al., 1999; Sathe, 2002). The kidney beans are consumed as dry beans. Legumes can be used as a substitute for expensive animal protein in human diets. They are also being used as part of the dietary treatment of diabetes (Jenkins et al., 1981; Thorne et al., 1983; Shehata et al., 1988). However, the high labour costs for harvesting the kidney beans are the main reason of the limitation in planting this crop. Kidney beans are more susceptible to breakage under impact loading, during harvesting and processing. This problem limited its mechanical harvesting.

During threshing, beans suffer significant mechanical damages, especially at the threshing stage when seeds undergo numerous impacts against the steel elements of threshing units. The consequence of those impacts is broken seeds and cracks, as well as invisible internal damages. The mechanical damage decreases the commercial values of seeds. It also decreases the biological values of seeds. The principal effect of the negative influence of the mechanical damage is the reduction of germination and yields (Grass and Tourkmani, 1999). This is a serious problem for seed production (Grass and Tourkmani, 1999).

The structure of threshing damage depends not only on the design characteristics of the threshing unit and its operating parameters, but also on the mechanical properties of the tested plant. The mechanical resistance of seeds to the impact of loading, among other mechanical and physical properties, plays a very important role in the design of harvesting and processing machine (Baryeh, 2002). The value of this basic information is not only important to engineers but also to food scientists, processors and other scientists who may exploit these properties and find new uses.

Researchers have used different methods to conduct impact tests on grains and seeds, like centrifugal impactor, pendulum impacting device and freefall test method (Ptasznik et al., 1995; LoCurto et al. 1997; Cooke and Dickens, 1971; Baryeh, 2002; Hughes et al. 1985, Tennes et al., 1988; and Zapp et al., 1990; Allen and Watts, 1997). Bergen et al. (1993), in a study on peas and lentils, used the free fall test to determine the effects of moisture content and height of falling on the mechanical damages occurring in seeds. Seeds with lower moisture content incurred more damages. Picket (1973) measured the mechanical damage in soybean during harvesting for the combine cylinder speeds from 7.2 to 15.2 m/s and at moisture contents between 15.7% and 22.7%, dry basis. He found out that the grain damage increased consistently with increasing the cylinder speed and decreasing the moisture content.

The amount of physical and physiological damages in grains and seeds is a complex interaction involving some parameters, which affect the final quality of the materials. These parameters must be considered during harvesting and processing. These factors range from the seed moisture content, impact velocity, seed variety, seed size to the number of loading times on seed. Each of them may have varying degrees of effect on physical and physiological damages (Khazaei et al., 2007). This necessitates the use of the accurate automatic system to control the threshers, harvesters, conveyors and other process units. Automatic controlling is a necessity to minimize costs, more consistent product quality and to early warning of problems. Automatic controlling needs to have a more powerful prediction model to be able to model the effects of several independent variables on several dependent variables. During the last decades, various forms of multiple linear regression models have been widely considered to estimate the physical damages in seeds and grains (Baryeh, 2002; Sosnowski and Kuzniar, 1999).

As the literature indicates, there is little published work on studying the mechanical properties of kidney beans. This study was undertaken (1) to determine the effect of impact velocity and moisture content on the mechanical damage sustained by this variety of soybean seed during processing, (2) to build up a mathematical model to approximate a nonlinear function relating percentage of physical damage of kidney beans to impact velocity and moisture content and (3) to evaluate the predictive performance of the models.

MATERIALS AND METHODS

Kidney beans used in this study were obtained from a local market of Tehran, Iran. The initial moisture content of beans was measured by the oven drying method (Singh and Goswami, 1996). In this method, a sample of grain is weighed, dried in the oven at 80^{o}C overnight until the weight remains constant and it is reweighed. The difference between the two weights of the grain, divided by the initial grain weight, multiplied by 100, yields the grain moisture content on wet basis. The grain mass was measured using an electronic scale of 0.001 g sensitivity. The initial moisture content of the grain was about 5% (wet basis).

The assessment device of the impact damage is shown in *Figure 1*. It is composed of a frame, seed folder and an electromotor rotating a disc. The disc consisted of two or four impact tips, having a striking face of 3 cm wide, mounted on a disk, rotating in the vertical plane. The impact point moves through a path having a radius of 30 cm. The seed holder contains 15 beans- supporting pedestals, made of flexible plastic tubing. Beans were held on the pedestals by gravity. Moving the seed holder toward the impact tips was taking the beans against the impactor tips. Using this method, the kidney beans were impacted one-by-one by moving the supporting pedestals toward the impactor tips. A cloth bag behind the machine caught the impacted beans. The testing rig part is guarded on the sides by a removable, vertical 1.5 m thick cloth guard, to prevent grains from flying off during testing. The impact velocity of the tips was adjusted by changing the velocity of the electromotor through an inverter set. The inverter is used to control the rotational speed of electromotors.

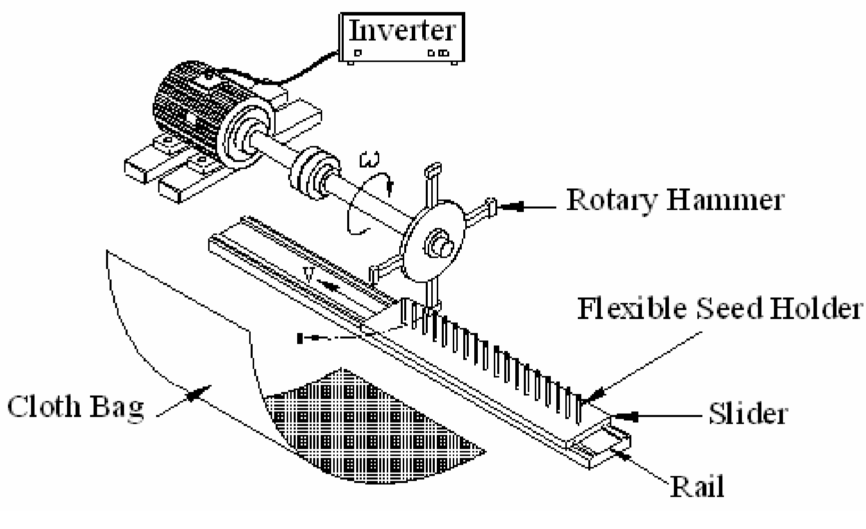

Fig. 1 - Schematic diagram of the impact device used in this study

The device was used to assess the impact damage on kidney beans. In this study, the effects of impact velocity (at 5, 7.5, 10, and 12 m/s) and moisture content (at 5, 10, 15 and 20% w.b.) were studied on percentage of physical damage in kidney beans. In this study, all the tests were conducted in laboratory conditions of about 25 ^{o}C and 50% relative humidity.

The selected impact velocities used in this study are in agreement with those happening in harvesters, separator, conveyors, storing system and other processing systems (Stout and Cheze, 1999). The effect of beans moisture content was investigated at the range of 5-20% wet basis, since processing and handling activities are performed in this moisture range. The kidney beans are harvested at about 25% dry basis moisture and dried to the desired moisture contents of 16% and 19% d.b. for safe module storage. Therefore, all the mechanical properties of beans were determined at five moisture contents in the range of 5% to 20% w.b. The factorial experiment was conducted as a randomized complete design with three replicates. Differences with $P < 0.05$ were considered meaningful and a least significant difference test ($P = 0.05$) was used as the basis of comparison between the treatment means.

The grains to be tested were initially at the moisture content of 5%. They were cleaned by a combination of manual and mechanical means to get rid of all foreign matter and broken and immature grains. The samples of the high moisture contents were prepared by adding the amount of distilled water as calculated from the following relation (Coskun et al., 2006):

$$Q = \frac{W_i (M_f - M_i)}{(100 - M_f)} \qquad (1)$$

Where Q is the amount of added water, g; W_i is the initial weight of the sample, g and M_f is the desired moisture content level, %.

The samples were then poured into separate polyethylene bags and the bags were sealed tightly. The samples were kept at 5^{o}C in a refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, the required quantity of beans was taken out of the refrigerator and allowed to equilibrate to the room temperature for about 2 hours (Singh and Goswami, 1996).

For each impact test, one hundred beans were used. The beans were impacted by using the impact device. After each test, the impacted seeds were sorted as physically damaged and undamaged seeds by visual inspection. The damaged seeds included broken seeds with visibly cracked seed coats and halves that were loosely held together.

RESULTS AND DISCUSSION

The data obtained from this study showed that the significant differences in the susceptibility of kidney beans to mechanical damages were revealed at different levels of moisture content and impact velocity. The analysis of the data variance (*Table 1*) indicated that impact velocity and moisture content significantly influenced the physical damages in kidney beans, at 1% and 5% significant level, respectively. Meanwhile, the interaction effects of the two variables were not significant for the physical damages of the beans. The results of Duncan's multiple range tests for comparing the mean values of the physical damage of beans are presented in *Table 2*.

Table 1 - Results of analyses of variance (Mean Square Error) for the percentage of physical damages in kidney beans

Variable	df	MS	F value
Model	15	625.2	15.2**
Moisture content (M)	3	164.4	4.01*
Impact velocity (V)	3	2848	69.4**
V*M	9	37.0	0.92ns
Error	32	41.0	

Table 2 - Effects of impact velocity and moisture content on the percentage of physical damages in lentil seeds

Independent variable	Physical damage (%)
Moisture content, (%)	
5	27.5A
10	24.75AB
15	18.92C
20	21.67BC
Impact velocity, (m/s)	
5	3.25D
7.5	19.08C
10	32.83B
12	37.5A

For each variable, the means followed by the same letter are not significantly different (P = 0.01).

It is evident that for all the levels of impact velocity, the differences between the mean values of the physical damaged seeds were significant (P=0.01). It was found that with increasing the impact velocity from 5 to 12 m/s, the mean value of damaged beans increased by 10.95 times. The corresponding values for increasing the impact velocity from 5 to 10 m/s, 5 to 7.5 m/s, 7.5 to 12 m/s, 7.5 to 10 m/s, and from 10 to 12 m/s were by 9.58, 5.57, 1.96, 1.72 and 1.14 times, respectively. Similar results have been reported by other researchers (Bartsch et al., 1986; Keller and Converse, 1972; Paulsen et al., 1981; Liu et al., 1990, Khazaei et al., 2002). Sosnowski (2006) reported that with increasing the impact velocity from 7 to 27 m/s, the mean value of damaged beans, Wiejska Variety, increased from about 0 to 35%. Keller et al. (1972) have also found that impact velocity, moisture content, impact surface, angle of impact and grain size have all significantly influenced the impact damage in maize kernels.

Figure 2 reveals that at all the considered moisture content, the seed damage increased with an increase in the impact velocity. The effect of impact velocity on the percentage of physical damages was stronger at lower moisture contents than at higher ones, except for the moisture content of 20%. At the moisture content of 20%, even at low impact velocities (5 m/s), the percentage of physically damaged beans was considerable, 6%. *Figure 3* also shows that the effect of impact velocity on the percentage of physical damages was gently linear. These results were in agreement with those reported by Bourgeois et al. (1995). Ptasznik et al. (1995) have also reported that at 14%, 17% and 21% grain moisture content, the bean damages increased linearly as the impact velocity increases from 1000 to 2500 rpm. Similar results were also reported for other grains by other investigators (Picket, 1973; Singh and Linvill, 1977). This can be also found from *Figure 5*, in which the rate of increase in the damaged seeds per 1 m/s increasing in impact velocity ($RIPPD_V$) is reported. The $RIPPD_V$ was determined by using the following equation:

$$RIPPD_{IV} = \frac{PPD_{V(i)} - PPD_{V(i+1)}}{V_i - V_{(i+1)}}, \ \%PD/m\ s^{-1} \qquad (2)$$

Where:

- $PPD_{V(i)}$ = mean value of percentage of physical damage at the i^{th} level of impact velocity, %
- $PPD_{V(i+1)}$ = mean value of percentage of physical damage at the $(i+1)^{th}$ level of impact velocity, %
- V_i and $V_{(i+1)}$ = i and $(i+1)^{th}$ levels of impact velocity, respectively, m/s

It is evident that, for all the levels of moisture content, the rate of increase in percentage of damaged beans displays a nonlinear relationship with the impact velocity. At lower moisture content, the rate of increasing in damaged beans was significantly higher than that at higher moisture contents. The maximum rate of increase in the percent of damaged beans was obtained when the impact velocity increased from 5 to 7.5 m/s. At this critical range of the impact velocity, the maximum rate of increase in damaged beans was found at the moisture content of 5% with the mean $RIPPD_V$ of 8 %/m. s^{-1}. This means that at the range of 5 to 7.5 m/s, the percent of damaged beans increased by about 8% per 1 m/s increase in the impact velocity. The corresponding values for the moisture contents of 15 and 20% were equal to 5.2 and 4.8 %/m. s^{-1} (*Figure 3*). The minimum rate of increase in the damaged seeds was found in beans with moisture contents of 20% when the impact velocity increased from 10 to 12 m/s (*Figure 3*). Baryeh (2002) has also reported similar results for the variation of the rate of increase in grain damages with impact velocity for bambara beans.

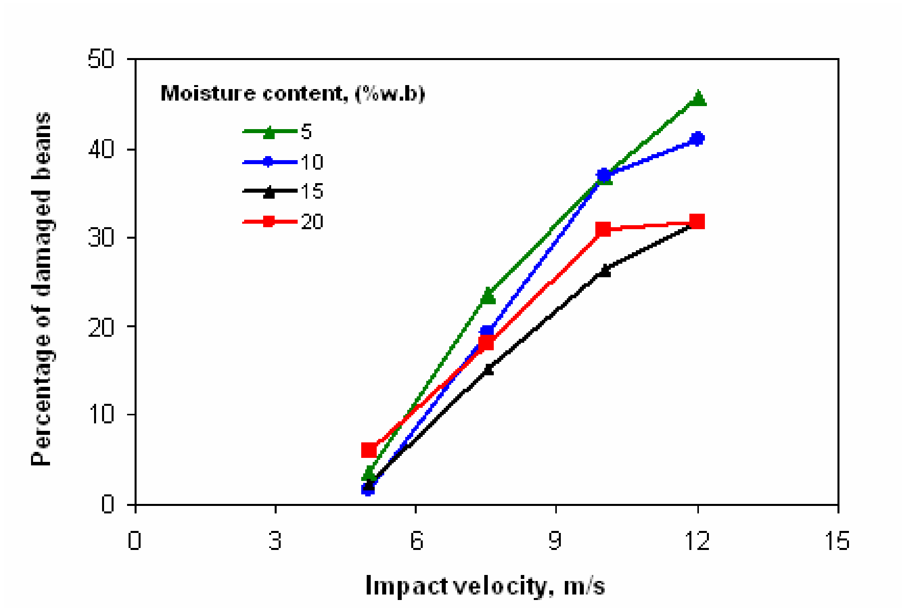

Fig. 2 - Effects of impact velocity on the percentage of physical damage in kidney beans

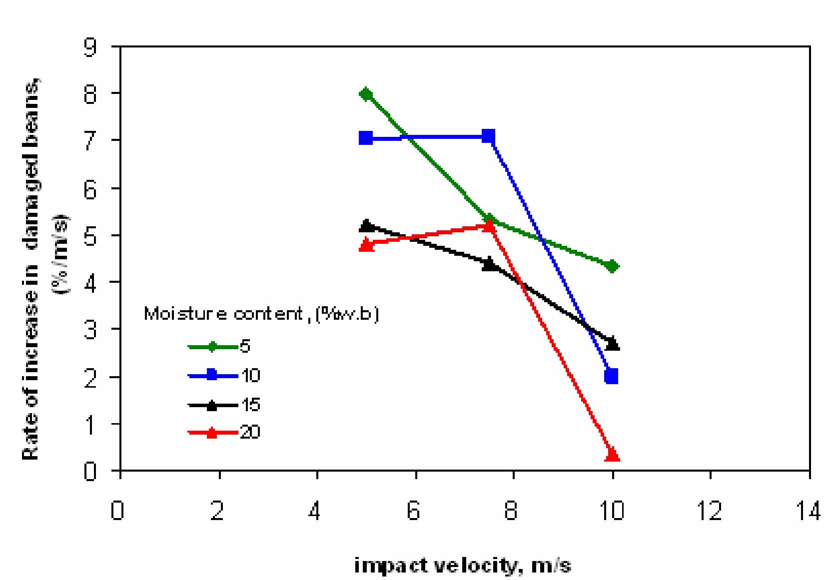

Fig. 3 - Rate of increase in physical damages of kidney beans versus impact velocity

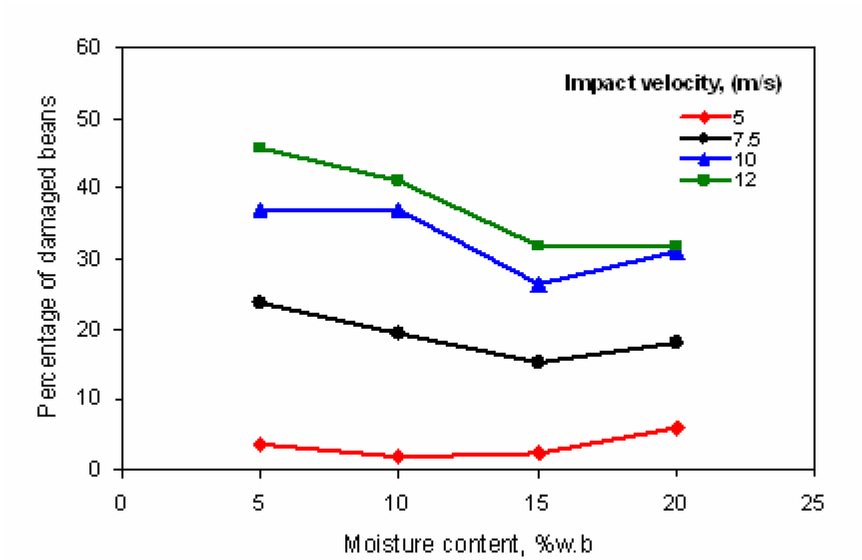

Fig. 4 - Effects of moisture content on the percentage of the physical damage in kidney beans

The results showed that with increasing the moisture content from 5 to 15%, the mean values of the percentage of damaged beans decreased by 1.4 times (*Table 2*). However, by a higher increase in the moisture content from 15 to 20%, the mean values of physically damaged beans showed a non-significant increasing trend (*Table 2*). Many researchers have also reported similar results for other seeds (Paulsen et al., 1981; Liu et al., 1990; Bergen et al., 1993; Fraczek and Slipek, 1998; Sosnowski and Kuzniar, 1999; Parde et al., 2002; Khazaei et al., 2007). Sosnowski (2006) concluded that PPD in beans showed a decreased trend as moisture content increased from 15 to 25%. However, with further increase in MC, from 25 to 29%, an increasing trend in PPD was observed. Khazaei et al. (2002) reported that the moisture content of chickpeas was a major factor in controlling the damage. A decrease in moisture content appeared to increase the brittleness of peas (Khazaei et al., 2002).

The effect of moisture content on the percentage of physical damage was stronger at higher impact velocities (*Figure 4*). This can also be found from Figure 5, which shows the rates of increase in the percentage of damaged beans per unit decrease in the moisture content ($RIPPD_M$) for different levels of the impact velocity. The $RIPPD_{MC}$ values were determined as follows:

$$RIPPD_M = \frac{PPD_{M(i)} - PPD_{M(i+1)}}{M_{(i+1)} - M_i}, \ \%PD / \%_{MC} \qquad (3)$$

Where:

- $PPD_{M(i)}$ = mean value of percent in damaged beans at the i^{th} level of moisture content, %
- $PPD_{M(i+1)}$ = mean value of percent in damaged beans at the $(i+1)^{th}$ level of moisture content, %
- M_i and $M_{(i+1)}$ = i and $(i+1)^{th}$ levels of moisture content, respectively.

Figure 5 shows that the rates of increase in PPD per unit decrease in MC were not the same for all the levels of impact velocities. At the critical range of threshing, when the moisture content decreased from 10% to 5% w.b, the maximum rate of increase in the damaged beans was obtained for the impact velocity of 12 m/s, which was equal to 0.94 %PD/ $\%_{MC}$ (*Figure 5*). This means that with decreasing the moisture content from 10% to 5%, the percent of physically damaged beans increased by about 0.94% per 1% decrease in moisture content (*Figure 5*). The corresponding values for impact velocities of 5, 7.5, and 10 m/s were equal to 0.4, 0.88 and 0.0 % PD $\%^{-1}$mc.

These results confirm that at low moisture contents, the seeds were more brittle, thus, more prone to physical damages, fact that was similarly reported by Bergen et al. (1993), Khazaei et al. (2002) and Evans et al. (1990). However, the results also showed that once with the moisture content increase, the mechanical strength of kidney beans decreased.

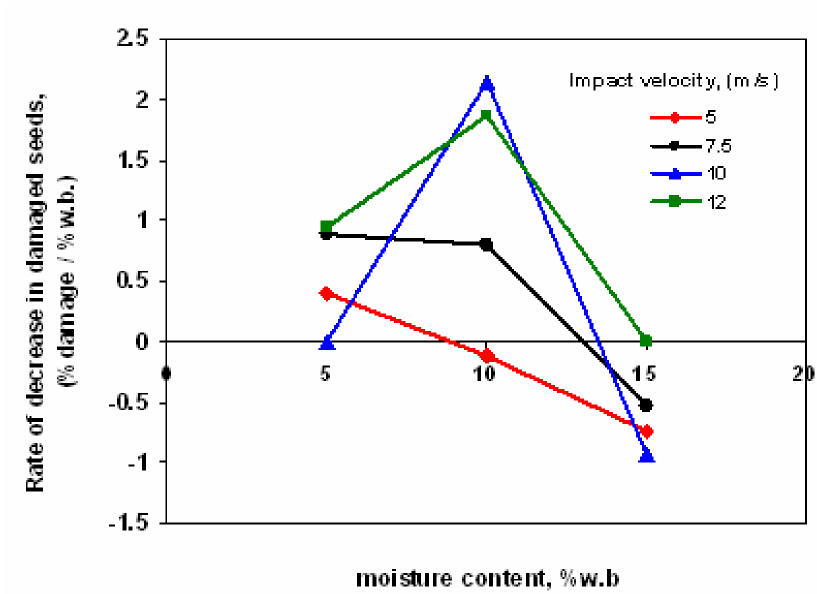

Fig. 5 - Rate of increase in the physical damages of kidney beans versus moisture content

The relationships between the percent of physical damages with impact velocity and the moisture content in beans may be expressed mathematically as:

$$PD = -49.018 - 0.509\,M + 13.519\,V + 0.055M^2 - 0.388\,V^2 - 0.156MV \quad R^2=0.972 \quad (4)$$

Where:

- PD = percentage of physically damaged beans, %
- V = impact velocity, m/s
- M = moisture content, % (w.b.)

The performance of the selected model for the prediction of percent physical damages in beans is shown in *Figure 6*. This picture shows the predicted percent of physical damage data versus the same set of measured data. The scatter plot showed no tendency for the model to under- or overestimate the predicted percent of physical damage data. It is observed that the predictive capability was good and data points were well compressed about the ideal of unity-slope line selected. The linear adjustment between the observed and estimated values gives a slope practically equal 1 (Y=0.9833X-0.341). The resulting correlation coefficient was 0.981 for the regression between observed and estimated values (*Figure 6*), indicating that the model provided satisfactory results over the whole set of values for the dependent variable.

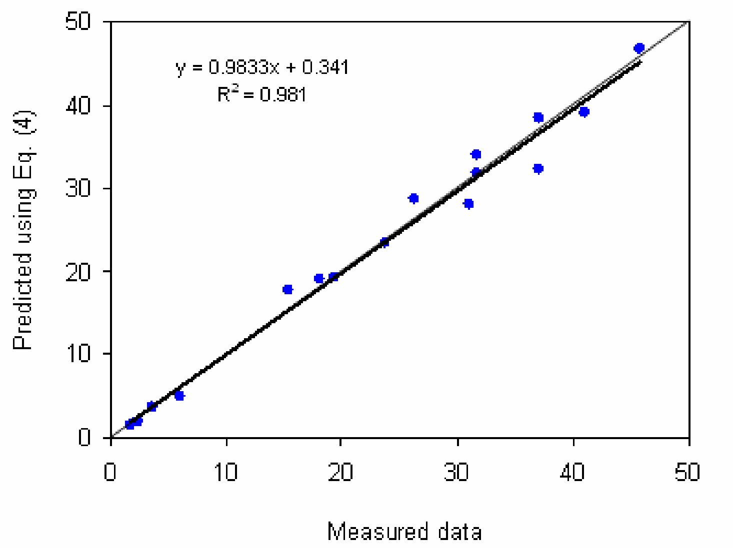

Fig. 6 - Correlation between the actual and the predicted data by the mathematical model (Eq. (4))

The high accuracy of this model makes possible the evaluation of the physical damages in kidney beans prior to harvesting and processing, by using the seed moisture content and loading velocity.

CONCLUSIONS

The results showed that impact velocity and moisture content significantly influenced the physical damages in kidney beans, at 1% and 5% significant level, respectively.

Increasing the impact velocity from 5 to 12 m/s caused an increase in the mean percent physical damage from 3.25 to 37.5%.

The corresponding data for beans at the moisture content of 5% were between 3.7% and 45.7%.

With increasing the moisture content from 5 to 15%, the mean values of damaged beans decreased by 1.4 times. However, with higher increase in the moisture content from 15 to 20%, the mean values of physically damaged beans showed a non-significant increasing trend.

The relationships between the physical damages with impact velocity and the beans moisture content were expressed mathematically.

It was found that the model provided satisfactory results over the whole set of values for the dependent variable.

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