Water Absorption by Cracked Mustard[1]

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ABSTRACT

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The water absorption rate was determined for whole mustard seed and for seed cracked by seven cracking treatments, including two types of mills, three roller-mill gaps, two hammer-mill feed rates, three seed-cracking temperatures, and two soaking temperatures. The absorption rate was obtained by measuring the amount of water that a sample imbibed from a water source during a given period. The parameters in a logarithmic model for water absorption as a function of soaking time did not vary with the different cracking treatments. The diffusion coefficient, computed to be 1.58×10^{-7} cm^2/sec for whole seeds, was used in the diffusion equation to derive an equivalent average particle diameter. The equivalent particle diameter ranged from 2.02 mm for whole mustard to 0.50 mm for finely cracked samples. The water absorption rate of mustard was less for larger roller mill gaps and a higher feed rate through the hammer mill. Seed-cracking temperature had no measurable effect on the water absorption rate. Higher soaking temperature produced a higher water absorption rate.

Mustard processing varies among manufacturers but always includes both size reduction and soaking operations. Mustard seed is basically spherical in shape and consists of starchy endosperm surrounded by highly impermeable layers of outer epidermis, subepidermal parenchyma, inner epidermis, and aleuron layer (Esau 1966). A hammer or roller mill is used to crack the whole seed so it is more receptive to liquid absorption and easier to grind (Brusewitz and Yu 1991). The cracked or whole seed then is soaked in water, vinegar, and spices for a specified time before it is ground into a fine paste with a stone mill. The combination of cracking condition and soaking time affects the energy consumption of the stone mill grinding process and the quality of the final product. Information on the mustard seed water absorption rate at different cracking conditions is needed. Further, determination of the water absorption rate theoretically requires knowing the water diffusion coefficient for cracked mustard, which is very irregular in shape and has a wide range in particle size.

Eckhoff and Okos (1989) found that gaseous sulfur dioxide diffused into corn by entering at the tip cap, moved up between the pericarp and seed coat, and then diffused into the endosperm. Muthukumarappan and Gunasekaran (1991) found that the time required for corn to reach 45% moisture content decreased with higher steeping pressure and temperature. Fan et al (1965) concluded that the absorption rate of water into corn and of water in SO_2 solution approximately followed the diffusion equation based on Fick's law. At 25°C, the diffusion coefficients for three varieties of corn ranged from 1.018 to 1.747×10^{-7} cm^2/sec. Different parts of a grain kernel have different diffusion coefficients, which affect the rate of water uptake for ground samples. Syarief et al (1987) reported that the diffusion coefficient of corn was an exponential function of moisture content with a coefficient that was five times larger for the germ than for the horny endosperm. Steffe and Singh (1980) used Fick's law of diffusion to model the thin-layer drying of white, brown, and rough rice. Diffusion coefficients were a function of temperature. For temperatures from 35.3 to 54.6°C, they found the diffusion coefficient ranged from 5.86 to 11.78×10^{-7} cm^2/sec for white rice, 1.367 to 4.328×10^{-7} cm^2/sec for bran, and 0.422 to 2.028 $\times 10^{-7}$ cm^2/sec for the hull, respectively. Diffusivities were described by an Arrhenius relation.

The diffusion equation for spherical particles, assuming diffusion only in the radial direction with constant diffusion coefficient, takes the form

$$\frac{dm}{dt} = D\frac{d^2m}{dr^2} + \frac{2}{r}\frac{dm}{dr} \tag{1}$$

where D is the diffusion coefficient, m is moisture content at any point for a given time, r is the distance from the center of a sphere, and t is diffusion time.

If the surface concentration is further assumed constant at m_e, the solution of equation 1 becomes (Crank 1957)

$$\frac{m - m_i}{m_e - m_i} = \frac{m - m_i}{M_e} = 1 + \frac{2R}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\frac{n\pi r}{R}e^{-Dn^2\pi^2 t/R^2} \tag{2}$$

where m_i is the initial moisture content (g/g), R is radius of the sphere, m_e is equilibrium moisture content (g/g), and $M_e = m_e - m_i$ is the maximum moisture increase possible (g/g).

Using average moisture content ($\bar{m}$) instead of moisture content (m) at a specific location in the sphere, the above solution can be approximated, for small times, as (Becker 1959, 1960; Fan et al 1961)

$$M/M_e = 1.128(S/V)(Dt)^{0.5} \tag{3}$$

This can be reduced to

$$M = kt^{0.5} \tag{4}$$

or

$$\bar{m} = m_i + kt^{0.5} \tag{5}$$

where

$$k = 1.128M_e(S/V)D^{0.5} \tag{6}$$

with S/V being the surface to volume ratio ($S/V = 3/R$ for a sphere). Equation 5 indicates that the moisture content at any time is a linear function of the square root of time with a slope of k and an intercept equal to the initial moisture content.

In investigating the effect of presoaking on the firmness of soybeans, Gandhi and Bourne (1991) found an initial rapid rate of softening followed by progressively slower softening until, after 3 hr, there was little change in firmness. Although firmness may not always be inversely proportional to water content, the water absorption rate does have a similar trend. As noted by Becker (1960), the absorption of liquid water by the wheat kernel proceeds by a heterogeneous mechanism. There is a very rapid initial absorption, followed by a subsequent absorption that is directly proportional to the square root of the time of immersion.

The objectives of this study were to evaluate the water diffusion coefficient for whole mustard seeds, experimentally measure the water absorption rate of mustard of different particle sizes, and determine the effects of various cracking and soaking treatments on the water absorption rate of mustard.

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MATERIALS AND METHODS

The seed used in this study was commercial whole yellow mustard with bulk density of 720 kg/m^3 and moisture content of about 10% (dry basis). The particle size was 90%, by weight, between 1.7 and 2.36 mm and 99% between 1.4 and 2.83 mm. The seed preparation factors tested that could influence water absorption rate were mill type (hammer versus roller), feed rate of the hammer mill, the gap between the rolls of the roller mill, and the temperature of mustard seed at cracking time. The hammer mill was a well-used W.W. Grinder model K33L machine with a 46-cm-wide screen having 3.2-mm-round openings. Two material flow rates of 17 and 29 kg/min were obtained for the hammer mill by adjusting the gravity feed slide gate opening from minimum to maximum flow. The mustard seed was put in plastic bags, sealed, and placed into either 5, 20, or 35°C controlled temperature storage for temperature and moisture equilibration before roller mill cracking. After two days, the samples were removed from storage and cracked immediately by a new H.C. Davis model 50 roller mill with two 23- × 15-cm-diameter corrugated rolls. The feed rate was held constant at 0.9 kg/min with gaps of 0.3, 0.5, and 0.7 mm selected to produce a range from slightly to fully cracked seeds. The seven combinations of parameters to form the various cracking treatments included cracked at 5°C with a roll gap of 0.3 mm; cracked at 20°C with gaps of 0.3, 0.5, and 0.7 mm; cracked at 35°C with 0.7 mm roll gap; and hammer milled at two feed rates of 17 and 29 kg/min.

The usual procedure for water uptake (Becker 1960, Fan et al 1961, Muthukumarappan and Gunasekaran 1991) does not work well for cracked mustard containing fine particles or whole mustard seeds because of their stickiness after soaking. A different method was needed to easily and effectively determine the water absorption rate of mustard.

Whole or cracked mustard seed was soaked in a temperature-controlled water bath. The amount of water the sample took from the water bath during soaking was measured by placing water and the whole or cracked sample in a closed-off funnel, waiting for the specified soaking time, and then allowing the water to drain out through a strainer. The ceramic funnel (10 cm in diameter) with connecting plastic (Tygon) tubing was held on a ring stand. A nylon strainer was placed in the funnel and initially wetted by adding some water and letting it drain for about 2 min. The plastic tubing at the end of the funnel was clamped tightly to control water flow. The dry mustard seed sample (30 g) was poured into the funnel, followed by 150 g of water. At the end of the specified soaking time, the clip on the plastic tubing was removed, and the water was drained into a container. At the same time, a dead weight of 1,000 g was placed on the top of the mustard sample to increase the drainage rate and decrease the time. The sample was allowed to drain for 30 sec, and the amount of collected water was weighed. The difference in mass of water added initially, and water collected was the amount of water lost in the process. The dead weight of 1,000 g and the draining time of 30 sec were chosen because this combination produced the best results, i.e., there was a negligible amount of water still draining out after 30 sec.

In this test procedure, some water was held between particles and between the particles and the funnel surfaces. A method was needed to assess the amount not absorbed but left in the system. Becker (1960) and Fan et al (1961, 1965) reported that moisture increase was proportional to the square root of absorption time with zero intercept. When "raw" experimental collected water data were fit to a linear regression model, the intercept to the moisture axis of the straight line was greater than zero. This intercept value was the amount of water loss to the hardware and was not due to diffusion into the sample. Therefore, this constant amount of water was subtracted from the "raw" experimental data.

Soaking water used for all experiments was at room temperature (22°C), except for one test where the water was 50°C with mustard cracked at 5°C and 0.3-mm roller-mill gap. For the first 3 min of soaking time, the procedure was the same as the 22°C tests except for the higher water temperature. For soaking times longer than 3 min, the sample and soaking water were maintained at 50 ± 1°C in a heated water bath. An 8-cm-diameter metal container was heated to 50°C before use. After the sample was poured into the container, 150 g of 50°C water from the same bath was added and the container was covered. About 1 min before the specified soaking time, the sample was poured into the funnel, and the same procedure was followed as for 22°C soaking. Nine soaking times of 0.5, 1.5, 3, 5, 8, 12, 17, 23, and 30 min were used, and each cracking treatment and soaking time combination was randomly replicated three times.

RESULTS AND DISCUSSION

Water Absorption

Water absorption data were converted to moisture increase (M) using the regression equation

$$M = \bar{m} - m_i = 0.687 + 0.0211t^{0.5} \quad (7)$$

with $r^2 = 0.98$. Where $\bar{m}$ is the average sample moisture content (g/g), t is soaking time (sec), and m_i is the initial moisture content obtained by drying the sample in an oven at 130°C for 4 hr (ASAE 1991). All moistures are reported on a dry basis. The regression line and the original data are plotted in Figure 1. The amount of water loss to the system was found to be 0.687 g/g, which was verified by letting water go through the sample and then measuring water loss. The amount of water loss using the same procedure for whole mustard with a soaking time of zero was 0.679 g/g, which was similar to the average for all cracking conditions. Therefore, 0.687 g/g was subtracted from the "raw" data.

The data of water absorbed per gram of dry mustard (M) for each test condition were used in the model,

$$M = A + B\ln(t) \quad (8)$$

where A and B are model parameters and t is soaking time in seconds.

The data (average of three replicates), the regression parameters A and B, and r^2 are given in Table I. All data fit the model well except the high soaking temperature treatment, which reached its equilibrium in 5 min. The data and regression constants indicated that for a constant roller mill gap, mustard temperature at the time of cracking had a slight effect on the water absorption rate. At a roller gap of 0.3 mm, the 5°C cracked mustard picked up moisture faster than did the 20°C cracking temperature for the first 3 min but thereafter was basically the same. For a constant

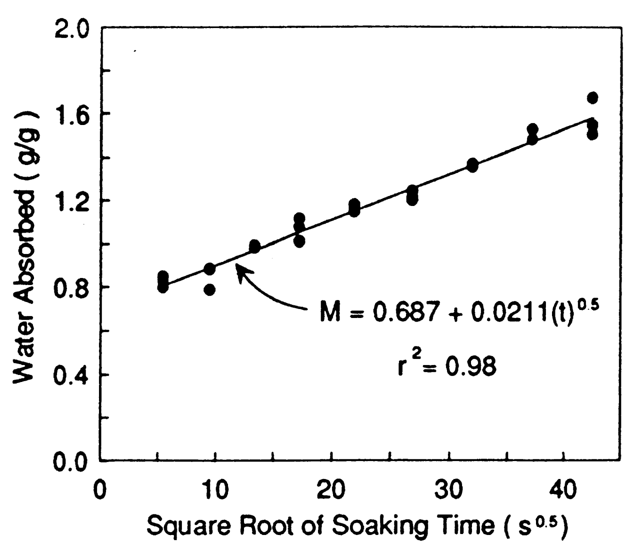

Fig. 1. Water absorption rate of whole mustard at 22°C. M = moisture increase; t = diffusion time.

TABLE I
Water (g) Absorbed Per Gram of Mustard (Average of Three Replicates), Model Parameters of $M = A + B \ln(t)$, and Equivalent Diameter (d_e) for Different Cracking and Soaking Conditions

	Roller Mill[a]						Hammer Mill[b]		Whole Seed
	T05G3	T20G3	T20G5	T20G7	T35G7	HWT	H29	H17	
Soaking time, min									
0.5	0.479	0.380	0.312	0.200	0.173	0.776	0.169	0.386	0.068
1.5	0.796	0.738	0.760	0.533	0.508	1.111	0.354	0.655	0.094
3.0	1.038	0.885	0.990	0.750	0.743	1.353	0.513	0.826	0.232
5.0	1.180	1.172	1.169	0.923	0.902	1.647	0.647	1.004	0.311
8.0	1.287	1.318	1.361	1.055	1.049	1.666	0.774	1.140	0.409
12.0	1.429	1.373	1.439	1.191	1.188	1.780	0.938	1.317	0.461
17.0	1.404	1.471	1.582	1.295	1.272	1.707	1.057	1.347	0.606
23.0	1.533	1.583	1.743	1.397	1.386	1.614	1.094	1.466	0.742
30.0	1.637	1.623	1.679	1.471	1.465	1.608	1.146	1.484	0.821
Log model									
A	−0.422	−0.659	−0.821	−0.866	−0.906	0.181	−0.763	−0.599	−0.703
B	0.274	0.310	0.346	0.312	0.316	0.219	0.255	0.282	0.189
r^2	0.957	0.979	0.966	0.991	0.992	0.735	0.963	0.973	0.893
d_e, mm	0.50	0.52	0.50	0.78	0.78		1.06	0.64	2.02
r^2 [c]	0.948	0.978	0.963	0.972	0.972		0.962	0.974	0.972

[a] The second and third characters refer to seed temperature at cracking time in °C, and the last character is the gap between rolls of roller mill in 1/10 of a millimeter. HWT = high temperature (50°C) soaking water with seed milled by T05G3.
[b] H refers to hammer mill; last two digits are feed rate in kg/min.
[c] r^2 for d_e (equivalent diameter) is from the regression using experimental data and values computed from the diffusion equation with evaluated equivalent diameter.

cracking temperature, the sample from a 0.7-mm roll gap absorbed water more slowly than did the samples cracked with either 0.3- or 0.5-mm roll gaps. The difference between the 0.3- and 0.5-mm gap was not statistically significant. A lower feed rate to the hammer mill should produce finer particles, which should absorb water faster. This hypothesis was supported by the results (Table I). As expected, whole mustard seed had the lowest water absorption rates, and seeds soaked at higher temperatures had the highest absorption rates.

The water absorption data and logarithmic model parameters did not easily allow for a good comparison between treatments. Another method of comparing treatments is to use the amount of water absorbed during a specified time interval. The time interval between 8 and 30 min was selected because 8 min seems to be a transition time from a fast to a slower water absorption rate. The amount of water absorbed in the first 8 min was computed as a percentage of the total amount of water absorbed in 30 min. A comparison of the percentage of water absorbed in the first 8 min divided the treatments into four groups. The seed soaked at a higher temperature (50°C) absorbed 100% of the water in less than 8 min. The next group, which absorbed approximately 85% water in the first 8 min, included the roller mill with 0.3- and 0.5-mm gaps and the hammer mill at a feed rate of 17 g/min. Samples from the 0.7-mm gap roller mill and a hammer mill at a feed rate of 29 kg/min absorbed about 80% and the slowest was whole mustard, which absorbed only 73% in the first 8 min.

From the analysis thus far, the effect of roll gap on the water absorption by mustard was not evident. Samples from 0.7-mm gap rolls absorbed, on the average, less water than did those from 0.5-mm gap rolls. But, unexpectedly, samples from 0.3-mm gap rolls absorbed an intermediate amount except for the first 30 sec. To clarify this apparent inconsistency, an additional experiment was conducted by cracking 20°C mustard through the roller mill with roll gaps at 0.2, 0.4, 0.6, 0.9, and 1.1 mm. The soaking procedure was the same as previously described but only for a single soaking time of 12 min. Water absorption was approximately linearly related (Fig. 2) to roll gap ($r^2 = 0.93$). The magnitude of the water absorption was less than the previous data, probably because of the initial moisture content difference, but the trend is similar. Samples cracked at 0.2-mm roll gap absorbed 50% more water in 12 min than did samples cracked at 1.1-mm roll gap.

It was not as easy as originally thought to differentiate among samples cracked with the different treatments. The data fit the logarithmic model for water absorption as a function of time with a high correlation coefficient, but the model parameters were not very sensitive to differences among treatments. Another parameter was needed that could be used to compare cracking treatments.

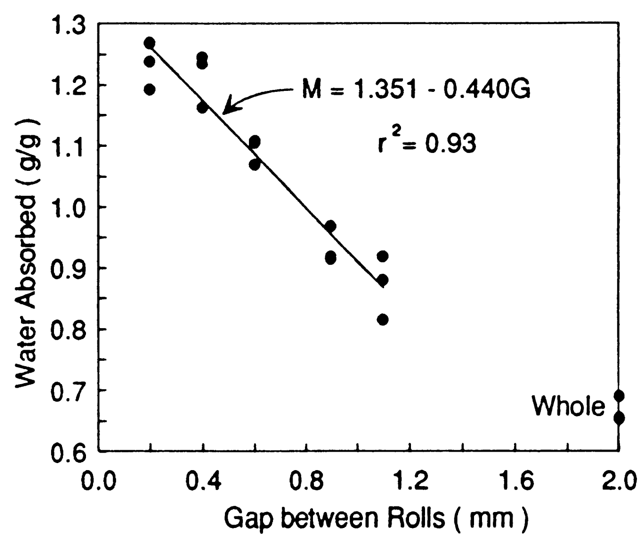

Fig. 2. Water absorption in first 12 min as a function of the gap between the rolls of the roller mill. M = moisture increase; G = gap.

Evaluation of Diffusion Coefficient

From our data, the slope k in equation 4 was 0.0211 for whole mustard (Fig. 1). Once k is known, the diffusion coefficient can be evaluated by rearranging equation 6 to become

$$D = 0.7854(kV/SM_e)^2 \qquad (9)$$

The value of effective surface moisture content, which is an equilibrium moisture content for the diffusion process, was evaluated as described by Fan et al (1961). The amount of water absorbed in 15 min by whole mustard seed at 4.08–68.53% moisture content, initially, was

$$M = 0.874 - 0.529\ m_i \qquad (10)$$

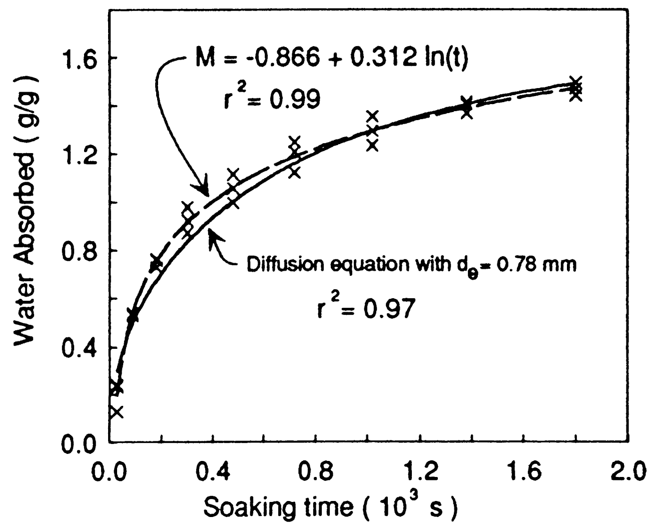

Fig. 3. Water absorption of mustard cracked at 20°C and with 0.7 mm roller mill gap. M = moisture increase; t = diffusion time.

When $m_i = m_e$, no water is absorbed by the sample, i.e., $m = m_i$. Solving equation 10 for m_i gives $m_e = 1.652$ g/g.

The average diameter of the mustard seed was evaluated from a size-distribution analysis obtained by using U.S. standard sieves 7–16 plus three additional intermediate screens (Brusewitz and Yu 1991). The weighted average diameter was calculated from

$$d = (\Sigma d_i w_i)/W \tag{11}$$

where d_i is the average screen opening, w_i is the weight between $(i-1)$th and ith sieve starting from the smallest number, and W is the total sample weight (Σw_i). The average diameter for whole mustard was 2.02 mm. By substituting these derived coefficients into equation 9, the water diffusion coefficient (D) of whole mustard seeds is 1.580×10^{-7} cm²/sec.

Equivalent Diameter Determination

An equivalent particle diameter was evaluated by solving the diffusion equation (Crank 1957) numerically for times from 0 to 30 min for cracked mustard using the experimentally derived diffusion coefficient for whole mustard. Assuming a radius (R), a set of moisture (M) versus time (t) data were obtained. This moisture curve, derived from an assumed radius in the diffusion equation, was compared with the experimental data. The assumed radius value then was adjusted until the derived moisture curve had the highest correlation with the experimental curve and this value of the diameter ($2R$) was assumed to be the equivalent average particle diameter for that particular sample.

The data evaluated from the diffusion equation using computed equivalent average particle diameters correlated well with the experimental data for the various cracking treatments, as r^2 values were 0.95 or higher (Table I). The solution from the diffusion equation for an equivalent diameter of 0.78 mm and the logarithmic model both fit the experimental data well for samples cracked at 20°C and a 0.7-mm roll gap (Fig. 3). For most treatments, the logarithmic model fit the data slightly better than did the equivalent diameter model.

Equivalent particle diameters (Table I) clearly show the effect of the treatments considered in this study. Comparing roller mill treatments, the temperature of the sample at cracking time had only a slight effect on the water absorption rate. At a roll gap of 0.3 mm, increasing the cracking temperature from 5 to 20°C increased the equivalent diameter an insignificant amount (from 0.50 to 0.52 mm). Samples cracked with a 0.7-mm roll gap yielded an equivalent diameter of 0.78 mm for both 20 and 35°C cracking temperatures. For a constant cracking temperature, increasing the gap between the rolls of a roller mill from 0.5 to 0.7 mm increased the equivalent average particle diameter from 0.50 to 0.78 mm, whereas decreasing the gap below 0.5 mm did not change the equivalent size.

Increasing the feed rate through the hammer mill had an effect on the equivalent diameter similar to that of enlarging the roller mill gap. When the hammer mill feed rate was increased from 17 to 29 kg/min, the equivalent diameter increased from 0.64 to 1.06 mm, which is almost a linear proportional between the two variables. The use of an equivalent particle diameter allows for a comparison between the roller mill and hammer mill. The hammer mill with a 17 kg/min feed rate produced a particle size equivalent to the sample cracked in the roller mill with roll gap between 0.5 and 0.7 mm. The hammer mill with a feed rate of 29 kg/min produced a particle size equivalent to particles larger than the 0.7-mm roll gap but still smaller than that of whole, uncracked seeds. The equivalent diameter for whole mustard seed was computed to be 2.02 mm, which is the same as that determined from sieve analysis. The whole seed equivalent diameter is four times larger than that of mustard cracked at 0.3- to 0.5-mm roll gap, which is why cracked seed absorbs water faster than does whole seed. The derived equivalent diameter model did not improve the correlation of the water absorbed versus soaking time data compared to the logarithmic model but did produce parameters that were significantly different among cracking treatments. This strongly supports its use as a good indicator for comparing various seed cracking treatments.

CONCLUSIONS

The following conclusions were made from this study. First, water absorption of mustard can be modeled as a logarithmic function of soaking time or by using the diffusion equation with an equivalent particle diameter. The equivalent diameters from the diffusion equation were more affected by mustard cracking treatments than were the logarithmic model parameters. Second, the water absorption rate of mustard was less for larger roller mill gaps and a higher hammer mill feed rate. Third, seed temperature at the time of cracking had no measurable effect on the water absorption rate by mustard. And fourth, a higher soaking temperature produced a greater water absorption rate by cracked mustard.

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