International Journal of Biological, Life and Agricultural Sciences
ISSN: 2415-6612
Vol:7, No:8, 2013

Finite Element Analysis and Feasibility of Simple Stochastic Modeling in the Analysis of Fissuring in Grains during Soaking

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***Abstract*—**A finite element analysis was conducted to determine the effect of moisture diffusion and hygroscopic swelling in rice. A parallel simple stochastic modeling was performed to predict the number of grains cracked as a result of moisture absorption and hygroscopic swelling. Rice grains were soaked in thermally (25°C) controlled water and then tested for compressive stress. The destructive compressive stress tests revealed through compressive stress calculation that the peak force required to cause cracking in grains soaked in water reduced with time as soaking duration was extended. Results of the experiment showed that several grains had their value of the predicted compressive stress below the von Mises stress and were interpreted as grains which become cracked and/or broke during soaking. The technique developed in this experiment will facilitate the approximation of the number of grains which will crack during soaking.

***Keywords*—**Cracking, Finite element analysis, hygroscopic swelling, moisture diffusion, von Mises stress.

I. INTRODUCTION

IN 2008, a low moisture content storage system for brown rice was suggested and developed by [1] because it was as effective as low temperature storage in maintaining quality. But with low moisture rice the system regarded as excessively dry with poor cooking quality, hence lower market value. The cause of deterioration in cooking quality with low moisture rice was open-crack formation [3], [4].

The diffusion of moisture in different soaking temperatures and its effect on the swelling of rice grains was reported by [5]. The general concept of the effect of temperature on the diffusion of moisture was proven to increase mass transfer in the grain. The increase in mass transfer also resulted in the rapid and increased swelling of the grain. This phenomenon lowered the yield stress in the grain hence lowering its breaking point. The effect of swelling of the starch granules on the outer layer of the grain prompted the buildup of stress and led to the occurrence of cracks. Normally, the outer layer of the grain experiences compressive stress while the inner portion is under tensile stress. This incident can be compared to a grain which is under compressive stress test.

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From the food engineers' and food processors' point of view, reducing the number of cracked grains during moisture absorption is a priority. The effect of several parameters in the occurrence of cracks and fissures on grains during soaking needs to be addressed. Recently, methods such as Finite Element Modeling and stochastic modeling gained significant popularity and have been adapted in the analysis, visualization and prediction of the effects of moisture movement and to understand the factors that contribute to the crack formation and possibly predict the number of grains that will undergo fissure during soaking, hence this study was conducted.

II. MATERIALS AND METHODS

A. Preparation of Samples

Rice samples were taken from a batch of short-grain japonica brown rice. Using a laboratory type abrasive mill (SKM-5B, Satake Co. Ltd.), the selected samples were polished to 90% milling. Standard procedures were used for triplicate determination of initial moisture content. The gravimetric method of determining the initial moisture content was used as specified by the Japanese Society of Agricultural Machinery. A 10g sample was heated in a laboratory oven for 24 h at 135°C. The initial moisture content of the samples was about 10.68% dry basis. Broken, cracked and damaged grains were manually separated and discarded.

B. Soaking of Samples

Before each experiment, the water bath was heated at the desired temperature of 25°C for almost an hour to attain thermal stability. Then the rice grain sample was immersed in the heated water under a specific duration. Samples were subsequently soaked in water for one to eight minutes. Other samples were also tested after 20 and 25min for comparison. The temperature of the water during the experiment was monitored using a thermocouple.

C. Testing for the Compressive Strength

Each grain of rice which was soaked in water was immediately tested for compression. After taking the sample out from the water, the individual grains were promptly wiped with paper towel. Each rice grain was then placed on a previously prepared thin sheet of black carbon paper placed over a piece of white paper laid in between the two parallel plates for the compression test. Using a digital force gauge (FGPX-50, NIDEC-SHIMPO Corporation) connected to a motorized force stand (FGS-50E-L, NIDEC-SHIMPO

Corporation), the sample was compressed at a rate of 8 mm/min (Fig. 1).

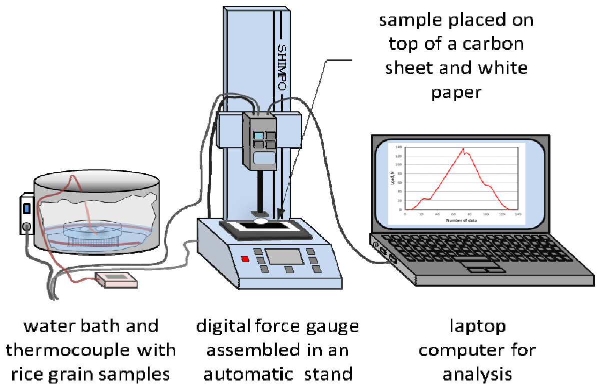

Fig. 1 Set-up for the compression test

D. Modeling the Moisture Absorption and Hygroscopic Swelling in Rice Grains

The evaluation of the moisture diffusion and hygroscopic swelling in rice grain was carried out using a commercial finite element modeling software, COMSOL Multiphysics 4.0a (COMSOL Inc.). The parameters used in the modeling were determined both from numerous trial and error experiments and from published literatures. In modeling the moisture diffusion, a new mathematical model was used in such a way that the diffusion coefficient is both a function of moisture content and temperature. The moisture movement and the distribution of moisture in the grain can be modeled using the following equation:

$$\frac{\partial M}{\partial t} = \nabla \cdot [D(M,T)\nabla M] \qquad (1)$$

Considering the moisture and temperature dependency of the diffusion coefficient, the governing equations are given as follows:

$$D = D_o exp - \left(\frac{aEs}{RgT}\right) \qquad (2)$$

$$D_o = (b)exp\left(\frac{c}{T}\right) = (3.89\ x\ 10^{-4})exp\frac{2424.25}{T} \qquad (3)$$

$$E_s(M,T) = (Q_{st})[1 + (75.5M^{-1.9})(T - 273.15)^{-0.37}] \qquad (4)$$

where the latent heat of vaporization of water is given by :

$$Q_{st} = 2500.8 - 2.3668(T - 273.15) \qquad (5)$$

Combining (3) and (4), it would become:

$$D = (3.89\ x\ 10^{-4})exp\left(\frac{Rgc - aEs}{RgT}\right) \qquad (6)$$

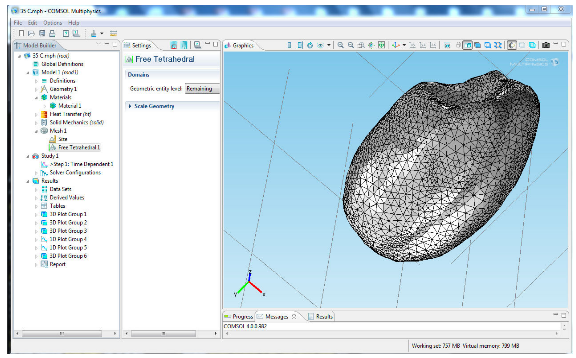

Fig. 2 Coupled simulation of the moisture diffusion and hygroscopic swelling

E. Feasibility of Stochastic Modeling on the Cracking of Rice Grains

A simple stochastic model was developed and investigated to explore the possibility of crack prediction. The model developed is presented below as:

$$\sigma_p = [A * \sigma_c + \sigma * n] \qquad (7)$$

where:

σ_p is the stochastically predicted stress
σ_c is the experimental value of the compressive stress
A an empirical constant equivalent to 0.707545
σ is the standard deviation of compressive stress
n is a normally distributed random number generated using MS Excel with a standard deviation of 0.5 and mean of zero.

III. Results and Discussion

A. Moisture Absorption Characteristics

Fig. 3 shows the gradual build-up and the distribution of moisture in the grain. The different shades correspond to the different values of the moisture field, which represented the distribution of moisture normalized with respect to the moisture concentration at equilibrium. It can be observed that during the first few minutes of soaking, the region near the surface gradually became saturated leaving the central core of the grain dry. However, the area occupied by enveloping color progressed during the first 20mins and eventually took up all the regions bounded by the geometry after 30mins. This is an indication that equilibrium moisture content was reached.

B. Von Mises Stress

Fig. 4 shows the distribution and the specific location of the highly stressed region of the rice grain. The stress in the grain built up during the first five minutes of soaking and gradually reduced in the succeeding minutes. Highly stressed sites were generally situated in the mid section and the embryonic region. It is believed that micro crack initiation and propagation usually start from these highly stressed sites and eventually progress to develop into open cracks. The open cracks develop either across the grain which is considered as a transverse crack or along the longitudinal axis of the grain. The continued swelling of the grain widens the crack opening thus extending it further to a few millimeters across or along the grain.

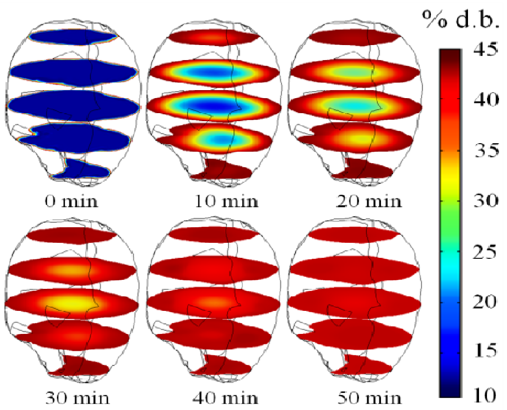

Fig. 3 Characteristics of moisture migration in grain at 25°C

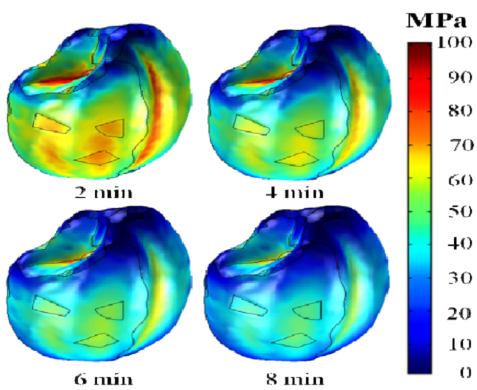

Fig. 4 Profile of the von Mises stress in the grain during soaking at 25°C

C. Changes in the Contact Area

Fig. 5 shows the contact area of rice undergoing compression tests. Apparently, there was an increase in the contact area as the soaking time progressed, an indication that the surface of the grain was softened and thus required a lesser amount of force to cause deformation. Because the amount of force loaded was constant, hence there was an increase in the grains' contact area. There was also an increase in the volume of the grain due to moisture absorption which increased the surface area of the grain.

D. Compressive Stress in Grains

Fig. 6 shows the peak value of the compressive stress obtained from the samples tested. The compressive stress was obtained by dividing the average breaking load of the different samples by the average contact area. There were at least 25 samples tested in each of the soaking time. It can be seen that the compressive stress of the grain slightly increased during the first two minutes after soaking and gradually decreased afterwards. Probable reason for this could be due to the hydration of the starch particles on the surface of the grain.

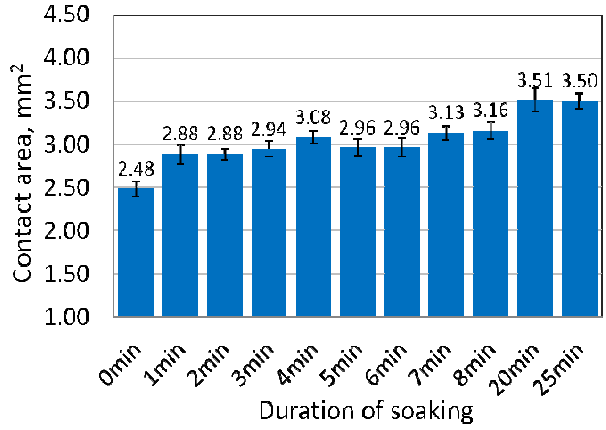

Fig. 5 Average contact area of rice samples tested for the compressive strength at different soaking time. Error bars shown reflects the standard error among the samples tested

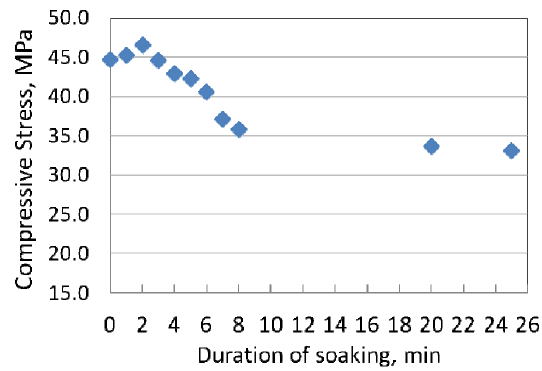

Fig. 6 Reduction of the compressive stress with soaking time

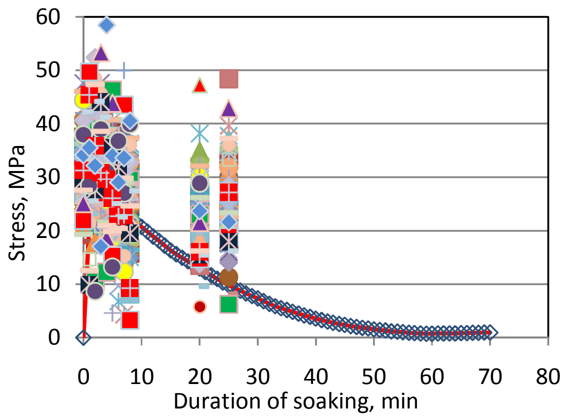

Fig. 7 Feasibility of simple stochastic modeling on the cracking of rice grains during soaking

E. Feasibility of Stochastic Modeling

Fig. 7 shows the results of the possibility of stochastic modeling on the cracking of rice grains during soaking. In the figure, the values of the compressive stress predicted using (7) were plotted over the von Mises stress curve. The results showed to have an intersection between predicted values of compressive stress and von Mises stress. The data point(s) with value(s) lower than the von Mises stress is interpreted as grains with crack. At the start of moisture absorption, fewer data points of the predicted compressive stress had intersected with the von Mises curve. However, its number increased as the soaking time progressed and afterwards, the number of data points diminished. Discussed further below is the frequency of the grains that were predicted as cracked grains as a result of moisture absorption.

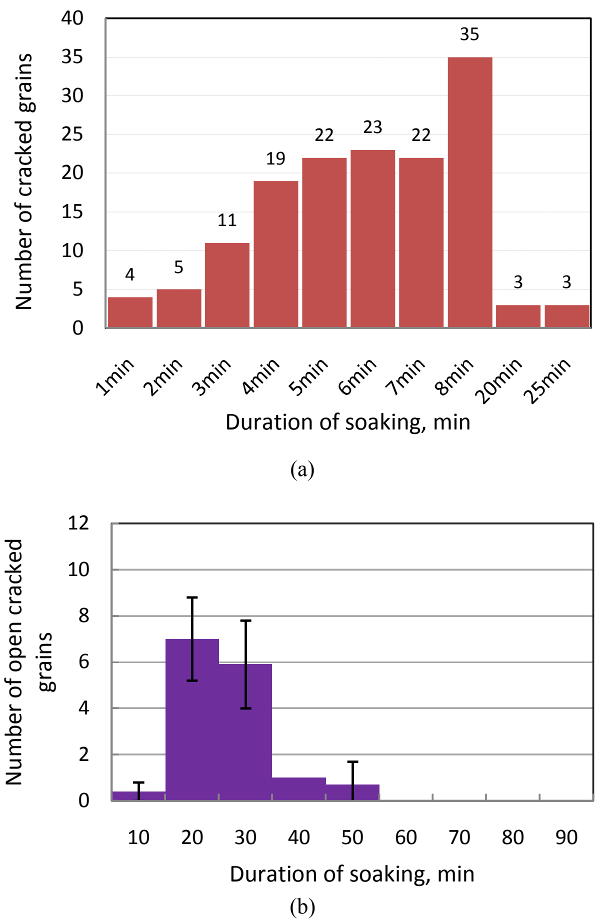

Fig. 8 A comparison of the frequency of cracking incidence in rice grains (a) shows the frequency and estimate of cracked grains (b) The frequency of open-cracked grains as reported by [1]. This data represents the same temperature at 25°C

It can be observed from Fig. 8 (a) that the frequency of cracked grains was higher than that in Fig. 8 (b). Moisture absorption caused several grains to crack. Some of the grains which cracked remained intact whereas, a fraction proceeded to break. The cracked opening widened to a few millimeters. In the experiment of [2], they defined this incident as open-cracked grains. In that experiment, the grains which had an open-crack were counted. The result of this experiment only predicted the number of grains which cracked and not the grains which eventually broke or open-cracked. This result can be proposed such that the possible number of grains that will crack resulting from moisture absorption during soaking can be estimated using this model.

IV. Conclusion

The results of this study showed that the numerical simulation of coupled moisture diffusion and hygroscopic swelling in rice grain satisfactorily represented the moisture movement and the deformation of the grain during soaking. The development and distribution of stress substantially matched the results from experimental data. These results can serve as a building block for more numerical simulation studies in accessing the moisture induced cracking in other commodities. The application of stochastic modeling on the cracking of rice grains is potentially feasible.

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