TECHNICAL NOTE:

USING DYNAMIC SHRINKAGE TESTS TO STUDY FISSURE PROPAGATION IN RICE KERNELS

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ABSTRACT. *Dynamic shrinkage behavior of rice kernels during drying was studied with a thermomechanical analyzer (TMA). Shrinkage kinetics data were obtained for brown rice kernels heated/dried in a TMA chamber. Seventeen rice kernels of long–grain variety Drew were tested for length change, and another seventeen kernels of the same variety were tested for thickness change. Each kernel was initially heated from room temperature to 59.7°C at a rate of 15°C/min and then maintained at 59.7°C to dry for 400 min. The shrinkage behavior of rice kernels could be described by an exponential decay relationship. Rice kernels did not shrink uniformly in thickness and length during the drying process but shrank a greater percentage in thickness than in length. Because of the non–uniform shrinkage, a tensile force along the direction of the longitudinal axis is speculated to exist during drying. This result may help explain why, with a small number of exceptions, fissures observed in rice kernels are perpendicular to the longitudinal axis of the kernel.*

Keywords. *Shrinkage, Rice, Drying, Fissure, Stress crack, TMA, Thermal analysis.*

Most grain kernels shrink during dehydration. Shrinkage is usually characterized or quantified by measuring the changes in volume and/or dimensions of a kernel. Several researchers have reported the volume and dimensional changes of rice kernels during drying (Kramer, 1951; Wratten et al., 1969; Morita and Singh, 1979; Steffe and Singh, 1980; Muthukumarappan et al., 1992). In a study of physical and thermal properties of rough rice, Wratten et al. (1969) related the physical dimensions of both long– and medium–grain rice kernels to their moisture content. Kramer (1951) measured physical dimensions of short–, medium–, and long–grain rough rice at storage moisture content levels. Muthukumarappan et al. (1992) measured the volumetric changes of rough, brown, and milled rice kernels during desorption and adsorption and correlated them with moisture content. However, there was no report found on a dynamic, time–dependent measurement of dimensional shrinkage, which represents a realistic and functional picture of rice kernel shrinkage during drying.

A thermal mechanical analyzer (TMA) is a very sensitive instrument that can detect dimensional changes of solid materials (Thakor et al., 1999) and is suitable to monitor the dynamic shrinkage of rice kernels during drying. It has been used to study the state transition behavior of rice kernels (Perdon et al., 2000; Sun et al., 2002).

Apart from the macroscopic shrinkage that is visible and measurable with a caliper or other displacement detector like the TMA, it is also believed that differences in shrinkage or expansion from the interior to the exterior of rice kernels can exist, depending on whether the localized portion of the kernel is in a glassy or rubbery state (Perdon et al., 2000). Cnossen and Siebenmorgen (2000) have hypothesized that non–uniform shrinkage or expansion within kernels due to glass transition effects is closely related to fissure formation or initiation inside rice kernels. Given this, the shrinkage dynamics of rice kernels could be an important area of study for fully understanding the fissuring of rice kernels.

There are also questions related to the shrinkage of rice kernels that directly impact the accuracy of predicting stresses by mathematical modeling and numerical solution. One such question pertains to the assumption of kernels being isotropic, i.e., is shrinkage in the longitudinal direction equal to that in the radial direction? Additionally, is the way a rice kernel shrinks in the longitudinal and radial directions related to the way a fissure propagates inside the kernel? The objective of this study was to investigate the dynamic shrinkage behavior of rice kernels in length and thickness by thermal mechanical analysis and to infer the way an internal fissure would propagate based on the observed dynamic shrinkage behavior of rice kernels.

THEORETICAL DEVELOPMENT

The exponential decay relationship is often used to describe moisture content change in grains during drying, as expressed in equation 1 (Brooker et al., 1974; *ASAE Standards*, 2000):

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$$\frac{MC - MC_e}{MC_i - MC_e} = \exp(-kt) \qquad (1)$$

where

MC = moisture content (dry basis)

t = time (i.e., drying duration; in s)

k = drying rate constant (1/s)

i and e = initial and equilibrium conditions, respectively.

Since the physical properties of rice kernels, such as length and thickness, were found to have linear relationships with moisture content (Kramer, 1951; Wratten et al., 1969; Morita and Singh, 1979; Steffe and Singh, 1980; Muthukumarappan et al., 1992), it would be logical to expect that the change in length and thickness of a rice kernel would follow the same type of relationship during drying as in equation 1, which can be expressed as:

$$\frac{X - X_e}{X_i - X_e} = \exp(-Kt) \qquad (2)$$

where

X = length or thickness of a rice kernel (in mm) after a drying duration t

X_i = initial length or thickness

X_e = equilibrium length or thickness

K = shrinkage rate constant.

Rearrangement of equation 2 gives:

$$\frac{X - X_i}{X_i} = A\left[\exp(-Kt) - 1\right] \qquad (3)$$

Note that $|(X - X_i)/X_i|$ or $(X_i - X)/X_i$ is the percentage shrinkage relative to the original dimension of a kernel and is referred to as the relative shrinkage ratio in this study, and:

$$A = \frac{X_i - X_e}{X_i} = 1 - \frac{X_e}{X_i} \qquad (4)$$

A and K in equation 3 are two important parameters related to the shrinkage kinetics of rice kernels. Parameter A represents the maximum possible percentage of dimensional change relative to its initial dimension. This can be seen by setting $t \rightarrow \infty$ in equation 3. Parameter K denotes how fast a rice kernel can reach its equilibrium dimension (e.g., length or thickness).

Materials and Methods

Materials

Long–grain rice variety Drew at a harvest moisture content (MC, expressed on a wet basis unless otherwise specified) of 21.7% was harvested from the University of Arkansas Rice Research and Extension Center at Stuttgart, Arkansas, in 1999. Immediately after harvest, the rice was cleaned with a Carter–Day Dockage tester (Carter–Day Co., Minneapolis, Minn.). The rice was stored in sealed plastic tanks in a walk–in cooler for 3 months before use in this study.

TMA Procedure for Measuring Length and Thickness Changes

A thermal mechanical analyzer (TMA7, Perkin–Elmer, Shelton, Conn.) was used to monitor the change in length or thickness of brown rice kernels during drying in the TMA. Individual rough rice kernels were randomly sampled and dehulled by hand. Before each measurement, the weight of each brown rice kernel was measured with an analytical balance. After weighing, the kernel was placed in a quartz dilatometer. The dilatometer comprised a cylinder with 7.1 mm inner diameter and 9 mm height. For thickness measurement, a rice kernel was oriented horizontally and a TMA displacement sensor (sometimes referred to as expansion probe) touched the side of the kernel. For length measurement, a rice kernel was glued vertically to a thin aluminum plate at one end and the TMA displacement sensor was placed in contact with the other end of the kernel. The dilatometer was then placed in the sample holder of the TMA, and the dimensional change of the sample during heating and drying was recorded by the displacement sensor. The sample was heated from room temperature to 59.7° C at a rate of 15° C/min and then maintained at 59.7° C for approximately 400 min. The relative humidity of the air in the TMA chamber during heating was estimated to be 7%. This estimate was obtained from a psychrometric chart based on the temperature and relative humidity of the ambient air in the room and the temperature within the heated TMA chamber. Seventeen kernels were measured with the TMA for length change, and another 17 were measured for thickness change. After TMA measurement, each kernel was re–weighed to enable calculation of its moisture loss. The MC was subsequently measured by drying each kernel for 24 h in an oven set at 130° C.

Statistical Analysis

It was desired to understand whether different initial MC levels (MC_i) and initial kernel length or thickness (X_i) affected parameters A and K in equation 3. Multiple regression (SAS, Version 7, SAS Systems, Inc., Cary, N.C.) with interaction was performed on the following general linear model (Neter et al., 1985):

$$A \text{ or } K = \alpha + \beta_1 MC_i + \beta_2 X_i + \beta_3 MC_i X_i \qquad (5)$$

If β_1, β_2, and β_3 are statistically equal to zero based on an overall F test, then it can be concluded that the effects of MC_i and X_i on A or K are not significant.

Results and Discussion

Shrinkage Behavior of Rice Kernels in Length and Thickness

For the TMA tests, 34 sets of shrinkage kinetic curves were obtained for brown rice of variety Drew, of which 17 sets were for length change and another 17 sets were for thickness change. Equation 3 was fit to each data set using the commercial curve–fitting software TableCurve 2D (Jadel Scientific, San Rafael, Cal.). The initial MCs, initial dimensions, and parameters A and K are listed in table 1 together with the coefficients of determination (R^2). As can be seen from table 1, the high R^2 values indicated that equation 3 closely represented the shrinkage data of brown rice kernels for both length and thickness changes during drying.

A general linear model, as shown in equation 5, was constructed to test whether initial kernel dimension and initial MC significantly affected parameters A and K in rice drying. The statistical results suggested that initial MC did not significantly affect shrinkage kinetics. Similarly, the

Table 1. Length and thickness shrinkage data of brown rice kernels (variety Drew) by a thermal mechanical analyzer at 59.7° C and approximately 7% RH.

Dimension	MC_i (%)	X_i (mm)	A	K (min^{-1})	R^2
Length					
Average	18.9	7.263	0.0261	0.00941	0.997
Std. Dev.	1.96	0.349	0.0034	0.00051	
Thickness					
Average	19.5	1.656	0.0343	0.00773	0.999
Std. Dev.	1.70	0.084	0.0034	0.00086	

initial kernel dimensions of length or thickness and the interaction between the initial MC and initial kernel dimensions did not affect the shrinkage kinetics of brown rice kernels.

Shrinkage Comparison Between Length and Thickness

By examining the difference in A and K values in table 1 corresponding to length and thickness kinetic parameters, it was found that even though both kernel length and thickness of brown rice followed a similar kinetic pattern (i.e., eq. 3) during the drying process, the kernels shrank unevenly. The value of parameter A for thickness was greater than that for length, indicating that the rice kernels incurred a larger percentage change in thickness than in length during drying. Meanwhile, the value of parameter K for length was greater than that for thickness, indicating that the rice kernels approached their equilibrium length faster than their equilibrium thickness.

The difference in shrinkage between length and thickness of rice kernels during drying can be clearly seen in figure 1. The shrinkage curves were generated using equation 3 and average values of parameters A and K from table 1. The curves show that the rice kernels shrank non–uniformly in thickness and length during the drying process. It is evident that the shrinkage in thickness was consistently more than that in length.

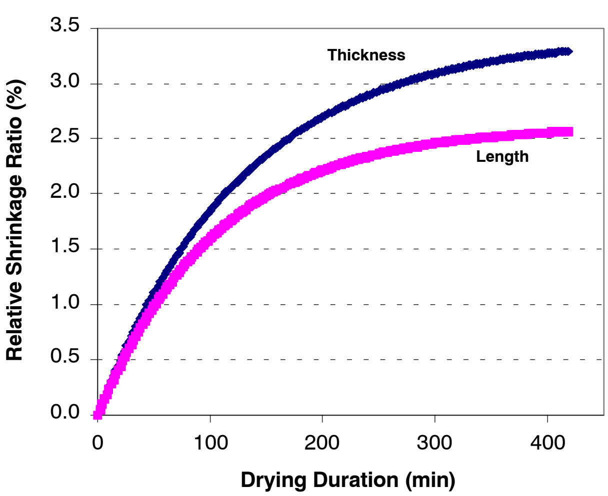

Figure 1. Comparison of relative shrinkage ratio between length and thickness using overall averaged A and K from table 1.

Is the Way Rice Kernels Shrink Related to the Way an Internal Fissure Propagates?

Because kernels showed a higher relative shrinkage ratio in thickness than in length, the net effect would be a tensile force created inside the kernel along the longitudinal axis of the kernel during drying. If any fissures were initiated within the kernel, either during drying or in a post–drying process, then the tensile pull would be very likely to result in the fissure propagating in the direction of the short axis (i.e., perpendicular to the longitudinal axis). This may explain why most fissures observed during drying are transverse to the long axis of the kernel.

Such an inference is supported by fissure patterns in rice reported by researchers such as Choudhury and Kunze (1972), Kunze and Prasad (1978), and Bautista et al. (2000). In general, with a limited number of exceptions, images of rice kernel fissures showed that fissures basically developed across the kernel and along the short axis (Kunze and Prasad, 1978; Bautista et al., 2000). Figure 2 shows two images of rice kernels taken with a video microscopy system, as described by Bautista et al. (2000). As can be seen, the fissures created were predominantly across the rice kernels. The experimental evidence well supports the inference derived from the data obtained in this study.

Conclusions

The shrinkage behavior of rice kernels closely followed an exponential decay relationship, as specified in equation 2. It was found that kernels shrank unevenly in length and thickness, with the percentage shrinkage in thickness consistently more than that in length. This may create a tensile force inside the kernel along the longitudinal axis of the kernel. This indicates that fissures inside a rice kernel would propagate more easily in the radial direction, or perpendicular to the kernel's longitudinal axis.

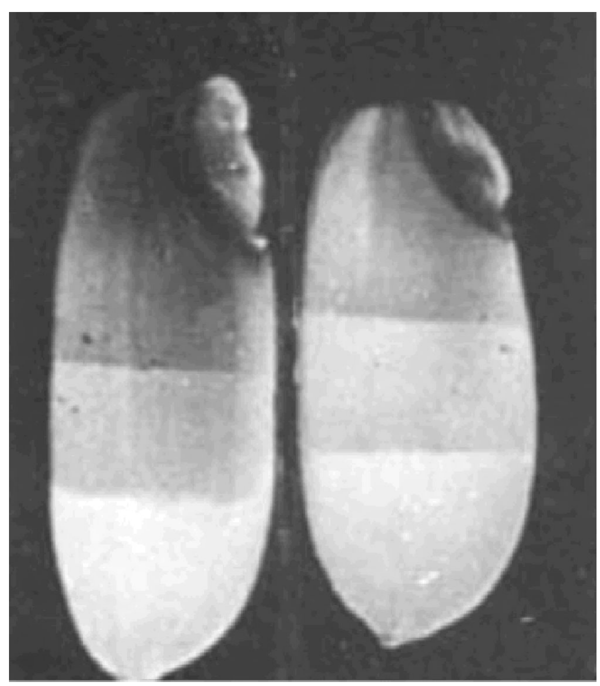

Figure 2. Images of rice kernels fissured after drying at 60° C and 17% RH for 40 min and then exposed to ambient air. The images were obtained with a video microscopy system (Bautista et al., 2000).

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