Thin-layer drying and rewetting characteristics of buckwheat

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Tabatabee, R., Jayas, D.S. and White, N.D.G. 2004. **Thin-layer drying and rewetting characteristics of buckwheat**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 3.19-3.24. Thin-layer drying and rewetting tests were conducted for seeds of buckwheat at various combinations of temperature (15.5 to 42.5°C), relative humidity (8 to 80%), and initial moisture content (10 to 20% wet basis) using a thin-layer drying unit. The loss or gain in the mass of the samples with time was recorded. The goodness-of-fit of five thin-layer drying equations to the experimental data was examined by a statistical regression technique. Standard error of the moisture content, mean relative percent error, and coefficient of determination were used as criteria for evaluating the goodness-of-fit. Page's equation described the thin-layer drying and rewetting data best giving a mean relative percent error ranging from 0.10 to 1.5% and standard error of moisture contents ranging from 0.02 to 0.33 with R^2 = 0.955 to 0.998. Two important drying constants of this equation were expressed as a function of temperature and relative humidity of the drying air.

Des tests de séchage en couches minces et de réhumidification ont été réalisés sur des grains de sarrasin pour différentes combinaisons de température (15,5 à 42,5°C), d'humidité relative (8 à 80%) et de teneur en eau initiale (10 à 20% base humide) en utilisant un séchoir à couches minces. Les variations de masse des échantillons en fonction du temps de séchage ont été mesurées. La corrélation des résultats prédits par cinq équations de séchage en couches minces a été comparée par régression statistique avec les données expérimentales recueillies. L'erreur standard de la teneur en eau, l'erreur relative en pourcentage et le coefficient de détermination ont été utilisés comme critères pour évaluer l'exactitude des équations. L'équation de Page décrit le mieux les données de séchage en couches minces et de réhumidification avec une erreur relative qui varie de 0,10 à 1,5% et une erreur standard pour la teneur en eau qui varie de 0,02 à 0,33 avec R^2 = 0,955 à 0,998. Deux constantes de séchage importantes de cette équation ont été exprimées en fonction de la température et de l'humidité relative de l'air de séchage.

INTRODUCTION

Buckwheat (*Fagopyrum esculentum moench*) originated in China and is cultivated all over the world (Ruffa and Jia 1998). Buckwheat is a fast-growing, warm-season, broad-leaf, and herbaceous plant that flowers prolifically over a period of several weeks (Myers and Meinke 1994). Seeds are close to tetrahedral in shape, and are triangular to nearly round in cross section. They vary in size from about 4 mm at the maximum width and 6 mm long to 2 mm wide and 4 mm long (Ruffa and Jia 1998). The seed consists of an outer layer or hull, an inner layer, the seed coat proper, and within this a starchy endosperm and the germ. The composition of buckwheat flour is approximately 63% carbohydrate, 11.7% protein, 2.4% fat, 9.9% fibre, 11% water, and 2% minerals (Pomeranz 1983). Noodles made from dough of buckwheat flour and water are popular in Japan. It is also common practice in many countries to prepare groats from buckwheat seeds, which are eaten as a cooked porridge (Ideka et al. 1991).

Manitoba is the major producer of buckwheat in Canada with about 70 percent of the acreage. Canadian processors use buckwheat in pancake mixes, breakfast cereals, breads, and poultry stuffing (Agriculture and Agri-Food Canada 1999). For the production of quality feed and food products from buckwheat, it is essential that the grain be stored safely at an optimal moisture level. Moisture of 16% (wet basis) is acceptable for short-term storage. For longer-term storage, grain should be at no more than 12 to 13% moisture content. Temperatures greater than 43.3°C should be avoided in drying buckwheat (Myers and Meinke 1994; Taylor 1998). Although a considerable amount of work has been reported in the literature on drying of agricultural products, no information is available for buckwheat.

Fundamental information on drying and rewetting characteristics of buckwheat is required for designing near-ambient drying and aeration systems. Thin-layer drying data are used in various computer-based deep-bed drying models (Pabis et al. 1998). Therefore, objectives of this study were: (1) to conduct thin-layer drying and rewetting tests to obtain experimental data for buckwheat at different air temperatures, relative humidities, and initial moisture contents; (2) to determine a suitable thin-layer drying equation which fits the data and describes the drying and rewetting behaviour.

SELECTION OF THIN-LAYER DRYING EQUATIONS

Mathematical models that describe drying mechanisms of grain and food can provide the required temperature and moisture information (Parti 1993). Thin-layer drying equations fall into three categories namely, theoretical, semi-theoretical, and empirical models. The comprehensive review of these equations is reported in detail by Jayas et al. (1991). Equations 1 to 5 have been used widely in the literature to describe thin-layer drying behaviour of grains and oilseeds and, therefore, were fitted to the experimental data for buckwheat.

Lewis (1921), cited by Jayas et al. (1991), suggested an equation that assumes the rate of change in moisture content is proportional to the difference between moisture content and equilibrium moisture content of the grains:

$$MR = \frac{M(t) - M_e}{M_0 - M_e} = \exp\left(-k_1 t\right) \quad (1)$$

where:

- MR = moisture ratio,
- M(t) = moisture content at time, t (% w.b.),
- M_e = equilibrium moisture content (% w.b.),
- M_0 = initial moisture content (% w.b.),
- k_1 = drying constant determined from experimental data (h^{-1}), and
- t = time (h).

Because of its simplicity, Eq. 1 has been widely used to describe drying of different crops (Bruce 1985; O'Callaghan et al. 1971; Sabbah et al. 1972). The equation, however, cannot describe the drying rate accurately throughout the drying period (Jayas et al. 1991).

A modified drying equation was obtained from Eq. 1 by Henderson and Pabis (1961), with another constant added:

$$MR = a \exp(-bt) \quad (2)$$

where:

- a = empirical drying constant and
- b = empirical drying constant (h^{-1}).

Equation 2 was used by several researchers to model drying of grains and oilseeds (Henderson and Pabis 1961; Wang and Singh 1978; Moss and Otten 1989).

To overcome shortcomings of the Lewis model (Eq. 1), Page (1949), cited by Jayas et al. (1991), suggested Eq. 3 as a drying model.

$$MR = \exp\left(-kt^n\right) \quad (3)$$

where:

- k = empirical drying constant (h^{-n}) and
- n = empirical drying constant.

Many researchers have used Eq. 3 to describe thin layer drying rates (Hulasare 1997; Misra and Brooker 1980; White et al. 1973; Syarief et al. 1984; Wang and Singh 1978; Hutchinson and Otten 1983; Bruce 1985; Pathak et al. 1991).

Equation 4 is the general form of a two-term model that uses the first two terms of a general series solution of Fick's second law.

$$MR = A \exp(-Bt) + C \exp(Dt) \quad (4)$$

where:

- A, B = empirical drying constants and
- C, D = empirical drying constants (h^{-1}).

Equation 4 has been used regardless of seed geometry (Sharma et al. 1982; Hutchinson and Otten 1983; Ezeike and Otten 1991; Palipane and Dirscoll 1994).

Overhults et al. (1973) used a modified form of Page's model (Eq. 3) to describe drying soybeans with heated air:

$$MR = \exp(-k_2 t)^{n_1} \quad (5)$$

where:

- k_2 = empirical drying constant (h^{-1}) and
- n_1 = empirical drying constant.

MATERIAL and METHODS

Thin layer drying apparatus

The apparatus consisted of a chamber with nine separated tray sections ventilated with air at the same temperature and relative humidity in each section (Sinicio 1994). The chamber was connected to a climate-lab-AA (C-L-AA) unit (Parameter Generation and Control Inc., Black Mountain, NC), which provided constant air temperature, relative humidity, and flow rate. The air was conditioned to the desired temperature and relative humidity by the C-L-AA unit. The average air temperature for each tray section was sensed by nine thermocouples installed 25 mm below the sample trays. The air temperatures were read by a digital thermometer (Model Pronto Plus, Thermo-Electric Instruments, Saddle Brook, NJ) with a resolution of ± 0.1°C. Dew point temperature was monitored at the air inlet section using a dew point sensor (Model Hygro-M1, General Eastern Instruments Inc., Watertown, MA) with a resolution of ± 0.1°C. The sample trays had 0.212×0.212 m inside dimensions and were made of square aluminum frames with wire mesh screen to hold the buckwheat seeds. The mass of seeds and tray was measured with an electronic balance (Model Mettler PE1600, Mettler Instruments Corporation, Zurich, Switzerland) with a resolution of ± 0.01 g. The chamber was insulated with 25 mm thick expanded polystyrene to minimize the effect of heat loss to the surroundings.

Sample preparation and drying test procedure

Buckwheat cultivar 'Koto', harvested in 2002, was obtained from the Agricore United grain handling company in Winnipeg, Manitoba. The buckwheat seeds were at initial moisture content of 5% wet basis. The seeds were stored at 5°C until used. The samples were conditioned to the desired moisture content by adding calculated quantities of distilled water and mixing for several hours. The rewetted samples were then kept in sealed plastic bags in a refrigerator at least 48 h for moisture content equilibration.

The thin-layer drying and rewetting tests were planned for nine constant relative humidity conditions. The air and dew point temperatures were selected accordingly. For a test at constant relative humidity, the temperature of the drying air and water were set at the air conditioning unit. Prior to starting the tests, the unit was left running at least 5 h to stabilize the air conditions. The unit was set to obtain air temperature ranging from 15 to 43°C and relative humidity of 8 to 80% for 27 tests. Based on a study by Hulasare (1997), air velocity up to 0.35 m/s has an insignificant effect on moisture transfer rate during the falling rate drying period. Therefore, the air velocity was fixed at 0.35 m/s. Three grain samples with initial moisture contents of 10-11, 15-16, and 19-20% wet basis in triplicate, were spread on trays which were placed in the chamber. Prior to putting trays in the chamber, empty trays were weighed and 100 g of buckwheat were uniformly spread over each tray to form a one-kernel thick layer. The mass of the tray with grains was recorded every hour for the first 6-8 h and every 9-15 h thereafter until the mass was within ± 0.01 g between two successive readings. The moisture content at this point was taken as the equilibrium moisture content. This is a valid assumption because based on an initial moisture content of 10-20% and a 100 g sample, the 0.01 g change in mass represents a change in moisture content of approximately 0.01 percentage

Table 1. Comparison of statistical parameters for five equations for a typical test at T = 42.5°, RH = 72%, and three initial moisture contents.

Equations	IMC* (% w.b.)	R^2 (%)	SEM**	e*** (%)
Page	19.2	99.4	0.0555	0.2738
	15.9	95.5	0.0849	0.1581
	10.8	99.6	0.1348	0.6794
Two-term	19.2	98.9	0.0732	0.3640
	15.9	94.8	0.0909	0.1600
	10.8	99.5	0.1363	0.7356
Lewis	19.2	97.5	0.1281	0.6819
	15.9	93.6	0.1121	0.3200
	10.8	97.7	0.3625	2.0780
Henderson and Pabis	19.2	97.6	0.1173	0.6175
	15.9	91.2	0.1223	0.2910
	10.8	97.8	0.3396	1.7537
Modified Page	19.2	99.4	0.0556	0.2775
	15.9	95.5	0.0849	0.1581
	10.8	99.5	0.1396	0.7500

\# These parameters were calculated for all conditions.
* Initial moisture content
** Standard error of moisture content
*** Mean relative percent error

point whereas moisture content measurement by the oven method can have an error of up to 0.2 percentage points. The air and water temperature in the C-L-AA unit, dew point temperature, and ambient temperature were also recorded at the time of weighing the trays with grain. The time to reach equilibrium ranged from 3 to 7 days depending on the air conditions. The initial and final moisture contents of the grain were measured using the oven-drying method in which 10 g of the grains of buckwheat were dried at 135°C for 24 h according to the standard of the Japanese Society of Agricultural Machinery (Ban and Suwa 1973, cited in Tagawa et al. 1993). The change of the grain moisture content, with time, was calculated from the mass change data.

Analysis of data

The experimental drying and rewetting data of buckwheat were fitted to the Lewis (Eq. 1), Henderson and Pabis (Eq. 2), Page (Eq. 3), two-term (Eq. 4), and modified Page (Eq. 5) equations using Graphical Analysis 3.0 (Vernier Software and Technology, Beaverton, OR) and parameters for each equation were determined. The values of the parameters were back-substituted into Eqs. 1-5 to predict moisture content at time t. The observed and predicted moisture contents were compared and statistically analyzed for determining the best-fit equation. The suitability of the equations was evaluated using the mean relative percent error (e), standard error of moisture content (SEM) and coefficient of determination (R^2). The mean relative percent error (e) was defined as:

$$e = \frac{100}{N} \sum \frac{|M_m - M_p|}{M_m} \tag{6}$$

where:
M_m = predicted moisture content (% w.b.),
M_p = predicted moisture content (% w.b.) and
N = number of observations.

The best-fit equation was then used to correlate the effects of temperature, relative humidity, and initial moisture content over the entire range of thin-layer drying and rewetting data.

RESULTS and DISCUSSION

Among the five equations, the values of e and SEM were the lowest, ranging from 0.10 to 1.5%, and 0.02 to 0.33, respectively, and R^2 was the highest, ranging from 95.5 to 99.8% for the Page's equation (based on all data points). The standard error of moisture content (SEM), e, and R^2 values for typical tests at a temperature of 42.5°C and relative humidity of 72% at three initial moisture contents are given in Table 1. These statistical parameters were calculated for all conditions. Therefore, for further analysis of data, only Page's equation was used.

Drying parameters of Page's equation

The parameters of the Page's equation were estimated using the regression technique of SAS 8.2 (SAS 2001). Values of these parameters were then related to the various drying and rewetting conditions. The parameters k and n were related to drying air temperature and relative humidity. The parameter k was described by a second order function of temperature:

$$k = -0.924 + 0.092T - 0.001T^2 \tag{7}$$

where: T = drying air temperature (°C).

The R^2 for this regression (Eq. 7) was 0.80 with standard error of 0.40. Based on values of k obtained from Eq. 7, new values of n were computed using Page's equation (Eq. 3). A multiple regression and analysis of variance yielded the relationship:

$$n = -1.23 + 0.043T + 0.057RH + 10^{-4}T^2 - 4.1\times 10^{-4} RH^2 - 7.2\times 10^{-4}\, T\, RH \tag{8}$$

where: RH = relative humidity of drying air (%).

The R^2 value for this regression (Eq. 8) was 0.91 with a standard error of 0.51.

Figures 1, 2, and 3 show a comparison of predicted drying curves versus experimental data for different test conditions. Predicted curves were calculated using Eq. 3 with n and k determined from Eqs. 7 and 8, respectively.

Figure 1 shows the effect of three different temperatures on the change of moisture content during drying at 68% RH and initial moisture content of 19.2%. The plot indicates that the rate of moisture loss decreases as the elapsed time increases (Fig. 1). During the first 7 h of drying time, 38, 45, and 58% of the moisture content was removed at drying air temperatures of 16, 27, and 35.8°C, respectively. Figure 2 shows the effect of increasing air temperature on rewetting of buckwheat at initial moisture content of 10.8%. Increasing of temperature by 19.8°C caused a decrease of moisture content of about 18% and the rate of moisture gain decreased as the elapsed time increased.

The effect of relative humidity on the drying characteristics of buckwheat at 16°C and initial moisture content of 19.3% is illustrated in Fig. 3. The rate of moisture loss at 69% relative

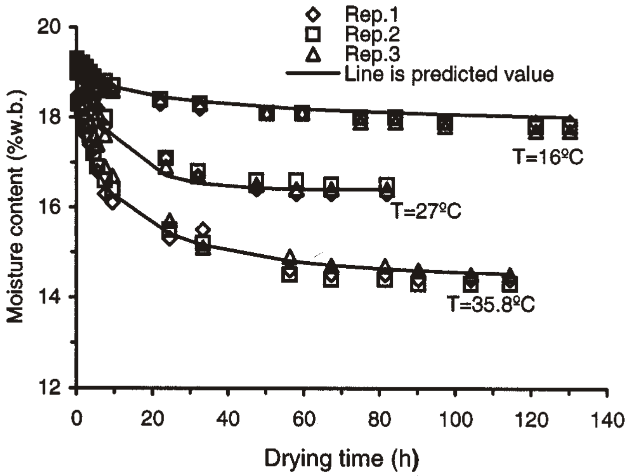

Fig. 1. Experimental and predicted moisture contents versus time for drying characteristics of buckwheat at 68% RH and initial moisture content of 19.2%. Standard deviation: s = 0.18 at T = 35.8°C; s = 0.11 at T = 27°C; and s = 0.06 at T = 16°C.

humidity is very high, specially during the initial stage of drying. A decrease in relative humidity by 23% resulted in a decrease of 33% in moisture content during the whole period of drying. As Fig. 4 shows, rewetting of buckwheat at higher relative humidity is faster and increasing of relative humidity by 30% caused an increase of moisture content of about 46%.

The initial moisture content affected the change of moisture content with drying time. During the first 60 h of drying, 56 and 26% of the moisture content was removed for buckwheat at

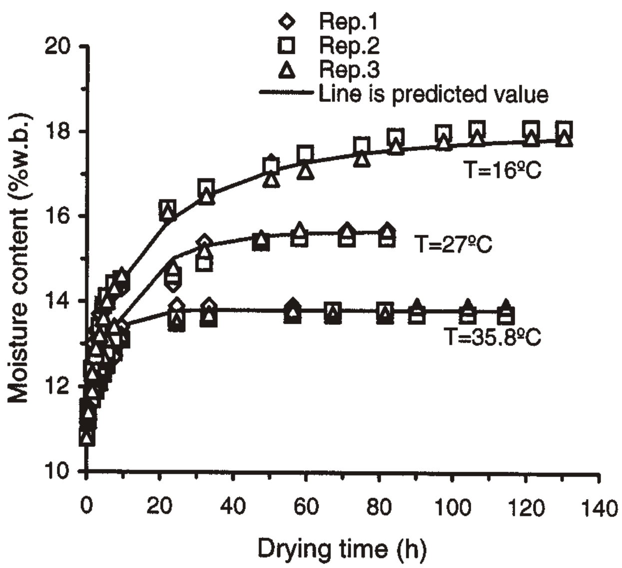

Fig. 2. Experimental and predicted moisture contents versus time for rewetting characteristics of buckwheat at 68% RH and initial moisture content of 10.8%. Standard deviation: s = 0.11 at T = 35.8°C; s = 0.16 at T = 27°C; and s = 0.15 at T = 16°C.

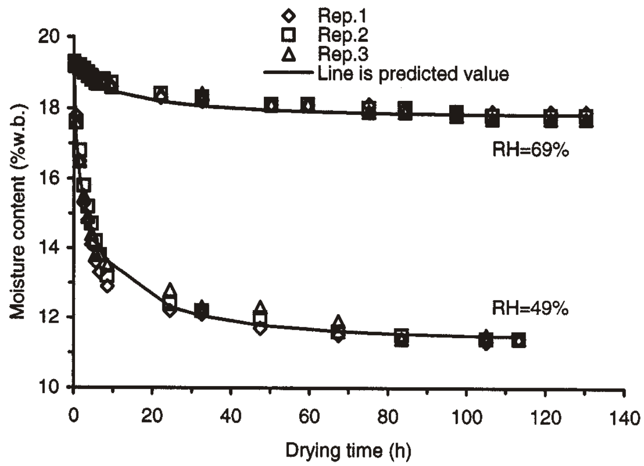

Fig. 3. Experimental and predicted moisture contents versus time for drying of buckwheat at 16°C and initial moisture content of 19.3%. Standard deviation: s = 0.1 at 49% RH and s = 0.6 at 69% RH.

initial moisture contents of 19.4 and 10.8%, respectively (Fig. 5). Figure 6 shows the effect of initial moisture content on rewetting of buckwheat at 16.2°C and relative humidity of 79%. The rate of moisture content gain at higher initial moisture content is lower. For the entire range of data, the relationship of k and n with initial moisture content could not be established. Therefore, only observed data were used to show the effect of initial moisture content on the changes of moisture content. Observed results are shown in Fig. 5, where buckwheat at three different initial moisture contents was dried at 24.4°C and 22% RH and rewetted at 16.2°C and 79% RH (Fig. 6).

The minimum and maximum difference between observed and predicted values were 0.1 and 1.5%, with only a few tests out of 81 tests having more than 1% difference between observed and predicted moisture content.

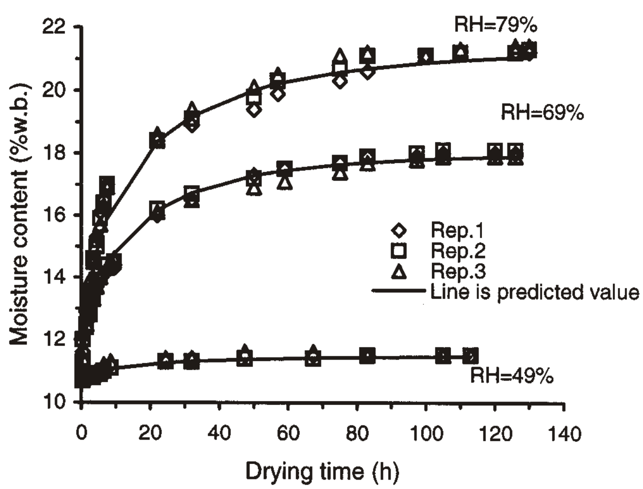

Fig. 4. Experimental and predicted moisture contents versus time for rewetting of buckwheat at 16°C and initial moisture content of 10.7%. Standard deviation: s = 0.05 at 49 % RH; s = 0.13 at 69% RH; and s = 0.17 at 79% RH.

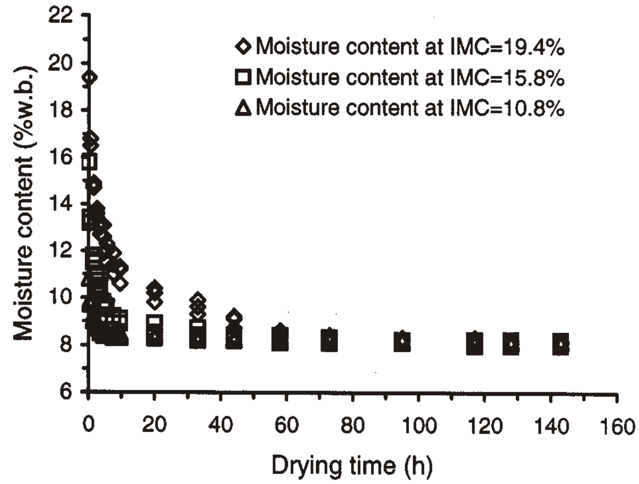

Fig. 5. Moisture content versus time for drying characteristics of buckwheat at 24.4°C and 22% RH. Standard deviation: s = 0.22 at 19.4% IMC; s = 0.14 at 15.8% IMC; and s = 0.07 at 10.8% IMC.

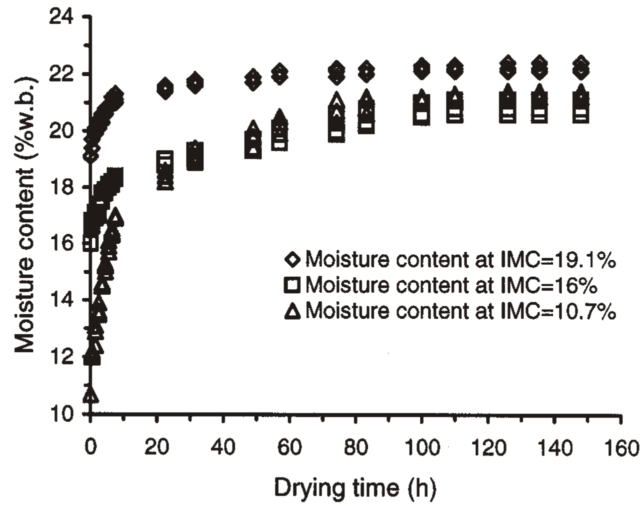

Fig. 6. Moisture content versus time for rewetting characteristics of buckwheat at 16.2°C and 79% RH. Standard deviation: s = 0.12 at 19.1% IMC; s = 0.18 at 16% IMC; and s = 0.18 at 10.7% IMC.

CONCLUSIONS

The effects of various parameters such as temperature, relative humidity, and initial moisture content were investigated on drying and rewetting characteristics of buckwheat. Five thin-layer drying equations were used to assess the goodness-of-fit to the experimental data. Page's equation was found to give the best fit. Among all the independent variables considered, the drying air temperature and the relative humidity most significantly ($P<0.05$) affected the parameter n in the thin-layer drying equation (R^2=0.91). The parameter k in the equation was found to be a function of the air temperature with R^2 value of 0.80. For the entire range of data, the relationship of k and n with initial moisture content could not be established.

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