THE UNIVERSITY OF MANITOBA

THIN-LAYER REWETTING RATES OF CANOLA (*Brassica campestris* L.)

by

PANKAJ SHATADAL

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ABSTRACT

Thin-layer rewetting tests were conducted for seeds of canola (*Brassica campestris* L.) in the temperature range of 7.5°C to 30.0°C at two relative humidities (80 and 90%) using a thin-layer wetting unit. Separate tests were done at 5.0, 7.0 and 10.0% initial moisture contents of seeds and 0.10, 0.25, and 0.43 m/s air velocities while the air was maintained at 30°C and 90% relative humidity. In the tests, a thin-layer (one to two kernels thick) of canola was held in the vertical plane and the conditioned air was passed through the layer, thus fully exposing the thin-layer of canola to the air. The gain in the mass of the thin-layer of canola with time was recorded using a micro-computer-based data acquisition system. The liquid diffusion equation for an isotropic and homogeneous sphere did not describe the rewetting rate of canola satisfactorily. The thin-layer rewetting rate data agreed well with Page's equation. The parameter n in Page's equation was assumed as a product-dependent constant which made it easy to compare the effects of independent variables on the rewetting rate without causing considerable error in predicting the rewetting rate for canola. A linear relationship was found between the parameter k, temperature and relative humidity. The initial moisture content, in the range from 5 to 10% wet mass basis, had no significant effect ($p > 0.05$) on the rewetting rate. The rewetting rate did not change significantly with air velocity in the range from 0.25 to 0.43 m/s ($p > 0.05$). The rewetting rate, however, was slower at 0.10 m/s air velocity. The thin-layer wetting model developed in

this study will be of importance in predicting seed moisture changes during near-ambient air drying of bulks of canola.

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c_b	specific heat of body, J kg^{-1} K^{-1}
D	diffusion coefficient, m^2 min^{-1}
H	relative humidity, decimal
J_ℓ	liquid flux, kg m^{-2} s^{-1}
J_q	heat flux, J m^{-2} s^{-1}
J_v	vapor flux, kg m^{-2} s^{-1}
K_ℓ	liquid conductivity, s^{-1}
K_t	apparent thermal conductivity, W m^{-1} K^{-1}
K_v	vapor conductivity, m^2 s^{-1}
k, n	parameters of Page's equation
L_v	specific latent heat of vaporization, J kg^{-1}
L_w	specific differential heat of wetting, J kg^{-1}
M	moisture content, % dry mass basis
MR	moisture ratio
M_o	initial moisture content, % dry mass basis
M_e	equilibrium moisture content, % dry mass basis
r	radial distance, m
R	radius of sphere, m
RH	relative humidity, %
Rv	universal gas constant as applied to water vapor, J kg^{-1} K^{-1}
T	temperature, °C
T'	temperature, K
ρ_ℓ	liquid density, kg m^3
ρ_s	dry solid density, kg m^3
ρ_{vo}	saturated vapor density, kg m^3

1. INTRODUCTION

Canola is the second most important crop of Canada with an annual average production worth $691.2 million (Anonymous, 1988). (In Canada, the term canola is used for low erucic acid and low glucosinolate content *Brassica campestris* L. and *Brassica napus* L. cultivars, and outside Canada the term rapeseed is used for all *B. campestris* and *B. napus* cultivars; rapeseed refers only to high erucic acid cultivars of this crop in Canada). Canola is crushed to extract vegetable oil for human consumption and canola meal for animal consumption.

The relative risk of quality deterioration when storing canola is higher than when storing wheat or barley (Mills, 1989), two other major crops in Canada. The moisture content limit for dry or straight grade canola is 10% wet mass basis (wb) but this is too high for long-term (5 months or more) safe storage because growth of storage fungi in the *Aspergillus glaucus* group occurs at 70% relative humidity which corresponds to 8.3% moisture content, wb, at 25°C for canola (Mills, 1989). Therefore, Mills (1989) suggested that canola should be binned at a maximum of 8% moisture content, wb, for long term safe storage. Friesen (1982) recommended that canola should be harvested when seeds are damp (over 12.5% moisture content) to reduce field losses and then should be dried to safe moisture levels. Wet weather during the harvest season or the chance of an early frost may also force farmers to harvest canola at high moisture contents. Drying of canola, therefore, may become essential.

The present trend in cereal and oilseed drying is towards using near-ambient air drying (Singh and Sokhansanj, 1984). In the prairies, the use of near-ambient drying is economically superior to the use of high-temperature drying systems (Fraser and Muir, 1980a,b). An additional advantage in near-ambient drying is that it delivers better quality dried grain. For canola, heated-air drying may cause heat damage to some seeds which subsequently will yield oil that is susceptible to oxidation (Appelqvist and Loof, 1972). If the seed-lot of canola contains green seeds, the chlorophyll level of the seeds is considerably reduced if the lot is dried naturally (Appelqvist and Loof, 1972). The same is not true for canola dried with heated air. The decrease in chlorophyll level gives a reduction in the refining cost of the oil. Natural or near-ambient drying, therefore, should be preferred for canola. In both near-ambient and natural air drying systems, ambient air is forced through a deep bed of stored grain. If the temperature of the ambient air is raised slightly by any means including frictional energy from a fan or motor, natural air drying is then termed as near-ambient drying.

Thin-layer moisture transfer equations are used in deep-bed grain drying simulation models. Such simulation models are extremely useful because they provide information on different drying systems, dryer design and testing, and related cost analysis without actually installing a drying system. A deep-bed grain drying simulation model works by dividing the total grain depth in several thin layers and calculating the change in grain moisture in each layer in small time steps for the constant drying air conditions. In a single time step, different thin layers in a grain bed are subject to different air conditions and these air conditions change with each subsequent time step. A thin layer of grain will dry if the vapor pressure of the drying air is lower than the vapor pressure in the grain, otherwise it will rewet. Calculation of moisture change in thin layers is based on heat and mass balance relationships and thin-layer moisture transfer characteristics of the grain. Moisture transfer characteristics of thin layer of grains are, therefore, required.

Most previous investigations in thin-layer moisture transfer relationships were concerned with thin-layer drying of cereals and oilseeds and very little work was done on thin-layer rewetting rates (Jayas et al., 1988; Misra and Brooker, 1980). Rewetting of grain can occur in typical near-ambient or natural air drying systems. For both systems it is common to run the fan continuously even if it involves running the fans during periods of high ambient relative humidity which can cause rewetting of grain (Friesen and Huminicki, 1986). It is desirable to know how fast a grain bed would rewet if fans are running during high ambient humidity periods. An in-bin heated-air drying system may also involve rewetting of the top layers of grain because air entering the top layers may have lost its drying potential by picking up moisture from the preceding layers of grain. A deep-bed grain drying simulation model, especially one for the near-ambient or natural air drying simulation, should have provisions to calculate the amount of rewetting. Thin-layer rewetting rates of cereals and oilseeds, therefore, would be the basic input to the deep bed drying simulation models.

To the knowledge of the author, no data exist in the literature on thin-layer rewetting rates of canola seeds. The objectives of this study were: (i) to determine the thin-layer rewetting rates of canola in the temperature range of 7.5 to 30°C which normally prevails during the harvest season in the Canadian Prairies; (ii) to develop a simple model to predict the rewetting rates of canola; and (iii) to investigate the effects of temperature, relative humidity, initial moisture content of canola and air velocity on the rewetting rate of canola.

2. REVIEW OF LITERATURE

2.1 Background

The moisture transfer to or from cereals, oilseeds, and other food materials has been a subject of considerable research in the past 40 years. Data on single-kernel drying or thin-layer drying rates of cereals and oilseeds are required for simulation and design of various drying systems (Brooker et al., 1974). The rewetting rates of cereals and oilseeds were given less attention than drying rates, probably because heated-air drying systems were commonly used where the problem of rewetting does not arise. However, the need for rewetting rate data has been recognized (Jayas et al., 1988) for simulating the possible occurence of rewetting of grain during natural or near-ambient air drying. The rewetting phenomenon is analogous to drying, and theories of drying can be applied to understand and describe the rewetting rates of cereals and oilseeds (Fortes et al., 1981). A review of theories and methods used in collecting and analysing thin-layer moisture transfer data of agricultural grains is given in this chapter.

2.2 Moisture Transfer Theories

Drying of cereals and oilseeds usually takes place in one or more falling rate periods (Brooker et al. 1974) when moisture transport within a kernel controls the overall moisture transfer rate to or from a kernel. Several mechanisms, summarized by Bakker-Arkema et al. (1978), have been suggested in the literature for moisture movement within a capillary-porous body:

1. Liquid diffusion due to moisture concentration gradients.

2. Liquid movement due to capillary forces.

3. Vapor diffusion due to partial vapor-pressure gradients, caused by temperature gradients.

4. Vapor diffusion due to moisture concentration gradients.

5. Liquid or vapor flow due to differences in total pressure.

The moisture transfer within a cereal grain or oilseed is a complex phenomenon. There is no definite knowledge on the mechanisms of moisture transport involved during drying or wetting of cereals and oilseeds and no single theory covers all the possible mechanisms of moisture transport to explain moisture transfer rates to or from a grain (Fortes and Okos, 1980). However, one common approach in analyzing moisture transfer rate data has been to use the liquid diffusion equation for a sphere or any other regular geometric shape which may resemble the grain kernel. Crank (1964) gave the following liquid diffusion equation for a homogeneous and isotropic sphere with radial symmetry:

$$\frac{\partial M}{\partial t} = \frac{1}{r^2}\left[\frac{\partial}{\partial r}(Dr^2 \frac{\partial M}{\partial r}) \right] \qquad \text{------(1)}$$

where: M is moisture content (% dry basis) at any time t (min) and radial distance r (m), and D is the diffusion coefficient (m^2 min^{-1}).

After simplification, Eq. (1) can be rewritten as:

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r} \right] + (\frac{\partial M}{\partial r})^2 \frac{\partial D}{\partial M} \qquad \text{------(2)}$$

Assuming that the diffusion coefficient is independent of moisture content, Eq. (2) becomes:

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r} \right] \qquad \text{------(3)}$$

The moisture content (M) in Eq. (3) can be replaced by moisture ratio (MR), a dimensionless variable, to give:

$$\frac{\partial MR}{\partial t} = D\left[\frac{\partial^2 MR}{\partial r^2} + \frac{2}{r}\frac{\partial MR}{\partial r}\right] \qquad \text{------(4)}$$

where: $MR = \frac{M(t,r) - Me}{Mo - Me}$

and, Me and Mo are equlibrium and initial moisture content, respectively.

The following boundry conditions can be taken:

$MR(t=0,r) = 1$ (moisture is uniformly distributed at time t=0).

$MR(t > 0,R) = 0$ (surface attains equilibrium instantaneously).

$\frac{\partial MR(t,r=0)}{\partial t} = 0$ (moisture ratio at center is finite).

where: R is total radius of sphere.

Arpaci(1966) solved Eq. (4) along with its associated boundary conditions to give:

$$MR(t,r) = \frac{2R}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n}\text{Sin}\left(\frac{n\pi r}{R}\right)\exp\left(-\frac{Dn^2\pi^2}{R^2}t\right) \qquad \text{------(5)}$$

Eq. (5) can be integrated over the volume of the sphere and then division by the total volume of the sphere would give the average MR for the sphere. The averaging procedure yields:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-n^2\pi^2(D/R^2)t) \qquad \text{------(6)}$$

where: $MR = \frac{M-Me}{Mo-Me}$ ------(7)

and, M is average moisture content of the grain at any time, t.

Eq. (6) or its equivalent form for a slab or cylinder have been used by several investigators (Becker and Sallans, 1955; Pabis and Henderson, 1961, 1962; Henderson and Pabis, 1961, 1962; Bakker-Arkema and Hall, 1965; Chittenden and Hustrulid, 1966; Hamdy and Johnson, 1968; Hamdy and Barre, 1969; Hustrulid, 1962, 1963; Young and Whitaker, 1971; Whitaker and Young, 1972; Rowe and Gunkel, 1972; Watson and Bhargava, 1974; Henderson 1974; Osborn et al., 1988) to describe the thin-layer moisture transfer rate data for various agricultural grains. The liquid diffusion equation (Eq. 3), however, has been shown to give inaccurate predictions of moisture transfer data (Fortes and Okos, 1980, 1981a; Bakker-Arkema et al., 1978). The apparent success of Eq. (3) in describing thin-layer moisture transfer data in some cases may be due to its logarithmic form which resembles a typical grain drying or rewetting curve. Theoretically Eq. (3) would give unrealistic representation of data (Fortes et al., 1981) because:

1. Liquid diffusion can not take place when there is no moisture continuity inside the kernel. Liquid diffusion, therefore, can not be used to explain moisture transport in conditions of low moisture content.
2. The liquid diffusion equation assumes no coupling between heat and moisture transfer processes which may not always be the case in reality.
3. The liquid diffusion equation does not take into account other possible mechanisms of moisture transport which may simultaneously be occuring during drying or rewetting of cereals or oilseeds.

A definite improvement in moisture transfer predictions would result if the liquid diffusion coefficient is taken as a function of moisture content and the solution of Eq. (2) is used. Bruce (1985) followed this approach and solved Eq. (2) numerically to model single kernel drying of barley. He found accurate predictions for his experimental drying data. This suggests that liquid diffusion may be the predominant moisture transport mechanism. A more complete theoretical analysis of heat and moisture transfer phenomena in capillary-porous bodies, including cereals and oilseeds, was given by Fortes and Okos (1981a,b). They derived the following equations using the principles of irreversible thermodynamics and the mechanistic approach to heat and mass transfer in porous media.

liquid flux:

$$J_\ell = -\rho_\ell K_\ell \ell n(H)\nabla T' - \rho_\ell K_\ell \frac{R_v T'}{H}\frac{\partial H}{\partial M}\nabla M \qquad \text{------(8a)}$$

vapor flux:

$$J_v = -K_v\left(\rho_{vo}\frac{\partial H}{\partial T'} + H\frac{d\rho_{vo}}{dT'}\right)\nabla T' - K_v\rho_{vo}\frac{\partial H}{\partial M}\nabla M \qquad \text{------(8b)}$$

heat flux:

$$J_q = -K_t\nabla T' - \left[\rho_\ell K_\ell R_v \ell n(H) + K_v\left(\rho_{vo}\frac{\partial H}{\partial T'} + H\frac{d\rho_{vo}}{dT'}\right)\right]\frac{R_v T'^2}{H}\frac{\partial H}{\partial M}\nabla M \qquad \text{------(8c)}$$

mass conservation:

$$\rho_s\frac{\partial M}{\partial T'} = -\nabla(J_\ell + J_v) \qquad \text{------(8d)}$$

energy conservation:

$$\rho_s c_b\frac{\partial T'}{\partial t} - \rho_s L_w\frac{\partial M}{\partial t} = -\nabla J_q - L_v\nabla J_v \qquad \text{------(8e)}$$

where: J_ℓ = liquid flux, kg m^{-2} s^{-1}

J_q = heat flux, J m^{-2} s^{-1}

J_v = vapor flux, kg m^{-2} s^{-1}

K_ℓ = liquid conductivity, s^{-1}

K_t = apparent thermal conductivity, W m^{-1} K^{-1}

K_v = vapor conductivity, m^2 s^{-1}

L_v = specific latent heat of vaporization, J kg^{-1}

L_w = specific differential heat of wetting, J kg^{-1}

Rv = universal gas constant for water vapor, J kg^{-1} K^{-1}

T' = thermodynamic temperature, K

H = relative humidity, decimal

c_b = specific heat of body, J kg^{-1} K^{-1}

ρ_ℓ = liquid density, kg m^3

ρ_s = dry solid density, kg m^3

ρ_{vo} = saturated vapor density, kg m^3

Fortes and Okos (1981a,b) used the above set of equations to describe the drying rates of corn and drying and rewetting rates of wheat successfully. They found that liquid flux was dominant in low temperature (26 to 47 °C) drying or rewetting of wheat and corn. In high temperature (100°C or higher) drying, vapor flux was of a higher order of magnitude than liquid flux throughout the entire drying period.

The theoretical equations described above and others in the literature (Berger and Pei, 1973; Luikov, 1966a,b, 1975; Mikhailov, 1973; Miller and Miller, 1955; Philip and De Vries, 1957; De Vries, 1958; Henry, 1939; Whitney and Porterfield, 1968; Young, 1969) are helpful in explaining the complex phenomenon of moisture movement inside capillary-porous bodies such as grain and for predicting the moisture profile within a kernel (Bruce, 1985; Fortes and Okos, 1981a) but they are often inconvenient and inefficient for use in deep-bed simulation models (Parry, 1985). Several researchers, therefore, have preferred to use simple semi-empirical or empirical equations for modelling thin-layer drying or rewetting of cereals and oilseeds.

2.3 Semi-Empirical and Empirical Equations

Analogous to Newton's law of cooling, Lewis (1921) suggested the following equation for description of the drying of a solid:

$$\frac{dM}{dt} = -k(M-Me) \qquad \text{------(9)}$$

where: k = drying constant, min^{-1}.

Upon integration, Eq. (9) becomes:

$$\frac{M(t) - Me}{Mo - Me} = MR = \exp(-k.t) \qquad \text{------(10)}$$

Eq. (9) (or Eq. (10)) is also based on liquid diffusion theory discussed earlier in this chapter but assumes that all the resistance to moisture transfer occurs in a thin outer layer of the kernel (Chittenden and Hustrulid, 1966). Eq. (10) has been widely used in grain drying simulation (Parry, 1985). However, it does not describe drying rate accurately over the complete drying period (Sokhansanj et al., 1987; Jayas et al., 1988).

Page (1949) modified Eq. (10) for better representation of his thin-layer drying data for shelled corn:

$$MR = \exp(-k.t^{n}) \qquad \text{------(11)}$$

where k and n are moisture transfer rate parameters.

Upon differentiation, Eq. (11) becomes:

$$\frac{dM}{dt}\frac{1}{Mo-Me} = \exp(-k.t^{n})(-n.k.t^{n-1})$$

Substitution from Eq (11) gives:

$$\frac{dM}{dt} = -n.k.t^{n-1}(M - Me) \qquad \text{------(12)}$$

Eq. (12) takes into account the concept of moisture transfer due to liquid diffusion with resistance to moisture transfer occuring in a thin outer layer of the kernel because it contains the terms used in Eq. (9). In addition, it shows that moisture transfer rate depends on time elapsed. It seems that effects of other factors (such as the presence of vapor flux due to temperature gradients, irregular shape and anisotropy of kernels, shrinkage or expansion of kernels) on moisture transfer are lumped together by making moisture transfer rate a function of time which gives the equation good prediction capability. In the case of low temperature drying or rewetting of grains, other factors affecting the moisture transfer rate may be product-dependent because liquid diffusion due to concentration gradient is the dominant moisture transport mechanism (Fortes and Okos, 1981a,b). Therefore, for low temperature drying or rewetting of cereals and oilseeds, parameter n of Eq. (11) or (12) can be assumed as a product-dependent constant. This assumption will make it easy to compare the effects of independent variables, such as temperature and relative humidity, on the moisture transfer rates by direct comparison of parameter k of Eq. (11) which otherwise is not possible because of the random adjustments in the parameters to give the best fitting curve (Jayas et al., 1988).

Many investigators (Sabbah, 1968; White et al., 1973; Agrawal and Singh, 1977; Misra and Brooker, 1980; Duggal et al., 1982; Hutchinson and Otten, 1982; Farmer et al., 1983; Syarief et al., 1984; Sokhansanj et al., 1984b; Bruce, 1985; Li et al., 1987; Osborn et al., 1988) have successfully used Eq. (11) to describe the thin-layer drying or wetting rates of various cereal grains and oilseeds. Based on the analysis of the data from various sources and using several different thin-layer moisture transfer models, Misra (1978) found that Eq. (11) was the most promising model for predicting drying and rewetting rates of shelled yellow corn. Syarief et al. (1984) found Eq. (11) to be the best for modelling thin-layer drying rates of sunflower seeds. Osborn et al. (1988) found a modified form of Eq. (11) to be the best for predicting the rewetting rates of soybean. Several other empirical equations have been developed and used by grain drying researchers. A comprehensive review of thin-layer moisture transfer equations is given by Sokhansanj et al. (1987).

2.4 Effect of Independent Variables on Moisture Transfer Rates

Four independent variables generally used in studies of thin-layer drying and rewetting rates for cereals and oilseeds are temperature, relative humidity, velocity of air and initial moisture content of grain. Temperature has the most significant effect on moisture transfer rates (Misra and Brooker, 1980; Syarief et al., 1984; Jayas and Sokhansanj, 1986; Osborn et al., 1988). Relative humidity of air has a significant effect on drying and rewetting rates especially at temperatures below 70°C (Park et al., 1971; Misra and Brooker, 1980; Sokhansanj et al., 1987). Air velocity does not seem to have any significant effect on moisture transfer rate if it is above a critical value of about 0.16 m/s (Simmonds et al., 1953; Chittenden and Hustrulid, 1966; Rugumayo, 1979; Misra, 1978; Hutchinson and Otten, 1982; Jayas and Sokhansanj, 1986). At sufficiently high velocities, the boundary layer would be very thin and therefore resistance to moisture flow due to the boundary layer would be negligible. There is no single opinion on the effect of initial moisture content of grain on moisture transfer rates. Some researchers (Park et al., 1971; Sharaf-

Eldeen et al., 1980) found that initial moisture content affects moisture transfer rates considerably whereas some other researchers (Syarief et al., 1984; Osborn et al., 1988) reported that initial moisture content does not have an appreciable effect on moisture trasfer rates.

The diffusion coefficient, D, in Eq. (6) is generally expressed as a function of temperature in an Arrhenius type relationship:

$$D = C_1 \exp(-\frac{C_2}{T'})$$

where: C_1 and C_2 are product-dependent constants and T' is temperature (K).

The parameters of Eq. (10) or (11) have also been related to independent variables. Different researchers have used different relationships for this purpose. A detailed list of such relationships along with the range of values for independent variables used by different researchers is given by Sokhansanj et al. (1987).

Different grains have different moisture transfer characteristics. Kreyger (1972) compared the ability to release moisture for a number of agricultural seeds. He classified broad beans, green peas, maize (corn) and lupines as slow drying seeds, wheat, rye, and oats as normal drying, and ryegrass, sugarbeet seed and rapeseed (canola) as quick drying seeds. At 20% moisture content (wet basis) the ability of rapeseed to release moisture was about 15 times higher than that of corn and 10 times higher than that of wheat. These differences in moisture transfer rates of different grains may be due to different composition and thicknesses of pericarp, aleurone layer, endosperm and germ. More research is needed to determine the resistance to moisture flow of different parts of a grain kernel. Very limited research has been done to study the effects of different varieties of a crop on drying or rewetting rates. Li et al. (1987) reported that different varieties of sunflower seeds with different oil contents had the same drying rates.

Methods and Equipment for Thin-Layer Moisture Transfer Tests

The equipment used for thin-layer moisture transfer studies were either a vertical type or a horizontal type (Sokhansanj et al., 1984a). In the vertical type equipment, the thin layer of sample was kept in a horizontal plane and air flow across the sample was in a vertical direction, whereas in the horizontal type equipment the thin layer of sample was kept in a vertical plane and air flow across the sample was in a horizontal direction. A comparision of the two types of equipment is given in detail by Sokhansanj et al. (1984a). Continuous weighing of samples can not be done in vertical type equipment because the weight readings are affected by the air lift. Either air flow has to be stopped or the sample has to be removed from the air stream to get the correct weight readings. The problem of weight lift did not occur in horizontal type equipment. The air velocity profile was more uniform in the vertical type equipment than that in horizontal type but this difference did not significantly affect the drying rates.

Sample preparation is an important aspect of thin-layer drying or rewetting tests. The most common and easy way to prepare a sample for a test is by either drying or remoistening the samples artificially. Such artificially prepared samples must be kept for sufficient time in a sealed container for uniform distribution of moisture in the seeds.

Hustrulid (1962,1963) found that frozen samples of corn and wheat dried at the same rate as naturally moist samples. For artificially moistened samples, he found that the drying rate was slightly faster in the beginning but later it dried at the same rate as naturally moist samples. Sokhansanj et al. (1984b) compared the drying rates of wheat, barley and canola subjected to repetitive wetting and drying cycles. For all three grains they found a definite change in drying rates between freshly harvested and first time rewetted grain. Further research is needed to quantify the effect of artificial drying or remoistening of samples on their drying and rewetting rates for all important cereals and oilseeds.

3. EXPERIMENTAL DESIGN

The important factors in the study were air temperature and air relative humidity. A 2X4 factorial design was planned using two relative humidity (RH) levels (80 and 90%) and four temperature levels (7.5, 15.0, 22.5 and 30.0°C). Three replications at each combination of temperature and relative humidity were done. Due to the limitations of the Climate-Lab-AA unit, the minimum temperature reached at 90% RH was 16°C. Therefore, tests were done at 16°C instead of 15°C and no test could be done at 7.5°C when the relative humidity level was 90%. The initial moisture content of the seed and the air velocity were kept constant in all tests at 7.0%, wb, and 0.43 m/s, respectively, to eliminate any variation from these two sources. Separate experiments were done at initial moisture contents of 5.0, 7.0 and 10%, wb, at 90% RH, 30°C temperature and 0.43 m/s air velocity to observe any significant effect of initial moisture content on rewetting of canola. Three replicates at each initial moisture content were done. Experiments were also done at 0.10, 0.25 and 0.43 m/s air velocity when other variables were kept constant (90% RH, 30°C temperature and 7.0% initial moisture content). Three replicates at each air velocity were carried out.

4. MATERIALS AND METHODS

4.1 Experimental Wetting Unit

A schematic drawing of the experimental unit used in thin-layer rewetting experiments is shown in Fig. 4.1 The unit consisted of a Climate-Lab-AA (C-L-AA) unit (Parameter Generation and Control, Inc. Black Mountain, NC), mixing and wetting chambers, a sample holder, an electronic weighing balance, and duct work. The air was conditioned to a desired relative humidity and temperature by the C-L-AA unit. The C-L-AA unit contained a water bath with heating and cooling coils immersed in the water. The water temperature was controlled electronically. Water was forced through spray nozzles which created a fine mist of water. Air was passed through the mist. Heat and water vapor transfer between droplets and air through a thin film of saturated air clinging to each droplet continued until an equilibrium condition was reached. This allowed control of air relative humidity through control of water temperature. The air was then heated to the desired dry-bulb temperature by electric heaters.

The conditioned air was delivered to the wetting chamber through the duct work and the mixing chamber. The wetting chamber was about 96 cm long and had a flow area of 122500 mm^2 (350 mm X 350 mm). The mixing chamber was 600 mm X 60 mm X 60 mm. A honeycomb screen was fitted at the inlet of the wetting chamber to smooth out the air velocity pattern. The sample holder was made of two detachable square frames with brass screens. The brass screens of the sample holder were supported by honeycomb screens. The sample holder was placed in an

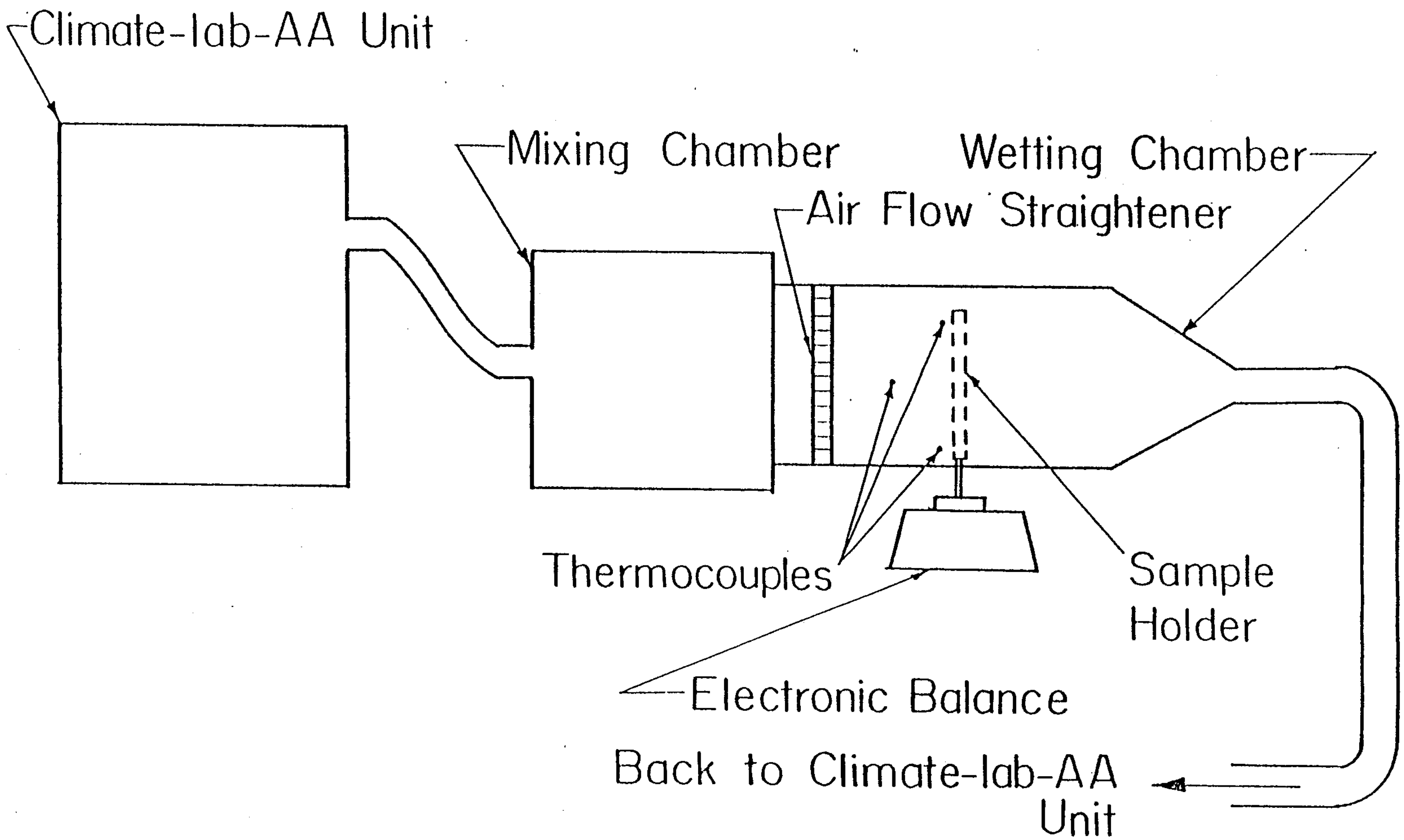

Fig. 4.1—Schematic of the Experimental thin—layer wetting unit

upright position with the thin layer of the sample held tightly in the vertical plane and exposed fully to the air flow. The stem of a frame supporting the sample holder was passed through a hole in the floor of the wetting chamber and rested on the platform of the weighing scale. The edges of the supporting frame were kept 25 mm clear from the side walls of the wetting chamber. The air from the outlet of the wetting chamber was recirculated to the C-L-AA unit to complete the air cycle. A by-pass duct with a slide gate and a by-pass valve was attached between the inlet and outlet ports of the C-L-AA unit. The slide gate and the by-pass valve were used to change the air velocity.

The temperature and relative humidity of the conditioned air were measured with a humidity and temperature probe (HMP 31UT Vaisala Oy, Helsinki, Finland). The temperature was also measured by a mercury-in-glass thermometer, and three type T thermocouples located 10 cm away from the top and bottom of the sample holder and 35 cm away from the middle of the sample holder (Fig. 4.1). The humidity sensor was calibrated once every two months using saturated salt solutions of lithium chloride (12% RH), sodium chloride (75% RH) and potassium sulphate (97% RH), with a HMK11 calibrator (Vaisala, Oy, Helsinki, Finland). The air velocity was measured by traversing a hot wire anemometer (Air Flow Measurements, Missisauga, ON) and taking the average of the air velocity at six equidistant points in the cross section of the wetting chamber. A Corona personal computer was used for on-line recording of the change in the mass of the wetting sample. The thermocouple readings were also recorded by the computer.

4.2 Sample Preparation

The canola, *B. campestris* L., used in the experiments was cultivar Tobin which is widely grown in Canada. Clean canola seed at about 6.0% moisture content, wb, was purchased from a local seed supplier. The seed were remoistened to the desired initial moisture contents for a test by sprinkling predetermined quantities of distilled water on a sufficient sample size of canola for a test. The remoistened sample was kept in a sealed container and tumbled gently but constantly for the first hour after adding the water to ensure uniform and complete mixing. The sample was then kept at least for another 48 h at room temperature with occasional tumbling. Sokhansanj et al. (1983) found that the artificially remoistened canola requires less than 2 h of tempering at 25°C for the even distribution of moisture in the seed. The initial moisture content of the sample was measured prior to the beginning of each test. All the moisture content determinations were done according to the procedure outlined in the ASAE standard S 352.1 (ASAE, 1987) by drying samples for 4 h at 130°C in an air convection oven.

4.3 Test Procedure

The C-L-AA unit was turned on and the air conditions for a test set, at least 24 h before the test was to begin. Minor adjustments in the settings were made before starting the test to achieve the desired conditions accurately. The sample size for all the tests was 140 g. This sample size was sufficient to form a one-kernel-thick layer on the screen of the sample holder. The canola sample was spread over the screen of a frame of the sample holder. The two frames of the sample holder were then clamped together at the sides and bottom using three plastic clamps and at the top using two metallic clamps. Some kernels slid as the sample holder was placed in the upright position in the wetting chamber and the actual thin-layer used in the tests was one to two kernels thick. A data acquisition program was started as soon as the loaded sample holder was placed inside the wetting chamber. The data on gain in mass of the sample with time and thermocouple readings were stored on diskettes.

Based on the trial runs of up to 46 or 70 h, it was concluded that 23 h of test run was sufficient for canola samples to reach equilibrium moisture at 15°C or higher. At 7.5°C, 46 h were required to reach equilibrium moisture. Accordingly, the tests were run for 23 h at 15°C or more and for 46 h at 7.5°C. The final moisture contents of the samples were determined after each test was over.

5. RESULTS AND DISCUSSION

5.1 Thin-layer rewetting and EMC data

Thin-layer rewetting-rate data for canola, in terms of change in moisture ratio (MR) and moisture content (dry mass basis) with time at different temperature and relative humidity combinations, are given in Appendix A (Tables A1 to Table A21). Raw data are included to facilitate further data analysis by other researchers in the future. The values of MR were calculated using Eq. (7). The final moisture content obtained in each test was taken as the equilibrium moisture content (EMC) for the test. The values of average equilibrium moisture content from three replicates done at different combinations of temperatures and relative humidities are given in Table 5.1.

Jayas et al. (1988) suggested that an investigator conducting thin-layer moisture transfer experiments should determine his own EMC values to eliminate most sources of variation affecting EMC values such as surface properties, physical structure, and prior moisture history of grain and volume changes during moisture sorption. If a thin-layer moisture transfer experiment is run for a sufficiently long time to allow grain to reach near-equilibrium moisture content, then any variation due to different methods of EMC determination would also be eliminated.

5.2 Comparison between liquid diffusion and Page's equation

The solution of the liquid diffusion equation for an isotropic and homogeneous sphere (Eq. (6)) and Page's equation (Eq. (11)) are the two commonly used equations to describe drying or rewetting of cereals and

Table 5.1. Adsorption equilibrium moisture contents of canola.

Temperature (°C)	RH (%)	Equilibrium moisture content, %db Mean (%)	S.D.* (%)
7.5	80	13.9	0.21
15.0	80	12.7	0.13
22.5	80	12.0	0.13
30.0	80	11.2	0.10
16.0	90	17.7	0.34
22.5	90	17.0	0.31
30.0	90	14.0	0.53

* S.D. is standard deviation based on three replicates

oilseeds. Nonlinear regressions were carried out using procedure NLIN of SAS (1985) to fit the data of four typical rewetting tests, T90301 (test conducted at 90% RH, 30°C, replicate# 1), T90161 (test conducted at 90% RH, 16°C, replicate# 1), T80221 (test conducted at 80% RH, 22.5°C, replicate# 1), and T80071 (test conducted at 80% RH, 7.5°C, replicate# 1), to both Eq. (6) and Eq. (11), separately. The two equations were compared for their ability to describe the experimental data. The criteria used to determine the better fitting equation were lower values of standard error (S.E.) of MR and randomness in residuals. Eq. (6) is in terms of an infinite series. However, to use Eq. (6) in nonlinear regression the infinite series was approximated by taking summation of the first 40 terms in the series. For typical test data, the value of S.E. of MR did not change at the fourth decimal place when the number of terms in the infinite series of Eq. (6) were increased beyond 40. Hence, 40 terms were adequate to approximate the infinite series of Eq. (6). The values of S.E. of MR obtained for the best nonlinear fit for four typical test data-sets using Eq. (6) with 40 term series and Eq. (11) are given in Table 5.2. The residual plots of MR obtained with Eq. (6) and Eq. (11) for a typical rewetting test are given in Fig. 5.1 and 5.2, respectively. The values of S.E. of MR for the liquid diffusion equation (Eq. (6)) were much higher than those for Page's equation (Eq. (11)) (Table 5.2 and, Fig. 5.1 and 5.2). Further, the residual plot for the liquid diffusion equation was patterned whereas residuals of Page's equation were randomly scattered. Therefore, it can be concluded that Page's equation is a better model

Table 5.2 Standard error of moisture ratio for the liquid diffusion and Page's equation.

Test	Temp (°C)	RH (%)	Equation: liquid diffusion	Equation: Page
T90301	30.0	90	0.0332	0.0104
T90161	16.0	90	0.0544	0.0079
T80221	22.5	80	0.0424	0.0082
T80071	7.5	80	0.0426	0.0083

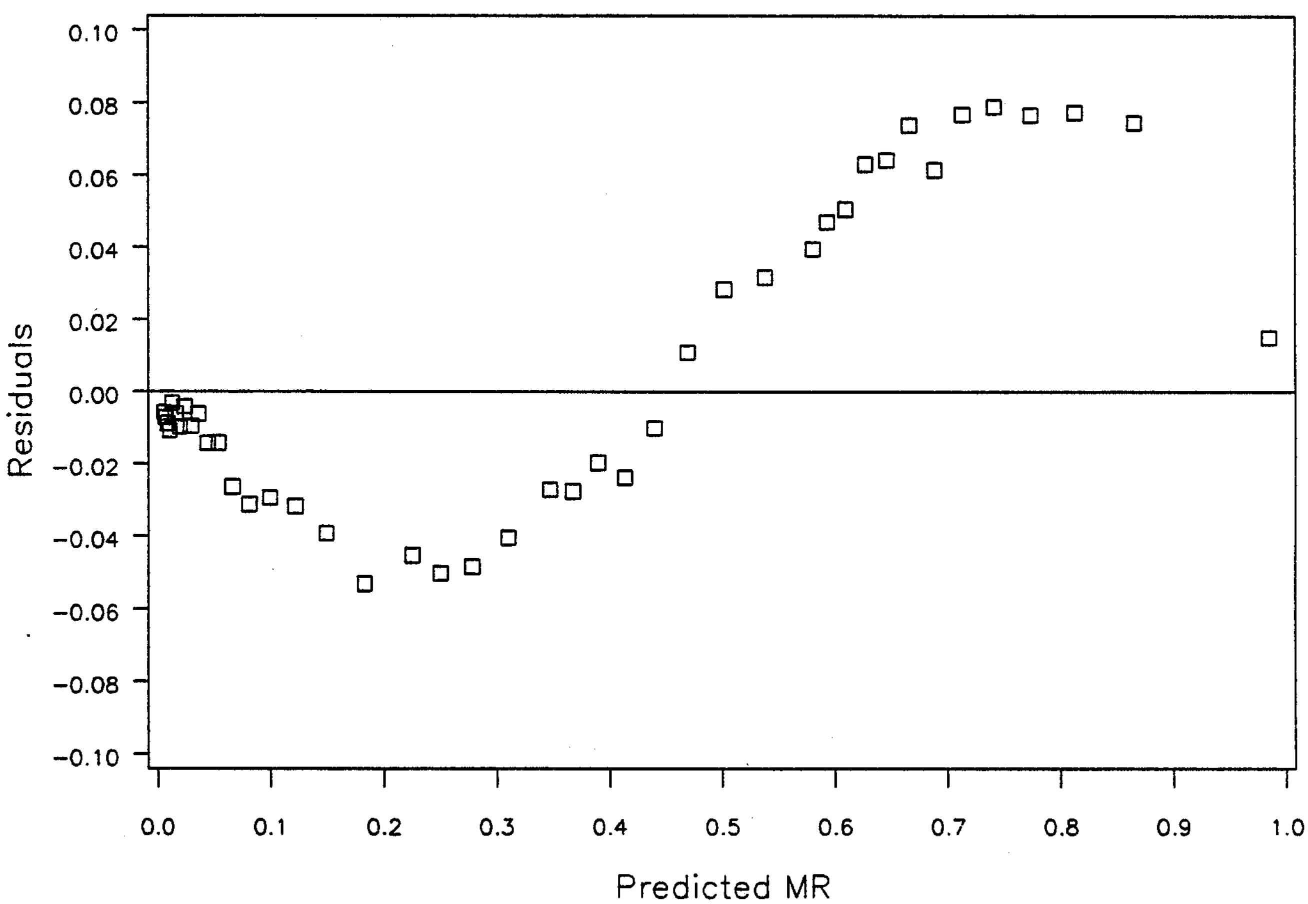

Fig. 5.1—Residual plot obtained with liquid diffusion equation for typical rewetting test data—set, T80221.

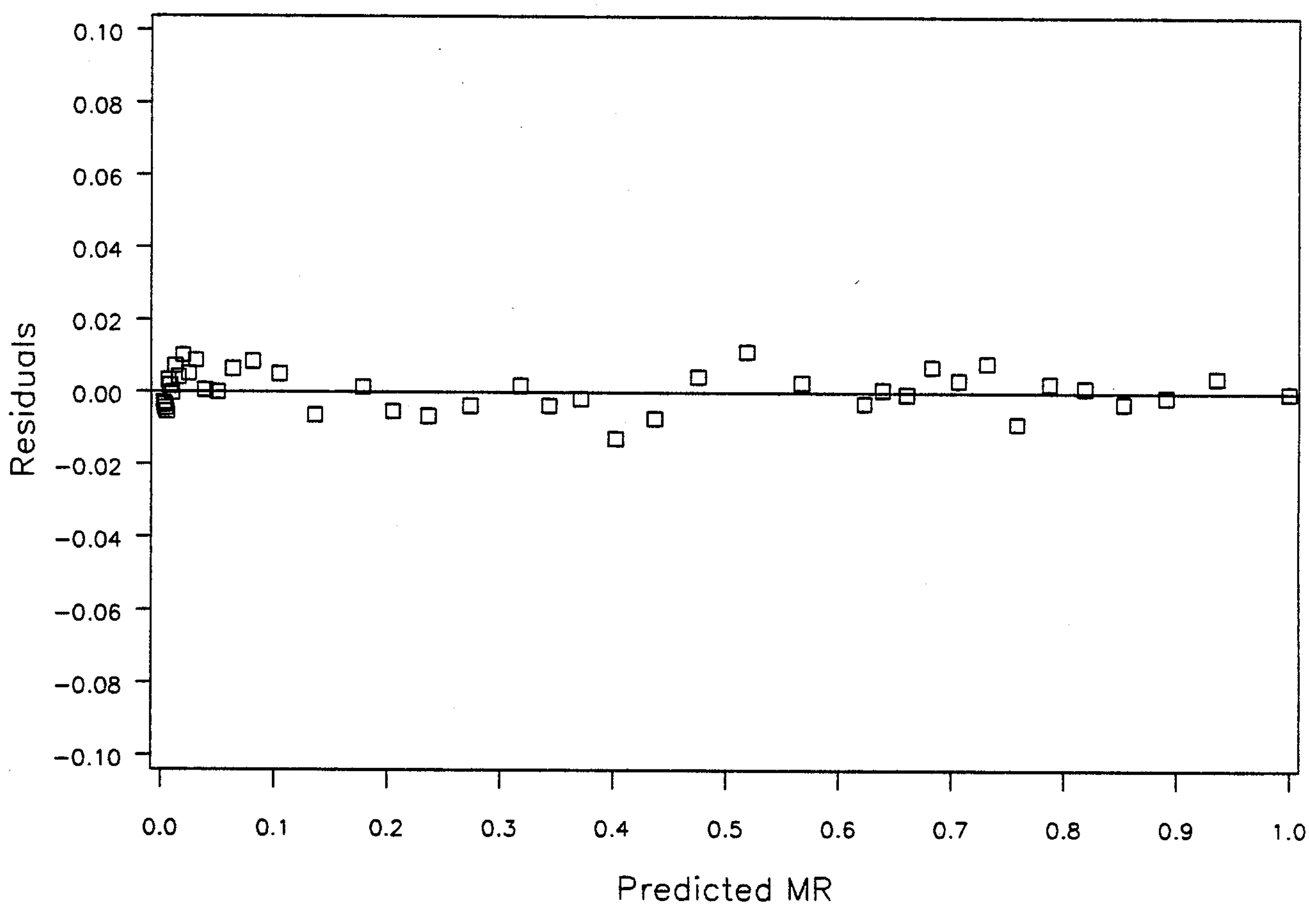

Fig 5.2—Residual plot obtained with Page's equation for typical rewetting test data—set, T80221.

for describing the rewetting rates of canola. Only Page's equation was used in further data analysis in this study.

5.3 Wetting parameters of Page's equation

Nonlinear regression, using procedure NLIN of SAS (1985), was done to estimate parameters k and n of Eq. (11). The values of parameters k and n of Eq. (11) and the corresponding S.E. of MR obtained by the regresion are given in Table 5.3. Page's equation described the experimental rewetting rate of canola at all the temperatures and relative humidities very well with S.E. of MR less than 0.01 in all but two tests (Table 5.3). The predicted and observed values of moisture content (dry mass basis) for typical rewetting tests at different combinations of temperature and relative humidity are shown in Appendix B (Fig. B1 to B9). Fig. B1 to B9 further illustrate that Page's equation described the experimental data successfully at all temperature and relative humidity combinations.

Based on the analysis of variance done using procedure GLM of SAS, the parameter n did not vary significantly with the temperature ($p > 0.05$). Hence the parameter n was averaged over all temperatures at 80 and 90% RH, separately. The average values of n were 0.790 and 0.856 at 80 and 90% RH, respectively. The modified k values and the corresponding S.E. of MR when the average values of n were used, are given in Table 5.4. The S.E. of MR was less than 0.01 for all but three tests which shows that the prediction of rewetting rates with average values of n was good. The k values from Table 5.4 can be compared between different temperature levels to show the effect of temperature on the rewetting rate. In the treatments among which

TABLE 5.3 The parameters k and n of Page's equation for thin-layer rewetting rates of canola.

Test No.	Temp.* (°C)	RH** (%)	k	n	S.E.***
1	30.0	90	0.0349	0.771	0.0104
2	30.0	90	0.0244	0.882	0.0057
3	30.0	90	0.0236	0.900	0.0008
4	22.5	90	0.0231	0.819	0.0072
5	22.5	90	0.0173	0.881	0.0045
6	22.5	90	0.0186	0.872	0.0058
7	16.0	90	0.0132	0.854	0.0079
8	16.0	90	0.0126	0.860	0.0061
9	16.0	90	0.0126	0.867	0.0049
10	30.0	80	0.0339	0.774	0.0082
11	30.0	80	0.0380	0.745	0.0099
12	30.0	80	0.0351	0.760	0.0085
13	22.5	80	0.0184	0.796	0.0056
14	22.5	80	0.0193	0.801	0.0082
15	22.5	80	0.0245	0.769	0.0059
16	15.0	80	0.0117	0.814	0.0071
17	15.0	80	0.0161	0.784	0.0083
18	15.0	80	0.0114	0.834	0.0134
19	7.5	80	0.0087	0.782	0.0083
20	7.5	80	0.0078	0.831	0.0067
21	7.5	80	0.0089	0.793	0.0086

* Temperature varied ±2°C

** Relative humidity varied ±3%

*** S.E. - standard error of moisture ratio

TABLE 5.4 The modified values of parameter k of Page's equation when the average values of parameter n are used.

Test No.	Temp.* (°C)	RH** (%)	k	S.E.***
1	30.0	90	0.0243	0.0177
2	30.0	90	0.0272	0.0068
3	30.0	90	0.0283	0.0078
4	22.5	90	0.0196	0.0095
5	22.5	90	0.0194	0.0061
6	22.5	90	0.0200	0.0063
7	16.0	90	0.0131	0.0078
8	16.0	90	0.0128	0.0068
9	16.0	90	0.0133	0.0078
10	30.0	80	0.0317	0.0086
11	30.0	80	0.0314	0.0125
12	30.0	80	0.0316	0.0104
13	22.5	80	0.0189	0.0056
14	22.5	80	0.0202	0.0083
15	22.5	80	0.0222	0.0073
16	15.0	80	0.0133	0.0088
17	15.0	80	0.0156	0.0083
18	15.0	80	0.0144	0.0162
19	7.5	80	0.0083	0.0084
20	7.5	80	0.0098	0.0105
21	7.5	80	0.0091	0.0086

* Temperature varied ±2°C

** Relative humidity varied ±3%

*** S.E. - standard error of moisture ratio

Note: At 80% RH, average n = 0.790
At 90% RH, average n = 0.856

parameter n is the same, a higher value of parameter k corresponds to a faster rewetting rate. At 80% RH, the rewetting rate increased sharply between 7.5 and 15.0°C (58% increase in k), a bit slowly between 15.0 and 22.5°C (42% increase in k) and sharply again between 22.5 and 30.0°C (54% increase in k). At 90% RH, the k value increased by 50% between 16.0 and 22.5°C and by 35% between 22.5 and 30°C.

5.3.1 Parameter n as a product-dependent constant

As discussed in chapter 2, parameter n of Eq. (11) may be assumed as a product-dependent constant for low temperature drying or rewetting of cereals and oilseeds. The assumption makes it possible to compare the effects of temperature and relative humidity on rewetting rates by direct comparisons of parameter k. For further analysis, the overall average value of n from all the 21 tests was assumed as a product-dependent constant for the rewetting of canola. The overall average for n was 0.818. Table 5.5 shows the values of parameter k for all the tests when the parameter n was fixed at 0.818, and the corresponding S.E. of MR values. The S.E. of MR values did not exceed 0.016 for any test, therefore, the assumption of taking n as a product-dependent constant seems valid for representing the rewetting rate data of canola. Maximum S.E. of MR was obtained for test 11 (Table 5.5) conducted at 80% RH and 30°C temperature. Fig. 5.3 shows the observed moisture content and the moisture content predicted by Page's equation when the value of parameter n was 0.818, for test 11. The difference between observed and predicted moisture content did not exceed 0.3 percentage points (Fig. 5.3). This further suggests that assumption of

TABLE 5.5 The modified values of parameter k of Page's equation when an overall average value of n = 0.818 is used.

Test No.	Temp.* (°C)	RH** (%)	k	S.E.***
1	30.0	90	0.0286	0.0130
2	30.0	90	0.0318	0.0114
3	30.0	90	0.0332	0.0133
4	22.5	90	0.0232	0.0071
5	22.5	90	0.0231	0.0117
6	22.5	90	0.0237	0.0107
7	16.0	90	0.0158	0.0104
8	16.0	90	0.0155	0.0101
9	16.0	90	0.0160	0.0105
10	30.0	80	0.0281	0.0111
11	30.0	80	0.0279	0.0159
12	30.0	80	0.0280	0.0126
13	22.5	80	0.0166	0.0069
14	22.5	80	0.0178	0.0087
15	22.5	80	0.0195	0.0112
16	15.0	80	0.0114	0.0071
17	15.0	80	0.0135	0.0109
18	15.0	80	0.0124	0.0136
19	7.5	80	0.0070	0.0114
20	7.5	80	0.0084	0.0071
21	7.5	80	0.0078	0.0099

* Temperature varied ±2°C

** Relative humidity varied ±3%

*** S.E. - standard error of moisture ratio

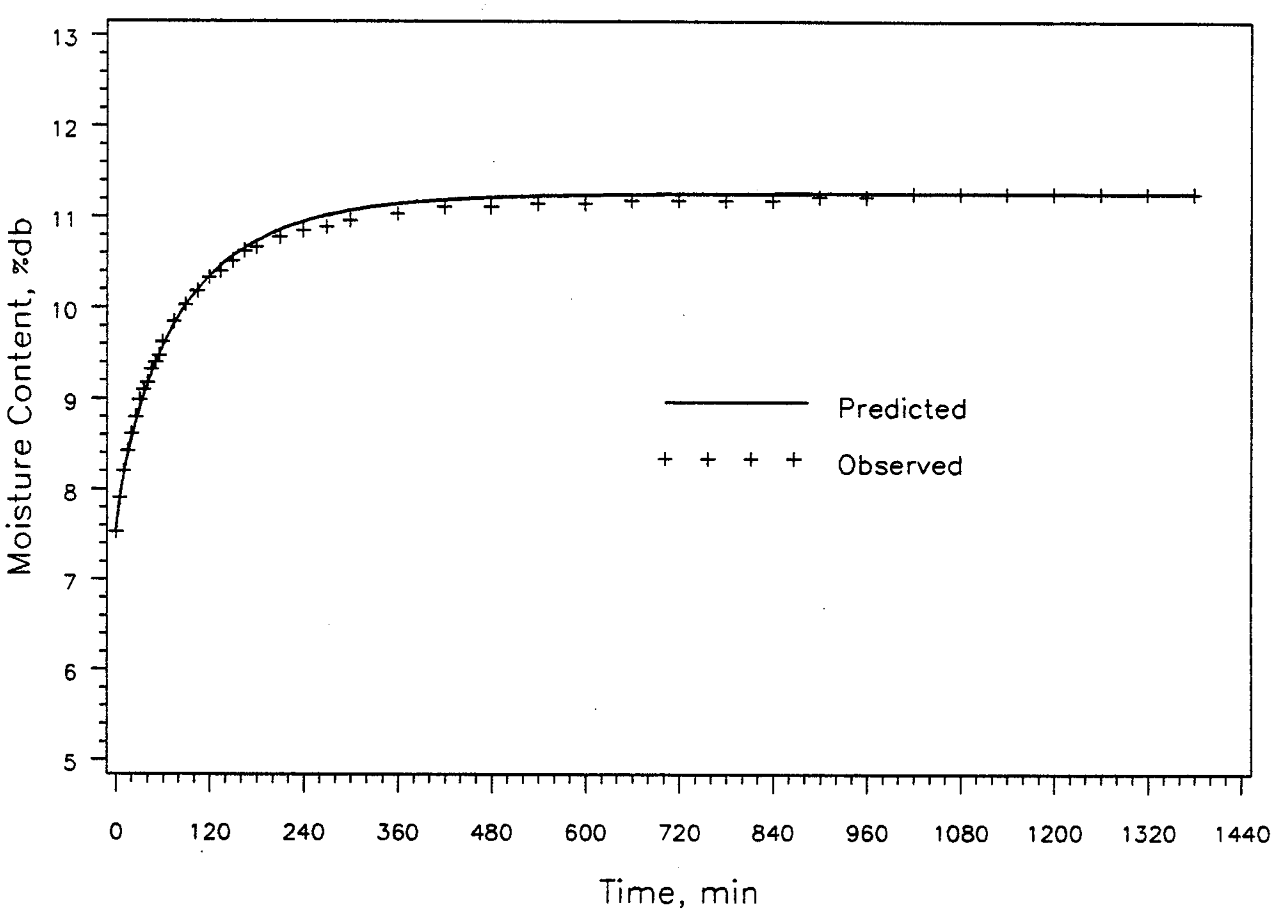

Fig. 5.3—Experimental wetting rate and the wetting rate predicted by Page's equation when n=0.818, for test 11 conducted at temperature=30°C, relative humidity=80% and air velocity=0.43 m/s.

taking n as product-dependent constant did not affect the accuracy of prediction appreciably.

5.4 Effects of temperature and relative humidity on rewetting

Analysis of variance was carried out to see the effects of temperature, relative humidity and interaction between temperature and relative humidity on the rewetting rate of canola. The interaction term was first included in the ANOVA model. The effect of interaction was not significant ($p > 0.05$). Therefore, the interaction term was dropped from the model and analysis of variance was re-done. Both temperature and relative humidity had a significant effect ($p < 0.05$) on rewetting rate of canola. Fig. 5.4 and 5.5 also illustrate the significant effect of temperature and relative humidity on the rewetting rate of canola.

5.4.1 Relating wetting parameter k with temperature and RH

To quantify the effect of temperature and relative humidity on the rewetting rate of canola, the procedure GLM of SAS was used to find a linear relationship between k as a dependent variable (Table 5.5), and temperature and relative humidity as independent variables. The relationship obtained was:

$$k = - 0.0257 + 0.00094\ T + 0.00031\ RH \qquad ------(13)$$

where:

T = temperature, °C

RH = relative humidity, %.

The value of r^2 obtained in the linear regression was 0.96 indicating a good fit. The p value associated with the coefficient of temperature in Eq. (13) was 0.0001 whereas p value associated with the

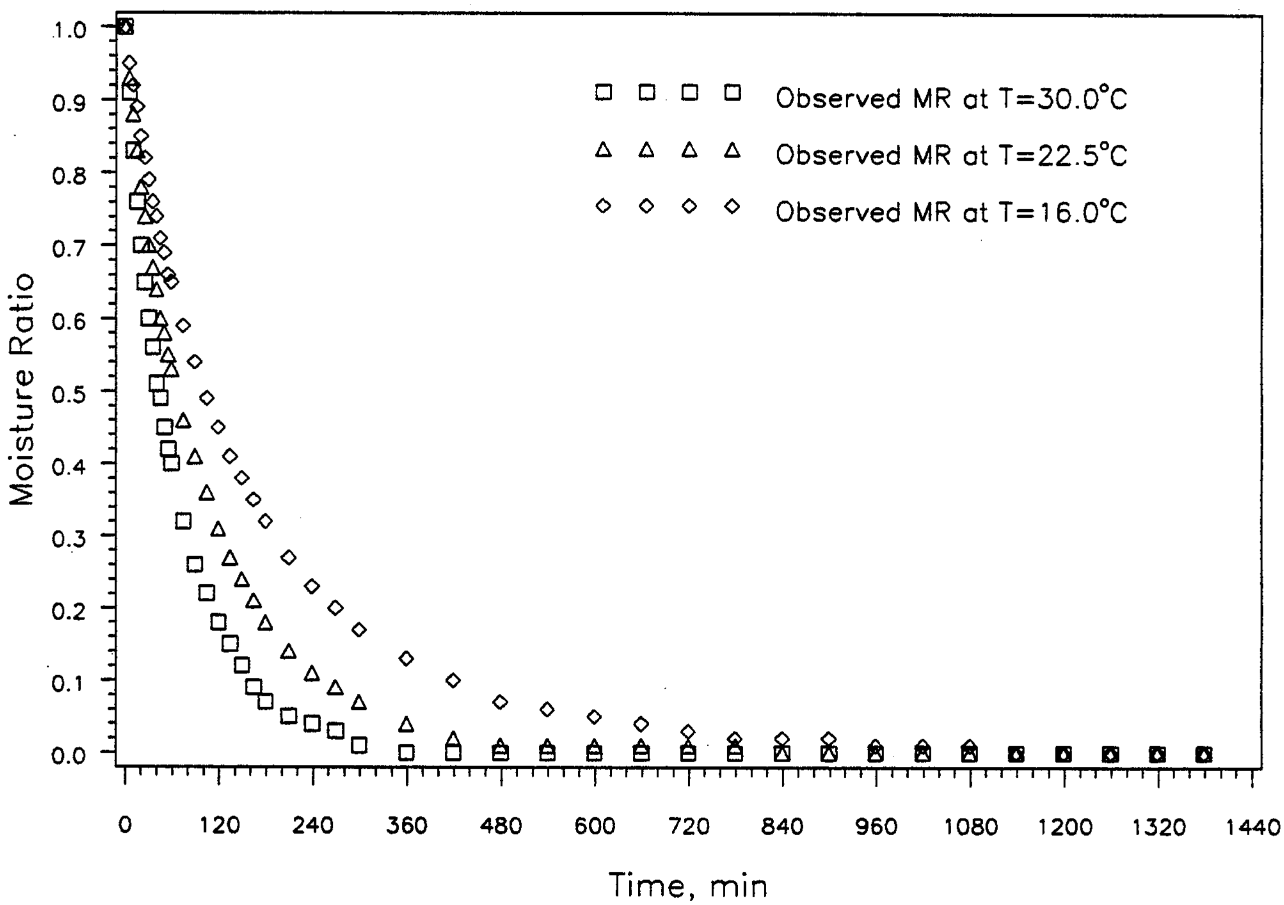

Fig. 5.4—Effect of temperature on rewetting rate of canola. Relative humidity=90%, initial moisture content=7.0% wb and air velocity=0.43 m/s.

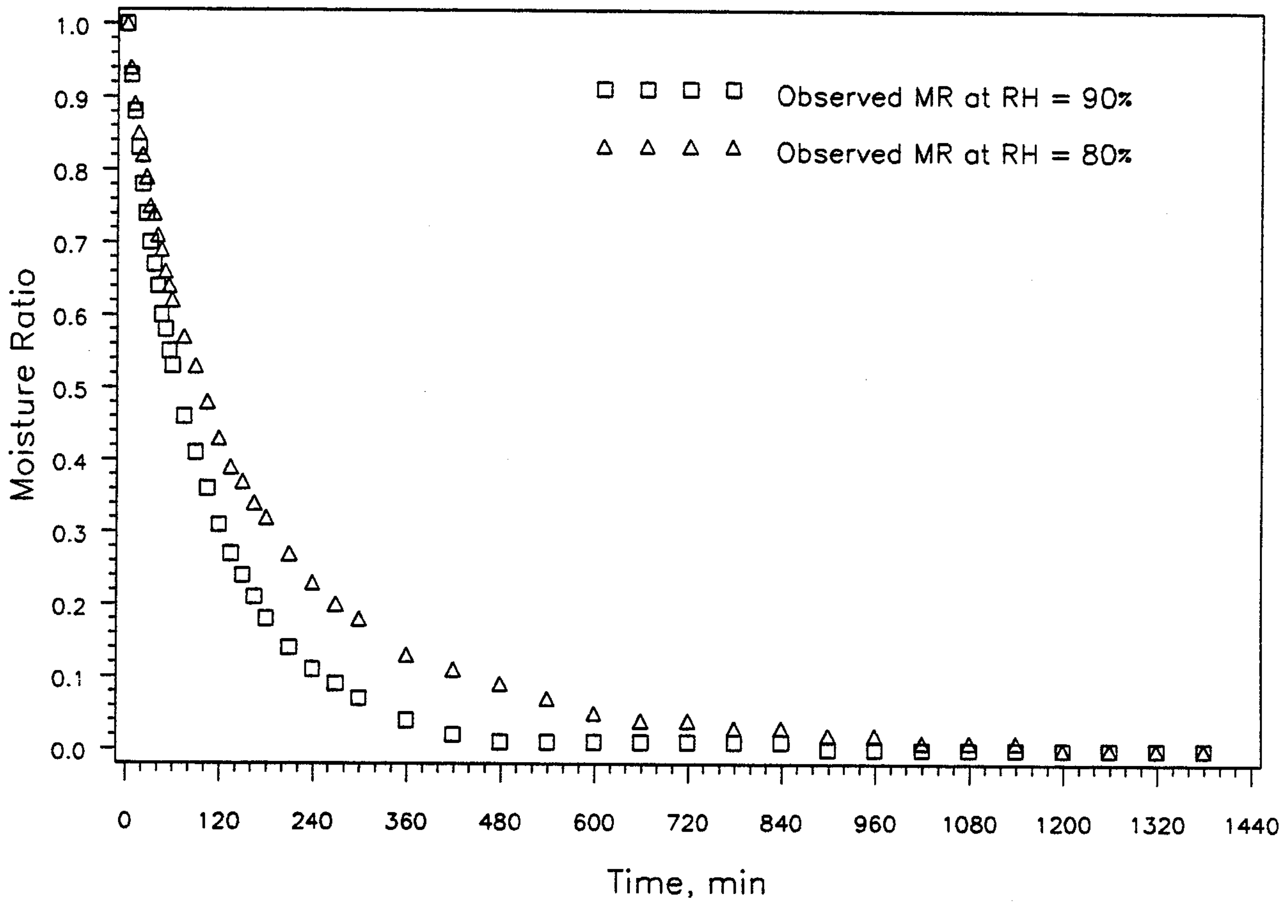

Fig. 5.5—Effect of relative humidity on rewetting rate of canola. Temperature=22.5°C, initial moisture content=7% wb and air velocity=0.43 m/s.

coefficient of RH was 0.0010. Temperature, therefore, has more significant effect on rewetting of canola than relative humidity. Values of coefficients associated with temperature and relative humidity in Eq. (13) also indicate the same. It has been reported that for other oilseeds and cereals, such as sunflower seed, soybean, shelled corn and barley, temperature had a more significant effect on moisture transfer rate than relative humidity (Syarief et al., 1984; Osborn et al., 1988; Misra, 1978; Jayas and Sokhansanj, 1986).
Substitution from Eq. (13) gives:

$$MR = \exp(-(-\ 0.0257 + 0.00094\ T + 0.00031\ RH)\ t^{0.818}) \qquad \text{------(14)}$$

Eq. (14) can directly be used in a deep bed drying simulation model to predict the rewetting under high ambient relative humidity conditions. Table 5.6 shows the S.E. of MR when equation (14) is used to predict the rewetting at the test conditions. Maximum S.E. of MR was obtained for test 20 (Table 5.6) conducted at 7.5°C and 80% RH. Fig. 5.6 shows the moisture content predicted by Eq. (14) and the observed moisture content for test 20. The maximum difference between the predicted and observed moisture content at any time for test 20 was 1.1 percentage points (Fig. 5.6). The difference between moisture content predicted using Eq. (14) and the observed moisture content were calculated for all the 21 tests. Based on these calculations, it was found that the difference between moisture content predicted by Eq. (14) and the observed moisture content did not exceed 0.4 percentage points for tests done at temperature and relative humidity combinations other than 7.5°C and 80% RH. This much error can be accepted for most practical purposes when working with biological products. Eq. (14),

TABLE 5.6 The values of standard error of moisture ratio when the parameter k in Page's equation is a linear function of temperature and relative humidity.

Test No.	Temp.* (°C)	RH** (%)	S.E.***
1	30.0	90	0.0175
2	30.0	90	0.0164
3	30.0	90	0.0247
4	22.5	90	0.0071
5	22.5	90	0.0117
6	22.5	90	0.0121
7	16.0	90	0.0207
8	16.0	90	0.0245
9	16.0	90	0.0177
10	30.0	80	0.0138
11	30.0	80	0.0171
12	30.0	80	0.0159
13	22.5	80	0.0438
14	22.5	80	0.0289
15	22.5	80	0.0131
16	15.0	80	0.0333
17	15.0	80	0.0145
18	15.0	80	0.0182
19	7.5	80	0.0609
20	7.5	80	0.0772
21	7.5	80	0.0397

* Temperature varied ±2°C

** Relative humidity varied ±3%

*** S.E. - standard error of moisture ratio

NOTE: $k = -0.0257 + 0.00094\,T + 0.00031\,RH$

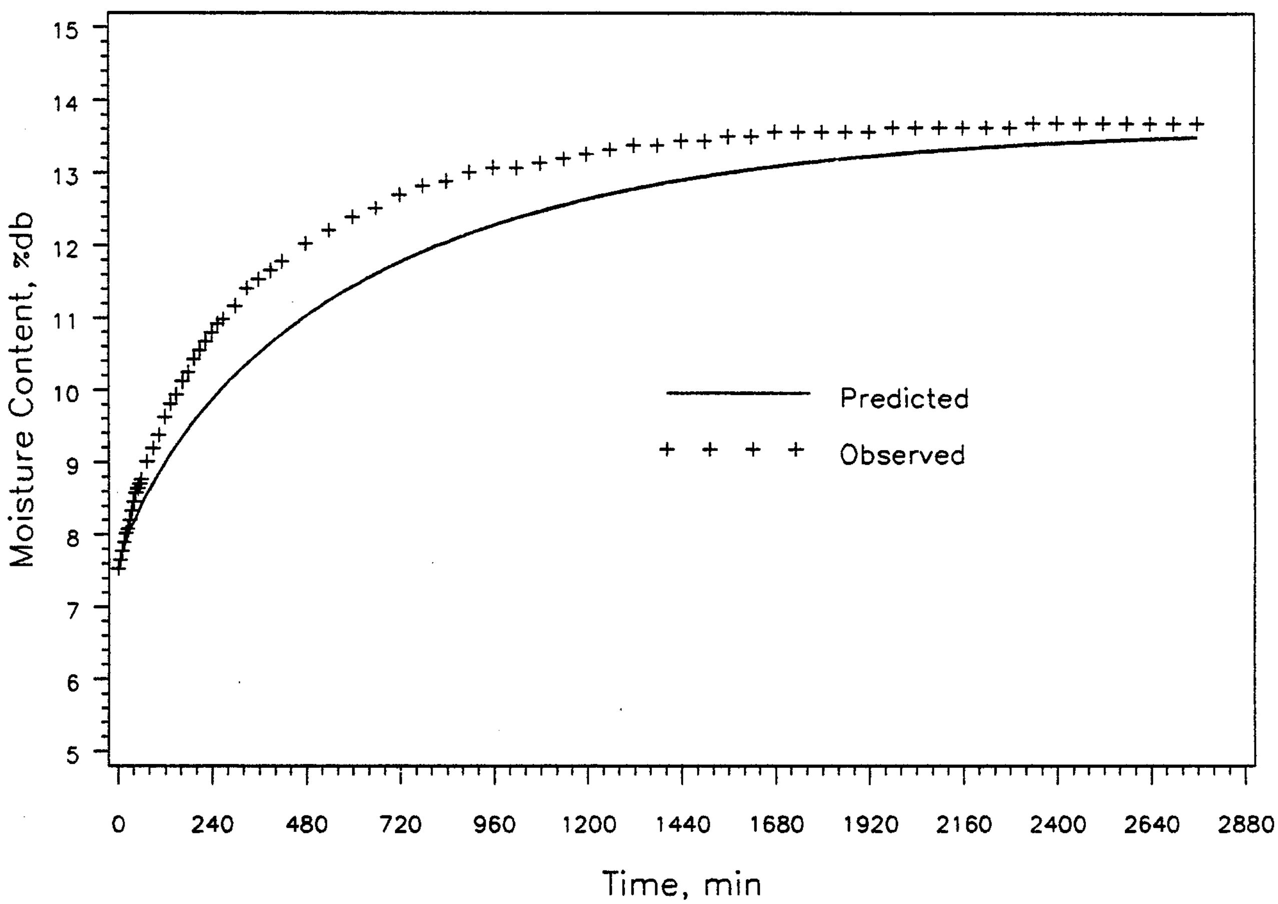

Fig. 5.6—Experimental wetting rate and the wetting rate predicted by Eq.(14) for test 20 conducted at temperature=7.5°C relative humidity=80% and air velocity=0.43 m/s.

therefore, can be used for prediction of rewetting of canola in the temperature range from 15 to 30°C. At temperatures lower than 15°C, Eq. (14) should be used with caution.

5.5 Effect of initial moisture content on rewetting

The rewetting rate data, in terms of change in moisture ratio and moisture content (dry mass basis) with time, at different initial moisture contents when other variables in the test were kept constant, are given in Appendix C (Tables C1 to C9). The k and n values for the tests done to study the effect of initial moisture content on rewetting rate are given in Table 5.7. Based on the analysis of variance, no significant difference ($p > 0.05$) was found in the parameter n among different initial moisture content levels. The values of n were, therefore, averaged over all the tests done at different initial moisture content levels. The average value of n was 0.858. The regressions were re-done to estimate the modified values of parameter k corresponding to the average value of parameter n (Table 5.7). Analysis of variance showed that the modified values of parameter k did not differ significantly among different initial moisture content levels ($p > 0.05$). It was concluded that, in the range tested, initial moisture content does not affect the wetting rate of canola. Fig. 5.7 also shows the insignificant effect of initial moisture content on rewetting rate. Syarief et al. (1984) found no effect of initial moisture content on drying rate of sunflower seeds. Osborn et al. (1988) found the effect of initial moisture content on rewetting rates of soybean to be insignificant. Results from this study and those reported by Syarief et al. (1984) and Osborn et al. (1988)

TABLE 5.7 The parameters k, n and modified k of Page's equation for various initial moisture content (IMC) tests when air conditions were maintained at 30 ± 2°C and 90 ± 3% RH.

IMC (% wet basis)	k	n	modified k*
5.0	0.0324	0.788	0.0262
5.0	0.0295	0.830	0.0263
5.0	0.0299	0.827	0.0242
7.0	0.0349	0.771	0.0242
7.0	0.0244	0.882	0.0270
7.0	0.0237	0.900	0.0281
10.0	0.0214	0.871	0.0226
10.0	0.0209	0.892	0.0242
10.0	0.0167	0.959	0.0259

* Modified k values correspond to the regression with average n = 0.858.

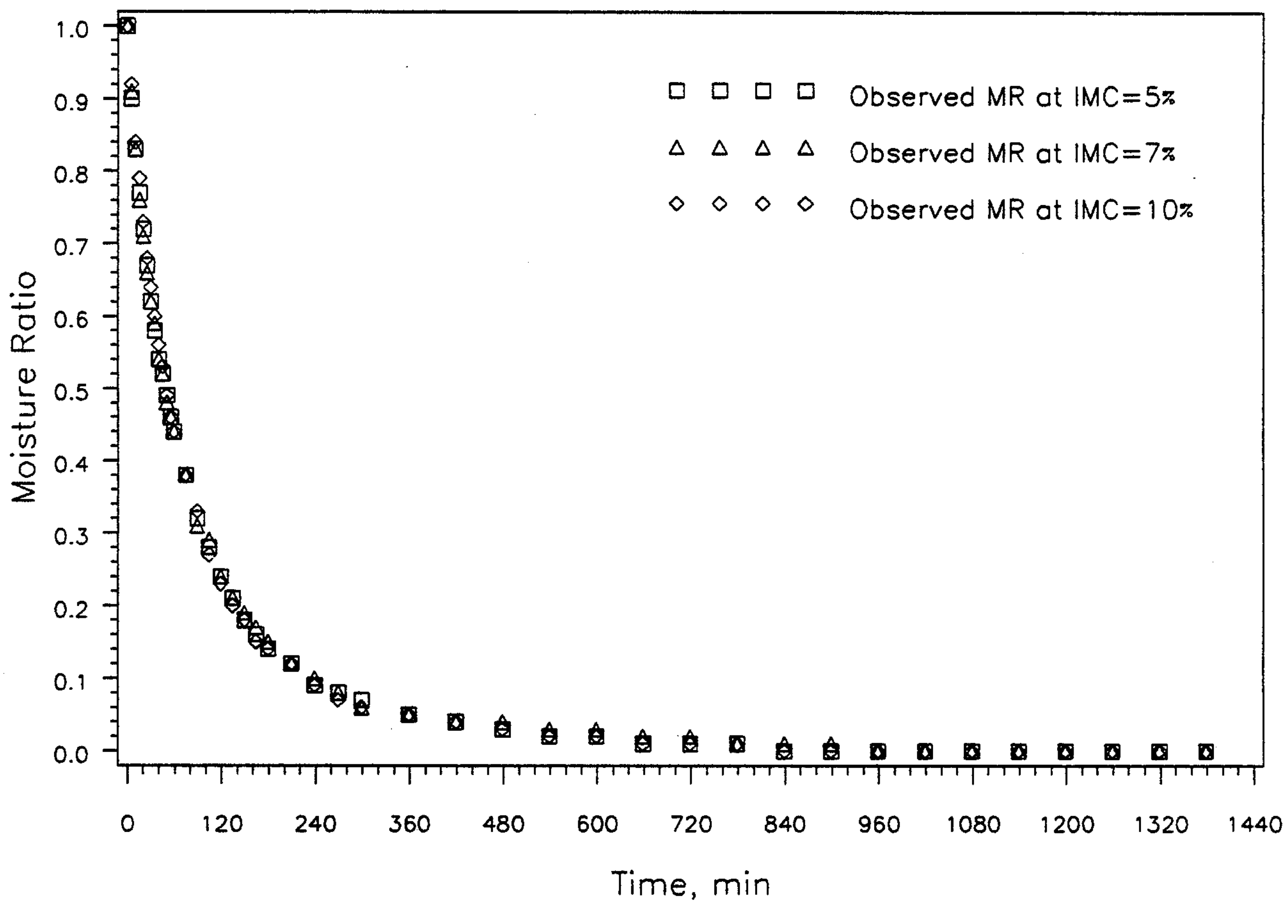

Fig. 5.7—Effect of initial moisture content on rewetting rate of canola. Temperature=30°C, relative humidity=90% and air velocity=0.43 m/s.

suggest that initial moisture content may not have an appreciable effect on moisture transfer rates of oilseeds.

5.6 Effect of air velocity on rewetting

The data of the tests conducted to investigate the effect of air velocity on the rewetting rate are given in Appendix D (Tables D1 to D9). The values of estimated parameters k and n of Eq. (11) and corresponding S.E. of MR are shown in Table 5.8. Parameter n did not differ significantly ($p > 0.05$) between different air velocity levels. The regressions were re-done with the average value of parameter n. The average of n was 0.848. The modified values of parameter k are given in Table 5.8. Duncan, T, and Scheffe multiple comparison tests (SAS 1985) were done. Results of multiple comparison tests showed that the rewetting rate did not differ significantly between 0.25 and 0.43 m/s air velocities. The rewetting rate, however, was slower at 0.10 m/s air velocity than at the other two velocities. Fig. 5.8 shows the same result. Studies done by Simmonds et al. (1953), Chittenden and Hustrulid (1966), Rugumayo (1979), and Misra (1978) suggest that air velocity may not have a significant effect on moisture transfer rate of cereals and oilseeds if it is above a critical value of about 0.16 m/s. For rewetting of canola, critical air velocity is between 0.10 and 0.25 m/s.

TABLE 5.8 The parameters k, n and modified k of Page's equation for various air velocity tests when air conditions were maintained at 30 ± 2°C and 90 ± 3% RH.

Air Velocity (m/s)	k	n	modified k*
0.10	0.0185	0.841	0.0180
0.10	0.0206	0.833	0.0193
0.10	0.0179	0.859	0.0189
0.25	0.0256	0.831	0.0238
0.25	0.0266	0.836	0.0253
0.25	0.0213	0.898	0.0263
0.43	0.0349	0.771	0.0252
0.43	0.0244	0.882	0.0282
0.43	0.0237	0.900	0.0293

* Modified k values correspond to the regression with average n = 0.848.

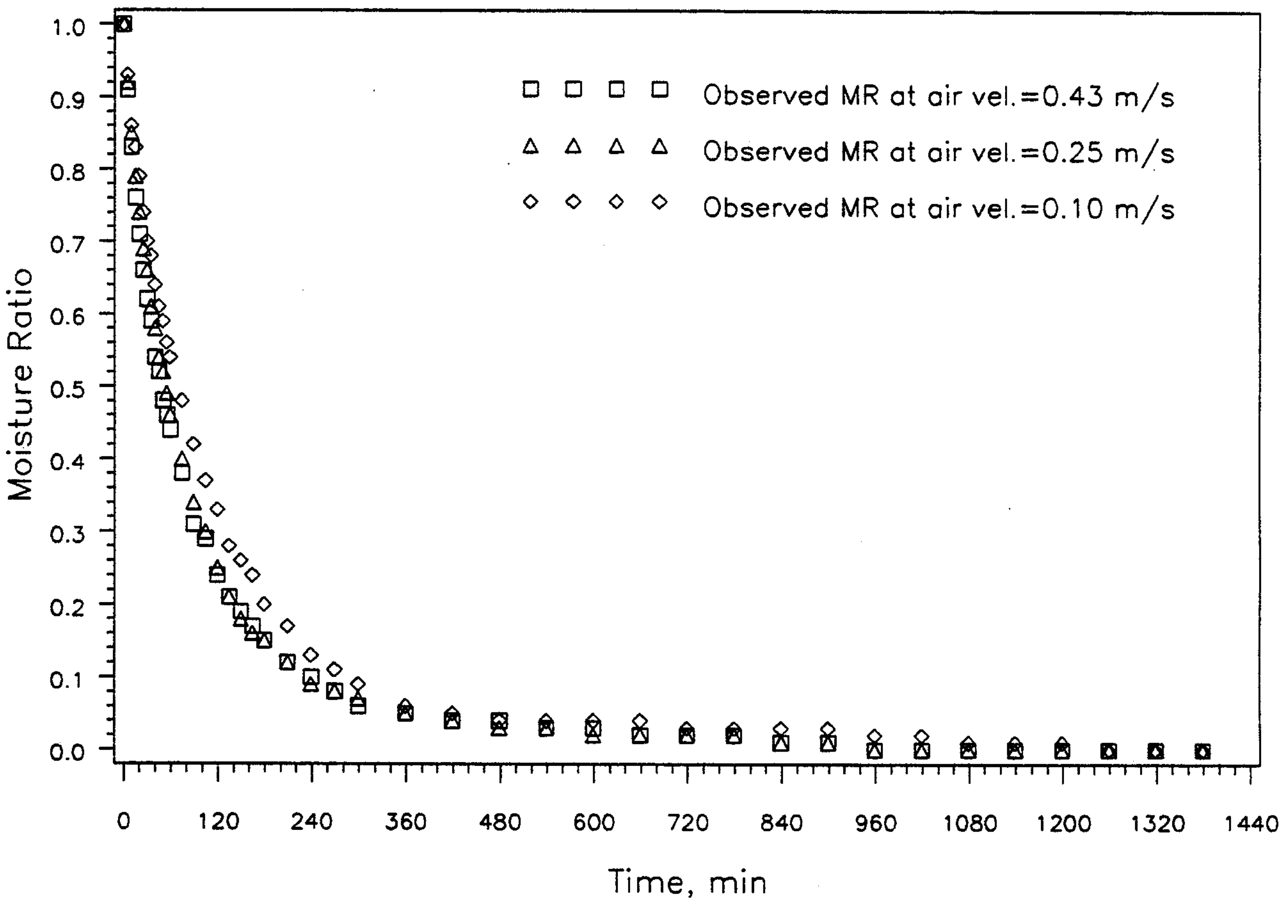

Fig. 5.8—Effect of air velocity on rewetting rate of canola. Temperature=30°C, relative humidity=90% and initial moisture content=7% wb.

6. CONCLUSIONS

Based on the results of this study the following specific conclusions can be drawn:

1. The liquid diffusion equation does not describe the rewetting rate data of canola satisfactorily.
2. The rewetting rates of canola agree well with Page's equation.
3. The parameter n of Page's equation can be assumed as a product-dependent constant because such an assumption does not appreciably increase the error in predicting the rewetting rate of canola.
4. The parameter k of Page's equation can be expressed as a function of temperature and relative humidity for canola:

   $$k = -0.0257 + 0.00094\ T + 0.00031\ RH$$

5. The initial moisture content does not affect the rewetting rate of canola significantly in the range from 5 to 10% wet mass basis.
6. The rewetting rate of canola does not change significantly with air velocity in the range from 0.25 m/s to 0.43 m/s. The rewetting rate, however, is slower at 0.10 m/s.

7. SUGGESTIONS FOR FUTURE RESEARCH

1. Thin-layer drying rates of canola in the low temperature range can be determined using the same experimental unit that was used in this study. The combined drying and wetting rate data can then be used in developing a deep-bed near-ambient drying simulation model for canola.

2. The moisture history of grain affects its drying and wetting rates, and equilibrium moisture content (Sokhansanj et al., 1984b; Jayas et al., 1989). The effect of moisture history of grain on its drying and wetting rates, and equilibrium moisture content should be studied in greater detail.

3. Moisture transfer rates through different components (endosperm, germ, aleurone layer, pericarp) of a grain kernel should be studied to facilitate theoretical explanation of moisture transport mechanisms involved in drying or wetting of grain.

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Appendix A

Table A1: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.16
10.00	0.83	8.72
15.00	0.76	9.21
20.00	0.71	9.56
25.00	0.66	9.91
30.00	0.62	10.19
35.00	0.59	10.40
40.00	0.54	10.75
45.00	0.52	10.89
50.00	0.48	11.17
55.00	0.46	11.31
59.00	0.44	11.45
74.00	0.38	11.87
89.00	0.31	12.36
104.00	0.29	12.50
119.00	0.24	12.85
134.00	0.21	13.06
149.00	0.19	13.20
164.00	0.17	13.34
179.00	0.15	13.48
209.00	0.12	13.69
239.00	0.10	13.83
269.00	0.08	13.97
299.00	0.06	14.11
359.00	0.05	14.18
419.00	0.04	14.25
479.00	0.04	14.25
539.00	0.03	14.32
599.00	0.03	14.32
659.00	0.02	14.39
719.00	0.02	14.39
779.00	0.02	14.39
839.00	0.01	14.46
899.00	0.01	14.46
959.00	0.00	14.53
1019.00	0.00	14.53
1079.00	0.00	14.53
1139.00	0.00	14.53
1199.00	0.00	14.53
1259.00	0.00	14.53
1319.00	0.00	14.53
1379.00	0.00	14.53

Table A2: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.10
10.00	0.84	8.53
15.00	0.78	8.91
20.00	0.71	9.35
25.00	0.65	9.73
30.00	0.61	9.98
35.00	0.57	10.23
40.00	0.53	10.48
45.00	0.49	10.73
50.00	0.46	10.92
55.00	0.43	11.11
59.00	0.41	11.24
74.00	0.34	11.67
89.00	0.28	12.05
104.00	0.23	12.37
119.00	0.19	12.62
134.00	0.16	12.81
149.00	0.12	13.06
164.00	0.11	13.12
179.00	0.09	13.24
209.00	0.07	13.37
239.00	0.06	13.43
269.00	0.05	13.50
299.00	0.03	13.62
359.00	0.02	13.68
419.00	0.01	13.75
479.00	0.01	13.75
539.00	0.01	13.75
599.00	0.00	13.81
659.00	0.00	13.81
719.00	0.00	13.81
779.00	0.00	13.81
839.00	0.00	13.81
899.00	0.00	13.81
959.00	0.00	13.81
1019.00	0.00	13.81
1079.00	0.00	13.81
1139.00	0.00	13.81
1199.00	0.00	13.81
1259.00	0.00	13.81
1319.00	0.00	13.81
1379.00	0.00	13.81

Table A3: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.07
10.00	0.83	8.54
15.00	0.76	8.96
20.00	0.70	9.32
25.00	0.65	9.62
30.00	0.60	9.92
35.00	0.56	10.16
40.00	0.51	10.46
45.00	0.49	10.57
50.00	0.45	10.81
55.00	0.42	10.99
59.00	0.40	11.11
74.00	0.32	11.59
89.00	0.26	11.95
104.00	0.22	12.19
119.00	0.18	12.43
134.00	0.15	12.60
149.00	0.12	12.78
164.00	0.09	12.96
179.00	0.07	13.08
209.00	0.05	13.20
239.00	0.04	13.26
269.00	0.03	13.32
299.00	0.01	13.44
359.00	0.00	13.50
419.00	0.00	13.50
479.00	0.00	13.50
539.00	0.00	13.50
599.00	0.00	13.50
659.00	0.00	13.50
719.00	0.00	13.50
779.00	0.00	13.50
839.00	0.00	13.50
899.00	0.00	13.50
959.00	0.00	13.50
1019.00	0.00	13.50
1079.00	0.00	13.50
1139.00	0.00	13.50
1199.00	0.00	13.50
1259.00	0.00	13.50
1319.00	0.00	13.50
1379.00	0.00	13.50

Table A4: Change in moisture ratio and moisture content with time for test at Temp=22.5°C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.93	8.21
10.00	0.87	8.80
15.00	0.81	9.38
20.00	0.77	9.77
25.00	0.73	10.16
30.00	0.69	10.55
35.00	0.65	10.94
40.00	0.62	11.23
45.00	0.59	11.53
50.00	0.57	11.72
55.00	0.54	12.01
59.00	0.52	12.21
74.00	0.45	12.89
89.00	0.40	13.38
104.00	0.35	13.87
119.00	0.31	14.26
134.00	0.28	14.55
149.00	0.25	14.84
164.00	0.22	15.13
179.00	0.20	15.33
209.00	0.15	15.82
239.00	0.12	16.11
269.00	0.11	16.21
299.00	0.09	16.40
359.00	0.07	16.60
419.00	0.04	16.89
479.00	0.04	16.89
539.00	0.03	16.99
599.00	0.02	17.08
659.00	0.02	17.08
719.00	0.02	17.08
779.00	0.02	17.08
839.00	0.01	17.18
899.00	0.01	17.18
959.00	0.01	17.18
1019.00	0.01	17.18
1079.00	0.01	17.18
1139.00	0.00	17.28
1199.00	0.00	17.28
1259.00	0.00	17.28
1319.00	0.00	17.28
1379.00	0.00	17.28

Table A5: Change in moisture ratio and moisture content with time for test at Temp=22.5°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.93	8.17
10.00	0.88	8.63
15.00	0.83	9.08
20.00	0.78	9.54
25.00	0.74	9.91
30.00	0.70	10.27
35.00	0.67	10.55
40.00	0.64	10.82
45.00	0.60	11.19
50.00	0.58	11.37
55.00	0.55	11.64
60.00	0.53	11.83
75.00	0.46	12.47
90.00	0.41	12.92
105.00	0.36	13.38
120.00	0.31	13.84
135.00	0.27	14.20
150.00	0.24	14.48
165.00	0.21	14.75
180.00	0.18	15.02
210.00	0.14	15.39
240.00	0.11	15.66
270.00	0.09	15.85
300.00	0.07	16.03
360.00	0.04	16.30
420.00	0.02	16.49
480.00	0.01	16.58
540.00	0.01	16.58
600.00	0.01	16.58
660.00	0.01	16.58
720.00	0.01	16.58
780.00	0.01	16.58
840.00	0.01	16.58
900.00	0.00	16.67
960.00	0.00	16.67
1020.00	0.00	16.67
1080.00	0.00	16.67
1140.00	0.00	16.67
1200.00	0.00	16.67
1260.00	0.00	16.67
1320.00	0.00	16.67
1380.00	0.00	16.67

Table A6: Change in moisture ratio and moisture content with time for test at Temp=22.5°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.93	8.19
10.00	0.87	8.75
15.00	0.82	9.22
20.00	0.77	9.69
25.00	0.74	9.98
30.00	0.69	10.45
35.00	0.66	10.73
40.00	0.62	11.11
45.00	0.60	11.29
50.00	0.57	11.58
55.00	0.54	11.86
59.00	0.53	11.95
74.00	0.45	12.71
89.00	0.40	13.18
104.00	0.35	13.65
119.00	0.30	14.12
134.00	0.27	14.40
149.00	0.23	14.78
164.00	0.20	15.06
179.00	0.17	15.34
209.00	0.13	15.72
239.00	0.10	16.00
269.00	0.08	16.19
299.00	0.07	16.28
359.00	0.05	16.47
419.00	0.03	16.66
479.00	0.03	16.66
539.00	0.02	16.75
599.00	0.02	16.75
659.00	0.01	16.85
719.00	0.01	16.85
779.00	0.01	16.85
839.00	0.00	16.94
899.00	0.00	16.94
959.00	0.00	16.94
1019.00	0.00	16.94
1079.00	0.00	16.94
1139.00	0.00	16.94
1199.00	0.00	16.94
1259.00	0.00	16.94
1319.00	0.00	16.94
1379.00	0.00	16.94

Table A7: Change in moisture ratio and moisture content with time for test at Temp=16.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.96	7.92
10.00	0.92	8.31
15.00	0.88	8.70
20.00	0.85	8.99
25.00	0.82	9.28
30.00	0.79	9.58
35.00	0.76	9.87
40.00	0.74	10.06
45.00	0.71	10.35
50.00	0.69	10.55
55.00	0.67	10.74
59.00	0.65	10.94
74.00	0.59	11.52
89.00	0.54	12.01
104.00	0.50	12.40
119.00	0.46	12.79
134.00	0.42	13.18
149.00	0.38	13.57
164.00	0.35	13.86
179.00	0.33	14.06
194.00	0.30	14.35
209.00	0.28	14.54
224.00	0.26	14.74
239.00	0.24	14.93
269.00	0.20	15.32
299.00	0.17	15.61
329.00	0.15	15.81
389.00	0.12	16.10
419.00	0.10	16.30
479.00	0.08	16.49
539.00	0.07	16.59
599.00	0.06	16.69
659.00	0.05	16.78
719.00	0.04	16.88
779.00	0.04	16.88
839.00	0.03	16.98
899.00	0.03	16.98
959.00	0.02	17.08
1019.00	0.02	17.08
1079.00	0.01	17.17
1139.00	0.01	17.17
1199.00	0.00	17.27
1259.00	0.00	17.27
1319.00	0.00	17.27
1379.00	0.00	17.27

Table A8: Change in moisture ratio and moisture content with time for test at Temp=16.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.96	7.94
10.00	0.92	8.36
15.00	0.89	8.67
20.00	0.85	9.08
25.00	0.82	9.39
30.00	0.79	9.70
35.00	0.77	9.91
40.00	0.74	10.22
45.00	0.72	10.43
50.00	0.70	10.63
55.00	0.67	10.94
59.00	0.66	11.05
74.00	0.60	11.67
89.00	0.55	12.18
104.00	0.50	12.70
119.00	0.48	12.91
134.00	0.42	13.53
149.00	0.39	13.84
164.00	0.36	14.15
179.00	0.33	14.46
194.00	0.31	14.66
209.00	0.29	14.87
224.00	0.27	15.08
239.00	0.24	15.39
269.00	0.21	15.70
299.00	0.18	16.01
329.00	0.16	16.22
389.00	0.12	16.63
419.00	0.10	16.84
479.00	0.09	16.94
539.00	0.07	17.15
599.00	0.06	17.25
659.00	0.05	17.35
719.00	0.04	17.46
779.00	0.03	17.56
839.00	0.02	17.66
899.00	0.02	17.66
959.00	0.01	17.77
1019.00	0.01	17.77
1079.00	0.01	17.77
1139.00	0.00	17.87
1199.00	0.00	17.87
1259.00	0.00	17.87
1319.00	0.00	17.87
1379.00	0.00	17.87

Table A9: Change in moisture ratio and moisture content with time for test at Temp=16.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.95	8.05
10.00	0.92	8.36
15.00	0.89	8.67
20.00	0.85	9.08
25.00	0.82	9.39
30.00	0.79	9.70
35.00	0.76	10.01
40.00	0.74	10.22
45.00	0.71	10.53
50.00	0.69	10.73
55.00	0.66	11.04
59.00	0.65	11.15
74.00	0.59	11.77
89.00	0.54	12.28
104.00	0.49	12.80
119.00	0.45	13.21
134.00	0.41	13.62
149.00	0.38	13.93
164.00	0.35	14.24
179.00	0.32	14.55
194.00	0.30	14.76
209.00	0.27	15.07
224.00	0.25	15.28
239.00	0.23	15.48
269.00	0.20	15.79
299.00	0.17	16.10
329.00	0.15	16.31
389.00	0.11	16.72
419.00	0.10	16.83
479.00	0.07	17.14
539.00	0.06	17.24
599.00	0.05	17.34
659.00	0.04	17.45
719.00	0.03	17.55
779.00	0.02	17.65
839.00	0.02	17.65
899.00	0.02	17.65
959.00	0.01	17.76
1019.00	0.01	17.76
1079.00	0.01	17.76
1139.00	0.00	17.86
1199.00	0.00	17.86
1259.00	0.00	17.86
1319.00	0.00	17.86
1379.00	0.00	17.86

Table A10: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=80% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.89	7.92
10.00	0.82	8.17
15.00	0.76	8.38
20.00	0.70	8.59
25.00	0.66	8.73
30.00	0.62	8.88
35.00	0.58	9.02
40.00	0.56	9.09
45.00	0.52	9.23
50.00	0.50	9.30
55.00	0.47	9.41
59.00	0.46	9.44
74.00	0.40	9.65
89.00	0.34	9.87
104.00	0.28	10.08
119.00	0.26	10.15
134.00	0.22	10.29
149.00	0.19	10.40
164.00	0.18	10.43
179.00	0.14	10.57
209.00	0.11	10.68
239.00	0.09	10.75
269.00	0.07	10.82
299.00	0.05	10.89
359.00	0.04	10.93
419.00	0.03	10.96
479.00	0.03	10.96
539.00	0.02	11.00
599.00	0.02	11.00
659.00	0.02	11.00
719.00	0.02	11.00
779.00	0.02	11.00
839.00	0.02	11.00
899.00	0.01	11.03
959.00	0.01	11.03
1019.00	0.00	11.07
1079.00	0.00	11.07
1139.00	0.00	11.07
1199.00	0.00	11.07
1259.00	0.00	11.07
1319.00	0.00	11.07
1379.00	0.00	11.07

Table A11: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=80% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.90	7.90
10.00	0.82	8.20
15.00	0.76	8.43
20.00	0.71	8.61
25.00	0.66	8.80
30.00	0.61	8.98
35.00	0.58	9.10
40.00	0.56	9.17
45.00	0.52	9.32
50.00	0.50	9.40
55.00	0.48	9.47
59.00	0.44	9.62
74.00	0.38	9.84
89.00	0.33	10.03
104.00	0.29	10.18
119.00	0.25	10.33
134.00	0.23	10.40
149.00	0.20	10.51
164.00	0.17	10.63
179.00	0.16	10.66
209.00	0.13	10.78
239.00	0.11	10.85
269.00	0.10	10.89
299.00	0.08	10.96
359.00	0.06	11.04
419.00	0.04	11.11
479.00	0.04	11.11
539.00	0.03	11.15
599.00	0.03	11.15
659.00	0.02	11.19
719.00	0.02	11.19
779.00	0.02	11.19
839.00	0.02	11.19
899.00	0.01	11.22
959.00	0.01	11.22
1019.00	0.00	11.26
1079.00	0.00	11.26
1139.00	0.00	11.26
1199.00	0.00	11.26
1259.00	0.00	11.26
1319.00	0.00	11.26
1379.00	0.00	11.26

Table A12: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=80% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.90	7.90
10.00	0.82	8.19
15.00	0.76	8.41
20.00	0.70	8.63
25.00	0.65	8.81
30.00	0.61	8.96
35.00	0.58	9.07
40.00	0.56	9.14
45.00	0.54	9.22
50.00	0.52	9.29
55.00	0.47	9.48
59.00	0.45	9.55
74.00	0.38	9.81
89.00	0.32	10.03
104.00	0.28	10.17
119.00	0.25	10.28
134.00	0.22	10.39
149.00	0.19	10.50
164.00	0.17	10.58
179.00	0.15	10.65
209.00	0.12	10.76
239.00	0.10	10.83
269.00	0.08	10.91
299.00	0.07	10.94
359.00	0.05	11.02
419.00	0.04	11.05
479.00	0.03	11.09
539.00	0.03	11.09
599.00	0.02	11.13
659.00	0.02	11.13
719.00	0.02	11.13
779.00	0.02	11.13
839.00	0.01	11.16
899.00	0.01	11.16
959.00	0.01	11.16
1019.00	0.01	11.16
1079.00	0.00	11.20
1139.00	0.00	11.20
1199.00	0.00	11.20
1259.00	0.00	11.20
1319.00	0.00	11.20
1379.00	0.00	11.20

Table A13: Change in moisture ratio and moisture content with time for test at Temp=22.5°C, RH=80% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.94	7.79
10.00	0.89	8.01
15.00	0.85	8.18
20.00	0.82	8.31
25.00	0.79	8.44
30.00	0.75	8.61
35.00	0.74	8.66
40.00	0.71	8.79
45.00	0.69	8.87
50.00	0.66	9.00
55.00	0.64	9.09
59.00	0.62	9.18
74.00	0.57	9.39
89.00	0.53	9.57
104.00	0.48	9.78
119.00	0.43	10.00
134.00	0.39	10.17
149.00	0.37	10.26
164.00	0.34	10.39
179.00	0.32	10.47
209.00	0.27	10.69
239.00	0.23	10.86
269.00	0.20	10.99
299.00	0.18	11.08
359.00	0.13	11.30
419.00	0.11	11.38
479.00	0.09	11.47
539.00	0.07	11.56
599.00	0.05	11.64
659.00	0.04	11.69
719.00	0.04	11.69
779.00	0.03	11.73
839.00	0.03	11.73
899.00	0.02	11.77
959.00	0.02	11.77
1019.00	0.01	11.82
1079.00	0.01	11.82
1139.00	0.01	11.82
1199.00	0.00	11.86
1259.00	0.00	11.86
1319.00	0.00	11.86
1379.00	0.00	11.86

Table A14: Change in moisture ratio and moisture content with time for test at Temp=22.5°C, RH=80% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.95	7.76
10.00	0.90	7.99
15.00	0.85	8.22
20.00	0.82	8.35
25.00	0.78	8.54
30.00	0.75	8.67
35.00	0.71	8.86
40.00	0.69	8.95
45.00	0.67	9.04
50.00	0.65	9.13
55.00	0.62	9.27
59.00	0.60	9.36
74.00	0.55	9.59
89.00	0.48	9.91
104.00	0.44	10.09
119.00	0.41	10.23
134.00	0.37	10.41
149.00	0.35	10.50
164.00	0.32	10.64
179.00	0.29	10.77
209.00	0.24	11.00
239.00	0.22	11.09
269.00	0.18	11.28
299.00	0.16	11.37
359.00	0.11	11.60
419.00	0.09	11.69
479.00	0.07	11.78
539.00	0.06	11.83
599.00	0.05	11.87
659.00	0.04	11.92
719.00	0.04	11.92
779.00	0.03	11.96
839.00	0.03	11.96
899.00	0.02	12.01
959.00	0.02	12.01
1019.00	0.01	12.05
1079.00	0.01	12.05
1139.00	0.01	12.05
1199.00	0.00	12.10
1259.00	0.00	12.10
1319.00	0.00	12.10
1379.00	0.00	12.10

Table A15: Change in moisture ratio and moisture content with time for test at Temp=22.5°C, RH=80% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.92	7.88
10.00	0.86	8.14
15.00	0.82	8.32
20.00	0.78	8.49
25.00	0.75	8.62
30.00	0.71	8.80
35.00	0.68	8.93
40.00	0.65	9.06
45.00	0.63	9.15
50.00	0.60	9.28
55.00	0.58	9.37
59.00	0.58	9.37
74.00	0.52	9.63
89.00	0.47	9.85
104.00	0.42	10.06
119.00	0.39	10.20
134.00	0.35	10.37
149.00	0.33	10.46
164.00	0.30	10.59
179.00	0.26	10.76
209.00	0.23	10.89
239.00	0.19	11.07
269.00	0.16	11.20
299.00	0.14	11.29
359.00	0.10	11.46
419.00	0.07	11.59
479.00	0.05	11.68
539.00	0.04	11.73
599.00	0.03	11.77
659.00	0.03	11.77
719.00	0.02	11.81
779.00	0.02	11.81
839.00	0.01	11.86
899.00	0.01	11.86
959.00	0.00	11.90
1019.00	0.00	11.90
1079.00	0.00	11.90
1139.00	0.00	11.90
1199.00	0.00	11.90
1259.00	0.00	11.90
1319.00	0.00	11.90
1379.00	0.00	11.90

Table A16: Change in moisture ratio and moisture content with time for test at Temp=15.0°C, RH=80% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.96	7.73
10.00	0.93	7.89
15.00	0.91	7.99
20.00	0.87	8.19
25.00	0.85	8.29
30.00	0.84	8.34
35.00	0.82	8.44
40.00	0.79	8.60
45.00	0.76	8.75
50.00	0.74	8.85
55.00	0.73	8.90
59.00	0.72	8.95
74.00	0.68	9.16
89.00	0.64	9.36
104.00	0.59	9.61
119.00	0.56	9.77
134.00	0.53	9.92
149.00	0.50	10.07
164.00	0.47	10.22
179.00	0.46	10.27
194.00	0.43	10.43
209.00	0.41	10.53
224.00	0.38	10.68
239.00	0.37	10.73
269.00	0.34	10.88
299.00	0.31	11.04
329.00	0.28	11.19
389.00	0.23	11.44
419.00	0.20	11.59
479.00	0.17	11.75
539.00	0.14	11.90
599.00	0.12	12.00
659.00	0.10	12.10
719.00	0.08	12.20
779.00	0.07	12.25
839.00	0.06	12.31
899.00	0.05	12.36
959.00	0.04	12.41
1019.00	0.03	12.46
1079.00	0.03	12.46
1139.00	0.02	12.51
1199.00	0.02	12.51
1259.00	0.01	12.56
1319.00	0.00	12.61
1379.00	0.00	12.61

Table A17: Change in moisture ratio and moisture content with time for test at Temp=15.0°C, RH=80% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.94	7.84
10.00	0.91	7.99
15.00	0.88	8.15
20.00	0.83	8.40
25.00	0.81	8.51
30.00	0.79	8.61
35.00	0.76	8.76
40.00	0.73	8.92
45.00	0.72	8.97
50.00	0.70	9.07
55.00	0.68	9.17
59.00	0.67	9.23
74.00	0.63	9.43
89.00	0.59	9.64
104.00	0.54	9.89
119.00	0.51	10.05
134.00	0.48	10.20
149.00	0.45	10.36
164.00	0.42	10.51
179.00	0.40	10.61
194.00	0.37	10.77
209.00	0.35	10.87
224.00	0.33	10.97
239.00	0.31	11.08
269.00	0.28	11.23
299.00	0.25	11.39
329.00	0.22	11.54
389.00	0.18	11.74
419.00	0.16	11.85
479.00	0.13	12.00
539.00	0.10	12.16
599.00	0.08	12.26
659.00	0.07	12.31
719.00	0.06	12.36
779.00	0.04	12.46
839.00	0.03	12.52
899.00	0.03	12.52
959.00	0.02	12.57
1019.00	0.01	12.62
1079.00	0.01	12.62
1139.00	0.01	12.62
1199.00	0.00	12.67
1259.00	0.00	12.67
1319.00	0.00	12.67
1379.00	0.00	12.67

Table A18: Change in moisture ratio and moisture content with time for test at Temp=15.0°C, RH=80% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.96	7.74
10.00	0.93	7.90
15.00	0.90	8.06
20.00	0.88	8.17
25.00	0.85	8.33
30.00	0.80	8.60
35.00	0.78	8.70
40.00	0.77	8.76
45.00	0.74	8.92
50.00	0.72	9.02
55.00	0.70	9.13
59.00	0.69	9.18
74.00	0.66	9.34
89.00	0.62	9.56
104.00	0.59	9.72
119.00	0.55	9.93
134.00	0.53	10.04
149.00	0.49	10.25
164.00	0.47	10.35
179.00	0.44	10.51
194.00	0.42	10.62
209.00	0.39	10.78
224.00	0.37	10.89
239.00	0.35	10.99
269.00	0.30	11.26
299.00	0.26	11.47
329.00	0.23	11.63
389.00	0.18	11.90
419.00	0.16	12.01
479.00	0.13	12.17
539.00	0.10	12.33
599.00	0.08	12.43
659.00	0.07	12.49
719.00	0.06	12.54
779.00	0.05	12.59
839.00	0.04	12.65
899.00	0.03	12.70
959.00	0.03	12.70
1019.00	0.02	12.75
1079.00	0.02	12.75
1139.00	0.01	12.81
1199.00	0.01	12.81
1259.00	0.00	12.86
1319.00	0.00	12.86
1379.00	0.00	12.86

Table A19: Change in moisture ratio and moisture content with time for test at Temp=7.5°C, RH=80% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.98	7.66
10.00	0.95	7.86
15.00	0.94	7.92
20.00	0.92	8.05
25.00	0.91	8.12
30.00	0.88	8.31
35.00	0.87	8.38
40.00	0.86	8.44
45.00	0.85	8.51
50.00	0.83	8.64
55.00	0.82	8.70
59.00	0.81	8.77
74.00	0.78	8.96
89.00	0.74	9.22
104.00	0.72	9.35
119.00	0.69	9.55
134.00	0.67	9.68
149.00	0.64	9.87
164.00	0.62	10.00
179.00	0.60	10.13
194.00	0.59	10.20
209.00	0.56	10.39
224.00	0.54	10.52
239.00	0.53	10.59
269.00	0.50	10.78
299.00	0.47	10.98
329.00	0.44	11.18
359.00	0.42	11.31
419.00	0.38	11.57
479.00	0.33	11.89
539.00	0.30	12.09
599.00	0.27	12.28
659.00	0.25	12.41
719.00	0.22	12.61
779.00	0.21	12.67
839.00	0.19	12.80
899.00	0.17	12.93
959.00	0.16	13.00
1019.00	0.15	13.06
1079.00	0.14	13.13
1139.00	0.13	13.19
1199.00	0.12	13.26
1259.00	0.11	13.32
1319.00	0.10	13.39
1379.00	0.10	13.39
1439.00	0.09	13.45
1499.00	0.08	13.52
1559.00	0.07	13.58
1619.00	0.06	13.65
1679.00	0.05	13.71
1739.00	0.05	13.71
1799.00	0.04	13.78
1859.00	0.04	13.78
1919.00	0.03	13.84
1979.00	0.03	13.84
2039.00	0.03	13.84
2099.00	0.02	13.91
2159.00	0.02	13.91
2219.00	0.02	13.91
2279.00	0.02	13.91
2339.00	0.01	13.97
2399.00	0.01	13.97
2459.00	0.01	13.97
2519.00	0.00	14.04
2579.00	0.00	14.04
2639.00	0.00	14.04
2759.00	0.00	14.04

Table A20: Change in moisture ratio and moisture content with time for test at Temp=7.5°C, RH=80% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.98	7.65
10.00	0.96	7.78
15.00	0.94	7.90
20.00	0.92	8.02
25.00	0.91	8.08
30.00	0.89	8.21
35.00	0.87	8.33
40.00	0.85	8.45
45.00	0.83	8.58
50.00	0.82	8.64
55.00	0.81	8.70
59.00	0.80	8.76
74.00	0.76	9.01
89.00	0.73	9.19
104.00	0.70	9.38
119.00	0.66	9.62
134.00	0.63	9.81
149.00	0.61	9.93
164.00	0.58	10.12
179.00	0.56	10.24
194.00	0.53	10.43
209.00	0.51	10.55
224.00	0.49	10.67
239.00	0.47	10.79
269.00	0.44	10.98
299.00	0.41	11.16
329.00	0.37	11.41
359.00	0.35	11.53
419.00	0.31	11.78
479.00	0.27	12.03
539.00	0.24	12.21
599.00	0.21	12.40
659.00	0.19	12.52
719.00	0.16	12.70
779.00	0.14	12.83
839.00	0.13	12.89
899.00	0.11	13.01
959.00	0.10	13.07
1019.00	0.10	13.07
1079.00	0.09	13.14
1139.00	0.08	13.20
1199.00	0.07	13.26
1259.00	0.06	13.32
1319.00	0.05	13.38
1379.00	0.05	13.38
1439.00	0.04	13.44
1499.00	0.04	13.44
1559.00	0.03	13.51
1619.00	0.03	13.51
1679.00	0.02	13.57
1739.00	0.02	13.57
1799.00	0.02	13.57
1859.00	0.02	13.57
1919.00	0.02	13.57
1979.00	0.01	13.63
2039.00	0.01	13.63
2099.00	0.01	13.63
2159.00	0.01	13.63
2219.00	0.01	13.63
2279.00	0.01	13.63
2339.00	0.00	13.69
2399.00	0.00	13.69
2459.00	0.00	13.69
2519.00	0.00	13.69
2579.00	0.00	13.69
2639.00	0.00	13.69
2759.00	0.00	13.69

Table A21: Change in moisture ratio and moisture content with time for test at Temp=7.5°C, RH=80% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.98	7.66
10.00	0.95	7.86
15.00	0.94	7.92
20.00	0.92	8.05
25.00	0.90	8.18
30.00	0.88	8.31
35.00	0.87	8.38
40.00	0.86	8.44
45.00	0.84	8.57
50.00	0.82	8.71
55.00	0.81	8.77
59.00	0.80	8.84
74.00	0.76	9.10
89.00	0.74	9.23
104.00	0.71	9.42
119.00	0.67	9.68
134.00	0.65	9.82
149.00	0.62	10.01
164.00	0.60	10.14
179.00	0.57	10.34
194.00	0.55	10.47
209.00	0.53	10.60
224.00	0.51	10.73
239.00	0.49	10.86
269.00	0.47	10.99
299.00	0.43	11.25
329.00	0.40	11.45
359.00	0.38	11.58
419.00	0.33	11.91
479.00	0.29	12.17
539.00	0.26	12.36
599.00	0.23	12.56
659.00	0.20	12.75
719.00	0.19	12.82
779.00	0.17	12.95
839.00	0.16	13.02
899.00	0.15	13.08
959.00	0.14	13.15
1019.00	0.13	13.21
1079.00	0.12	13.28
1139.00	0.11	13.34
1199.00	0.10	13.41
1259.00	0.09	13.47
1319.00	0.08	13.54
1379.00	0.07	13.60
1439.00	0.06	13.67
1499.00	0.05	13.73
1559.00	0.05	13.73
1619.00	0.04	13.80
1679.00	0.04	13.80
1739.00	0.04	13.80
1799.00	0.03	13.86
1859.00	0.03	13.86
1919.00	0.03	13.86
1979.00	0.03	13.86
2039.00	0.02	13.93
2099.00	0.02	13.93
2159.00	0.02	13.93
2219.00	0.02	13.93
2279.00	0.02	13.93
2339.00	0.01	13.99
2399.00	0.01	13.99
2459.00	0.01	13.99
2519.00	0.00	14.06
2579.00	0.00	14.06
2639.00	0.00	14.06
2759.00	0.00	14.06

Appendix B

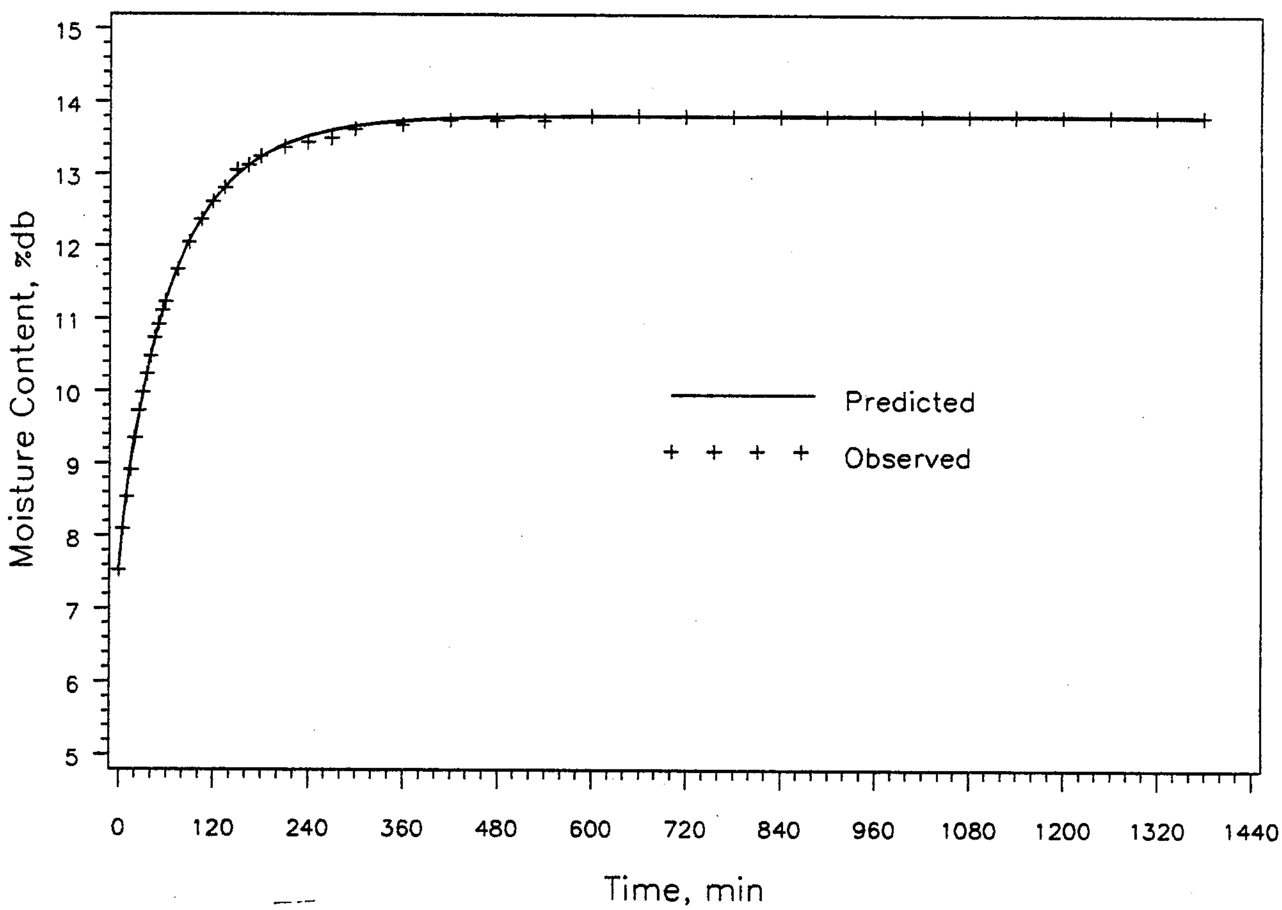

Fig. B1—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=30.0°C, relative humidity=90% and air velocity=0.43 m/s.

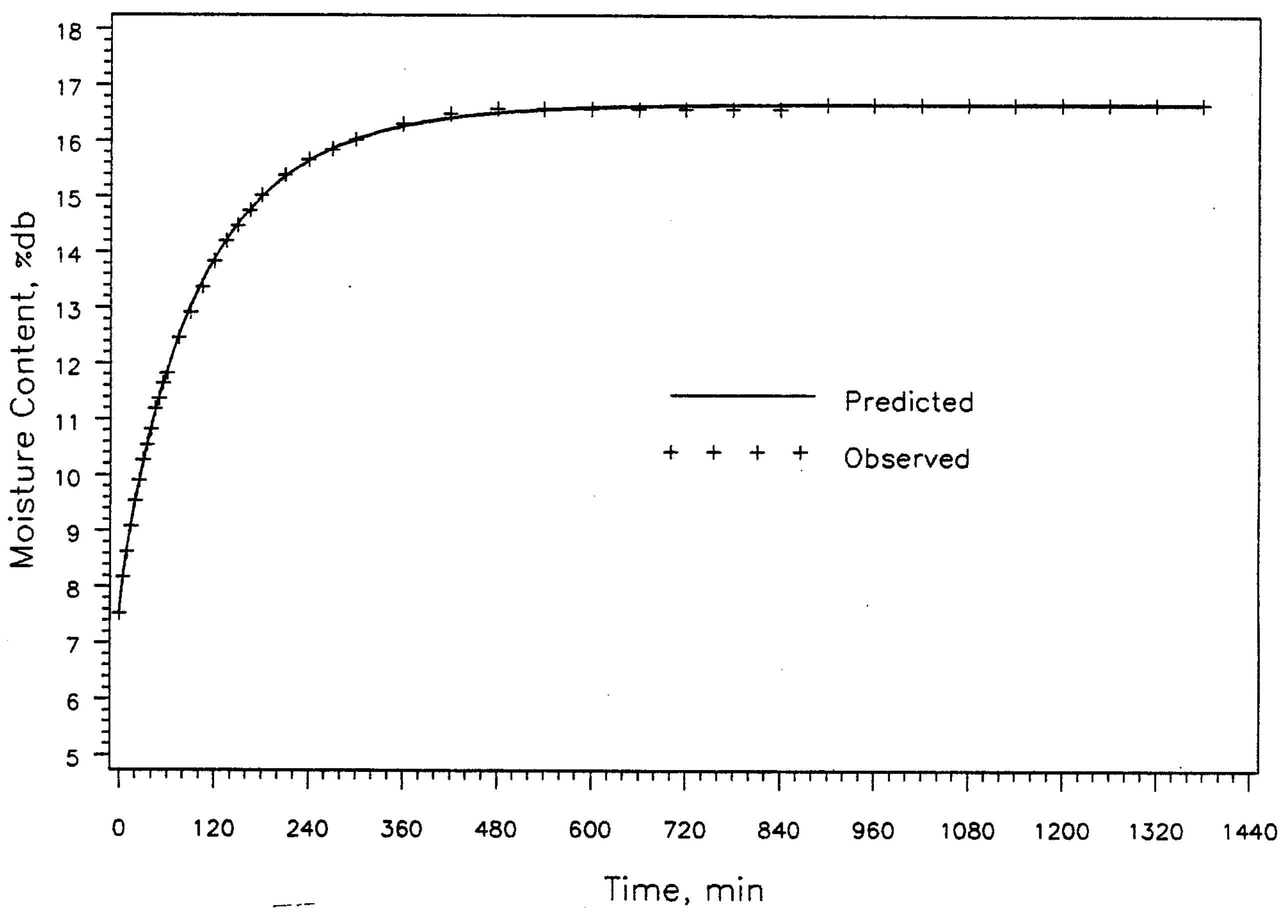

Fig. B2—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=22.5°C, relative humidity=90% and air velocity=0.43 m/s.

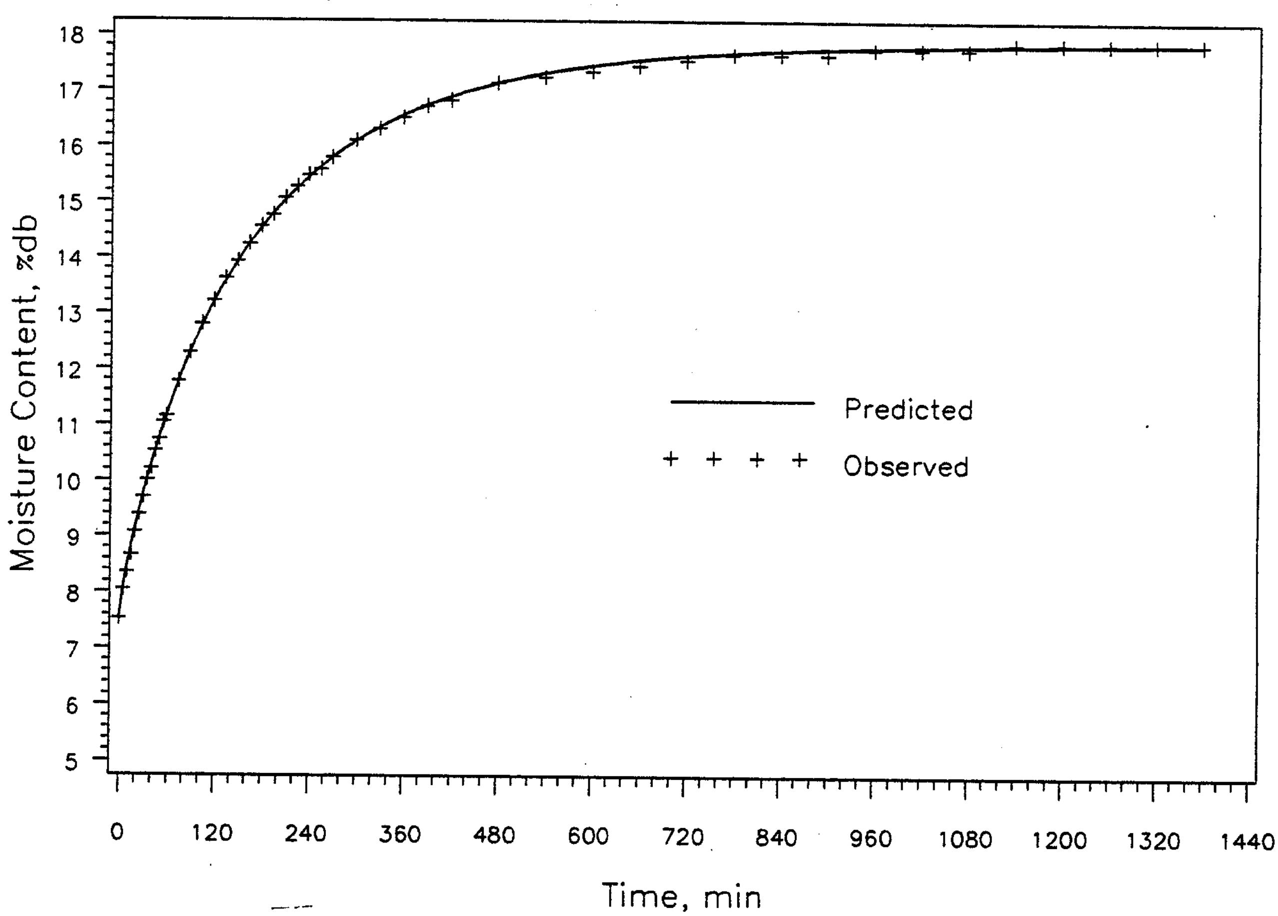

Fig. B3—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=16.0°C, relative humidity=90% and air velocity=0.43 m/s.

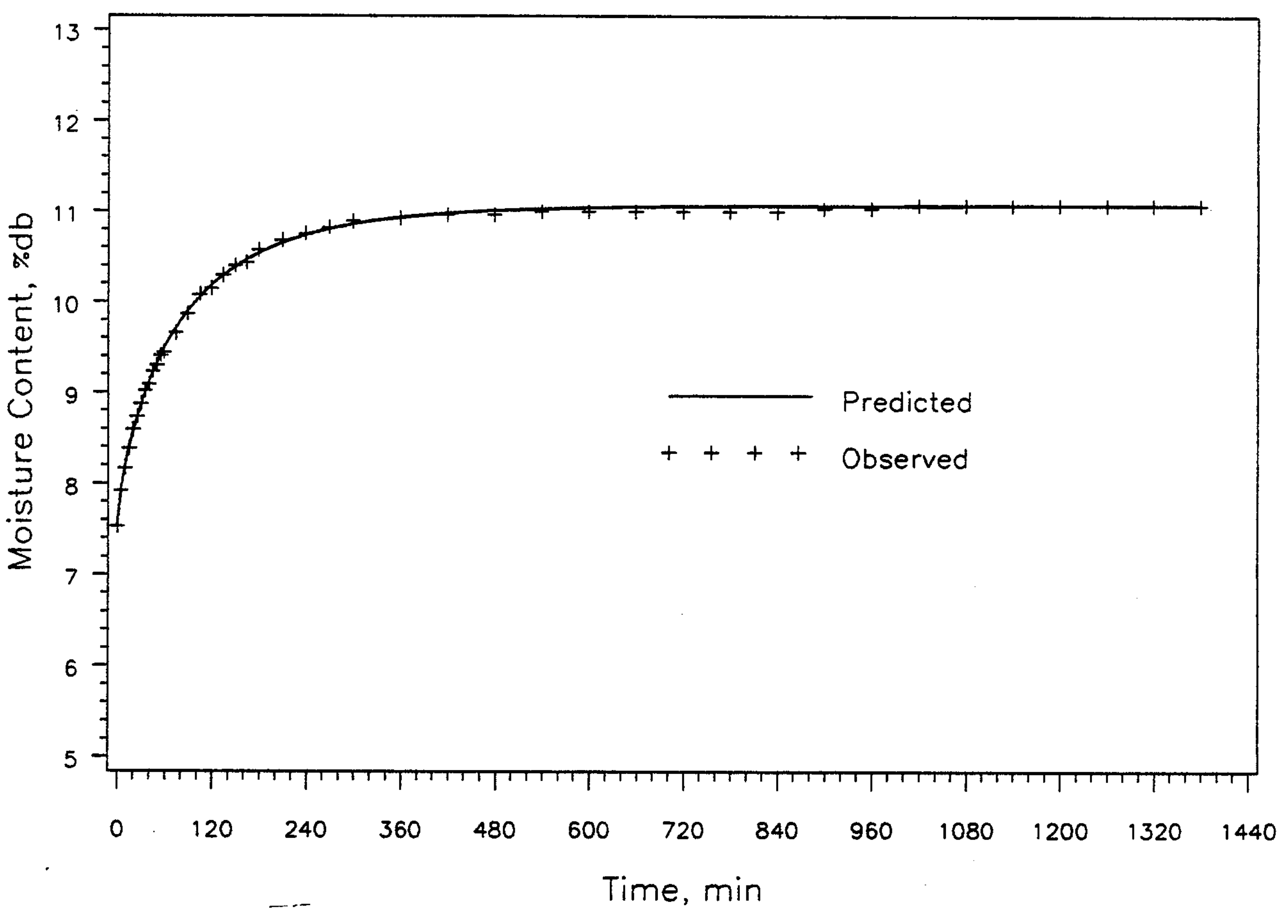

Fig. B4—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=30.0°C, relative humidity=80% and air velocity=0.43 m/s.

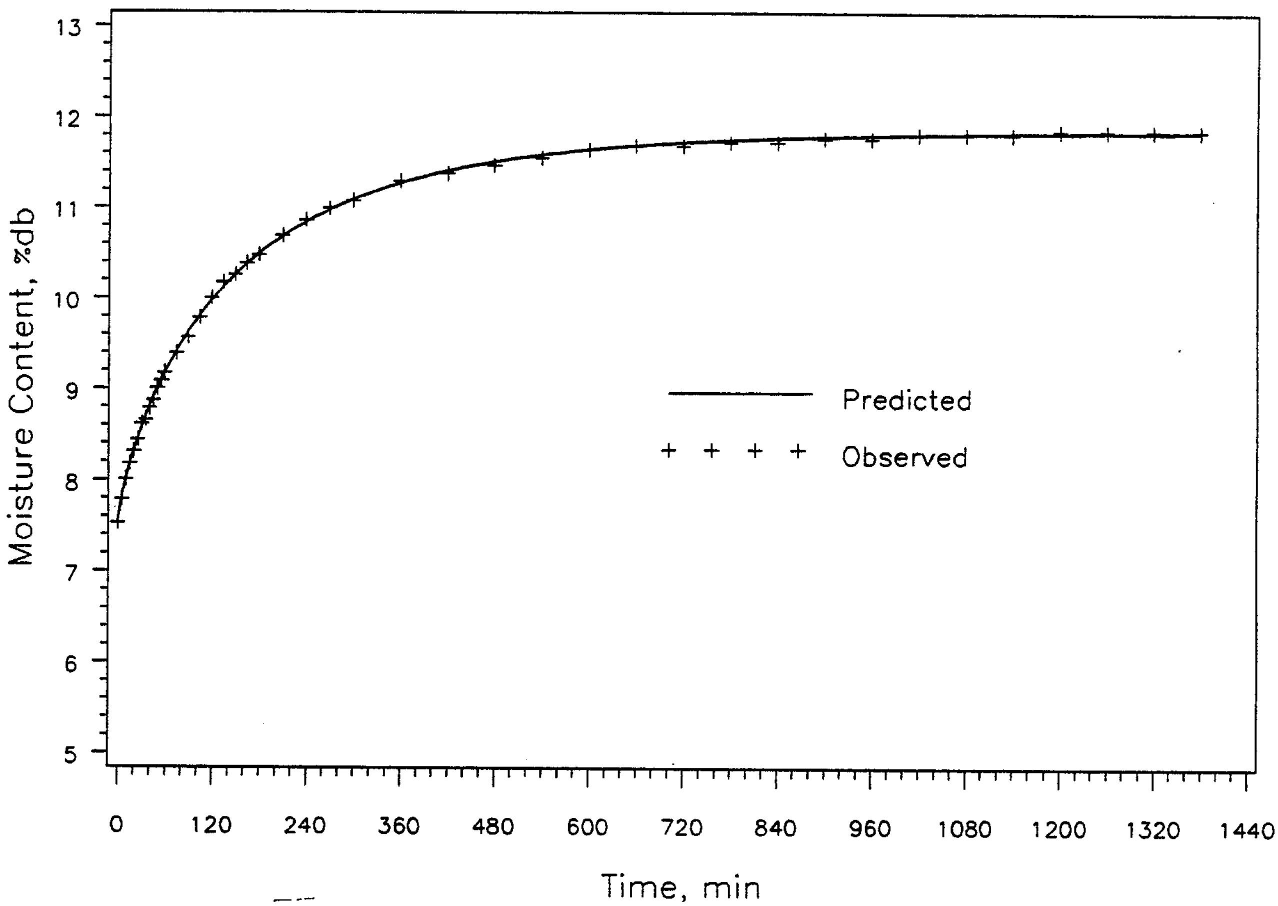

Fig. B5—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=22.5°C, relative humidity=80% and air velocity=0.43 m/s.

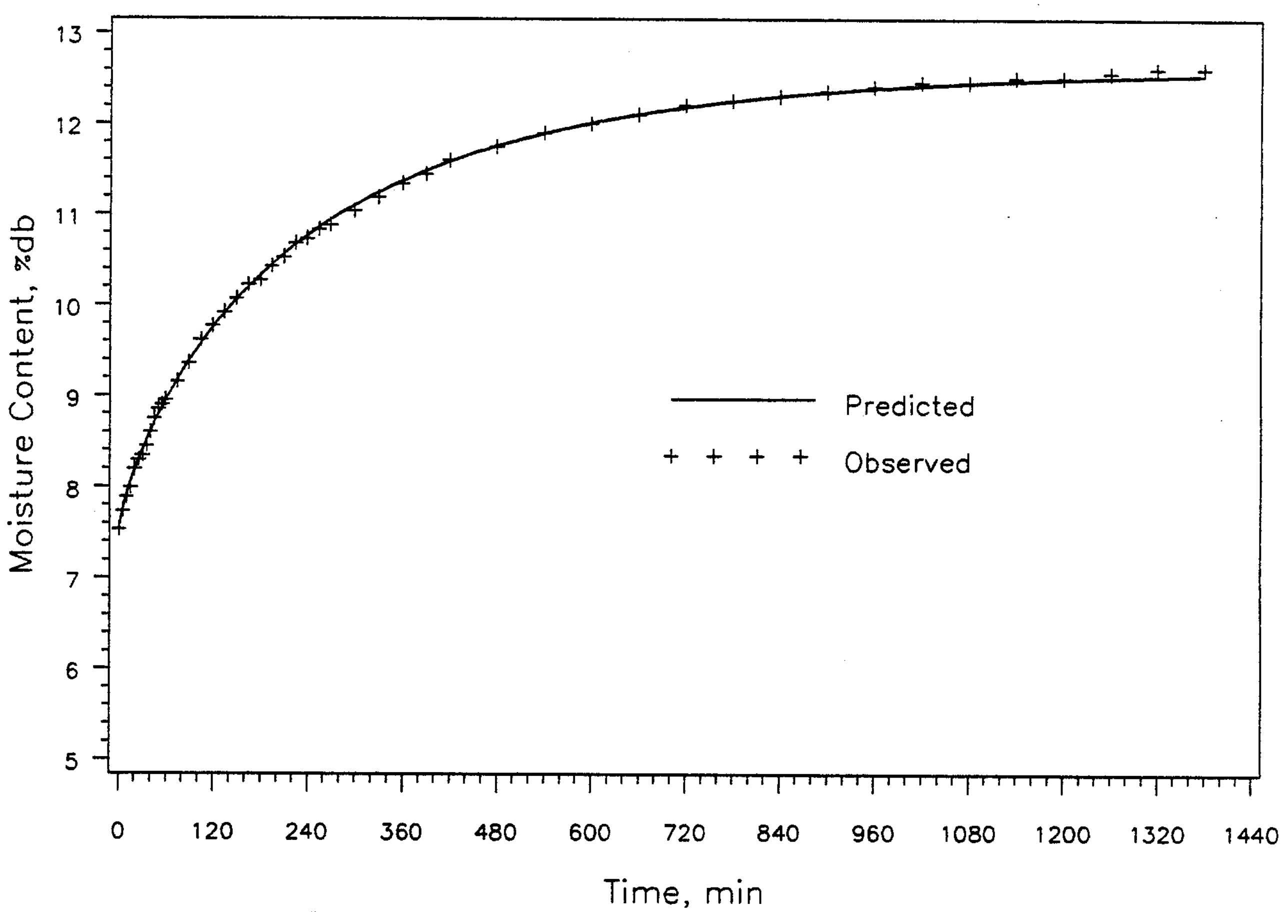

Fig. B6—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=15.0°C, relative humidity=80% and air velocity=0.43 m/s.

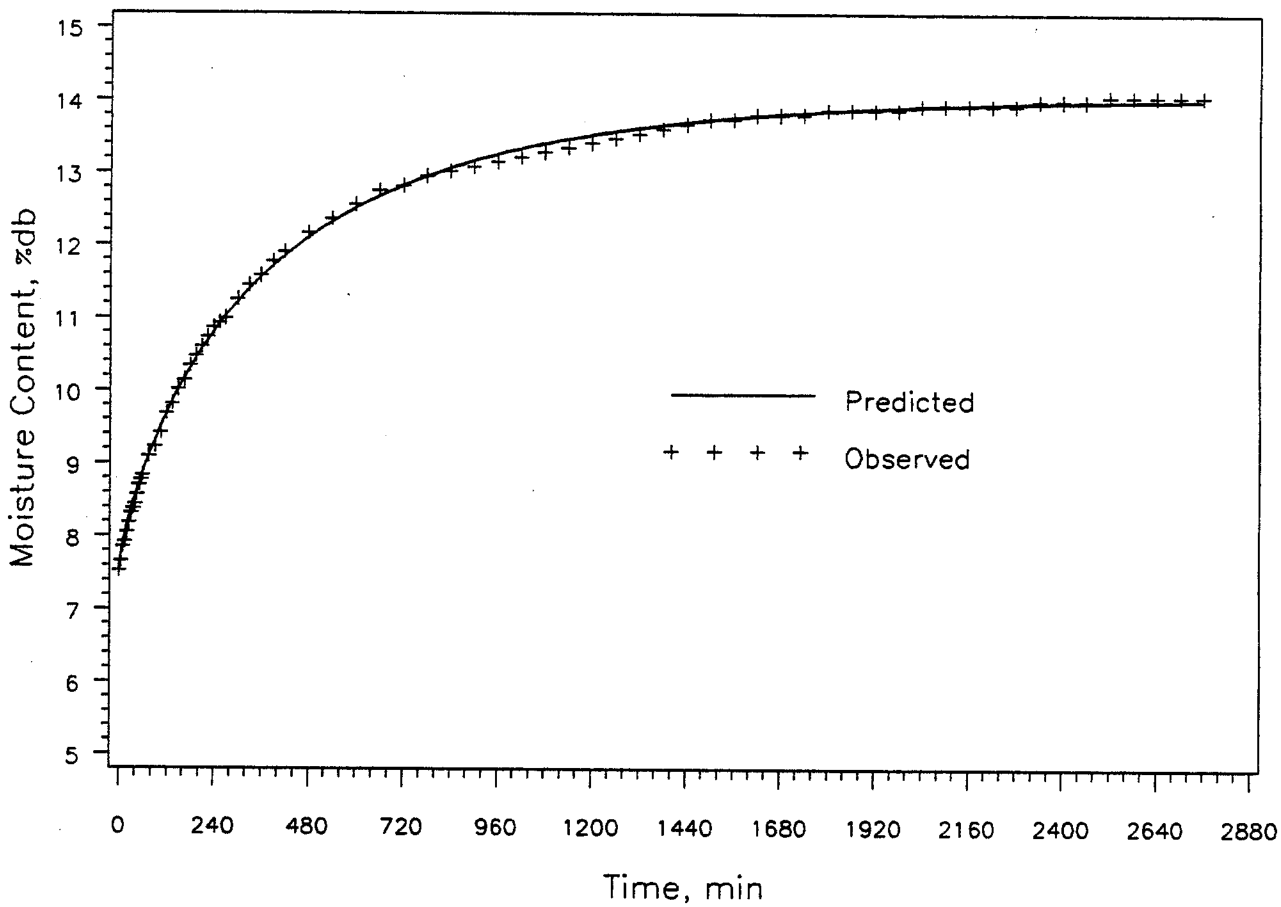

Fig. B7—Experimental wetting rate and the wetting rate predicted by Page's equation at temperature=7.5°C, relative humidity=80% and air velocity=0.43 m/s.

Appendix C

Table C1: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	5.26
5.00	0.90	6.15
10.00	0.83	6.76
15.00	0.77	7.30
20.00	0.72	7.74
25.00	0.67	8.18
30.00	0.62	8.62
35.00	0.58	8.98
40.00	0.55	9.24
45.00	0.52	9.51
50.00	0.49	9.77
55.00	0.46	10.04
59.00	0.44	10.22
74.00	0.38	10.75
89.00	0.32	11.28
104.00	0.28	11.63
119.00	0.24	11.99
134.00	0.21	12.25
149.00	0.18	12.52
164.00	0.16	12.69
179.00	0.14	12.87
209.00	0.12	13.05
239.00	0.09	13.31
269.00	0.08	13.40
299.00	0.07	13.49
359.00	0.05	13.67
419.00	0.04	13.76
479.00	0.03	13.84
539.00	0.02	13.93
599.00	0.01	14.02
659.00	0.01	14.02
719.00	0.00	14.11
779.00	0.00	14.11
839.00	0.00	14.11
899.00	0.00	14.11
959.00	0.00	14.11
1019.00	0.00	14.11
1079.00	0.00	14.11
1139.00	0.00	14.11
1199.00	0.00	14.11
1259.00	0.00	14.11
1319.00	0.00	14.11
1379.00	0.00	14.11

Table C2: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	5.26
5.00	0.90	6.14
10.00	0.82	6.85
15.00	0.76	7.38
20.00	0.70	7.91
25.00	0.65	8.35
30.00	0.61	8.70
35.00	0.56	9.15
40.00	0.53	9.41
45.00	0.50	9.68
50.00	0.47	9.94
55.00	0.44	10.20
59.00	0.42	10.38
74.00	0.35	11.00
89.00	0.29	11.53
104.00	0.25	11.88
119.00	0.22	12.15
134.00	0.18	12.50
149.00	0.15	12.77
164.00	0.12	13.03
179.00	0.11	13.12
209.00	0.08	13.38
239.00	0.06	13.56
269.00	0.05	13.65
299.00	0.04	13.74
359.00	0.02	13.91
419.00	0.02	13.91
479.00	0.01	14.00
539.00	0.01	14.00
599.00	0.01	14.00
659.00	0.01	14.00
719.00	0.01	14.00
779.00	0.00	14.09
839.00	0.00	14.09
899.00	0.00	14.09
959.00	0.00	14.09
1019.00	0.00	14.09
1079.00	0.00	14.09
1139.00	0.00	14.09
1199.00	0.00	14.09
1259.00	0.00	14.09
1319.00	0.00	14.09
1379.00	0.00	14.09

Table C3: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	5.26
5.00	0.90	6.14
10.00	0.82	6.85
15.00	0.75	7.47
20.00	0.70	7.91
25.00	0.65	8.35
30.00	0.61	8.70
35.00	0.57	9.06
40.00	0.53	9.41
45.00	0.50	9.68
50.00	0.47	9.94
55.00	0.44	10.20
59.00	0.42	10.38
74.00	0.35	11.00
89.00	0.30	11.44
104.00	0.25	11.88
119.00	0.21	12.24
134.00	0.18	12.50
149.00	0.15	12.77
164.00	0.14	12.85
179.00	0.11	13.12
209.00	0.08	13.38
239.00	0.06	13.56
269.00	0.05	13.65
299.00	0.03	13.83
359.00	0.03	13.83
419.00	0.02	13.91
479.00	0.01	14.00
539.00	0.01	14.00
599.00	0.00	14.09
659.00	0.00	14.09
719.00	0.00	14.09
779.00	0.00	14.09
839.00	0.00	14.09
899.00	0.00	14.09
959.00	0.00	14.09
1019.00	0.00	14.09
1079.00	0.00	14.09
1139.00	0.00	14.09
1199.00	0.00	14.09
1259.00	0.00	14.09
1319.00	0.00	14.09
1379.00	0.00	14.09

Table C4: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.16
10.00	0.83	8.72
15.00	0.76	9.21
20.00	0.71	9.56
25.00	0.66	9.91
30.00	0.62	10.19
35.00	0.59	10.40
40.00	0.54	10.75
45.00	0.52	10.89
50.00	0.48	11.17
55.00	0.46	11.31
59.00	0.44	11.45
74.00	0.38	11.87
89.00	0.31	12.36
104.00	0.29	12.50
119.00	0.24	12.85
134.00	0.21	13.06
149.00	0.19	13.20
164.00	0.17	13.34
179.00	0.15	13.48
209.00	0.12	13.69
239.00	0.10	13.83
269.00	0.08	13.97
299.00	0.06	14.11
359.00	0.05	14.18
419.00	0.04	14.25
479.00	0.04	14.25
539.00	0.03	14.32
599.00	0.03	14.32
659.00	0.02	14.39
719.00	0.02	14.39
779.00	0.02	14.39
839.00	0.01	14.46
899.00	0.01	14.46
959.00	0.00	14.53
1019.00	0.00	14.53
1079.00	0.00	14.53
1139.00	0.00	14.53
1199.00	0.00	14.53
1259.00	0.00	14.53
1319.00	0.00	14.53
1379.00	0.00	14.53

Table C5: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.10
10.00	0.84	8.53
15.00	0.78	8.91
20.00	0.71	9.35
25.00	0.65	9.73
30.00	0.61	9.98
35.00	0.57	10.23
40.00	0.53	10.48
45.00	0.49	10.73
50.00	0.46	10.92
55.00	0.43	11.11
59.00	0.41	11.24
74.00	0.34	11.67
89.00	0.28	12.05
104.00	0.23	12.37
119.00	0.19	12.62
134.00	0.16	12.81
149.00	0.12	13.06
164.00	0.11	13.12
179.00	0.09	13.24
209.00	0.07	13.37
239.00	0.06	13.43
269.00	0.05	13.50
299.00	0.03	13.62
359.00	0.02	13.68
419.00	0.01	13.75
479.00	0.01	13.75
539.00	0.01	13.75
599.00	0.00	13.81
659.00	0.00	13.81
719.00	0.00	13.81
779.00	0.00	13.81
839.00	0.00	13.81
899.00	0.00	13.81
959.00	0.00	13.81
1019.00	0.00	13.81
1079.00	0.00	13.81
1139.00	0.00	13.81
1199.00	0.00	13.81
1259.00	0.00	13.81
1319.00	0.00	13.81
1379.00	0.00	13.81

Table C6: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.07
10.00	0.83	8.54
15.00	0.76	8.96
20.00	0.70	9.32
25.00	0.65	9.62
30.00	0.60	9.92
35.00	0.56	10.16
40.00	0.51	10.46
45.00	0.49	10.57
50.00	0.45	10.81
55.00	0.42	10.99
59.00	0.40	11.11
74.00	0.32	11.59
89.00	0.26	11.95
104.00	0.22	12.19
119.00	0.18	12.43
134.00	0.15	12.60
149.00	0.12	12.78
164.00	0.09	12.96
179.00	0.07	13.08
209.00	0.05	13.20
239.00	0.04	13.26
269.00	0.03	13.32
299.00	0.01	13.44
359.00	0.00	13.50
419.00	0.00	13.50
479.00	0.00	13.50
539.00	0.00	13.50
599.00	0.00	13.50
659.00	0.00	13.50
719.00	0.00	13.50
779.00	0.00	13.50
839.00	0.00	13.50
899.00	0.00	13.50
959.00	0.00	13.50
1019.00	0.00	13.50
1079.00	0.00	13.50
1139.00	0.00	13.50
1199.00	0.00	13.50
1259.00	0.00	13.50
1319.00	0.00	13.50
1379.00	0.00	13.50

Table C7: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	11.11
5.00	0.97	11.19
10.00	0.89	11.40
15.00	0.83	11.56
20.00	0.76	11.74
25.00	0.72	11.84
30.00	0.66	12.00
35.00	0.62	12.11
40.00	0.58	12.21
45.00	0.55	12.29
50.00	0.50	12.42
55.00	0.49	12.45
59.00	0.47	12.50
74.00	0.38	12.73
89.00	0.33	12.87
104.00	0.27	13.02
119.00	0.23	13.13
134.00	0.21	13.18
149.00	0.19	13.23
164.00	0.16	13.31
179.00	0.15	13.34
209.00	0.13	13.39
239.00	0.12	13.42
269.00	0.08	13.52
299.00	0.07	13.55
359.00	0.06	13.57
419.00	0.04	13.63
479.00	0.04	13.63
539.00	0.03	13.65
599.00	0.03	13.65
659.00	0.03	13.65
719.00	0.02	13.68
779.00	0.02	13.68
839.00	0.02	13.68
899.00	0.01	13.70
959.00	0.01	13.70
1019.00	0.00	13.73
1079.00	0.00	13.73
1139.00	0.00	13.73
1199.00	0.00	13.73
1259.00	0.00	13.73
1319.00	0.00	13.73
1379.00	0.00	13.73

Table C8: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	11.11
5.00	0.97	11.19
10.00	0.89	11.40
15.00	0.81	11.61
20.00	0.75	11.77
25.00	0.70	11.91
30.00	0.64	12.06
35.00	0.61	12.14
40.00	0.56	12.28
45.00	0.53	12.36
50.00	0.47	12.51
55.00	0.45	12.57
59.00	0.42	12.65
74.00	0.38	12.75
89.00	0.34	12.86
104.00	0.25	13.10
119.00	0.21	13.20
134.00	0.19	13.26
149.00	0.17	13.31
164.00	0.14	13.39
179.00	0.14	13.39
209.00	0.09	13.52
239.00	0.07	13.57
269.00	0.06	13.60
299.00	0.06	13.60
359.00	0.05	13.63
419.00	0.04	13.65
479.00	0.03	13.68
539.00	0.02	13.71
599.00	0.01	13.73
659.00	0.01	13.73
719.00	0.00	13.76
779.00	0.00	13.76
839.00	0.00	13.76
899.00	0.00	13.76
959.00	0.00	13.76
1019.00	0.00	13.76
1079.00	0.00	13.76
1139.00	0.00	13.76
1199.00	0.00	13.76
1259.00	0.00	13.76
1319.00	0.00	13.76
1379.00	0.00	13.76

Table C9: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	11.11
5.00	0.96	11.21
10.00	0.89	11.39
15.00	0.82	11.57
20.00	0.75	11.75
25.00	0.69	11.90
30.00	0.63	12.05
35.00	0.59	12.16
40.00	0.55	12.26
45.00	0.52	12.33
50.00	0.47	12.46
55.00	0.44	12.54
59.00	0.41	12.61
74.00	0.33	12.82
89.00	0.29	12.92
104.00	0.23	13.07
119.00	0.20	13.15
134.00	0.15	13.28
149.00	0.13	13.33
164.00	0.12	13.35
179.00	0.09	13.43
209.00	0.08	13.46
239.00	0.06	13.51
269.00	0.04	13.56
299.00	0.03	13.58
359.00	0.01	13.63
419.00	0.00	13.66
479.00	0.00	13.66
539.00	0.00	13.66
599.00	0.00	13.66
659.00	0.00	13.66
719.00	0.00	13.66
779.00	0.00	13.66
839.00	0.00	13.66
899.00	0.00	13.66
959.00	0.00	13.66
1019.00	0.00	13.66
1079.00	0.00	13.66
1139.00	0.00	13.66
1199.00	0.00	13.66
1259.00	0.00	13.66
1319.00	0.00	13.66
1379.00	0.00	13.66

Appendix D

Table D1: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.10 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
1.00	1.00	7.53
5.00	0.93	7.98
10.00	0.88	8.30
15.00	0.85	8.49
20.00	0.80	8.81
25.00	0.76	9.07
30.00	0.73	9.26
35.00	0.69	9.52
40.00	0.67	9.65
45.00	0.63	9.91
50.00	0.61	10.03
55.00	0.58	10.23
59.00	0.56	10.35
74.00	0.50	10.74
89.00	0.44	11.13
104.00	0.39	11.45
119.00	0.35	11.70
134.00	0.31	11.96
149.00	0.29	12.09
164.00	0.25	12.35
179.00	0.23	12.47
209.00	0.18	12.79
239.00	0.16	12.92
269.00	0.13	13.12
299.00	0.11	13.24
359.00	0.08	13.44
419.00	0.06	13.56
479.00	0.05	13.63
539.00	0.04	13.69
599.00	0.03	13.76
659.00	0.03	13.76
719.00	0.02	13.82
779.00	0.02	13.82
839.00	0.01	13.89
899.00	0.01	13.89
959.00	0.01	13.89
1019.00	0.01	13.89
1079.00	0.00	13.95
1139.00	0.00	13.95
1199.00	0.00	13.95
1259.00	0.00	13.95
1319.00	0.00	13.95
1379.00	0.00	13.95

Table D2: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.10 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.93	7.96
10.00	0.86	8.40
15.00	0.83	8.59
20.00	0.79	8.83
25.00	0.74	9.14
30.00	0.70	9.39
35.00	0.68	9.52
40.00	0.64	9.77
45.00	0.61	9.95
50.00	0.59	10.08
55.00	0.56	10.26
59.00	0.54	10.39
74.00	0.48	10.76
89.00	0.42	11.13
104.00	0.37	11.44
119.00	0.33	11.69
134.00	0.28	12.00
149.00	0.26	12.13
164.00	0.24	12.25
179.00	0.20	12.50
209.00	0.17	12.68
239.00	0.13	12.93
269.00	0.11	13.06
299.00	0.09	13.18
359.00	0.05	13.43
419.00	0.05	13.43
479.00	0.04	13.49
539.00	0.04	13.49
599.00	0.04	13.49
659.00	0.04	13.49
719.00	0.03	13.55
779.00	0.03	13.55
839.00	0.03	13.55
899.00	0.03	13.55
959.00	0.02	13.62
1019.00	0.02	13.62
1079.00	0.01	13.68
1139.00	0.01	13.68
1199.00	0.01	13.68
1259.00	0.00	13.74
1319.00	0.00	13.74
1379.00	0.00	13.74

Table D3: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.10 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.93	7.97
10.00	0.88	8.29
15.00	0.83	8.60
20.00	0.80	8.79
25.00	0.76	9.04
30.00	0.71	9.36
35.00	0.69	9.48
40.00	0.65	9.74
45.00	0.63	9.86
50.00	0.60	10.05
55.00	0.56	10.30
59.00	0.55	10.36
74.00	0.48	10.81
89.00	0.43	11.12
104.00	0.38	11.44
119.00	0.33	11.75
134.00	0.30	11.94
149.00	0.26	12.19
164.00	0.24	12.32
179.00	0.21	12.51
209.00	0.16	12.82
239.00	0.13	13.01
269.00	0.11	13.14
299.00	0.09	13.26
359.00	0.07	13.39
419.00	0.05	13.51
479.00	0.04	13.58
539.00	0.03	13.64
599.00	0.02	13.70
659.00	0.02	13.70
719.00	0.02	13.70
779.00	0.01	13.77
839.00	0.01	13.77
899.00	0.00	13.83
959.00	0.00	13.83
1019.00	0.00	13.83
1079.00	0.00	13.83
1139.00	0.00	13.83
1199.00	0.00	13.83
1259.00	0.00	13.83
1319.00	0.00	13.83
1379.00	0.00	13.83

Table D4: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.25 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.92	8.01
10.00	0.85	8.43
15.00	0.79	8.79
20.00	0.74	9.09
25.00	0.69	9.39
30.00	0.66	9.57
35.00	0.61	9.87
40.00	0.58	10.05
45.00	0.54	10.29
50.00	0.52	10.41
55.00	0.49	10.59
59.00	0.46	10.77
74.00	0.40	11.13
89.00	0.34	11.49
104.00	0.30	11.73
119.00	0.25	12.03
134.00	0.21	12.27
149.00	0.18	12.45
164.00	0.16	12.57
179.00	0.15	12.63
209.00	0.12	12.81
239.00	0.09	12.99
269.00	0.08	13.05
299.00	0.07	13.11
359.00	0.05	13.23
419.00	0.04	13.29
479.00	0.03	13.35
539.00	0.03	13.35
599.00	0.02	13.41
659.00	0.02	13.41
719.00	0.02	13.41
779.00	0.02	13.41
839.00	0.01	13.47
899.00	0.01	13.47
959.00	0.00	13.53
1019.00	0.00	13.53
1079.00	0.00	13.53
1139.00	0.00	13.53
1199.00	0.00	13.53
1259.00	0.00	13.53
1319.00	0.00	13.53
1379.00	0.00	13.53

Table D5: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.25 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.06
10.00	0.84	8.47
15.00	0.78	8.83
20.00	0.73	9.12
25.00	0.68	9.42
30.00	0.63	9.71
35.00	0.60	9.89
40.00	0.56	10.13
45.00	0.52	10.36
50.00	0.49	10.54
55.00	0.47	10.66
59.00	0.44	10.83
74.00	0.38	11.19
89.00	0.32	11.54
104.00	0.27	11.84
119.00	0.23	12.07
134.00	0.20	12.25
149.00	0.18	12.37
164.00	0.15	12.55
179.00	0.13	12.66
209.00	0.10	12.84
239.00	0.08	12.96
269.00	0.06	13.08
299.00	0.05	13.14
359.00	0.04	13.19
419.00	0.03	13.25
479.00	0.02	13.31
539.00	0.01	13.37
599.00	0.01	13.37
659.00	0.01	13.37
719.00	0.01	13.37
779.00	0.01	13.37
839.00	0.00	13.43
899.00	0.00	13.43
959.00	0.00	13.43
1019.00	0.00	13.43
1079.00	0.00	13.43
1139.00	0.00	13.43
1199.00	0.00	13.43
1259.00	0.00	13.43
1319.00	0.00	13.43
1379.00	0.00	13.43

Table D6: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.25 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.92	7.99
10.00	0.85	8.39
15.00	0.79	8.74
20.00	0.72	9.14
25.00	0.67	9.43
30.00	0.65	9.54
35.00	0.60	9.83
40.00	0.57	10.00
45.00	0.53	10.23
50.00	0.49	10.46
55.00	0.46	10.64
59.00	0.43	10.81
74.00	0.35	11.27
89.00	0.29	11.61
104.00	0.25	11.84
119.00	0.21	12.07
134.00	0.17	12.30
149.00	0.14	12.47
164.00	0.12	12.59
179.00	0.09	12.76
209.00	0.08	12.82
239.00	0.08	12.82
269.00	0.07	12.88
299.00	0.05	12.99
359.00	0.02	13.16
419.00	0.01	13.22
479.00	0.01	13.22
539.00	0.01	13.22
599.00	0.00	13.28
659.00	0.00	13.28
719.00	0.00	13.28
779.00	0.00	13.28
839.00	0.00	13.28
899.00	0.00	13.28
959.00	0.00	13.28
1019.00	0.00	13.28
1079.00	0.00	13.28
1139.00	0.00	13.28
1199.00	0.00	13.28
1259.00	0.00	13.28
1319.00	0.00	13.28
1379.00	0.00	13.28

Table D7: Change in moisture ratio and moisture content with time for test at Temp=30.0 °C, RH=90% and air velocity=0.43 m/s. Replicate# 1.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.16
10.00	0.83	8.72
15.00	0.76	9.21
20.00	0.71	9.56
25.00	0.66	9.91
30.00	0.62	10.19
35.00	0.59	10.40
40.00	0.54	10.75
45.00	0.52	10.89
50.00	0.48	11.17
55.00	0.46	11.31
59.00	0.44	11.45
74.00	0.38	11.87
89.00	0.31	12.36
104.00	0.29	12.50
119.00	0.24	12.85
134.00	0.21	13.06
149.00	0.19	13.20
164.00	0.17	13.34
179.00	0.15	13.48
209.00	0.12	13.69
239.00	0.10	13.83
269.00	0.08	13.97
299.00	0.06	14.11
359.00	0.05	14.18
419.00	0.04	14.25
479.00	0.04	14.25
539.00	0.03	14.32
599.00	0.03	14.32
659.00	0.02	14.39
719.00	0.02	14.39
779.00	0.02	14.39
839.00	0.01	14.46
899.00	0.01	14.46
959.00	0.00	14.53
1019.00	0.00	14.53
1079.00	0.00	14.53
1139.00	0.00	14.53
1199.00	0.00	14.53
1259.00	0.00	14.53
1319.00	0.00	14.53
1379.00	0.00	14.53

Table D8: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 2.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.10
10.00	0.84	8.53
15.00	0.78	8.91
20.00	0.71	9.35
25.00	0.65	9.73
30.00	0.61	9.98
35.00	0.57	10.23
40.00	0.53	10.48
45.00	0.49	10.73
50.00	0.46	10.92
55.00	0.43	11.11
59.00	0.41	11.24
74.00	0.34	11.67
89.00	0.28	12.05
104.00	0.23	12.37
119.00	0.19	12.62
134.00	0.16	12.81
149.00	0.12	13.06
164.00	0.11	13.12
179.00	0.09	13.24
209.00	0.07	13.37
239.00	0.06	13.43
269.00	0.05	13.50
299.00	0.03	13.62
359.00	0.02	13.68
419.00	0.01	13.75
479.00	0.01	13.75
539.00	0.01	13.75
599.00	0.00	13.81
659.00	0.00	13.81
719.00	0.00	13.81
779.00	0.00	13.81
839.00	0.00	13.81
899.00	0.00	13.81
959.00	0.00	13.81
1019.00	0.00	13.81
1079.00	0.00	13.81
1139.00	0.00	13.81
1199.00	0.00	13.81
1259.00	0.00	13.81
1319.00	0.00	13.81
1379.00	0.00	13.81

Table D9: Change in moisture ratio and moisture content with time for test at Temp=30.0°C, RH=90% and air velocity=0.43 m/s. Replicate# 3.

Time (min)	Moisture Ratio	Moisture Content (dry mass basis)
0.00	1.00	7.53
5.00	0.91	8.07
10.00	0.83	8.54
15.00	0.76	8.96
20.00	0.70	9.32
25.00	0.65	9.62
30.00	0.60	9.92
35.00	0.56	10.16
40.00	0.51	10.46
45.00	0.49	10.57
50.00	0.45	10.81
55.00	0.42	10.99
59.00	0.40	11.11
74.00	0.32	11.59
89.00	0.26	11.95
104.00	0.22	12.19
119.00	0.18	12.43
134.00	0.15	12.60
149.00	0.12	12.78
164.00	0.09	12.96
179.00	0.07	13.08
209.00	0.05	13.20
239.00	0.04	13.26
269.00	0.03	13.32
299.00	0.01	13.44
359.00	0.00	13.50
419.00	0.00	13.50
479.00	0.00	13.50
539.00	0.00	13.50
599.00	0.00	13.50
659.00	0.00	13.50
719.00	0.00	13.50
779.00	0.00	13.50
839.00	0.00	13.50
899.00	0.00	13.50
959.00	0.00	13.50
1019.00	0.00	13.50
1079.00	0.00	13.50
1139.00	0.00	13.50
1199.00	0.00	13.50
1259.00	0.00	13.50
1319.00	0.00	13.50
1379.00	0.00	13.50