DRYING CHARACTERISTICS AND MOISTURE ISOTHERMS OF HULLESS OATS (*Avena sativa* L.)

by

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

of

MASTER OF SCIENCE

ABSTRACT

A vertical-type thin-layer drier was used to obtain the thin-layer drying and rewetting data of hulless oats (*Avena sativa* L., cv. 'AC Belmont'). The experimental data were obtained by drying or rewetting 70% hulless oats in the thin-layer drier using air at constant relative humidity conditions. The data were collected for various combinations of initial grain moisture content (11 to 22% dry basis), temperature (15 to 36°C), and relative humidity (27 to 93%). A thin layer (one or two kernels thick) of oats was held in a horizontal plane and conditioned air was passed vertically through the layer. The gain or loss in mass of oats with time was recorded until the grain mass was constant or within ± 0.01 g between two successive readings. The equilibrium moisture content (EMC) was presumed to have been reached at this stage. Depending on the air conditions and the initial moisture content, equilibrium was attained by both sorption and desorption processes. The sorption and desorption EMC data were determined by oven drying the samples after the drying or rewetting process was stopped. The EMC data were used to determine a suitable EMC-equilibrium relative humidity (ERH) relationship of hulless oats.

Thin-layer drying or rewetting data were analyzed using liquid diffusion, Lewis' and Page's equations. The liquid diffusion equation for an isotropic and homogeneous sphere did not describe the drying and rewetting rate of oats satisfactorily. The thin-layer drying and rewetting rates at constant relative humidities agreed well with the Page's equation. The effects of temperature, relative humidity, initial moisture content and air velocities were investigated on parameters k and n of Page's equation. The temperature, relative humidity, and initial moisture content had significant effect ($p > 0.05$) on k. The relative humidity and initial moisture content had significant effect on parameter n. The air velocity did not have significant effect ($p > 0.05$) on drying or rewetting rate. Due to the nonlinear distribution of k and n among experimental tests, it was not possible to correlate k or n in terms of temperature and relative humidity for all the experimental tests.

Numerous empirical and semi empirical equations have been proposed by scientists to describe the EMC-ERH relationship of crops. The suitability of five commonly used equations (modified equations of Chung-Pfost, Guggenheimer-Anderson-de Boer (GAB), Halsey, Henderson, and Oswin) was evaluated to describe the EMC-ERH relationship of oats. Nonlinear regression was performed to estimate the three parameters of each of the equations. Based on the standard error of humidity, mean relative percent error, and randomness of residual plots, the modified Oswin equation best described the EMC-ERH relationship for 'AC Belmont' hulless oats.

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Dedicated

to my mother 'Akkā'

and

In memory of my father 'Appā'

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LIST OF SYMBOLS

A, B, C	parameters of isotherm equations
c_b	specific heat of body, J kg $^{-1}$ K $^{-1}$
D	diffusion coefficient, m^2/h
J_ℓ	liquid flux, kg m $^{-2}$ s $^{-1}$
J_q	heat flux, J m $^{-2}$ s $^{-1}$
J_v	vapour flux, kg m $^{-2}$ s $^{-1}$
K_ℓ	liquid conductivity, 1/s
K_t	apparent thermal conductivity, W m $^{-1}$ K $^{-1}$
k	parameter of Page's equation, 1/s
K_v	vapour conductivity, m ^{2}/s
L_v	specific latent heat of vapourization, J/kg
L_w	specific differential heat of wetting, J/kg
M	moisture content, % dry mass basis
MR	moisture ratio
Mo	initial moisture content, % dry mass basis
Me	equilibrium moisture content, % dry mass basis
n	parameter of Page's equation
r	radial distance, m
R	radius of sphere, m
RH	relative humidity, decimal
R_v	universal gas constant for water vapour, J K $^{-1}$ Mol^{-1}
T	temperature, ^{0}C
T′	thermodynamic temperature, K
ρ_ℓ	liquid density, kg/m ^{3}
ρ_s	dry solid density, kg/m^3
ρ_{vo}	saturated vapour density, kg/m ^{3}

1. INTRODUCTION

Oats rank sixth in world cereal production following wheat, maize, rice, barley and sorghum (Hoffman 1995). Oats are the fourth most important cereal crop in Canada. During the period from 1986 to 1995, an average of 2.97 Mt of oats were produced and stored annually in Canada worth about Can$ 163/t (Canada Grains Council 1996). Canada ranks second in oat production in the world, next to the USA, followed by Argentina, Australia, and the former Soviet Union. Canada is the foremost exporter of oats in the world with an average of 48% of its exports going to the USA and the balance to Japan, Cuba, Belgium, Luxemberg, and the Netherlands (Baker 1995).

Oats are used for feed and food purposes. Oats contain seven B vitamins, vitamin E, and nine minerals: Fe, Ca, Mg, Na, K, P, Cu, Mn, and Zn. Oats also have the highest protein content of any cereal grain, and they are a good source of complex carbohydrates and water-soluble dietary-fibre. Oats play a major role in maintaining human health through diet due to their water-soluble dietary-fibre content. The oats seem reduce the cholesterol levels (a major factor in coronary heart diseases), have an impact on gastrointestinal cancer and related disorders (Hill and Fernandez 1990), and lower post-meal blood glucose levels in insulin-dependent diabetics (Holm et al. 1992). The digestibility of protein of oatmeal is equal to that of wheat and soya flour, i.e., a similar digestibility to that of other grain proteins (Welch 1995).

Oats are normally consumed where they are produced, especially when used for feed. Oat hulls are low in nutritive and energy value, therefore, reducing the hull percentage of the oats improves their value for animal feed and human food. Several cultivars of hulless oats have been developed with yields comparable to currently grown hulled cultivars (e.g. 'Terra' and 'Tibor' in Canada, and 'Pennuda' from the USA).

Oats are principally fed to dairy cattle, horses, mules, replacement layer chickens and turkeys, with lesser quantities fed to hogs, beef cattle, and sheep. Food products that use oats include oatmeal, oat flour, natural cereals, meat product extenders, cookies, breads, granola, baby food, and oat bran.

The present trend in cereal and oilseed drying is to use near-ambient air drying (Singh (Jayas) 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,1980b). An additional advantage of near-ambient drying is that it delivers better-quality, dried grain.

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

The EMC of seeds is needed in thin-layer drying equations and thus needs to be determined for new crops. The EMC-ERH relationship for a crop is useful in predicting the drying and rewetting behaviour of grains during storage. For hulless oats, limited data on thin-layer drying characteristics and equilibrium moisture contents have been reported in the published literature.

2. OBJECTIVES

The objectives of this study were :

(1) to determine the drying characteristics of 'AC Belmont' hulless oats using a thin-layer drying-rewetting apparatus;

(2) to evaluate the ability of liquid diffusion, Lewis', and Page's equations for describing thin-layer drying and rewetting data of hulless oats;

(3) to obtain by the thin layer drying method, the EMC data for hulless oats at several relative humidities (27, 37, 48, 61, 68, 69, 75, 88, and 93%) and drying temperatures between 15 to 36°C; and

(4) to evaluate the suitability of five commonly used isotherm models i.e. the modified Chung-Pfost, GAB, Halsey, Henderson, and Oswin equations to describe the EMC-ERH relationship of hulless oats.

3. REVIEW OF LITERATURE

3.1 Background

The moisture transfer to or from cereals, oilseeds, and food materials has been a subject of considerable research in the past 50 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). Considerable work has been done on thin-layer drying of grains but very little research has been done on thin-layer rewetting of grains (Misra and Brooker 1980). The need for rewetting rate data has been recognized (Jayas et al. 1988) for simulating the possible occurrence of rewetting of grain during near-ambient air drying. The rewetting process is similar to drying, and drying theories can be applied to understand and describe the rewetting rates of cereals and oilseeds (Fortes et al. 1981). Compared to many other engineering materials, grain is nonhomogeneous, and this nonhomogeneity precludes a simple yet definitive model based on classical heat and mass transfer. Input air conditions are seldom constant, especially in near-ambient drying, in which temperature and relative humidity are constantly changing. To take into account the many variables in grain drying, a model or an equation needs to be so complex that it is of questionable value, despite the awesome numerical capability of modern computers. This is not to suggest that less complex models with simplifying assumptions are not useful. For example, a grain can be represented by a sphere of equivalent volume rather than including the relationship of surface area to volume and the shape factor. Other simplifying assumptions frequently used are: negligible temperature gradient within the grain, moisture diffusion to the kernel surface is in liquid form, moisture evaporates only at the kernel surface. A review of theories of thin-layer drying and the various theoretical, empirical, and semi-empirical equations used to fit the data of thin-layer drying of agricultural grains is given in this chapter.

3.2 Moisture Transfer Theories

The term "thin-layer " has been applied to (Jayas et al. 1991):

1. a single kernel freely suspended in the drying air or one layer of grain kernels.
2. a polylayer of many grain thicknesses if the temperature and the relative humidity of the drying air, can be considered for the purpose of the drying process calculations, as being in the same thermodynamic state at any time of drying.

Based on the above definition it can be concluded that:

1. a mathematical model of drying of a single grain kernel is also a model for grains drying in a thin-layer using any of the drying methods,
2. thickness of a thin-layer may change with the velocity, temperature, and relative humidity of the drying air.

This would mean that the thickness of a thin-layer can increase if the velocity of the drying air increases and also if the thermodynamic state of the drying air approaches the equilibrium state in heat and mass transfer with grain dried in this layer.

In classical treatises, drying rate is divided into a constant rate period and one or more falling rate periods (Foster 1982). Constant rate drying occurs when there is free water at the material surface and resistance to water vapour removal is limited to that of the air or gas film surrounding the material. In grain drying this condition occurs only when drying very wet grain or briefly after moisture condenses or rain wets the grain. The point at which the constant rate drying stops and falling rate drying starts is called the critical point.

In falling rate drying, either the extent of the surface with free water diminishes or evaporation recedes within the material, or both. With a receding evaporation front, drying becomes almost entirely diffusion-dependent. Drying of cereal grains occurs almost exclusively during the falling rate period (Brooker et al. 1974) when moisture transport within the kernel controls the overall moisture rate to or from a kernel. Bakker-Arkema et al. (1978) have summarised the several mechanisms that 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. Vapour diffusion due to partial vapour-pressure gradients, caused by temperature gradients.
4. Vapour diffusion due to moisture concentration gradients.
5. Liquid or vapour flow due to differences in total pressure.

The moisture transfer within a cereal grain or oilseed is a complex phenomenon. Grain is a biological material with no two grains or seeds totally alike. The factors affecting the moisture transfer and their inter-relationships are too complex to be integrated in one specific equation or model. Hukill (1974) stated that grain drying will remain essentially an empirical operation until an equation is developed that will account for all the variables involved in at least the simplest case. The simplest case referred to was a kernel fully exposed to air of constant temperature and humidity. There is no definite knowledge on the mechanisms of moisture transport involved during drying or rewetting 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). It is generally agreed that the mechanism of moisture movement within a grain is controlled by diffusion phenomenon as stated by Fick's law (Parry 1985). Crank (1964, cited by Shatadal 1989) gave the following liquid diffusion equation for a homogeneous and isotropic sphere with radial symmetry:

$$\frac{\partial M}{\partial t} = \frac{1}{r^2}\left[\frac{\partial}{\partial r}\left(D\, r^2 \frac{\partial M}{\partial r}\right)\right] \tag{1}$$

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

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

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

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

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right] \tag{3}$$

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

$$\frac{\partial MR}{\partial t} = D\left[\frac{\partial^2 MR}{\partial r^2} + \frac{2}{r}\frac{\partial MR}{\partial r}\right] \tag{4}$$

where

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

and Me and Mo are the equilibrium and initial moisture content, respectively.

The following boundary 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 centre is finite).

Arpaci (1966, cited by Shatadal 1989) solved Eq. 4 along with its associated boundary conditions to give :

$$MR(t,\ r) \;=\; \frac{2R}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n}\sin\frac{(n\pi r)}{R}\exp(\frac{Dn^2\pi^2}{R^2}t) \tag{5}$$

Integrating Eq. 5 over the volume of the sphere and then division by the total volume of sphere gives the average MR for the sphere.

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

where MR = (M - Me) / (Mo - Me) (7)

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

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

$$D = C_1 \exp(-C_2/T') \quad (8)$$

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

Equation (6) or its equivalent form for a slab or a cylinder have been used by several investigators to describe the thin-layer moisture transfer rate data for various agricultural grains (Becker and Sallans 1955; Pabis and Henderson 1961, 1962; Bakker-Arkema and Hall 1965; Chittenden and Hustrulid 1966; Hamdy and Johnson 1968; Hamdy and Barre 1969; Hustruid 1962, 1963; Whitaker and Young 1972; Rowe and Gunkel 1972; Watson and Bhargava 1974; Henderson 1974; Osborn et al. 1988). The liquid diffusion equation (Eq. 3), however, has been shown to give inaccurate predictions of moisture transfer data (Fortes and Okos 1980; Bakker-Arkema et al. 1978). The researchers mentioned above have used Eq. (3) to describe thin-layer transfer data mainly because its logarithmic form 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 cannot take place when there is no moisture continuity inside the kernel. Liquid diffusion, therefore, cannot 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 occurring during drying and rewetting of cereals and oilseeds.

Moisture transfer predictions are more accurate when the liquid diffusion coefficient is considered as a function of moisture content in solution of Eq. (2). Bruce (1985) followed this approach and solved Eq. (2) numerically to model single kernel drying of barley and compared predicted with the experimental drying data. This suggests that liquid diffusion may be the predominant moisture transport mechanism.

The principles of irreversible thermodynamics and the mechanistic approach to heat and mass transfer in porous media were applied by Fortes and Okos (1981a, 1981b) to derive the following equations for describing drying of cereals.

Liquid flux:

$$J\ell = -\rho_\ell \; K_\ell \; \ln H \; \nabla T' - \rho_\ell \; K_\ell \; Rv \; \frac{T'}{H} \frac{\partial H}{\partial M} \; \nabla M \tag{9a}$$

Vapour flux:

$$Jv = -Kv \; (\rho vo \frac{\partial H}{\partial T'} + H \; \frac{d\rho vo}{dT'}) \; \nabla T' - Kv \; \rho vo \frac{\partial H}{\partial M} \; \nabla M \tag{9b}$$

Heat flux :

$$Jq = -Kt \; \nabla T' - [\rho_\ell \; K_\ell \; Rv \; \ell n(H) + Kv \; (\rho vo \frac{\partial H}{\partial T'} + H \frac{d\rho vo}{dT'})] \; \frac{RvT'^2}{H} \frac{\partial H}{\partial M} \; \nabla M \tag{9c}$$

where : H is relative humidity, decimal.

Mass conservation:

$$\rho_s \frac{\partial M}{\partial T'} = -\nabla \; (J_\ell + J_v) \tag{9d}$$

Energy conservation:

$$\rho_s\, c_b \frac{\partial T'}{\partial t} - \rho_s\, L_w \frac{\partial M}{\partial t} = \nabla J_q - L_v\, \nabla J_v \tag{9e}$$

The drying rates of corn and drying and wetting rates of wheat were successfully described using the above set of equations by Fortes and Okos (1981a, 1981b). They found that the liquid flux was dominant in the low temperature (26 to 47 °C) drying or rewetting of wheat and corn. At high temperatures (100 °C or higher) of drying, the vapour flux was of a higher order of magnitude than the liquid flux throughout the entire drying period.

The theoretical equations described above and others in the literature (Berger and Pei 1973; Luikov 1966a, 1966b, 1975; Mikhailov 1973; Miller and Miller 1955; Philip and De Vries 1957; De Vries 1958; Henry 1939; Whitney and Porterfield 1968; Young 1969; Jayas et al. 1991) are helpful in explaining the complex phenomenon of moisture movement inside capillary-porous bodies such as grains 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). Bakker-Arkema (1984, cited by Jayas et al. 1991) stated, "for several major small grains such as wheat and barley, the empirical drying rate equations need updating, and diffusion-type drying equations need to be developed for most grains." Several researchers, therefore, have preferred to use simple semi-empirical equations for modelling thin-layer or rewetting of cereals and oilseeds.

3.3 Semi-Empirical and Empirical Equations

Lewis (1921, cited by Jayas et al. 1991) suggested an equation that is analogous to Newton's law of cooling and gave the following equation for drying of a solid:

$$\frac{dM}{dt} = -k(M-Me) \tag{10}$$

Upon integration, Eq. (9) becomes:

$$\frac{M(t)-Me}{Mo-Me} = MR = \exp(-k \cdot t) \tag{11}$$

where k = moisture transfer rate parameter, 1/s.

Chittenden and Hustrulid (1966, cited by Shatadal 1989) assumed that all the resistance to moisture transfer occurs in a thin outer layer of the kernel. Equation (10) (or Eq. (11)) which is based on liquid diffusion makes this assumption also. Because of its simplicity Eq. (11) has been widely used in grain drying simulations. The equation, however, cannot describe the drying rate accurately throughout the drying period (Sokhansanj et al. 1987; Jayas et al. 1991).

Page (1949, cited by Jayas et al. 1991) modified Eq. (11) by adding an exponent n to time t to improve the fit to thin layer data for shelled corn and since then the modified equation has been used extensively for characterizing thin layer drying of cereals, oilseeds, ear corn and clover (White et al. 1973; Jayas and Sokhansanj 1986, 1989; Singh (Jayas) et al. 1983; Pabis and Henderson 1962; Bruce 1985). Page's equation is:

$$MR = \exp(-k \cdot t^{n}) \tag{12}$$

where k and n are moisture transfer rate parameters and are dependent on the product being dried.

On differentiation, Eq. (12) becomes :

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

Substitution from Eq. 12 gives:

$$\frac{dM}{dT} = -n \cdot k \cdot t^{n-1}(M-Me) \tag{13}$$

The parameters of Eq. (11) or (12) have also been related to independent variables. Different researchers have used different relationships for this purpose. A detailed list of various relationships along with the range of values for independent variables used by different researchers is given by Sokhansanj et al. (1987) and Jayas et al. (1991). Equation (12) takes into account the concept of moisture transfer due to liquid diffusion with resistance to moisture transfer occurring in a thin outer layer of the kernel because it has the terms used in Eq. (10). Additionally, it shows that rate of moisture transfer depends on the time elapsed. The moisture transfer rate is expressed as a function of time which apparently also accounts for the effects of other factors like vapour flux due to temperature gradients, irregular shape and anisotropy of kernels, shrinkage and expansion of kernels, thus giving the equation a 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, 1981b). Therefore, for low temperature drying or rewetting of cereals and oilseeds, parameter n of Eq. (12) or (13) can be assumed to be product-dependent constant. This assumption makes 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. (12) which otherwise is not possible because of the random adjustments in the parameters to give the best fitting curve (Jayas et al. 1988).

Equation (12) has been used successfully to describe the thin-layer drying and wetting rates of various cereal grains and oilseeds by many researchers (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; Bruce 1985; Li et al. 1987; Osborn et al. 1988). Syarief et al. (1984) found Eq. (12) to be the best equation for modelling thin-layer drying rates of sunflower seeds. Overhults et al. (1973) found that modified Eq. (12) was better fit to the drying data of soybeans than the unmodified Eq. (11). 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 Jayas (1991).

3.4 Effect of Independent Variables on Moisture Transfer Rates

Moisture transfer rate in grains is affected by many parameters such as temperature, relative humidity, initial moisture content, velocity of drying air, and grain characteristics. The factors like the stage of maturity, dimensions, physical or chemical changes during processing or storage also affect the moisture transfer (Chirife and Iglesias 1978).

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 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), because it controls the rate of water vapour transport from the grain surface to the air and influences the value of equilibrium moisture content. Singh (Jayas) et al. (1983) compared drying rates of barley, wheat and canola at low temperatures (13 to 22 °C) and found that an increase in relative humidity from 56% to 90% reduced the moisture content of grain by 30% after 90 min of drying.

The opinion on effect of initial moisture content on rate of moisture transfer is not conclusive. According to some researchers (Syarief et al. 1984; Osborn et al. 1988) the initial moisture content does not have appreciable effect on moisture transfer rates, whereas others (Park et al. 1971, Sharaf-Eideen et al. 1980) found that initial moisture content affects moisture transfer rates considerably.

Researchers generally agree that the velocity of air during drying grain in thin-layers has little effect on drying rate (Jayas et al. 1991). Misra and Brooker (1980) compiled drying rate data for corn and showed that air velocities ranging from 0.025 to 2.33 m/s had some effect on k (1/s) in Page's equation. Airflows from 0.1 to 0.5 m/s had little effect on the half-time drying of sunflower seed (Syarief et al. 1984). 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.

Different grains have different moisture transfer characteristics. These differences in moisture transfer rates of different grains may be due to different compositions and differences in thickness and configuration of pericarp, aleurone layer, endosperm, and germ. Very limited research has been done to study the effects of different varieties of a crop on drying and rewetting rates. Li et al. (1987) reported that different varieties of sunflower seeds with different oil contents had the same drying rates. Stroshine et al. (1981) found significant differences in field drying rates of corn inbreds and hybrids.

From the above discussed parameters, only four variables (temperature, relative humidity, air velocity and initial moisture content) are generally used in studies of thin-layer drying and rewetting rates for cereals and oilseeds.

3.5 Methods and Equipment for Thin-Layer Moisture Transfer Tests

On the basis of path of air flow through the sample, equipment used for thin-layer moisture transfer studies is classified as the vertical type or the horizontal type (Sokhansanj et al. 1984a). In the vertical type equipment, the thin layer of sample is kept in a horizontal plane and air flows vertically through the sample. In the horizontal type equipment the thin layer of sample is kept in a vertical plane and air flows horizontally through the sample. Sokhansanj et al. (1984a) compared the two types of equipment in detail. In the vertical type equipment, continuous weighing is not possible because the mass readings are affected by the air lift. In this case, either the air flow has to be stopped or the sample has to be moved away from the air stream to get correct mass readings. This problem (air lift) does not occur in horizontal type equipment. The air velocity profile is more uniform in the vertical type equipment than in the horizontal type but this difference does not significantly affect the drying rates.

Methodologies used for obtaining drying or rewetting characteristics are characterized by an exceptional diversity of apparatus and methods (Gal 1981). As indicated by Gal (1981), experimental data on EMC should be accompanied by detailed descriptions of the material, experimental procedures and apparatus. He stressed that the temperature and water vapour pressure in the space around the sample should be precisely maintained constant. He also indicated that only moderate accuracy could be attained using methods in which the water vapour is maintained constant by controlling the vapour content in the space around the sample.

Careful planning is required to conduct the thin-layer drying experiments. A detailed sample preparation procedure and data collection schedule will reduce the risk of loss of time and valuable data. It is often difficult to have freshly-harvested samples for use in thin-layer drying tests. Therefore dried or remoistened samples have to be used for the studies. There is no agreement among researchers on how to prepare the samples so that the test sample resembles the freshly harvested grain. Sokhansanj et al. (1984b) compared the drying rates of wheat, barley, and canola that were repeatedly rewetted and then dried in 60 °C air. Drying times for wheat and barley did not change significantly while drying times for canola decreased. In all samples, however, they found a definite change in drying rate between freshly harvested and rewetted grain. Hustrulid (1962, cited by Jayas et al. 1991) 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.

(1983) found that in preparing the samples for drying, temperature during tempering has a strong influence on the time required for moisture distribution in the kernel to become uniform. 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 grains.

3.6 Isotherm Equations

More than 200 equations have been proposed to describe the sorption data for biological materials alone (Van den Berg and Bruin 1981). No unique model, however, has been found to accurately describe the equilibrium moisture content (EMC) and equilibrium relative humidity (ERH) relationship of various types of materials in a broad range of relative humidities and temperatures. The absence of such an equation is due to differences in biological materials. A few comparatively versatile models are available for the isotherms of food and other biological materials. These include the Halsey (1948, cited by Fasina and Sokhansanj 1993), the Oswin (1946, cited by Fasina and Sokhansanj 1993), the Henderson (1952, cited by Yang 1992), the Chung-Pfost (1967), and Guggenheim-Anderson-de Boer (GAB) equation (1946, cited by Jayas et al. 1991). The equations are:

Modified Henderson equation:

$$\mathrm{RH} = [1- \{\exp(-\mathrm{A}(\mathrm{T}+\mathrm{C})\ \mathrm{M}^{\mathrm{B}}\}] \tag{14}$$

Modified Chung-Pfost equation:

$$RH = \exp(-\frac{A}{T+C}\exp(-B{\cdot}M^{*}/100)) \tag{15}$$

Modified Halsey equation:

$$RH = \exp(-\exp(A+B\cdot T)M^{-C}) \tag{16}$$

Modified Oswin equation:

$$RH = 1 / [\{(A + B\cdot T)/M\}^{C} + 1] \tag{17}$$

Modified GAB equation:

$$RH = \frac{-(B(A\cdot C-C\cdot M+2M\cdot T)) \mp \sqrt{C}\cdot B\sqrt{A^2C-2A\cdot C\cdot M+C\cdot M^2+4A\cdot M\cdot T}}{2B^2M(C-T)} \tag{18}$$

where RH is the equilibrium relative humidity in decimal, M is equilibrium moisture content in decimal (dry basis), M* is the equilibrium moisture content in percent (dry basis), A, B, and C are model specific coefficients, and T is temperature in °C.

Halsey's equation was developed for high protein and high oil content food products, Iglesias and Chirife (1976) modified this equation to account for temperature dependence of the constants of the equation. Oswin's equation is a mathematical representation of the sigmoid shape of the isotherm curves. The modified Henderson and the Chung-Pfost equations are commonly used to describe the EMC-ERH relationships for starchy foods. A lot of regional tests of the goodness of fit of some popular equations, as applied to individual foods or crops, were also reported. For example, Chen and Clayton (1971) tested different models and their temperature dependence using the EMC data of corn, and found that the empirically modified Chen's equation (Chen 1971) adequately described the temperature dependency of corn isotherms between 4.4 °C and 60.0 °C. Pfost et al. (1976) determined parameters of Modified-Henderson (1952), Chung-Pfost (1967) equations to describe the isotherm data for grains and oilseeds. Asijegiri and Sopade (1990) used the Bradley (1936, cited by Yang 1992), Halsey (1948), Henderson (1952), Chung-Pfost (1967), and Caurie (1970) equations to assess the goodness of fit to the isotherm data of Nigerian millet at the temperatures of 20, 25 and 40 °C, and found that the Chung-Pfost equation gave the best fit. Recently, Jayas and Mazza (1993) modified the GAB equation by incorporating the effect of temperature of drying air. They fitted this modified equation, as well as modified equations of Chung-Pfost, Halsey, Henderson, and Oswin, to the EMC data of oats at temperatures of 10, 25, 40, and 55 °C. They concluded that the modified Chung-Pfost equation was the best and the modified GAB equation was the second best in describing the moisture isotherms of oats. Moisture isotherms include both sorption and desorption phenomena occurring due to rewetting and drying of grains respectively. Sorption isotherms include moisture uptake by adsorption and absorption.

The Modified-Henderson and Chung-Pfost equations are adopted as the ASAE Standard D245.4, Moisture Relationship of Grains (ASAE 1993) for cereal grains and oil seeds. These two equations were found not to describe well the isotherms of many crops such as lentil (Cenkowski et al. 1989b), canola (Sokhansanj et al. 1986), and sunflower seeds (Mazza and Jayas 1990). This is especially true when the relative humidity ranges from 80 to 100%. Chen and Morey (1989a) compared the Modified-Halsey, Modified-Oswin, Modified-Henderson, and Modified-Chung-Pfost equations by using the isotherm data of variety of crops. They concluded that the Modified-Henderson and Modified-Chung-Pfost equations could serve as good models for many starchy grains and fibrous materials and these were not suitable for high protein and oil products since they indicated clear patterns in residual plots and had large values of mean relative percent errors and the standard errors of the estimated parameter. Therefore, Chen and Morey (1989a) suggested that part of the ASAE standard regarding moisture relationship should be revised.

4. MATERIALS AND METHODS

4.1 Thin-layer Drying Equipment

The equipment (Fig. 4.1) consisted of a chamber with nine separated tray sections ventilated with air at the same temperature and relative humidity in each section. The chamber was connected to a Climate-Lab-AA (C-L-AA) unit (Parameter Generation and Control Inc., Black Mountain, NC) which provided constant air temperature, relative humidity, and airflow. A return-air duct recirculated the exhaust air to the C-L-AA unit. The air was conditioned to desired relative humidity and temperature by the C-L-AA unit. This 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, creating a fine mist of water. Air was passed through the mist. Heat and water vapour transfer between droplets and air through a thin film of saturated air clinging to each droplet continued until an equilibrium condition was reached. The control of water temperature thus allowed the control of relative humidity. Air was then heated to the desired dry bulb temperature by an electric heater installed as part of the C-L-AA unit. The conditioning chamber and transitions from the chamber to the ducts were constructed from wooden-particle boards 12.7 mm thick and surfaced with non-absorbing melamine. The chamber and transitions were thermally insulated with extruded polystyrene 50.8 mm thick. All joints were sealed to prevent leaking. The ducts were thermally insulated with fibre-glass, 76.2 mm thick. The thin-layer drying-wetting equipment explained above, was designed and constructed by Sinicio (1994).

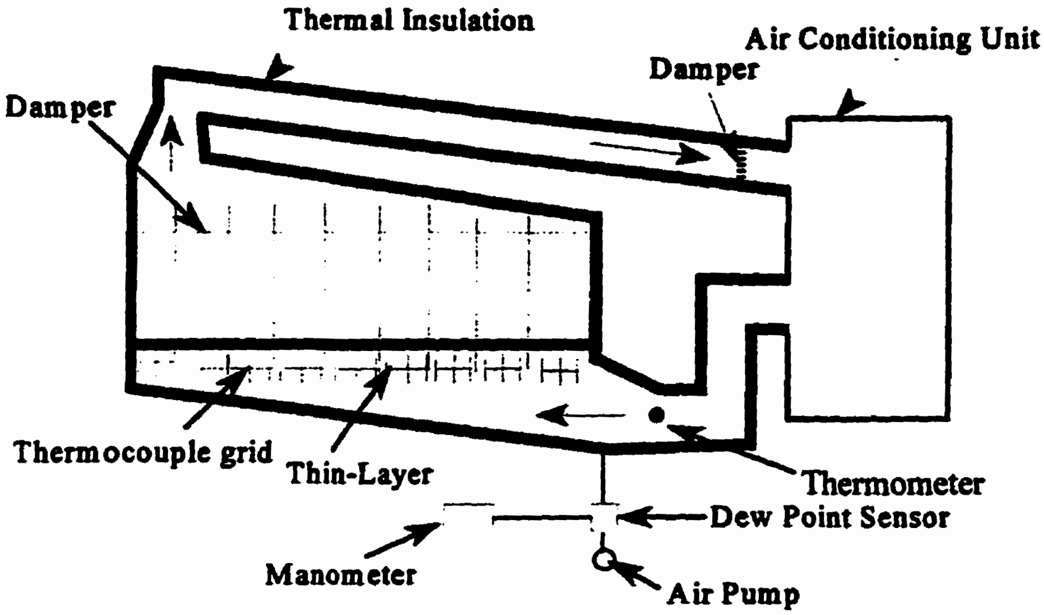

Fig. 4.1 Experimental equipment for thin-layer drying and wetting tests.
Source: Sinicio (1994).

The air velocities were controlled by the valves located in each tray section. The air velocities were measured between the air valves and the trays at nine points for each tray section using a hot-wire anemometer (Model TA400, Airflow Developments Ltd, Mississauga, ON) with a precision of ±0.01 m/s. For each test, the air velocity was measured twice, at the beginning and after the equilibrium was reached.

The average air temperature for each tray section was sensed by nine type-T thermocouples arranged in parallel. The thermocouples were installed 25 mm below the grain trays. The air temperatures were read by a digital thermometer (Model Pronto Plus, Thermo-Electric Instruments, Saddle Brook, NJ) with a precision of ±0.1 °C connected to a manual switch box. Dew point temperature was measured at the air inlet section using a dew-point humidity sensor (Model Hygro-M1, General Eastern Instruments Inc., Watertown, MA) with a precision of ±0.1 °C. An aquarium type air pump forced the air from five collecting points at the air inlet section over the dew point sensor.

The sample holders or trays were made of square, extruded-aluminium frames with aluminium screens 212 x 212 mm to hold the grains. The aluminium screens were held in place by compressing them with plastic splinters. The mass of grain and tray was measured using an electronic balance (Model Mettler PE1600, Mettler Instruments Corporation, Greifensee, Zurich, Switzerland) with a precision of ±0.01 g.

4.2 Sample Conditioning

The hulless oats, *Avena sativa* L. cv. 'AC Belmont' used in the experiments were purchased from a grain company, United Grain Growers and transported from Saskatoon to

Winnipeg. The oats were at an initial moisture content of 11.6% db. The seeds were stored at -15°C until used. The samples were conditioned to moisture contents of 11 (11-12), 16 (16-17), and 21 (21-22) % db for thin layer drying and rewetting tests. The seeds were remoistened or dried to the desired moisture contents either by adding calculated quantities of distilled water or drying at 40 °C in a convection air oven, respectively. The rewetted samples were kept in a sealed container and tumbled gently but constantly for 1 h after adding the distilled water, to ensure uniform and complete mixing. The samples were kept for 24 h at ambient temperature with occasional tumbling before being used for tests to get uniform distribution of moisture. The initial moisture content and equilibrium moisture content were determined according to the procedure outlined for oats, in the ASAE standard S352.2 (ASAE 1996) by drying triplicate sub-samples in a convection air oven at 130 °C for 22 h.

4.3 Test Procedure

4.3.1 Thin-layer equipment

The thin layer drying and rewetting tests were planned for nine constant relative humidity conditions. Accordingly, the air and water temperatures were selected as shown in Table 4.1. For a test at constant relative humidity, the temperature of air and water were set at the C-L-AA unit. The unit was left running for 24 h to ensure stable air conditions for the test. The unit was set to obtain relative humidities of 27, 37, 48, 61, 68, 69, 75, 88, and 93% for the nine tests. Three grain samples with initial moisture contents of 11, 16 and 21% db in triplicate, spread on trays, were placed in the chamber. Prior to putting trays in the chamber, empty trays were weighed and 100 g of hulless oats, sufficient to form a one-kernel-thick layer, were uniformly spread over the aluminium screens of each tray. The mass of trays with grains was recorded at 30 min, every hour for 6 h and every 8 to 12 h thereafter till the mass was within ±0.01 g between two successive readings. The moisture content at this point was presumed to be the EMC. The first reading at 30 min was taken after considering the time taken to spread thin-layer of oat kernels on all trays and putting them inside the drying chamber. The initial readings were recorded at shorter intervals because of the predicted exponential behaviour in loss or gain of moisture by the grains initially.

Table 4.1 Air and water temperatures for constant relative humidities in the C-L-AA unit

Air (°C)	36.2	25.8	15.2	35.4	25.8	15.5	35.5	15.4	25.7
Water (°C)	11.0	6.5	1.4	26.9	19.0	9.5	31.0	13.7	24.8
RH (%)	27	37	48	61	68	69	75	88	93

The air and water temperatures in the C-L-AA unit, ambient temperature, dew point temperature, and average air temperature for each tray section were also recorded at the time of recording mass of trays with grain. The time to reach equilibrium ranged from 3 to 8 d depending on the air conditions. The EMCs of the samples were determined by oven drying method and used for further analysis.

4.3.2 Determination of equivalent radius

The 'AC Belmont' oat samples in triplicate at three initial moisture contents (11, 16, and 21% db) were used for the determination of radius of a sphere equivalent in volume of a single oat kernel. Eight hundred oat kernels were placed in the sample holder of the pycnometer (Model 930, Beckman Instruments Inc., Fullerton, CA) and standard operating procedure was followed for compression of sample. The equivalent volume of air displaced was directly measured in mL. The volume divided by the total number of kernels gave the volume of one kernel which was equated with volume of sphere to calculate the equivalent radius of sphere. The mean of all the nine radii was taken. The mean equivalent radius of sphere was used in Eq. (6) for evaluation for fitness of the equation to describe the thin layer drying and rewetting data of 'AC Belmont' oats.

4.4 Analysis of Thin-layer Drying and Rewetting data

The thin-layer drying or rewetting data were fitted to liquid diffusion (Eq.(6)), Lewis' (Eq.(11)), and Page's (Eq.(12)) equations, using linear and non-linear regression (SigmaPlot 3.02, Jandel Scientific, San Rafael, CA) to each of the experimental data sets (42 for drying and 39 for rewetting). The parameters k of Lewis' equation, and k and n of Page's equation were calculated from the experimental data. The values of parameters were back-substituted in Eqs. (11) and (12) to predict the moisture contents at time t. The observed and the predicted moisture contents were compared (Appendix B, Fig. B1-B27) and statistically analyzed for evaluating the best fit equation.

The best fit of the equations was evaluated on the basis of standard error of moisture content (SEM), average relative percent error (e), and randomness of residuals. The best fit equation was then used to correlate the effects of temperature, relative humidity (RH), initial moisture content (IMC), and air velocity over the entire range of thin-layer drying and rewetting data.

4.5 Analysis of EMC-ERH Data

The EMC-ERH data of hulless oats were analyzed using five (Eqs. 14 - 18), three-parameter equations (modified equations of Chung-Pfost, Halsey, Henderson, GAB, and Oswin).

For the quadratic solution of the GAB equation, the positive value of predicted ERH was taken. The parameters for each equation were determined using non linear regression (SigmaPlot 3.02, Jandel Scientific, San Rafael, CA). The suitability of the equations was evaluated using the mean relative percent error, standard error of relative humidity, and randomness of residual plots determined visually.

The mean relative precent error (e) was defined as:

$$e = \frac{100}{N} \sum \frac{| Y - Y' |}{Y}$$

and the standard error of relative humidity (SEH) was defined as :

$$SEH = \sqrt{\frac{\sum (Y - Y')^2}{df}}$$

where:

Y = measured equilibrium relative humidity (decimal)

Y' = equilibrium relative humidity predicted by the ERH model (decimal)

N = number of experimental data points

df = degree of freedom of the regression model (N minus the number of constants in the model).

The differences between the measured (mean) and predicted ERH values at various equilibrium moisture contents were defined as residuals. The residuals were plotted against measured values of ERH and randomness in the residuals indicated a superior model.

5. RESULTS AND DISCUSSION

5.1 Comparison among Liquid Diffusion, Lewis' and Page's Equations

The liquid diffusion (Eq. (6)), Lewis'(Eq. (11)), and Page's (Eq. (12)) equations have been used by several researchers to describe the drying or rewetting of agricultural crops as discussed in section 3.3. Linear and nonlinear regressions (SigmaPlot 3.02, Jandel Scientific, San Rafael, CA) were preformed to fit the drying and rewetting data of 'AC Belmont' hulless oats. The three equations were evaluated for their suitability in describing the experimental data on basis of SEM, e, and randomness of residuals. The equivalent radii of a sphere for the oat kernels as required in Eq. (6), was determined by using an air comparison pycnometer and the results are given in Appendix C (Table C3). Liquid diffusion equation (Eq. (6)) was evaluated by one, two, and three terms of the infinite series.

The SEM, and e values for typical tests of first replicates at nine relative humidities are given in Table 5.1. The mean relative percent errors, ranged from 0.14 to 7.13%, 0.07 to 4.05%, and 0.04 to 1.69% for liquid diffusion, Lewis', and Page's equations, respectively. The SEM values ranged from 0.05 to 1.7, 0.01 to 0.80, and 0.01 to 0.64 for liquid diffusion, Lewis', and Page's equations, respectively. The values of e and SEM were the lowest for Page's equation and therefore it described the data better than the liquid diffusion and Lewis' equations. The plot of residuals versus time for the liquid diffusion equation was patterned, whereas it was scattered for both Lewis' and Page's equations (Figs. 5.1, 5.2, and 5.3, respectively). Therefore, it can be concluded that Page's equation is the best model among the models tested to describe the thin layer drying or rewetting rates of hulless oats. For

Table 5.1 Standard error of moisture content and mean relative percent error for liquid diffusion, Lewis', and Page's equations.

Test	Equation					
	Liquid diffusion		Lewis		Page	
	SEM*	e**(%)	SEM	e(%)	SEM	e(%)
T2736H1†	0.6038	2.0078	0.5572	3.2709	0.2205	1.3555
T2736M1	0.4073	1.7534	0.4279	2.6556	0.0774	0.5086
T2736L1	0.1747	1.1052	0.2276	1.6958	0.0346	0.2730
T3726H1	0.4995	1.9880	0.5921	3.1618	0.1326	0.8318
T3726M1	0.4856	2.5555	0.3341	2.1522	0.1258	0.7683
T3726L1	0.1275	0.8516	0.1420	1.0117	0.0285	0.2091
T4815H1	1.0228	5.1066	0.7983	4.0467	0.2448	1.2977
T4815M1	0.3672	2.1353	0.4143	2.0770	0.1353	0.7305
T4815L1	0.0951	0.6454	0.0153	0.1103	0.0153	0.0992
T6136H1	0.4236	1.0175	0.0943	0.4028	0.0856	0.3320
T6136M1	0.1409	0.4568	0.0848	0.4163	0.0490	0.2059
T6136L1	0.1217	0.3371	0.0629	0.2798	0.0122	0.0613
T6826H1	0.2960	0.6703	0.1377	0.5695	0.1165	0.4286
T6826M1	0.0474	0.1580	0.0565	0.2536	0.0169	0.0709
T6826L1	0.2143	0.8028	0.0632	0.3137	0.0350	0.1529
T6915H1	0.1468	0.3281	0.1836	0.5978	0.0341	0.1029
T6915M1	0.1603	0.7888	0.0188	0.0902	0.0160	0.0717
T6915L1	0.6831	4.0178	0.3489	1.9215	0.1688	0.7629
T7536H1	0.2107	0.5764	0.1219	0.5031	0.0807	0.3090
T7536M1	0.0637	0.1423	0.0477	0.1566	0.0149	0.0529
T7536L1	0.3746	1.3703	0.0898	0.4581	0.0334	0.1200
T8815H1	0.6800	1.9402	0.6119	1.6876	0.6404	1.6861
T8815M1	0.9063	3.4430	0.4771	1.4278	0.4918	1.4630
T8815L1	0.8664	3.2028	0.4800	1.5360	0.5023	1.5171
T9326H1	0.4699	0.8751	0.1766	0.4247	0.0706	0.1546
T9326M1	0.7123	1.5537	0.3677	1.0836	0.1006	0.2518
T9326L1	1.6507	7.1300	0.4971	1.6731	0.1325	0.3985

* Standard error of moisture content

** Mean relative percent error

† The meaning of characters in the code are: T = test; next two digits represent relative humidity in %; next two digits represent temperature in °C; next charac refers to high (H, 21-22% db), medium (M, 16-17% db), and low (L, 11-12% d moisture contents; and the last digit refers to the replicate number (i.e. T2736H means a test conducted at 27% RH, 36°C, at high initial moisture content, and for the first replicate).

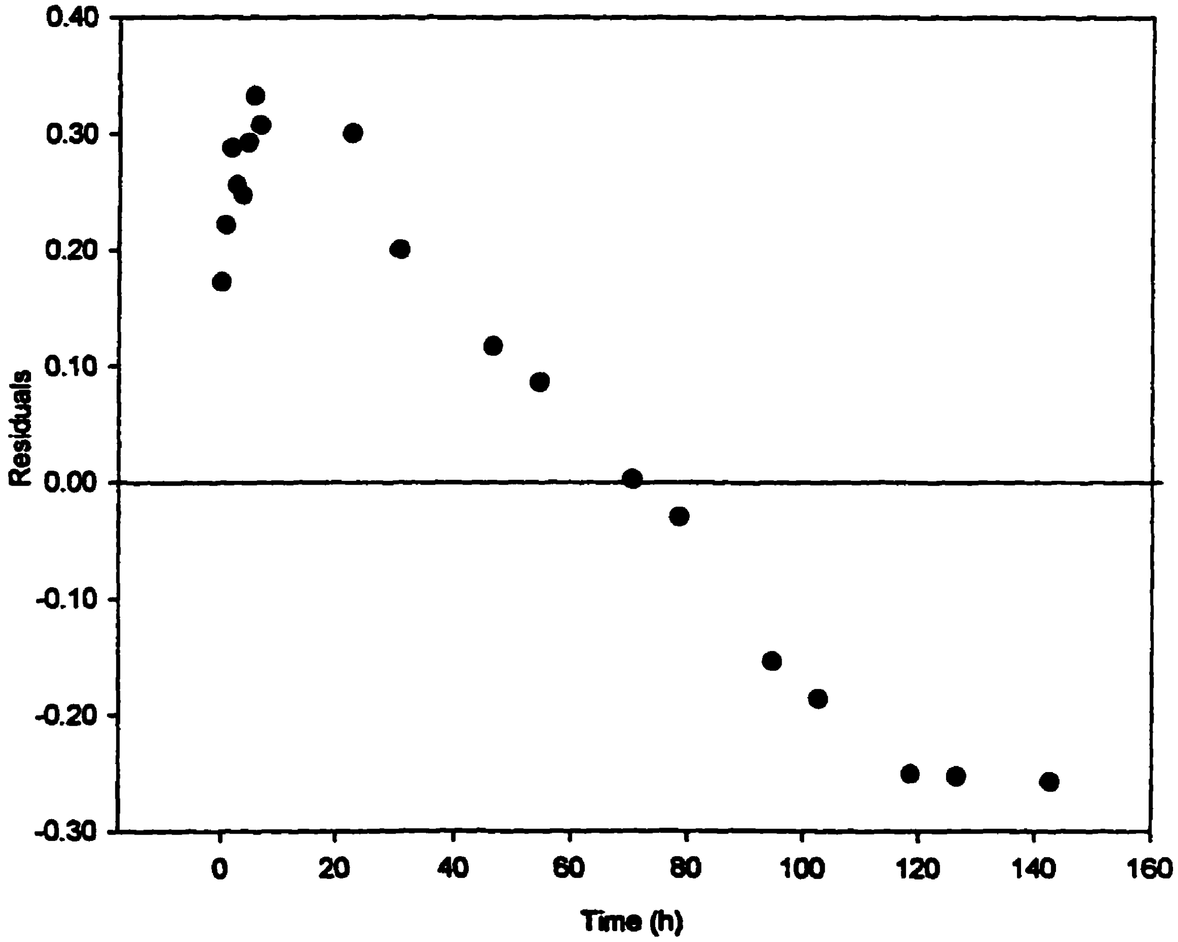

Fig. 5.1 Residual plot obtained with liquid diffusion equation for a typical rewetting test data-set, T4815L1.

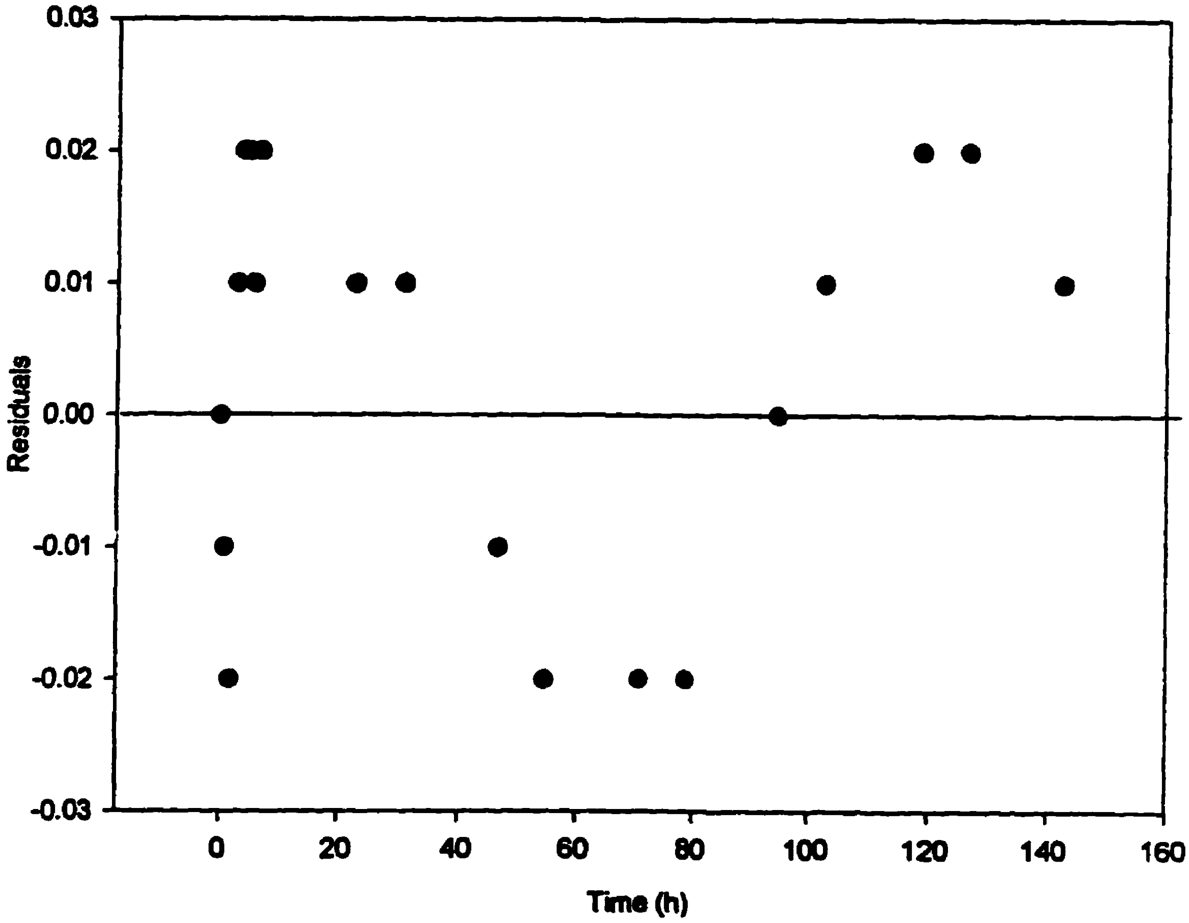

Fig. 5.2 Residual plot obtained with Lewis' equation for a typical rewetting test data-set, T4815L1.

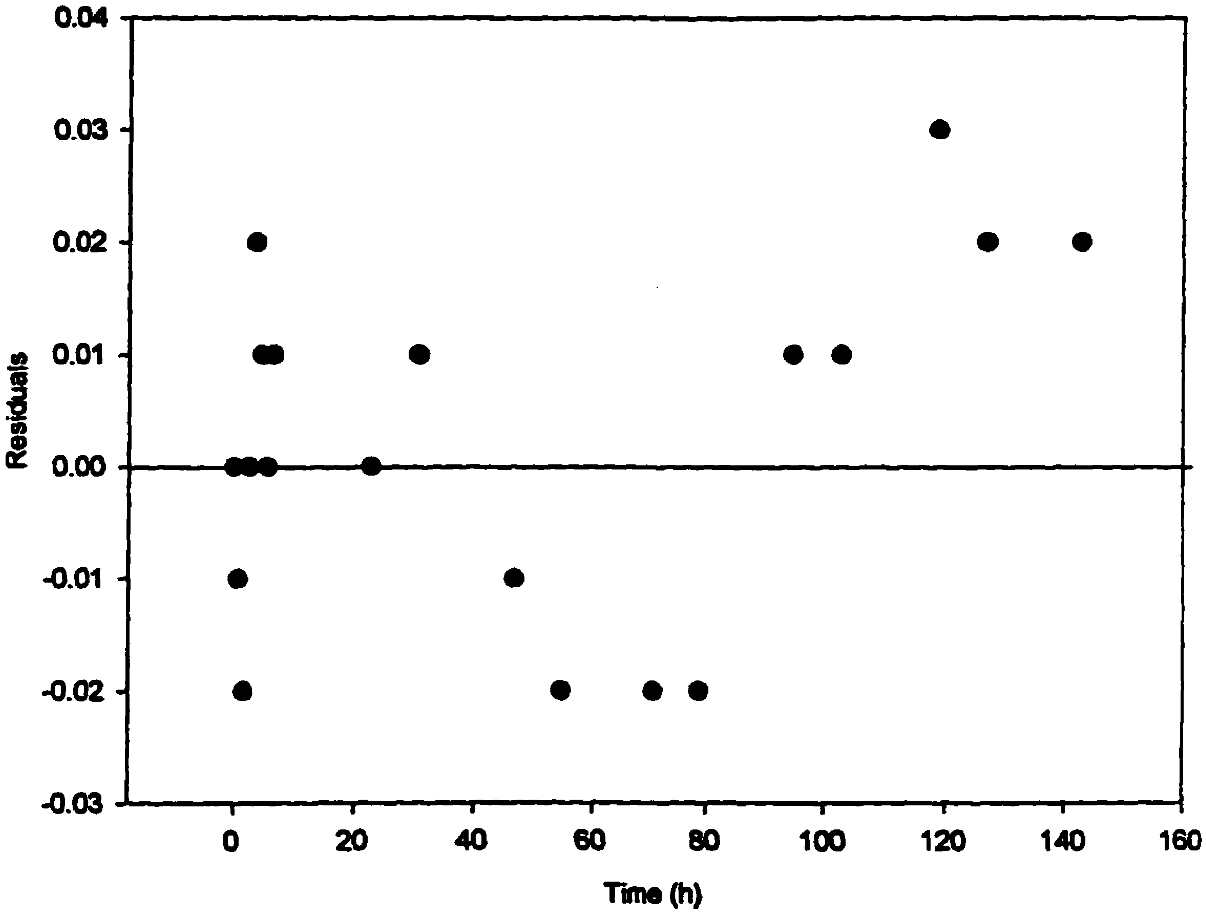

Fig. 5.3 Residual plot obtained with Page's equation for a typical rewetting test data-set, T4815L1.

further analyses of the data, only Page's equation was used.

5.2 Drying and Wetting Parameters of Page's Equation

The parameters k and n of Eq. (12), were estimated using nonlinear regression (SigmaPlot 3.02, Jandel Scientific, San Rafael, CA). The values of parameters k and n are given in Table 5.2. Using these values moisture contents were predicted and compared against the measured data (Appendix B, Figs. B1 - B27). Page's equation described the experimental drying and rewetting rate for all individual experimental tests at constant relative humidities except for the rewetting rate at 88% RH (Appendix B, Figs. B22b-B24b). The rewetting rate was described successfully by Lewis' equation for this test. This may be attributed to the alternating drying and rewetting of grain samples which was unexpected. All the three samples in triplicate behaved in the same way, indicating that perhaps at RH of 88%, the moisture condensed and was sorbed by grain and then dried again or the growth of mould may have caused the behaviour. This behaviour, however, was not at 93% RH. The mould growth was observed on kernels for two RH conditions at 88% (15°C) and 93% (25°C). The mould growth was probably due to *Penicillium* spp. at 15°C and *Aspergillus* spp. at 25°C. The values of k of Lewis' equation (Eq. (11)) estimated using linear regression are given in Table 5.3. The values of diffusion coefficients (m^2/h) for one, two, and three terms of infinite series of liquid diffusion equation (Eq. (6)) are given in Table 5.4.

The procedure GLM of SAS (1995), was used to analyse the effect of temperature, RH, IMC, and velocity on the parameters k and n of Page's equation. In the GLM model, k and n were dependent variables as a function of temperature, relative humidity, and IMC.

Table 5.2 The parameters k and n of Page's equation (Eq. 12) for thin-layer drying and rewetting of 'AC Belmont' hulless oats.

Test No.	Data set	k	n
1	T2736H1*	0.5331	0.5529
1	T2736H2	0.4681	0.6043
1	T2736H3	0.6017	0.5129
1	T2736M1	0.4662	0.5282
1	T2736M2	0.4046	0.5612
1	T2736M3	0.5004	0.5019
1	T2736L1	0.2407	0.5979
1	T2736L2	0.2876	0.5647
1	T2736L3	0.3065	0.5390
2	T3725H1	0.5077	0.5081
2	T3725H2	0.4444	0.5516
2	T3725H3	0.5476	0.4766
2	T3725M1	0.3588	0.5450
2	T3725M2	0.4238	0.5017
2	T3725M3	0.4438	0.4865
2	T3725L1	0.4880	0.3783
2	T3725L2	0.3536	0.4316
2	T3725L3	0.4215	0.3949
3	T4815H1	0.3419	0.4730
3	T4815H2	0.3150	0.5465
3	T4815H3	0.4024	0.4715
3	T4815M1	0.2509	0.5271
3	T4815M2	0.2479	0.5654
3	T4815M3	0.2900	0.4971
3	T4815L1	0.0336	0.9164
3	T4815L2	0.0562	0.8516
3	T4815L3	0.0425	0.8938
4	T6136H1	0.4049	0.9218
4	T6136H2	0.3962	0.9333
4	T6136H3	0.6338	0.7197
4	T6136M1	0.5322	0.6945
4	T6136M2	0.1747	1.3702
4	T6136M3	0.5969	0.7005
4	T6136L1	0.4064	0.7366
4	T6136L2	0.4114	0.7502
4	T6136L3	0.3979	0.7387
5	T6825H1	0.3070	0.8540
5	T6825H2	0.6061	0.5397
5	T6825H3	0.7270	0.4848
5	T6825M1	0.7195	0.4661
5	T6825M2	0.2602	0.9515
5	T6825M3	0.6394	0.4380
5	T6825L1	0.1893	0.8566
5	T6825L2	0.2069	0.7946
5	T6825L3	0.1913	0.8750
6	T6915H1	0.6987	0.4909
6	T6915H2	0.4189	0.6372
6	T6915H3	0.5333	0.5870
6	T6915M1	0.0301	1.0896
6	T6915M2	0.0051	1.5713
6	T6915M3	0.0815	0.8561
6	T6915L1	0.1069	0.7142
6	T6915L2	0.1233	0.6969
6	T6915L3	0.1275	0.6986
7	T7536H1	0.5291	0.7813
7	T7536H2	0.2684	1.0171
7	T7536H3	0.7448	0.5842
7	T7536M1	0.7579	0.7011
7	T7536M2	1.2027	0.4362
7	T7536M3	0.6306	0.7560
7	T7536L1	0.3079	0.8843
7	T7536L2	0.4095	0.8823
7	T7536L3	0.4204	0.8999
8	T8815H1	0.2106	0.9974
8	T8815H2	0.1515	1.0713
8	T8815H3	0.2799	0.9565
8	T8815M1	0.0983	1.1011
8	T8815M2	0.1786	0.9950
8	T8815M3	0.2126	0.9457
8	T8815L1	0.1429	0.9890
8	T8815L2	0.0909	1.0347
8	T8815L3	0.1762	0.9364
9	T9325H1	0.2397	0.8459
9	T9325H2	0.0856	0.9546
9	T9325H3	0.2805	0.8184
9	T9325M1	0.2525	0.7825
9	T9325M2	0.1494	0.7904
9	T9325M3	0.3082	0.7386
9	T9325L1	0.1425	0.8239
9	T9325L2	0.2226	0.8585
9	T9325L3	0.2552	0.8640

* Refer to Table 5.1 for explanation of the code.

Table 5.3 The parameter k of Lewis' equation (Eq. 11) for thin-layer drying and rewetting of 'AC Belmont' hulless oats.

Test No.	Data set	k
1	T2736H1*	0.3554
1	T2736H2	0.3227
1	T2736H3	0.3904
1	T2736M1	0.2903
1	T2736M2	0.2564
1	T2736M3	0.3047
1	T2736L1	0.1263
1	T2736L2	0.1567
1	T2736L3	0.1638
2	T3725H1	0.2764
2	T3725H2	0.2519
2	T3725H3	0.2873
2	T3725M1	0.1934
2	T3725M2	0.2180
2	T3725M3	0.2249
2	T3725L1	0.2063
2	T3725L2	0.1482
2	T3725L3	0.1747
3	T4815H1	0.1610
3	T4815H2	0.1661
3	T4815H3	0.1941
3	T4815M1	0.1139
3	T4815M2	0.1242
3	T4815M3	0.1314
3	T4815L1	0.0242
3	T4815L2	0.0334
3	T4815L3	0.0288
4	T6136H1	0.3756
4	T6136H2	0.3714
4	T6136H3	0.5065
4	T6136M1	0.4038
4	T6136M2	0.2632
4	T6136M3	0.4614
4	T6136L1	0.3074
4	T6136L2	0.3171
4	T6136L3	0.3026
5	T6825H1	0.2552
5	T6825H2	0.3700
5	T6825H3	0.4368
5	T6825M1	0.4256
5	T6825M2	0.2449
5	T6825M3	0.3386
5	T6825L1	0.1527
5	T6825L2	0.1521
5	T6825L3	0.1589
6	T6915H1	0.4151
6	T6915H2	0.2677
6	T6915H3	0.3364
6	T6915M1	0.0401
6	T6915M2	0.0337
6	T6915M3	0.0554
6	T6915L1	0.0468
6	T6915L2	0.0562
6	T6915L3	0.0607
7	T7536H1	0.4151
7	T7536H2	0.2677
7	T7536H3	0.3364
7	T7536M1	0.0401
7	T7536M2	0.0337
7	T7536M3	0.0554
7	T7536L1	0.0468
7	T7536L2	0.0562
7	T7536L3	0.0607
8	T8815H1	0.2092
8	T8815H2	0.1754
8	T8815H3	0.2617
8	T8815M1	0.1186
8	T8815M2	0.1775
8	T8815M3	0.1962
8	T8815L1	0.1404
8	T8815L2	0.0974
8	T8815L3	0.1594
9	T9325H1	0.1917
9	T9325H2	0.0773
9	T9325H3	0.2183
9	T9325M1	0.1837
9	T9325M2	0.1003
9	T9325M3	0.2152
9	T9325L1	0.1026
9	T9325L2	0.1808
9	T9325L3	0.2110

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* Refer to Table 5.1 for explanation of the code.

Table 5.4 The values of diffusion coefficients for the first, second, and third series of liquid diffusion equation (Eq. 6).

Test No.	Data set	1 term	2 terms		3 terms		
		D1	D1	D2	D1	D2	D3
1	T2736H1*	4.8E-08	5.8E-08	4.6E-08	7.8E-08	5.4E-08	5.2E-10
1	T2736H2	4.1E-08	8.7E-08	2.8E-09	8.0E-08	3.3E-08	6.2E-10
1	T2736H3	5.6E-08	6.1E-08	7.5E-08	6.1E-08	1.0E-07	4.2E-08
1	T2736M1	3.1E-08	7.4E-08	2.1E-09	7.3E-08	2.8E-08	5.3E-10
1	T2736M2	2.5E-08	6.5E-08	2.0E-09	7.5E-08	2.7E-08	3.3E-10
1	T2736M3	3.4E-08	3.6E-08	7.4E-08	3.7E-08	9.0E-08	3.8E-08
1	T2736L1	1.1E-08	2.4E-08	1.5E-09	4.5E-08	1.3E-09	5.3E-10
1	T2736L2	1.3E-08	3.0E-08	1.5E-09	7.2E-08	2.4E-08	5.5E-11
1	T2736L3	1.3E-08	3.3E-08	1.3E-09	7.1E-08	2.3E-08	9.6E-11
2	T3725H1	3.9E-08	8.1E-08	1.9E-09	4.2E-08	7.4E-08	3.7E-08
2	T3725H2	3.4E-08	7.1E-08	1.9E-09	7.7E-08	3.0E-08	3.0E-10
2	T3725H3	4.1E-08	4.3E-08	8.2E-08	4.3E-08	1.0E-07	5.2E-08
2	T3725M1	2.1E-08	5.0E-08	1.2E-09	7.5E-08	2.5E-08	1.3E-10
2	T3725M2	2.5E-08	6.0E-08	1.3E-09	7.6E-08	3.1E-08	1.8E-10
2	T3725M3	2.7E-08	6.1E-08	1.3E-09	3.0E-08	6.3E-08	2.7E-08
2	T3725L1	1.9E-08	1.7E-08	1.1E-07	4.9E-08	8.1E-09	1.2E-07
2	T3725L2	1.0E-08	5.4E-08	3.2E-10	7.1E-08	2.3E-08	-3.3E-11
2	T3725L3	1.3E-08	5.2E-08	3.3E-10	6.3E-08	1.7E-08	-3.7E-11
3	T4815H1	1.3E-08	4.7E-08	5.4E-10	7.0E-08	2.0E-08	-1.4E-10
3	T4815H2	1.6E-08	4.1E-08	1.0E-09	5.4E-08	1.3E-09	9.5E-10
3	T4815H3	2.0E-08	5.2E-08	9.0E-10	7.3E-08	2.6E-08	5.4E-11
3	T4815M1	8.1E-09	4.6E-08	3.9E-10	5.4E-08	2.0E-09	-2.9E-11
3	T4815M2	1.0E-08	3.5E-08	7.6E-10	4.5E-08	1.1E-09	5.4E-10
3	T4815M3	9.2E-09	4.1E-08	5.3E-10	7.2E-08	2.3E-08	-9.5E-11
3	T4815L1	3.5E-09	5.3E-09	7.5E-10	4.0E-08	-9.4E-11	-3.3E-11
3	T4815L2	4.7E-09	6.4E-09	2.2E-09	4.1E-08	1.1E-10	3.9E-11
3	T4815L3	4.1E-09	6.1E-09	1.0E-09	3.4E-08	-4.4E-11	4.7E-10
4	T6136H1	5.9E-08	8.6E-08	1.8E-08	9.6E-08	2.2E-08	7.9E-09
4	T6136H2	5.8E-08	8.5E-08	1.8E-08	9.4E-08	2.4E-08	7.5E-09
4	T6136H3	8.7E-08	1.0E-07	4.4E-08	9.9E-08	7.4E-08	3.0E-08
4	T6136M1	6.3E-08	8.4E-08	2.9E-08	7.7E-08	5.4E-08	2.3E-08
4	T6136M2	3.6E-08	5.5E-08	1.2E-08	7.2E-08	1.2E-08	3.8E-09
4	T6136M3	7.7E-08	9.4E-08	3.8E-08	8.9E-08	6.4E-08	3.1E-08
4	T6136L1	4.2E-08	6.7E-08	1.4E-08	7.6E-08	2.1E-08	3.5E-09
4	T6136L2	4.4E-08	6.9E-08	1.4E-08	7.9E-08	2.2E-08	3.3E-09
4	T6136L3	4.1E-08	7.2E-08	8.4E-09	7.8E-08	2.1E-08	2.0E-09
5	T6825H1	3.7E-08	6.6E-08	5.7E-09	7.3E-08	1.4E-08	9.2E-10
5	T6825H2	6.0E-08	6.3E-08	7.3E-08	6.3E-08	9.4E-08	4.1E-08
5	T6825H3	7.2E-08	7.3E-08	1.8E-07	7.7E-08	1.3E-07	2.1E-07
5	T6825M1	7.0E-08	7.1E-08	1.3E-07	7.1E-08	1.6E-07	6.8E-08
5	T6825M2	3.4E-08	6.7E-08	2.6E-09	7.2E-08	1.2E-08	4.3E-10
5	T6825M3	5.1E-08	5.1E-08	1.4E-07	5.1E-08	1.6E-07	7.3E-08
5	T6825L1	1.8E-08	3.1E-08	5.0E-09	4.0E-08	6.2E-09	1.4E-09
5	T6825L2	1.7E-08	3.1E-08	4.3E-09	4.1E-08	5.2E-09	1.2E-09
5	T6825L3	1.9E-08	3.2E-08	5.5E-09	5.0E-08	3.3E-09	1.8E-09

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[*] Refer to Table 5.1 for explanation of the code.

(continued)

Table 5.4 (continued) The values of diffusion coefficients for the first, second, and third series of liquid diffusion equation (Eq. 6).

Test	Data set	1 term	2 terms		3 terms		
No.		D1	D1	D2	D1	D2	D3
6	T6915H1*	6.8E-08	6.9E-08	1.4E-07	6.9E-08	1.8E-07	7.7E-08
6	T6915H2	3.9E-08	7.5E-08	3.1E-09	7.7E-08	2.5E-08	4.4E-10
6	T6915H3	5.4E-08	5.8E-08	5.1E-08	7.9E-08	5.8E-08	6.8E-10
6	T6915M1	5.7E-09	8.6E-09	2.2E-09	3.4E-08	2.3E-10	6.1E-10
6	T6915M2	4.9E-09	7.9E-09	7.0E-10	3.9E-08	-3.7E-11	9.3E-11
6	T6915M3	7.1E-09	9.8E-09	3.1E-09	3.8E-08	7.2E-10	5.6E-10
6	T6915L1	5.8E-09	9.6E-09	1.4E-09	3.8E-08	3.2E-10	3.8E-10
6	T6915L2	6.5E-09	1.4E-08	8.1E-10	3.7E-08	3.8E-10	1.2E-10
6	T6915L3	6.8E-09	1.5E-08	8.4E-10	3.8E-08	4.4E-10	1.9E-10
7	T7536H1	7.5E-08	9.1E-08	3.3E-08	9.0E-08	4.8E-08	2.2E-08
7	T7536H2	4.3E-08	6.3E-08	1.3E-08	7.6E-08	1.4E-08	4.6E-09
7	T7536H3	9E-08	9.3E-08	1.2E-07	9.3E-08	1.5E-07	6.4E-08
7	T7536M1	1.1E-07	1.2E-07	7.1E-08	1.2E-07	5.0E-08	3.1E-07
7	T7536M2	1.6E-07	1.2E-07	7.2E-07	1.1E-07	1.7E-07	3.2E-07
7	T7536M3	9.3E-08	1.2E-07	2.6E-08	1.1E-07	6.1E-08	2.5E-08
7	T7536L1	4.1E-08	6.0E-08	1.2E-08	7.3E-08	1.4E-08	4.1E-09
7	T7536L2	6.2E-08	8.5E-08	1.8E-08	9.2E-08	2.4E-08	7.7E-09
7	T7536L3	6.7E-08	8.9E-08	2.1E-08	9.6E-08	2.5E-08	8.9E-09
8	T8815H1	3.6E-08	4.8E-08	9.5E-09	6.8E-08	1.2E-08	3.3E-09
8	T8815H2	3.1E-08	3.7E-08	9.3E-09	4.8E-08	7.1E-09	3.7E-09
8	T8815H3	4.6E-08	6.0E-08	1.3E-08	6.9E-08	1.5E-08	4.7E-09
8	T8815M1	1.7E-08	2.3E-08	4.5E-09	6.0E-08	4.2E-09	1.1E-09
8	T8815M2	2.7E-08	3.9E-08	7.2E-09	6.6E-08	7.6E-09	1.7E-09
8	T8815M3	2.9E-08	4.6E-08	7.8E-09	5.2E-08	9.1E-09	4.2E-09
8	T8815L1	2E-08	2.8E-08	5.8E-09	3.4E-08	6.6E-09	2.0E-09
8	T8815L2	1.3E-08	1.7E-08	5.6E-09	3.4E-08	2.4E-09	1.0E-09
8	T8815L3	2.2E-08	3.3E-08	6.1E-09	3.9E-08	6.8E-09	2.9E-09
9	T9325H1	2.6E-08	4.0E-08	8.2E-09	4.7E-08	8.3E-09	5.2E-09
9	T9325H2	1E-08	1.5E-08	3.0E-09	3.4E-08	1.5E-09	7.2E-10
9	T9325H3	3E-08	4.8E-08	8.9E-09	5.8E-08	1.1E-08	2.8E-09
9	T9325M1	2.3E-08	3.9E-08	6.7E-09	4.8E-08	8.2E-09	2.0E-09
9	T9325M2	1.1E-08	1.9E-08	2.8E-09	4.6E-08	9.8E-10	4.6E-10
9	T9325M3	2.9E-08	4.9E-08	7.0E-09	6.2E-08	8.3E-09	1.6E-09
9	T9325L1	1.2E-08	2.0E-08	3.0E-09	4.3E-08	1.2E-09	8.4E-10
9	T9325L2	2.4E-08	3.7E-08	8.0E-09	4.6E-08	8.6E-09	3.2E-09
9	T9325L3	2.9E-08	4.6E-08	9.1E-09	5.6E-08	1.0E-08	2.9E-09

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* Refer to Table 5.1 for explanation of the code.

Based on ANOVA, the significance of these variables was analysed ($p > 0.05$).

5.2.1 Effect of temperature and relative humidity on k and n

Both temperature and RH had significant effects on k ($p > 0.05$) with the r^2 value of 0.83. Temperature and relative humidity also had significant effect on the value of k and n ($p > 0.05$) with a p value of 0.0001. This indicated that the parameters k and n varied significantly with temperature and RH. This can also be seen from Table 5.2, wherein k and n vary for all nine experimental tests.

A three dimensional scatter plot of k and n each, versus RH and temperature was done to visualize the distribution of k and n (Figs. 5.4 and 5.5). The distribution of k was nonlinear. A linear correlation between temperature and RH with k was therefore not possible. The procedure REG (regression) with selection MAXR (for improvement of r^2), of SAS (1995) was used to analyze the effect of temperature, RH, IMC and velocity on k and n.

The procedure REG of SAS (1995) indicated that for k, temperature was highly significant ($p > 0.05$). The effect of IMC also was significant ($p > 0.05$). The effect of temperature was more significant than IMC. The value of r^2 for the k model was 0.53 indicating poor correlation between the variables for the entire data set. For the n model, RH had a significant effect ($p > 0.05$). The value of r^2 for the n model was also 0.53 indicating poor correlation between the variables for the entire data set.

The effects of temperature on drying and rewetting rates are illustrated in Figs. 5.6 and 5.7 for 15.5°C and 25.8°C, respectively. From Fig. 5.6, it can be seen that drying is faster at higher temperatures and a similar trend was observed for rewetting (Fig. 5.7). The

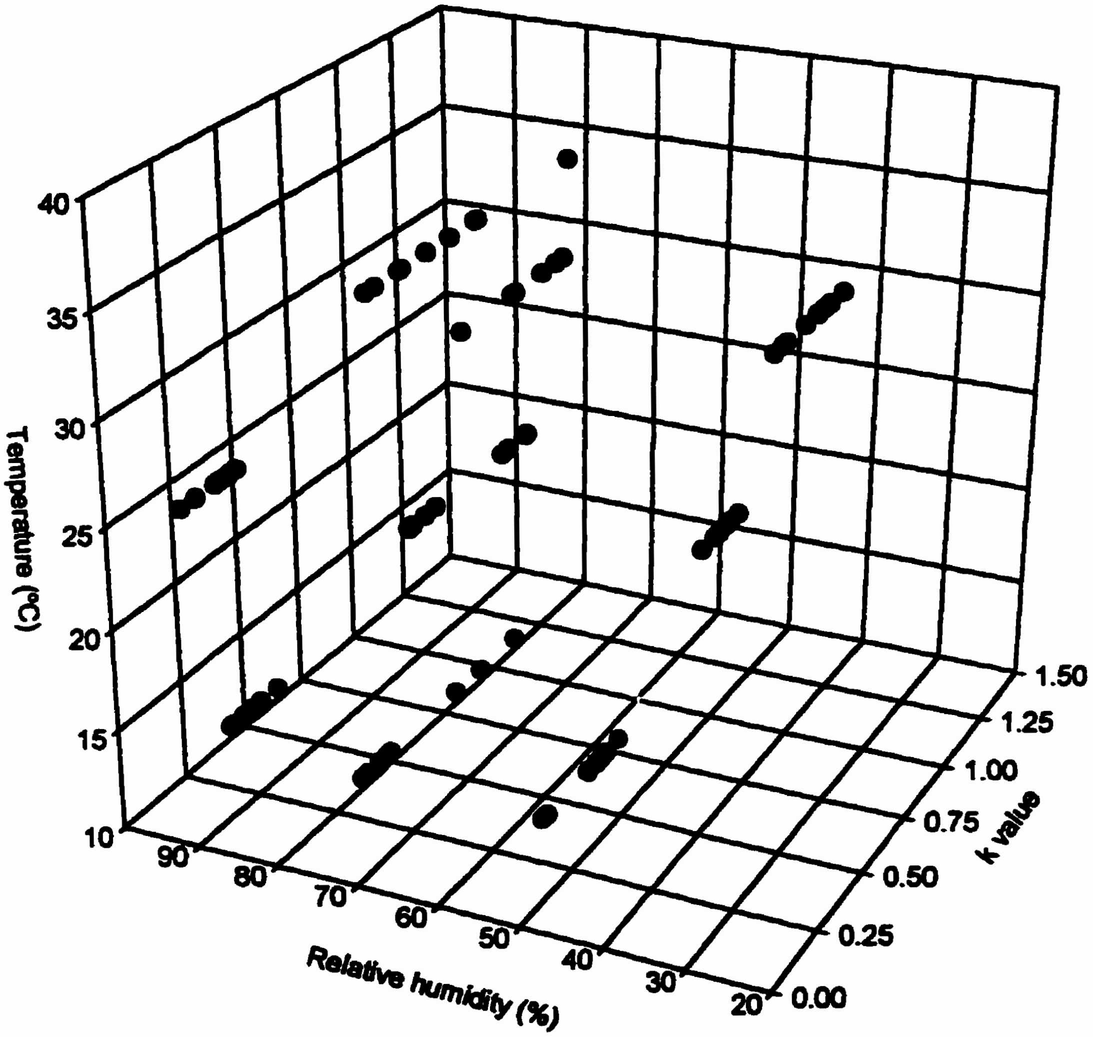

Fig. 5.4 Three dimensional scatter plot of k of Page's equation at various temperatures and relative humidities.

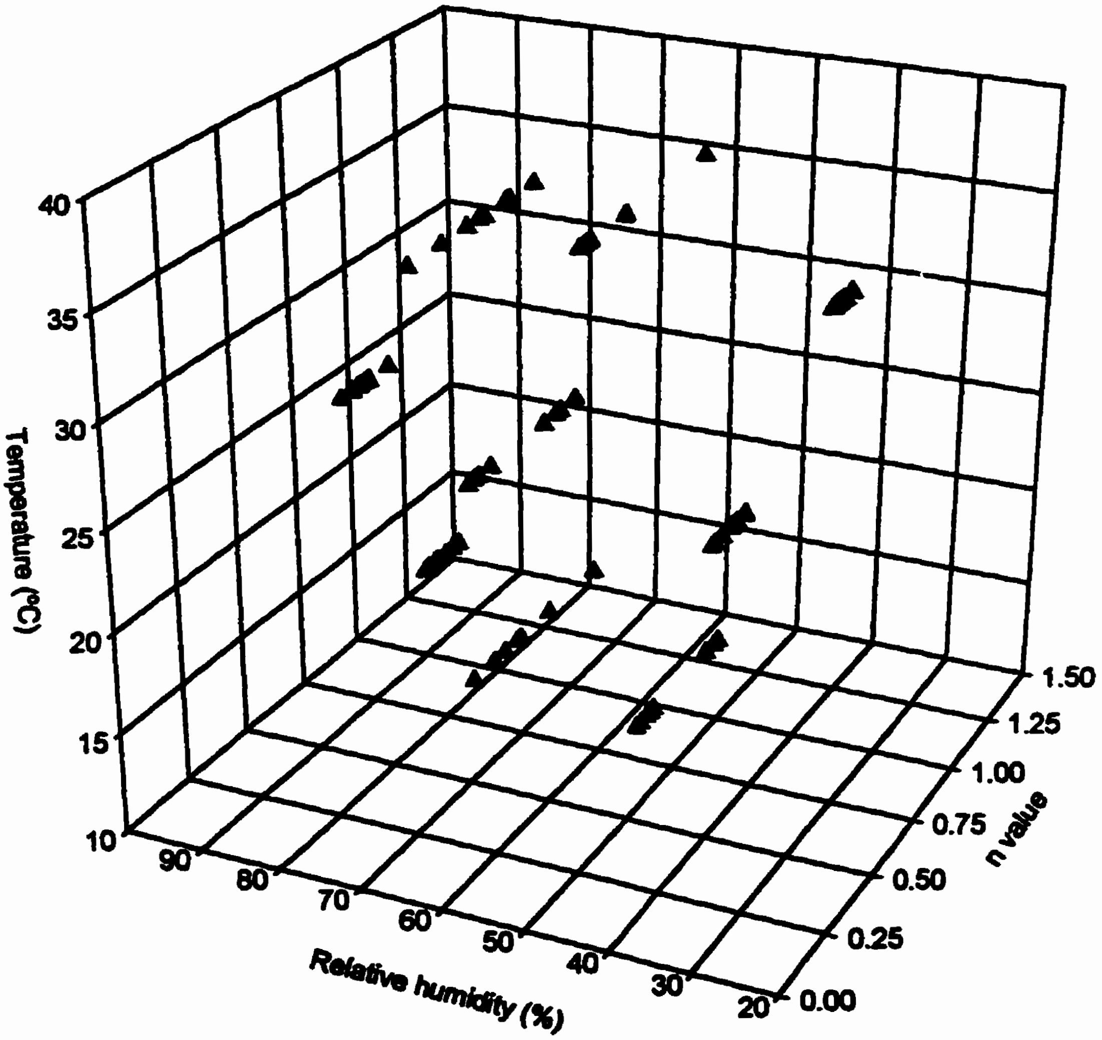

Fig. 5.5 Three dimensional scatter plot of n of Page's equation at various temperatures and relative humidities.

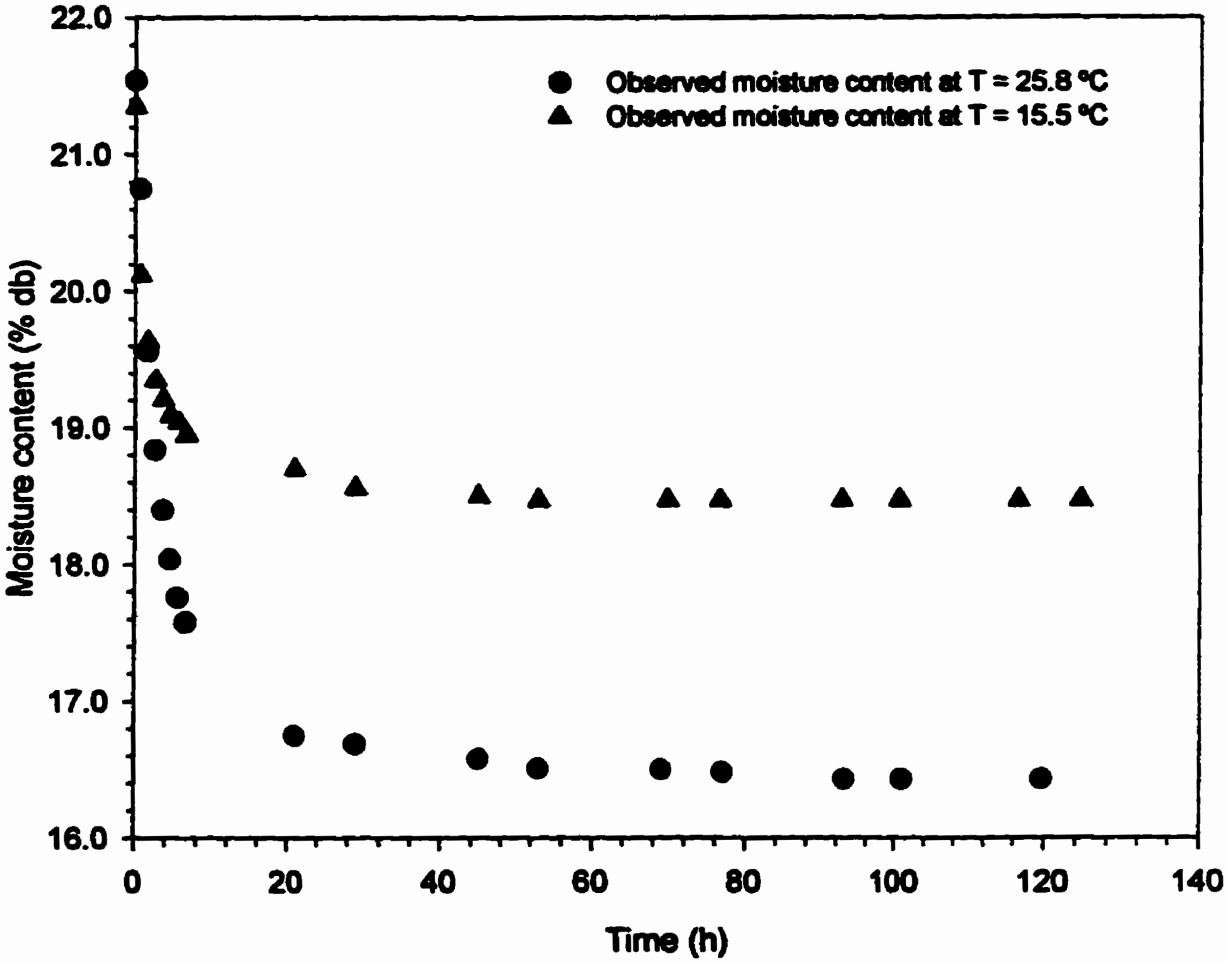

Fig. 5.6 Effect of temperature on drying rate of hulless oats.
Relative humidity = 68%, initial moisture content = 22% db.

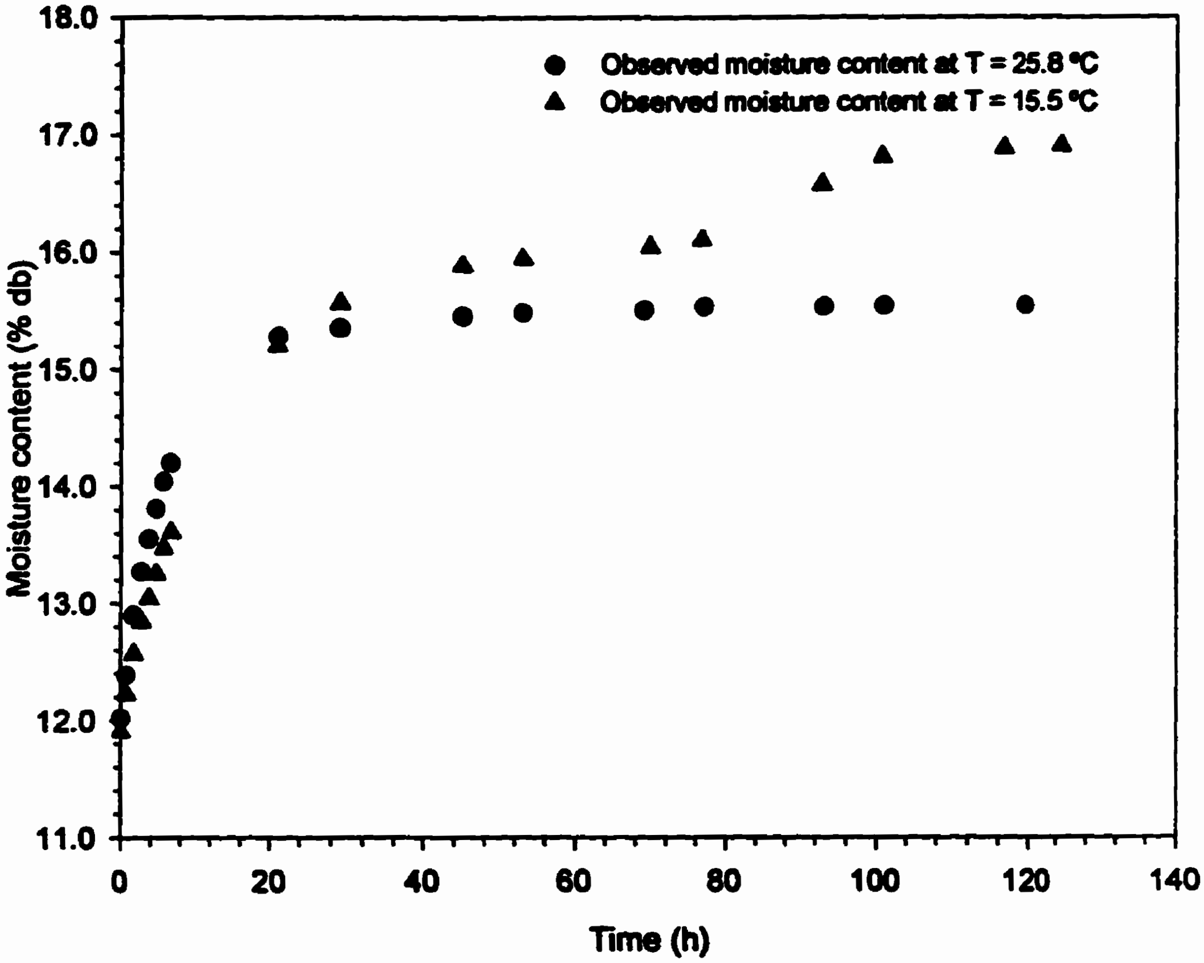

Fig. 5.7 Effect of temperature on rewetting rate of hulless oats.
Relative humidity = 68%, initial moisture content = 11% db.

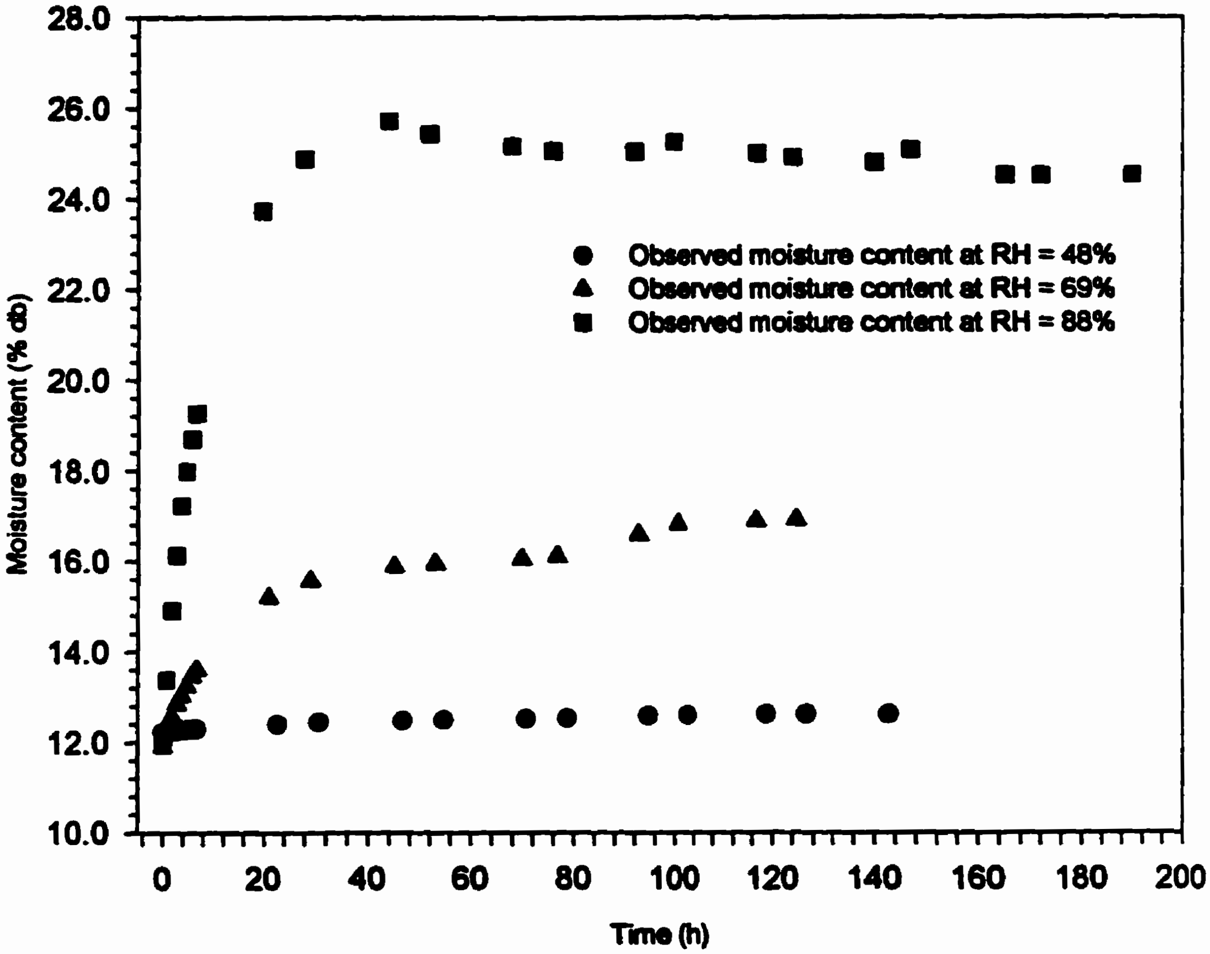

Fig. 5.8 Effect of relative humidity on rewetting rate of hulless oats.
Temperature =15°C, initial moisture content = 11% db.

effect of RH on rewetting is illustrated in Fig. 5.8 at 15°C for 48, 69, and 88%.

5.2.2 Effect of initial moisture content and air velocity on k and n

The effect of IMC and air velocity was analyzed using procedure GLM of SAS (1995) on k and n. The procedure REG was also used to fit all the variables for the entire data set.

The IMC had significant effect ($p > 0.05$) on k and n. The opinions of previous researchers on the effect of IMC on moisture transfer rates is divided as discussed in Section 3.4. The velocity did not have any significant effect on k and n, i.e. there was no significant effect on drying or rewetting rate. Studies done by Simmonds et al. (1953), Chittenden and Hustrulid (1966), and Misra (1978) suggest that air velocities may not have significant effect on moisture transfer rate of cereals and oilseeds if it is above critical value of 0.16 m/s. In the present experiment, the minimum and maximum air velocities were 0.05 and 0.97 m/s, respectively. The insignificant effect ($p > 0.05$) of air velocity was because velocity varied among experimental tests (Appendix A (Table A19)).

Procedure REG of SAS (1995) was used to develop models of both k and n, taking temperature, RH, IMC, and air velocity as independent variables. The value of r^2 for both the k and n model was 0.53 indicating poor correlation between the variables for the entire data set.

The effect of IMC on drying rate is illustrated in Fig. 5.9 at RH of 27% for IMC values of 12.0, 16.5, and 21.5% db. Drying rate was higher for higher moisture content samples compared with samples with lower moisture content. The effect of IMC on rewetting rate is illustrated in Fig. 5.10.

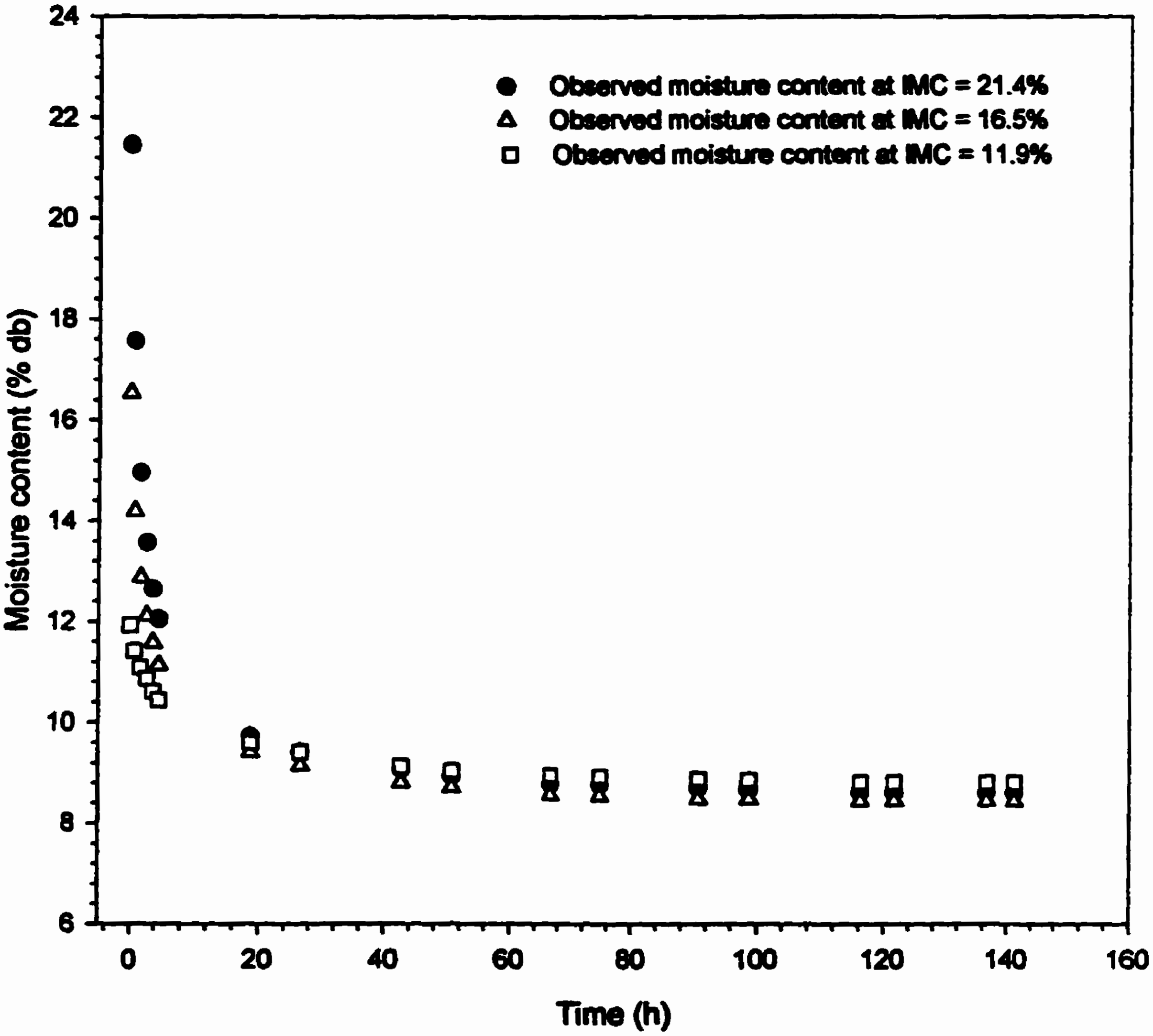

Fig. 5.9 Effect of initial moisture content on drying rate of hulless oats.
Temperature = 36°C, relative humidity = 27%.

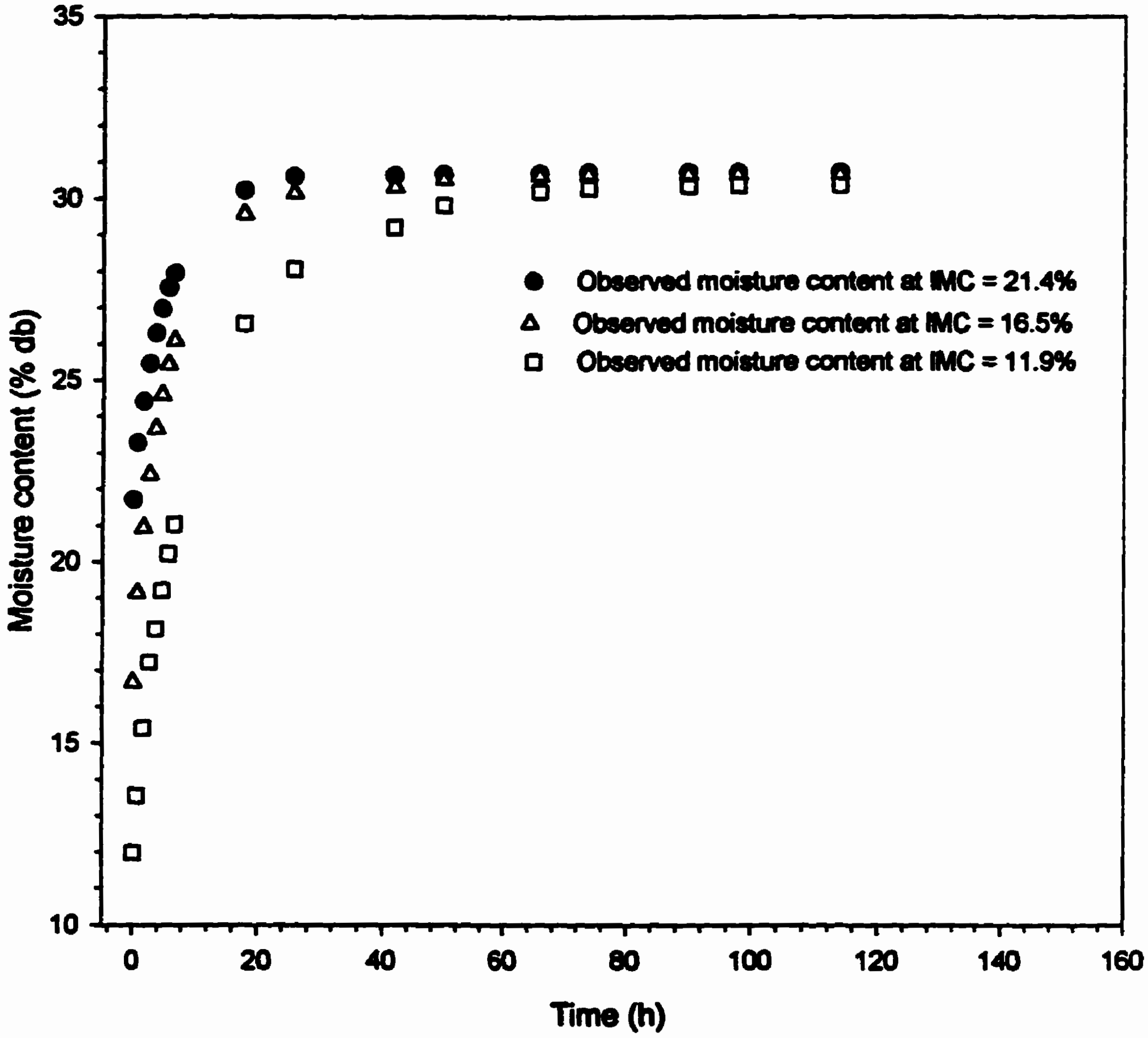

Fig. 5.10 Effect of initial moisture content on rewetting rate of hulless oats. Temperature = 25°C, relative humidity = 93%.

5.2.3 Parameter n as a product-dependent constant

The thin-layer drying and rewetting data were also analysed assuming parameter n as a product-dependent constant. The assumption makes it possible to compare the effects of temperature and RH on drying or rewetting rates by direct comparison of k (Section 3.3).

The parameter n was averaged for experimental tests at 27, 37, 48, 61, 68, 69, 75, 88, and 93% relative humidities. The average values of n and the corresponding modified values of k along with SEM and e are given in Table 5.5. Nonlinear regression (SigmaPlot 3.02, Jandel Scientific, San Rafael, CA) was performed to fit the model for k as dependent variable, and temperature and RH as independent variables. The model did not fit satisfactorily with an r^2 value of 0.45 indicating a poor correlation between parameter k, temperature, and RH. Another model was attempted using mean values of n for all nine experimental tests with the corresponding modified values of k (Table 5.6). This model too did not fit well, with an r^2 value of 0.42 indicating a poor correlation between parameter k, temperature, and RH. Other researchers (Jayas et al. 1991) have reported equations for k as a function of temperature and RH. The reason for such a poor correlation of k with temperature and RH cannot be explained.

5.3 Equilibrium Moisture Content of Sorption and Desorption

Depending on the air conditions in the thin layer drying chamber, samples with three initial moisture contents in triplicate (11, 16, and 21% db), underwent either drying (desorption) or rewetting (sorption). The data in terms of increase or decrease in moisture content (% db), and moisture ratio, with time (h) in nine experimental tests (at constant

Table 5.5 The modified values of parameter k of Page's equation (Eq. (12)) when the average values of parameter n for each RH were used.

Test No.	Data set	k	n	SEM*	e** (%)	Test No.	Data set	k	n	SEM	e (%)	Test No.	Data set	k	n	SEM	e (%)
1	T2736H1†	0.5339	0.5514	1.3486	0.2205	4	T6136H1	0.4495	0.8112	0.4015	0.1234	7	T7536H1	0.5344	0.7714	0.3045	0.0808
1	T2736H2	0.4947	0.5514	1.1315	0.2569	4	T6136H2	0.4449	0.8112	0.4437	0.1371	7	T7536H2	0.3640	0.7714	0.3403	0.1310
1	T2736H3	0.5800	0.5514	0.9893	0.1580	4	T6136H3	0.5888	0.8112	0.4081	0.0977	7	T7536H3	0.6301	0.7714	0.0528	0.0224
1	T2736M1	0.4525	0.5514	0.6160	0.0907	4	T6136M1	0.4802	0.8112	0.2505	0.0578	7	T7536M1	0.7154	0.7714	0.0597	0.0205
1	T2736M2	0.4102	0.5514	0.5120	0.1023	4	T6136M2	0.3210	0.8112	0.3415	0.1113	7	T7536M2	1.0084	0.7714	0.2564	0.0708
1	T2736M3	0.4703	0.5514	0.7053	0.1060	4	T6136M3	0.5432	0.8112	0.1583	0.0359	7	T7536M3	0.6218	0.7714	0.0484	0.0219
1	T2736L1	0.2694	0.5514	0.4823	0.0577	4	T6136L1	0.3756	0.8112	0.0839	0.0230	7	T7536L1	0.3551	0.7714	0.4741	0.1050
1	T2736L2	0.2962	0.5514	0.3154	0.0349	4	T6136L2	0.3863	0.8112	0.1036	0.0230	7	T7536L2	0.4640	0.7714	0.4082	0.1013
1	T2736L3	0.2981	0.5514	0.3360	0.0413	4	T6136L3	0.3690	0.8112	0.1136	0.0234	7	T7536L3	0.4841	0.7714	0.4925	0.1187
2	T3725H1	0.5317	0.4749	0.7872	0.1499	5	T6825H1	0.3737	0.6956	0.5049	0.1495	8	T8815H1	0.2082	1.0030	1.6891	0.6404
2	T3725H2	0.4965	0.4749	0.9995	0.2263	5	T6825H2	0.5137	0.6956	0.6318	0.1483	8	T8815H2	0.1744	1.0030	1.6021	0.5913
2	T3725H3	0.5489	0.4749	0.6170	0.0924	5	T6825H3	0.5870	0.6956	0.6698	0.1678	8	T8815H3	0.2606	1.0030	1.6005	0.6126
2	T3725M1	0.4063	0.4749	0.7527	0.1602	5	T6825M1	0.5724	0.6956	0.1459	0.0329	8	T8815M1	0.1179	1.0030	1.4273	0.4988
2	T3725M2	0.4433	0.4749	0.5486	0.0932	5	T6825M2	0.3539	0.6956	0.2122	0.0554	8	T8815M2	0.1767	1.0030	1.6542	0.5859
2	T3725M3	0.4525	0.4749	0.5032	0.0777	5	T6825M3	0.4753	0.6956	0.1631	0.0428	8	T8815M3	0.1953	1.0030	1.6784	0.5838
2	T3725L1	0.3987	0.4749	0.4033	0.0564	5	T6825L1	0.2452	0.6956	0.4322	0.0976	8	T8815L1	0.1397	1.0030	1.5443	0.5024
2	T3725L2	0.3162	0.4749	0.3122	0.0414	5	T6825L2	0.2431	0.6956	0.3630	0.0803	8	T8815L2	0.0968	1.0030	1.4284	0.4346
2	T3725L3	0.3487	0.4749	0.3683	0.0508	5	T6825L3	0.2535	0.6956	0.4320	0.0977	8	T8815L3	0.1587	1.0030	1.6617	0.5160
3	T4815H1	0.2510	0.6381	2.4958	0.4914	6	T6915H1	0.4988	0.8157	0.4279	0.1358	9	T9325H1	0.2451	0.8308	0.1669	0.0724
3	T4815H2	0.2695	0.6381	1.3295	0.2745	6	T6915H2	0.3367	0.8157	0.3145	0.1089	9	T9325H2	0.1138	0.8308	0.7464	0.2654
3	T4815H3	0.3082	0.6381	1.7868	0.3910	6	T6915H3	0.4143	0.8157	0.3552	0.1117	9	T9325H3	0.2758	0.8308	0.2023	0.0788
3	T4815M1	0.1907	0.6381	1.0154	0.2012	6	T6915M1	0.0722	0.8157	0.2280	0.0458	9	T9325M1	0.2350	0.8308	0.2967	0.1325
3	T4815M2	0.2112	0.6381	0.6606	0.1326	6	T6915M2	0.0625	0.8157	0.3047	0.0625	9	T9325M2	0.1377	0.8308	0.4100	0.1459
3	T4815M3	0.2101	0.6381	1.1088	0.2095	6	T6915M3	0.0911	0.8157	0.0858	0.0189	9	T9325M3	0.2711	0.8308	0.4564	0.2266
3	T4815L1	0.0964	0.6381	0.2044	0.0317	6	T6915L1	0.0788	0.8157	1.0665	0.2172	9	T9325L1	0.1406	0.8308	0.3674	0.1328
3	T4815L2	0.1176	0.6381	0.1755	0.0260	6	T6915L2	0.0886	0.8157	1.1740	0.2434	9	T9325L2	0.2320	0.8308	0.3094	0.1069
3	T4815L3	0.1068	0.6381	0.1668	0.0249	6	T6915L3	0.0932	0.8157	1.1039	0.2387	9	T9325L3	0.2674	0.8308	0.2608	0.1055

* Standard error of moisture content

** Mean relative percent error

† Refer to Table 5.1 for explanation of the code.

Table 5.6 The modified values of parameter k of Page's equation (Eq. (12)) when an overall average value of parameter n =0.7357 was used.

Test No.	Data set	k	n	SEM*	e** (%)
1	T2736H1†	0.4533	0.7357	2.1059	0.3447
1	T2736H2	0.4143	0.7357	1.7682	0.3028
1	T2736H3	0.4957	0.7357	2.3081	0.3966
1	T2736M1	0.3744	0.7357	1.7142	0.2807
1	T2736M2	0.3317	0.7357	1.5467	0.2426
1	T2736M3	0.3925	0.7357	1.8862	0.3131
1	T2736L1	0.1794	0.7357	0.8925	0.1141
1	T2736L2	0.2085	0.7357	1.0128	0.1396
1	T2736L3	0.2126	0.7357	1.2306	0.1667
2	T3725H1	0.3836	0.7357	2.1222	0.3578
2	T3725H2	0.3519	0.7357	1.9614	0.3187
2	T3725H3	0.3980	0.7357	2.2468	0.4044
2	T3725M1	0.2734	0.7357	1.4363	0.2225
2	T3725M2	0.3072	0.7357	1.5139	0.2389
2	T3725M3	0.3161	0.7357	1.5687	0.2526
2	T3725L1	0.2866	0.7357	0.8153	0.1189
2	T3725L2	0.2025	0.7357	0.8194	0.1134
2	T3725L3	0.2411	0.7357	0.7977	0.1144
3	T4815H1	0.2212	0.7357	3.0975	0.6326
3	T4815H2	0.2345	0.7357	1.7842	0.3910
3	T4815H3	0.2724	0.7357	2.3545	0.5144
3	T4815M1	0.1562	0.7357	1.5062	0.2871
3	T4815M2	0.1761	0.7357	1.0227	0.2033
3	T4815M3	0.1778	0.7357	1.5339	0.2922
3	T4815L1	0.0670	0.7357	0.1458	0.0227
3	T4815L2	0.0841	0.7357	0.0972	0.0164
3	T4815L3	0.0754	0.7357	0.0997	0.0162
4	T6136H1	0.4822	0.7357	0.5558	0.1743
4	T6136H2	0.4774	0.7357	0.5811	0.1889
4	T6136H3	0.6257	0.7357	0.2462	0.0606
4	T6136M1	0.5133	0.7357	0.2219	0.0501
4	T6136M2	0.3482	0.7357	0.4267	0.1284
4	T6136M3	0.5793	0.7357	0.0913	0.0212
4	T6136L1	0.4068	0.7357	0.0614	0.0123
4	T6136L2	0.4176	0.7357	0.0505	0.0097
4	T6136L3	0.3992	0.7357	0.0422	0.0092
5	T6825H1	0.3556	0.7357	0.4760	0.1340
5	T6825H2	0.4923	0.7357	0.7277	0.1686
5	T6825H3	0.5642	0.7357	0.7601	0.1946
5	T6825M1	0.5504	0.7357	0.1622	0.0365
5	T6825M2	0.3375	0.7357	0.2057	0.0535
5	T6825M3	0.4553	0.7357	0.1810	0.0469
5	T6825L1	0.2292	0.7357	0.3205	0.0742
5	T6825L2	0.2273	0.7357	0.2893	0.0662
5	T6825L3	0.2374	0.7357	0.3354	0.0754
6	T6915H1	0.5410	0.7357	0.3443	0.1082
6	T6915H2	0.3711	0.7357	0.2340	0.0882
6	T6915H3	0.4526	0.7357	0.2727	0.0917
6	T6915M1	0.0933	0.7357	0.3087	0.0615
6	T6915M2	0.0814	0.7357	0.3651	0.0739
6	T6915M3	0.1142	0.7357	0.1379	0.0308
6	T6915L1	0.1001	0.7357	0.7369	0.1717
6	T6915L2	0.1104	0.7357	0.8239	0.1837
6	T6915L3	0.1151	0.7357	0.8122	0.1838
7	T7536H1	0.5536	0.7357	0.2927	0.0841
7	T7536H2	0.3803	0.7357	0.3943	0.1464
7	T7536H3	0.6499	0.7357	0.0618	0.0225
7	T7536M1	0.7364	0.7357	0.0542	0.0168
7	T7536M	1.0190	0.7357	0.2340	0.0651
7	T7536M	0.6424	0.7357	0.0585	0.0221
7	T7536L1	0.3714	0.7357	0.6123	0.1371
7	T7536L2	0.4829	0.7357	0.5477	0.1344
7	T7536L3	0.5034	0.7357	0.6228	0.1523
8	T8815H1	0.3272	0.7357	1.7456	0.6552
8	T8815H2	0.2928	0.7357	1.6837	0.6038
8	T8815H3	0.3958	0.7357	1.6262	0.6183
8	T8815M1	0.2031	0.7357	2.1252	0.6326
8	T8815M	0.2754	0.7357	1.9523	0.6543
8	T8815M	0.2981	0.7357	1.8080	0.6324
8	T8815L1	0.2243	0.7357	2.4356	0.6947
8	T8815L2	0.1722	0.7357	2.7869	0.7130
8	T8815L3	0.2473	0.7357	2.1132	0.6409
9	T9325H1	0.2825	0.7357	0.3512	0.1638
9	T9325H2	0.1431	0.7357	1.3537	0.4520
9	T9325H3	0.3150	0.7357	0.3492	0.1419
9	T9325M1	0.2711	0.7357	0.3568	0.1537
9	T9325M	0.1674	0.7357	0.6342	0.2012
9	T9325M	0.3094	0.7357	0.2692	0.1249
9	T9325L1	0.1707	0.7357	1.3483	0.3705
9	T9325L2	0.2682	0.7357	1.0538	0.3664
9	T9325L3	0.3064	0.7357	0.9916	0.3518

* Standard error of moisture content

** Mean relative percent error

† Refer to Table 5.1 for explanation of the code.

relative humidity conditions) are given in Appendix A (Tables A1 to A18). The values for transient EMCs (or dynamic EMCs before final EMC is reached at near-equilibrium) were calculated using Eq. (7). After equilibration, the moisture content of samples, in triplicate, was confirmed by oven drying (ASAE 1996) method. The mean EMC (g of H_2O/100 g dry matter) of sorption and desorption are given in Table 5.7. The sorption and desorption EMC for all the experimental tests are shown in Fig. 5.11.

5.4 Evaluation of Equations for EMC-ERH Relationship

Seven of 14 mean EMC values, presented in Table 5.7, were attained by desorption and the same number by sorption. Therefore, the parameters of the modified Chung-Pfost, GAB, Halsey, Henderson, and Oswin equations (Eqs. 14 - 18)were determined separately for sorption and desorption data by nonlinear regression (SigmaPlot 3.02, Jandel Scientific, San Rafael, CA). The parameters of the equations together with the values of mean relative percent error (e), and standard error of relative humidity (SEH) are given in Table 5.8 . The residual plots for all the models are given in Appendix C (Figs. C1 and C2). The residual plots were random for all the five equations, suggesting that this parameter can be ignored in selection of the best fit model. Therefore, further assessment was done based on other statistical parameters. Based on the SEH and e values, the modified Oswin equation was the best model for describing both desorption and sorption data of oats for all the temperatures. The second best models were the modified Chung-Pfost for sorption and the modified Halsey for desorption data of 'AC Belmont' oats.

Using the parameters determined for sorption and desorption for various models, the

Table 5.7 Mean equilibrium moisture contents (g H_2O/100 g dry matter) of 'AC Belmont' hulless oat equilibrated from 27 to 93% relative humidity at 15, 26, and 36°C.

ERH	Temperature	Sorption		Desorption	
(%)	(°C)	Mean	S.D.*	Mean	S.D.
27	36.2			8.63	0.10
37	25.8			10.59	0.12
48	15.2	12.60	0.02	13.28	0.28
61	35.4	13.57	0.05	14.48	0.19
68	25.8	15.48	0.03	16.22	0.23
69	15.5	17.25	0.20	18.31	0.17
75	35.5	17.50	0.15	18.21	0.10
88	15.4	24.00	0.53		
93	25.7	30.72	0.21		

* S.D. is the standard deviation based on n=3.

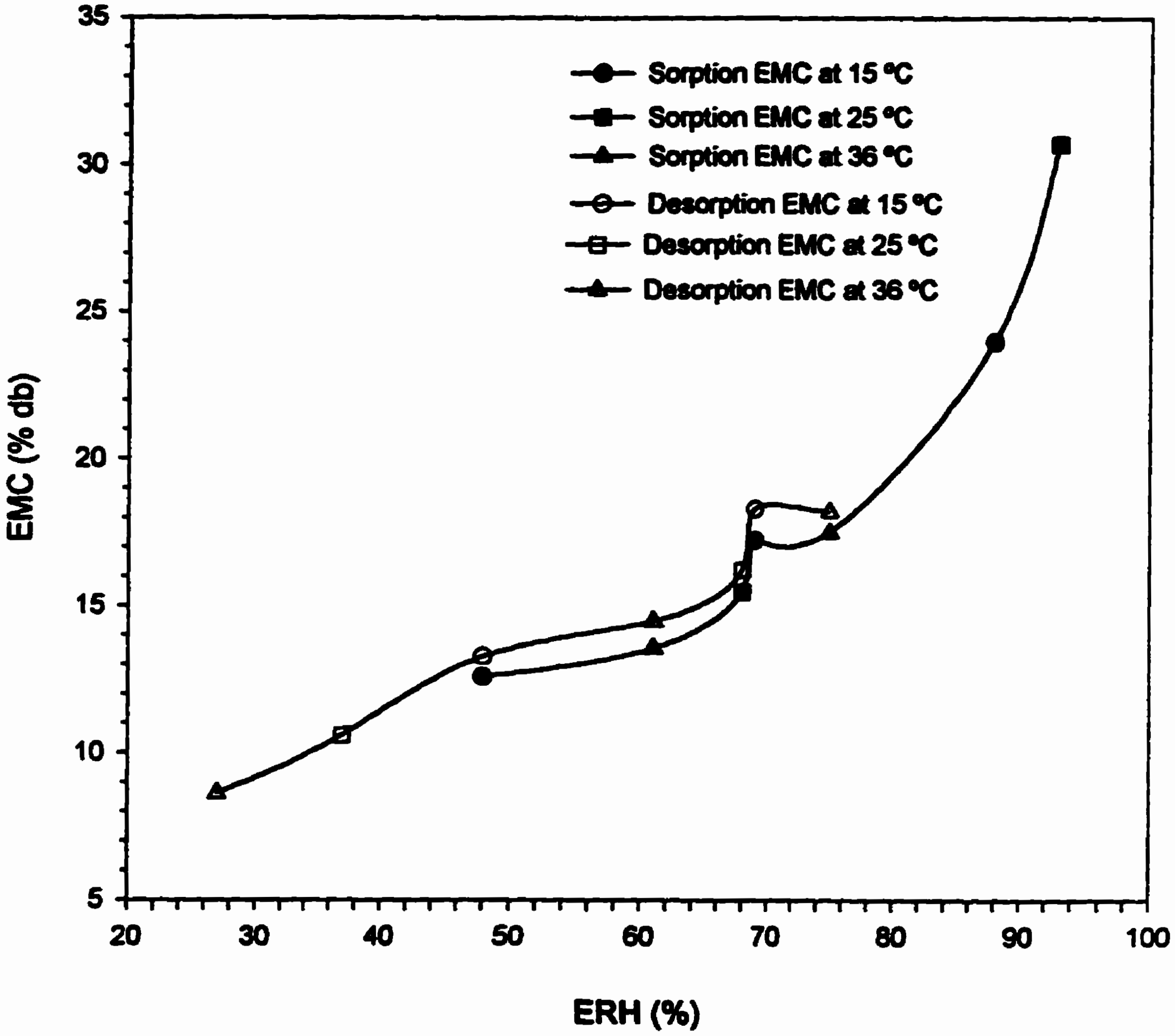

Fig. 5.11 Sorption and desorption EMCs of hulless oats various temperatures and relative humidities for all the experimental tests.

Table 5.8 Estimated parameters, percent deviation and standard error for the modif Oswin, modified Halsey, modified Henderson, modified Chung-Pfost, and modified GAB equations used to predict equilibrium relative humidity for 'AC Belmont' 70% hulless oats at 27 to 93% relative humidity and at 15 to 36°C.

		Moisture content range, % dry basis	
		Sorption conditions	Desorption conditions
Equation	Parameter	12.6 to 30.7	8.6 to 18.21
Modified Chung-Pfost	A	314.6456	543.1072
	B	14.3149	15.7558
	C	56.8793	74.8481
	e	1.44	2.49
	SEH	0.0174	0.0193
Modified GAB	A	8.7552	9.4333
	B	0.7593	0.6998
	C	197.3682	396.9396
	e	2.3	2.71
	SEH	0.0253	0.0217
Modified Halsey	A	6.067	5.1556
	B	-0.0101	-0.0128
	C	2.4529	2.0466
	e	1.48	1.42
	SEH	0.0175	0.0145
Modified Henderson	A	0.0001048	3.9E-05
	B	1.6459	1.9711
	C	86.7599	86.2355
	e	4.52	2.29
	SEH	0.42	0.019
Modified Oswin	A	13.7526	14.5866
	B	-0.0568	-0.0662
	C	2.9514	2.8257
	e	1.5	1.42
	SEH	0.0161	0.0135

A, B, C = parameters of modified equations
e = mean relative percent error, %
SEH = standard error of relative humidity, %

predicted values of RH were calculated and isotherms were plotted at 15, 26, and 36°C temperatures (Fig. 5.12). For higher relative humidities, at all the temperatures, all models except Halsey and Oswin described the EMC-ERH data of oats for desorption (Fig. 5.12). For lower relative humidities, at all the temperatures, all models except Halsey and Oswin described the EMC-ERH data of oats for sorption (Fig. 5.12). Overall for the 15 to 36°C range, the modified Oswin model described the EMC-ERH the best.

5.4.1 Comparison of EMC with the published data

Jayas and Mazza (1993) determined the EMC of 'Tibor' hulless oats by the static method using salt solution. The EMC of 'AC Belmont' oats determined by the thin-layer drying method at 25°C was compared with the reported data (Jayas and Mazza 1993) of 'Tibor' hulless oats in Fig. 5.13. The measured values of EMC in the present study are slightly higher than those measured by Jayas and Mazza (1993). The higher values may be due to cultivar and growing year.

5.4.2 Comparison of thin-layer characteristics with other cereals

The moisture contents predicted by Page's equation (Eq. (12)) for hulless oats at 36.2°C, and 27% RH were compared with wheat and barley for an initial moisture content of 21%, db. The values of parameters k and n for wheat and barley were taken from a study done by Sokhansanj et al. (1984b). The EMCs for wheat and barley at 36.2°C and 27% RH were obtained using the values of parameters of the Modified-Henderson equation (Eq. (14)) from ASAE Standard D245.4 (ASAE 1993). These EMC values were used in Page's equation to obtain predicted moisture contents at various time intervals. The predicted

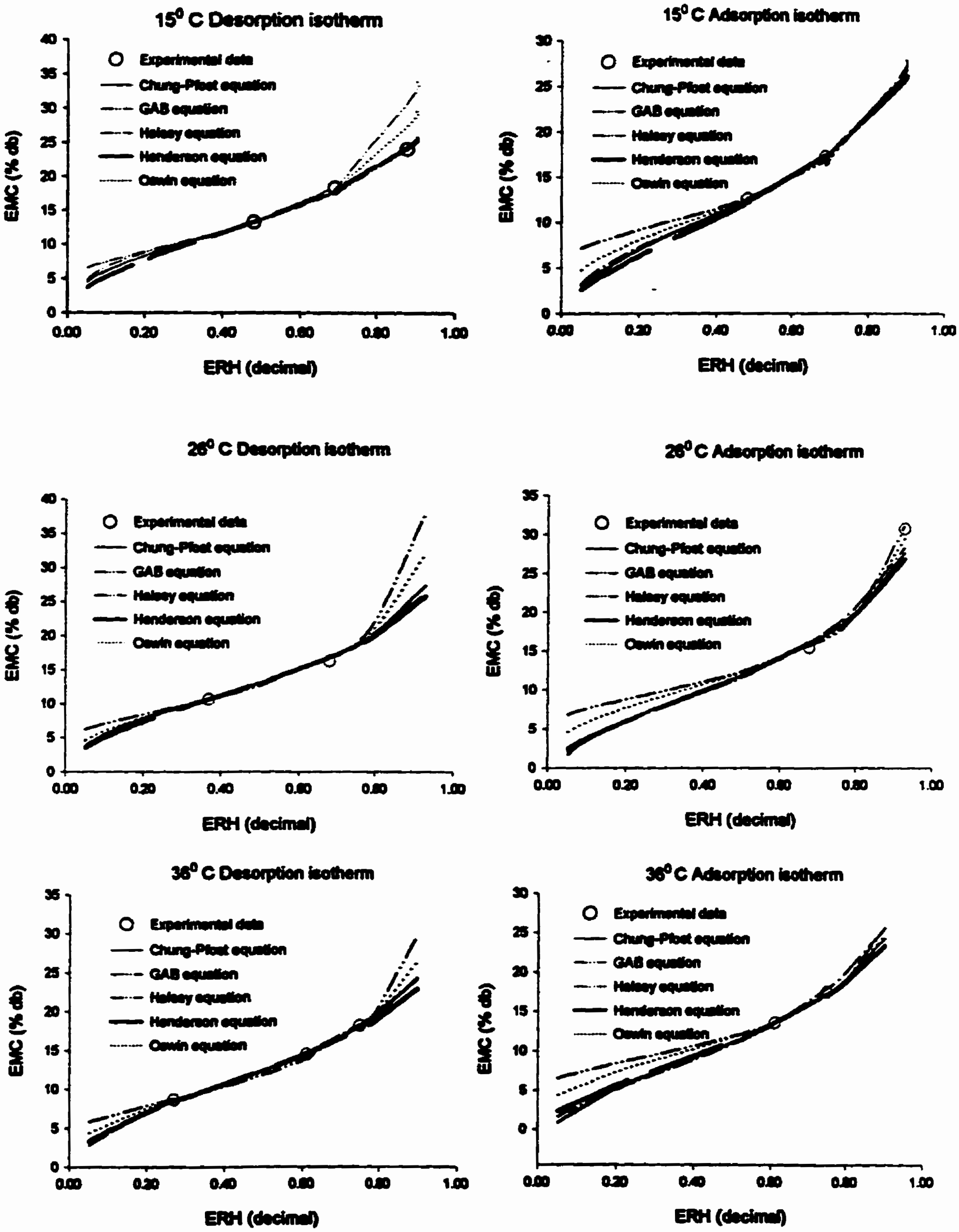

Fig. 5.12 Experimental data and the predicted desorption and adsorption isotherms at 15, 26, and 36°C. The predicted lines beyond the dataset points are extrapolated lines.

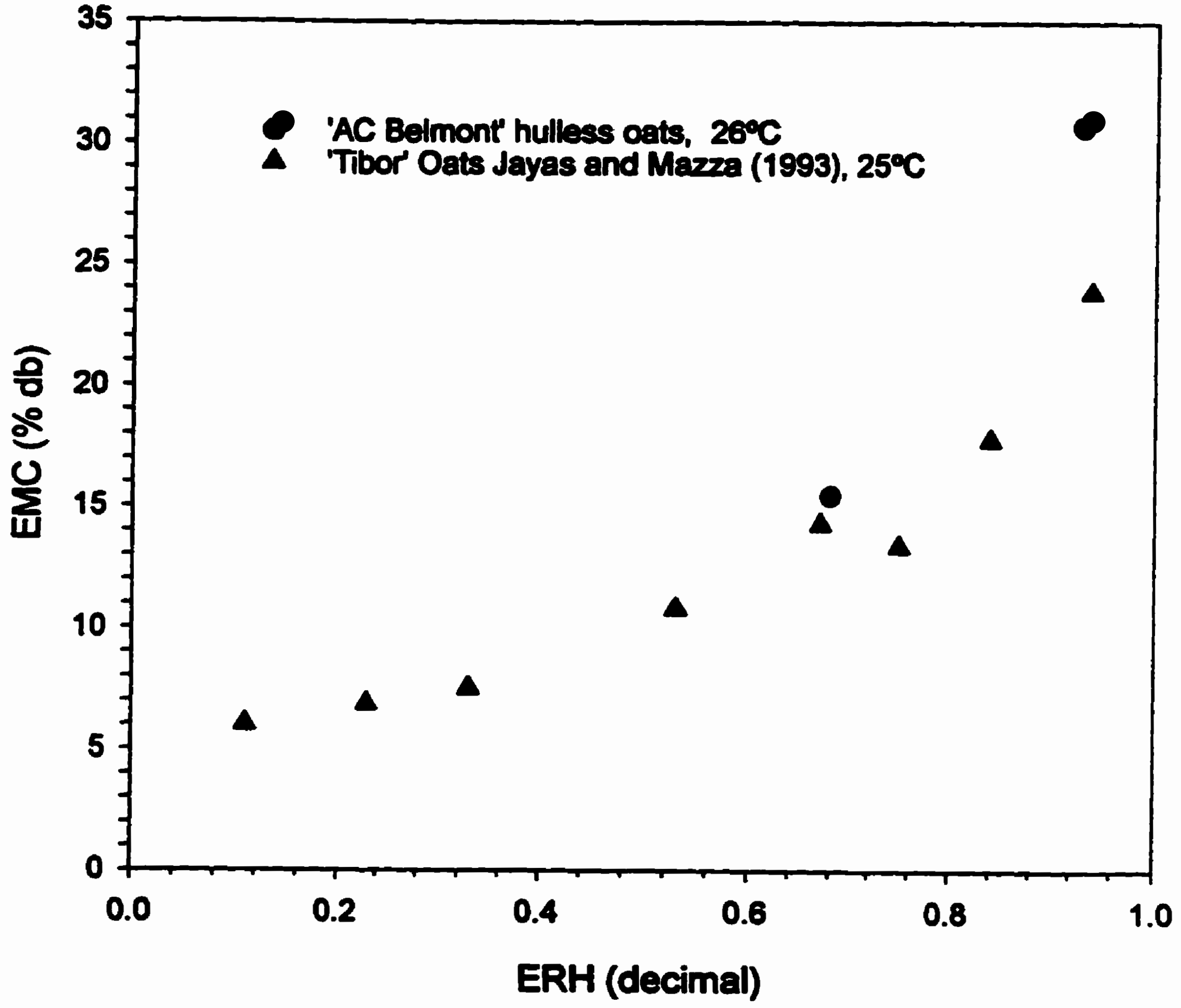

Fig. 5.13. Comparison of sorption EMC of oats measured by thin-layer drying method with published data of hulless oats at 25°C.

moisture contents of hulless oats, wheat, and barley were compared and are illustrated in Fig. 5.14. It is observed that hulless oats dry faster than both wheat and barley. For example, hulless oats dry from 21%, db to 16%, db in 1 h whereas it takes 16 h for wheat, and 17 h for barley to dry to 16%, db. Several factors such as oil content, cultivar, grain or oilseeds type, kernel dimensions, density, and crop year (Neuber 1981) contribute towards higher drying rate of oat compared with wheat and barley.

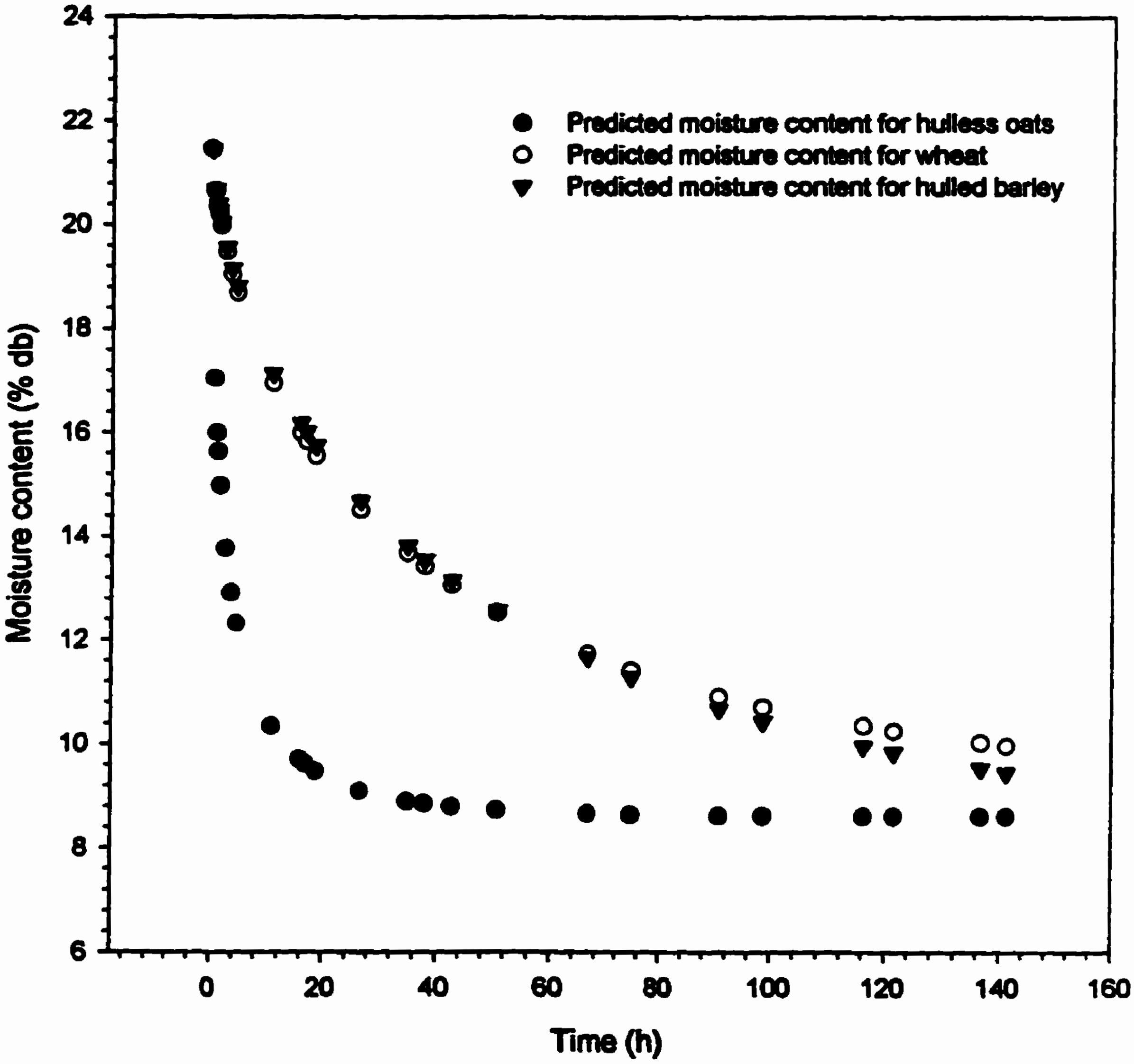

Fig. 5.14 Comparison of thin-layer drying characteristics for hulless oats, wheat, and barley. Temperature = 36°C, RH = 27%.

6. CONCLUSIONS

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

1. The liquid diffusion equation does not satisfactorily describe the drying and rewetting data of hulless oats .
2. The drying and rewetting rates of hulless oats at constant relative humidity conditions agreed well with the Page's equation except for the rewetting at 88% relative humidity.
3. A relationship of parameter k with temperature and relative humidity for the entire range of data could not be established although there was a significant effect of temperature and relative humidity on k.
4. The initial moisture content significantly affected the drying and rewetting rates of hulless oats.
5. The air velocity did not significantly affect the drying or rewetting rates.
6. The modified Oswin model was the best model in describing the EMC-ERH relationship of 'AC Belmont' hulless oats.

8. REFERENCES

Agrawal Y.C. and R.D. Singh. 1977. Thin-layer drying studies for short grain rice. ASAE Paper No. 77-3531. St. Joseph, MI: ASAE.

Asijegiri, E.S. and P.A. Sopade. 1990. Moisture sorption isotherms of Nigerian millet at varying temperatures. *Journal of Food Engineering* 12:283-292.

Anderson, R.B. 1946. Modifications of the Brunauer, Emmet and Teller equation. Journal of American Chemical Society 68:686-691 (cited by Yang 1992).

Arpaci, V.S. 1966. Conduction Heat Transfer. Addision-Wesley, Reading, MA (cited by Shatadal 1989).

ASAE. 1993. ASAE standards D245.4: Moisture Relationship of Grains. St. Joseph, MI: ASAE.

ASAE. 1996. ASAE standards S352.2: Moisture measurement - Unground Grains and Seeds. St. Joseph, MI: ASAE.

Backer, H.A. and H.R. Sallans. 1955. A study of internal moisture movement in the drying of wheat kernel. Cereal Chemistry 32:212-226 (cited by Shatadal, 1989).

Baker, N.R. 1995. International trade in oats. In *The Oat Crop Production and Utilization*, 1st ed. R.W. Welch (ed.), 65-67. London, UK : Chapman and Hall.

Bakker-Arkema, F.W. and C.W. Hall. 1965. Importance of boundary conditions in solving the diffusion equations for drying forage wafer. Transactions of the ASAE 8:382-383.

Bakker-Arkema, F.W., R.C. Brook and L.E. Lerew. 1978. Cereal grain drying. *Advances in Cereal Science and Technology*. Vol. II. Y. Pomeranz (ed.), 1-90. American Association of Cereal Chemists, St. Paul, MN.

Bakker-Arkema, F.W. 1984. Selected aspects of crop processing and storage: A review. Journal of Agricultural Engineering Research 30:1-22 (cited by Jayas et al. 1991).

Berger, D. and D.C.T. Pei. 1973. Drying of hygroscopic capillary porous solids: a theoretical approach. International Journal of Heat and Mass Transfer 16:293-302.

Bradley, R.S. 1936. Polymolecular adsorbed films. Part 1. The adsorption of argon on salt crystals at low temperature and the determinations of surface fields. Journal of American Chemical Society 58:1467-1474 (cited by Yang 1992).

Brooker, D.B., F.W. Bakker-Arkema and Hall, C.W. 1974. *Drying cereal grains*. Westport, CO: AVI Publishing Company Inc.

Bruce, D.M. 1985. Exposed-layer barley drying: three models fitted to new data up to 150°C. Journal of Agricultural Engineering Research 32:337-348.

Canada Grains Council. 1996. *Statistical Handbook*. Winnipeg, MB: Canada Grains Council.

Caurie, M. 1970. A new model equation for predicting safe storage moisture levels for optimum stability of dehydrated foods. Journal of Food Technology 5:301-307.

Cenkowski, S., S. Sokhansanj and F.W. Solsuski. 1989a. The effect of drying temperature on green color chlorophyll content of canola seed. Canadian Institute of Food Science and Technology Journal 22:383-386.

Cenkowski, S., S. Sokhansanj and F.W. Solsuski. 1989b. Equilibrium moisture content of lentils. Canadian Agricultural Engineering 31:159-162.

Chen, C.C. and R.V. Morey. 1989a. Comparison of four EMC/ERH equations. Transactions of the ASAE 32:983-990.

Chen, C.S. 1971. Equilibrium moisture curves for biological materials. Transactions of the ASAE 14:924-926.

Chen, C.S. and J. T. Clayton. 1971. The effect of temperature on sorption isotherms of biological materials. Transactions of the ASAE 14:927-929.

Chirife, J. and H.A. Iglesias. 1978. Equations for fitting water sorption isotherms of foods: Part 1 - a review. Journal of Food Technology. 13:159-174.

Chittenden, D.H. and A. Hustrulid. 1966. Determining drying constants for shelled corn. Transactions of the ASAE 9:52-55 (cited by Jayas et al. 1991).

Chung, D.S. and H.B. Pfost. 1967. Adsorption and desorption of water vapour by cereal grains and their products. Part I. Heat and free energy changes of adsorption and desorption. Transactions of the ASAE 10:549-555.

Crank, J. 1964. The mathematics of diffusion. Oxford, UK: Claredon Press (cited by Shatadal, 1989).

De Vries. 1958. Simultaneous transfer of heat and moisture in porous media. Transactions of American Geophysics Union 39:909-916.

Duggal, A.K., W.E. Muir and D.B. Brooker. 1982. Thin-layer rewetting of wheat straw and heads. Canadian Agricultural Engineering 24:11-14.

Farmer, G.S., G.H. Brusewitz and R.W. Whitney. 1983. Drying properties of bluestem grass seed. Transactions of the ASAE 26:234-237.

Fasina, O.O. and S. Sokhansanj. 1993. Equilibrium moisture relations and heat of sorption of alfalfa pellets. Journal of Agricultural Engineering Research 56:51-63.

Fortes, M. and M.R. Okos. 1980. Drying theories: Their bases and limitations as applied to foods and grains. *Advances in Drying*, Vol. I., New York, NY: Hemisphere Pub. Co.

Fortes, M. and M.R. Okos. 1981a. Non-equilibrium thermodynamics approach to heat and mass transfer in corn kernels. Transactions of the ASAE 24:761-769.

Fortes, M. and M.R. Okos. 1981b. A non-equilibrium thermodynamics approach to transport phenomena in capillary-porous media. Transactions of the ASAE 24:756-760.

Fortes, M., M.R. Okos and J.R. Barrett Jr. 1981. Heat and mass transfer analysis of intra-kernel wheat drying and rewetting. Canadian Agricultural Engineering 26:109-125.

Foster, G.H. 1982. Drying Cereal Grains. *Storage of Cereal Grains and Their Products*. Vol. V. C.M. Christensen (ed.), 79-73. St. Paul, MN: American Association of Cereal Chemists,.

Fraser, B.M. and W.E. Muir. 1980a. Energy consumption predicted for drying grain with ambient and solar heated air in Canada. Canadian Agricultural Engineering 25:325-331.

Fraser, B.M. and W.E. Muir. 1980b. Cost predictions for drying grain with ambient and solar heated air in Canada. Canadian Agricultural Engineering 22:55-59.

Gal, S. 1981. Recent development for obtaining full range moisture sorption isotherms. In *Water Activity: Influence on Food Quality*, L.B. Rockland and G.F. Stewart(eds.), 89-110. New York, NY: Academic Press.

Halsey, G. 1948. Physical adsorption in non-uniform surfaces. Journal of Chemical Physics 16:931-937 (cited by Fasina and Sokhansanj 1993).

Hamdy, M.Y. and W.H. Johnson. 1968. Analog computer simulation of unidirectional moisture diffusion in hay wafers. Transactions of the ASAE 11:153-154.

Hamdy, M.Y. and J.H. Barre. 1969. Evaluating film coefficient in single kernel drying.

Transactions of the ASAE 17:1167-1168, 1172.

Henderson, S.M. 1952. A basic concept of equilibrium moisture. Agricultural Engineering 33:29-32 (cited by Yang 1992).

Henderson, S.M. 1974. Progress in developing the thin-layer drying equations. Transactions of the ASAE 17:1167-1168, 1172.

Henry, P.S.H. 1939. Diffusion in absorbing media. Proceedings of Royal Society of London. 171A:215-241 (cited by Shatadal 1989).

Hill, M.J. and. F. Fernandez. 1990. Bacterial metabolism, fibre, and colorectal cancer. In *Dietary Fibre: Chemistry, Physiology, and Health Effects,* Kritchvesky D.C. Bonfield and J.W. Anderson (eds.), 417-429. New York , NY: Plenum Press.

Hoffman, L.A.1995. World production and use of oats. In *The Oat Crop Production and Utilization,* 1st Ed, R.W. Welch (ed.), 34-61. London, UK: Chapman and Hall.

Holm, J., B. Kiellereutter and P. Würsch. 1992. Influence of sterilization, drying and oat bran enrichment of pasta on glucose and insulin responses in healthy subjects and on the rate and extent of in vitro starch digestion. European Journal of Clinical Nutrition 46:629-640.

Hukill, W.V. 1974. Grain drying. *Storage of Cereal Grains and Their Products.* Vol. III. C.M. Christensen (ed.), 481-508. American Association of Cereal Chemists, St. Paul, MN (cited by Foster 1982).

Hustrulid, A. 1962. Comparative drying rates of naturally moist, remoistened, and frozen shelled corn. Transactions of the ASAE 5:64-67 (cited by Jayas et al. 1991).

Hustrulid, A. 1963. Comparative drying rates of naturally moist, remoistened, and frozen wheat. Transactions of the ASAE 6:304-308.

Hutchinson, D and L. Otten. 1982. Thin-lyer drying of soybeans and white beans. CSAE Paper No. 82-104. Saskatoon, SK: CSAE.

Iglesias, H.A. and J. Chirife. 1976. Prediction of the effect of temperature on water sorption isotherms of food material. Journal of Food Technology 11:109-116.

Jandel Scientific. 1995. Transforms and Nonlinear Regressions. San Rafael, CA: Jandel Scientific.

Jayas, D.S. and S. Sokhansanj. 1986. Thin-layer drying of wheat at low temperature. In *Drying '86*, A.S. Mujumdar (ed.), 844-847. New York, NY: Hemisphere Pub. Co.

Jayas, D.S., S. Cenkowski and W.E. Muir. 1988. A discussion of the thin-layer drying equation. ASAE Paper No. 88-6557. St. Joseph, MI: ASAE.

Jayas, D.S. and S. Sokhansanj. 1989. Thin-layer drying of barley at low temperature. Canadian Agricultural Engineering 31:21-23.

Jayas, D.S., S., Cenkowski, S. Pabis and W.E. Muir. 1991. Review Of Thin Layer Drying And Wetting Equations. Drying Technology 9(3):551-558.

Jayas, D.S. and G. Mazza. 1993. Comparison of modified GAB equation with four other three-parameter equations for the description of sorption data of oats. ASAE Paper No. MNSK91-115. St. Joseph, MI: ASAE.

Kapsalis, J.G. 1987. Influence of hysteresis and temperature on moisture sorption isotherms. In *Water Activity: Theory and Applications to Food*, L.B. Rockland and L.R. Beuchat,(eds.), 143-177. New York, NY: Academic Press.

Lewis, W.K. 1921. The rate of drying of solids materials. Industrial Engineering Chemistry

13:427 (cited by Jayas et al. 1991).

Li, H., R.V. Morey and M. Afinrud. 1987. Thin-layer drying rates of oilseed sunflower. Transactions of the ASAE 30:1172-1175, 1180.

Luikov, A.V. 1966a. Application of irreversible thermodynamic methods for investigation of heat and mass transfer. International Journal of Heat and Mass Transfer 9:139-152.

Luikov, A.V. 1966b. Heat and Mass Transfer in Capillary-Porous Bodies. Oxford, UK: Pergamon Press. 523 p.

Luikov, A.V. 1975. Systems of differential equations of heat and mass transfer in capillary-porous bodies. International Journal of Heat and Mass Transfer 18:1-14.

Mazza, G. and D.S. Jayas. 1990. Equilibrium moisture content- equilibrium humidity relationships of sunflower seeds, hulls and kernels. CSAE Paper No.90-406. Saskatoon, SK: CSAE.

Mikhailov, M.V. 1973. General solutions of the diffusion equations coupled at boundary conditions. International Journal of Heat and Mass Transfer 16:2155-2164.

Miller, E.E. and R.D. Miller. 1955. Theory of capillary flow: I Practical implications. Proceedings of Soil Science Society of America 19:271-275.

Misra, M.K. and D.B. Brooker. 1980. Thin-layer drying and rewetting equations for shelled yellow corn. Transactions of the ASAE 23:1254-1260.

Neuber, E. E. 1981. Evaluation of critical parameters for developing moisture sorption isotherms of cereal grains. In *Water Activity: Influence on Food Quality*, L.B. Rockland and G.F. Stewart(eds.), 199-222. Toronto, ON: Academic Press.

Osborn, G.S., G.M. White and L.R. Walton. 1988. Thin-layer rewetting equation for soybeans.

ASAE Paper No. 88-6066. St. Joseph, MI: ASAE.

Oswin, C.R. 1946. The kinetics of package life III-Isotherm. Journal of Industrial Chemistry (London) 65:419-421 (cited by Fasina and Sokhansanj 1993).

Overhults, D.G., H.E. White, H.E. Hamilton and I.J. Ross. 1973. Drying soybeans with heated air. Transactions of the ASAE 16:112-113 (cited by Jayas et al. 1991).

Pabis, S. and S.M. Henderson. 1961. Grain drying theory: II. A critical analysis of the drying curve of the shelled maize. Journal of Agricultural Engineering Research 6:272-277.

Pabis, S. and S.M. Henderson. 1962. Grain drying theory: III. The air grain temperature relationship. Journal of Agricultural Engineering Research 7:21-28.

Page, G. 1949. Factors influencing the maximum rates of air drying shelled corn in thin layer. Unpublished M.Sc. thesis, Purdue University (cited by Jayas et al. 1991).

Park, S.W., D.S. Chung and C.A. Watson. 1971. Adsorption kinetics of water vapour by yellow corn: I. Analysis of kinetic data for sound corn. Cereal Chemistry 48:14-22.

Parry, J.L. 1985. Mathematical modelling and computer simulation of heat and mass transfer in agricultural grain drying: A review. Journal of Agricultural Engineering Research 32:1-29.

Pfost, H.B., S.G. Mourer, D.S. Chung and G.A. Milliken. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520. St. Joseph., MI: ASAE.

Philip, J.R. and D.A. De Vries. 1957. Moisture movement in porous materials under temperature gradients. Transactions of American Geophysics Union 38:222-232.

Rowe, R.J. and W.W. Gunkel. 1972. Simulation of temperature and moisture content of alfalfa during thin-layer drying. Transactions of the ASAE 15:805-810.

SAS. 1995. SAS User's Guide: Statistics. Statistical Analysis System Inc., Raleigh, NC.

Sharaf-Eideen, Y.I., J.L. Blaisdell and M.Y. Hamdy. 1980. A model of ear corn drying. Transactions of the ASAE 23:1261-1265.

Shatadal, P. 1989. Thin-Layer Rewetting Rates of Canola (*Brassica Campestris* L.). Unpublished M.Sc. thesis. Department of Agricultural Engineering, University of Manitoba. Winnipeg, MB.

Simmonds, M.A., G.T. Ward and E. McEwen. 1953. The drying of wheat grain. I. The mechanism of drying. Transactions of Institute of Chemical Engineering 31:265-278.

Singh(Jayas), D., S. Sokhansanj and B. Middleton. 1983. Drying characteristics of wheat, barley and canola at low temperatures. ASAE Paper No. NCR 83-207. St.Joseph, MI: ASAE.

Singh (Jayas), D. and S. Sokhansanj. 1984. Recent developments in natural air drying of cereals with respect to system design. In *Drying '84.* A.S. Majumdar (ed.), 456-467. New York, NY: Hemisphere Pub. Co.

Sinicio, Roberto. 1994. Computer Simulation of Aerated Wheat Stored in Tropical and Subtropical Climates. Unpublished Ph.D. thesis, Department of Biosystems Engineering, University of Manitoba. Winnipeg, MB.

Sokhansanj, S., W.P. Lampman and J.D. MacAulay. 1983. Investigation of grain tempering on drying tests. Transactions of the ASAE 26:293-296.

Sokhansanj, S., S.L. Sturton and D.S. Singh (Jayas). 1984a. Comparative studies on thin layer drying equipments. ASAE Paper No. 84-3527. St. Joseph, MI: ASAE.

Sokhansanj, S.,D.S. Singh (Jayas) and J.D. Wasserman. 1984b. Drying characteristics of wheat, barley and canola subjected to repetitive wetting and drying cycles. Transactions of the ASAE 27:903-906, 914.

Sokhansanj, S., W. Zhijie, D. S.Jayas and T. Kameoka. 1986. Equilibrium relative humidity-moisture content of rapeseed (canola) from 5 °C to 25 °C. Transactions of the ASAE 29:837-939.

Sokhansanj, S., S. Cenkowski and D.S. Jayas. 1987. Equipments and methods of thin-layer drying. ASAE Paper No. 87-6556. St. Joseph, MI: ASAE.

Stroshine, R.L., A. Emam, J. Tutie, F. Cantone, A. Kirleis, L.F. Bauman and M.R. Okos. 1981. Comparison of drying rates and quality parameters for selected corn inbreds/hybrids. ASAE Paper No. 81-3529. St. Joseph, MI: ASAE.

Syarief, A.M., R.V. Morey and R.J. Gustafson. 1984. Thin layer drying rates of sunflower seed. Transactions of the ASAE 27:195-200.

Van den Berg, C and S. Bruin. 1981. Water activity and its estimation in food systems: theoretical aspects. In *Water Activity: Influence on Food Quality*. L.B. Rockland and G.F. Stewart (eds.), 1-43. New York, NY: Academic Press.

Watson, E.L. and V.K. Bhargava. 1974. Thin-layer drying studies on wheat. Canadian Agricultural Engineering 16:18-22.

Welch, R.W. 1995. Oats in human nutrition and health. In *The Oat Crop Production and Utilization*, 1st Ed, R.W. Welch (ed.), 433-443. London, UK: Chapman and Hall.

Whitaker, T.B. and J.H. Young. 1972. Simulation of moisture movement in peanut kernels: Evaluation of the diffusion equation. Transactions of the ASAE 51:163-166.

White, G.M., I.J. Ross and P.W. Westerman. 1973. Drying rate and quality of white shelled corn as influenced by dew point temperature. Transactions of the ASAE 16:118-120.

Whitney, J.D. and Porterfield. 1968. Moisture movement in porous hygroscopic solid. Transactions of the ASAE 11:716-723.

Yang, W. 1992. Thermodynamic properties and moisture equilibrium characteristics of rapeseed (canola) during multiple adsorption and desorption cycles. Unpublished M.Sc. thesis. Department of Agricultural Engineering, University of Manitoba, Winnipeg, MB.

Young, J.H. 1969. Simultaneous heat and mass transfer in a porous hygroscopic solids. Transactions of the ASAE 12:720-725.

Appendix A

Table A1 Moisture content (% db) with time for test at Temp = 36.2°C, RH=27%

Cumulative	Moisture content (% dry mass basis)								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	H1*	M1**	L1***	H2	M2	L2	H3	M3	L3
0.00	21.5	16.5	11.9	21.5	16.5	11.9	21.5	16.5	11.9
0.65	17.6	14.2	11.4	18.2	14.6	11.2	16.8	13.9	11.2
1.65	15.0	12.9	11.1	15.5	13.3	10.9	14.5	12.8	10.8
2.65	13.6	12.1	10.9	14.1	12.5	10.7	13.4	12.1	10.7
3.67	12.6	11.6	10.6	12.9	11.8	10.5	12.4	11.4	10.5
4.62	12.0	11.1	10.4	12.4	11.5	10.3	11.8	11.2	10.3
18.77	9.7	9.4	9.6	9.9	9.6	9.4	9.6	9.5	9.5
26.70	9.4	9.2	9.4	9.5	9.3	9.3	9.3	9.2	9.3
42.72	9.1	8.8	9.1	9.1	9.0	9.0	8.9	8.9	9.1
50.78	8.9	8.7	9.0	9.0	8.9	9.0	8.9	8.8	9.0
66.73	8.8	8.6	9.0	8.8	8.7	8.8	8.7	8.6	8.9
74.83	8.8	8.5	8.9	8.8	8.7	8.8	8.7	8.6	8.9
90.75	8.7	8.5	8.9	8.8	8.7	8.8	8.6	8.6	8.8
98.70	8.7	8.5	8.9	8.8	8.7	8.7	8.6	8.5	8.8
116.27	8.6	8.5	8.8	8.7	8.6	8.7	8.6	8.5	8.8
121.70	8.6	8.5	8.8	8.7	8.6	8.7	8.6	8.5	8.8
136.70	8.6	8.5	8.8	8.7	8.6	8.7	8.6	8.5	8.8
141.27	8.6	8.5	8.8	8.7	8.6	8.7	8.6	8.5	8.8

* H1, H2, and H3 represent high mc, 21-22% db in replicates I, II, and III.

** M1, M2, and M3 represent medium mc, 16-17% db in replicates I, II, and III .

*** L1, L2, and L3 represent low mc, 11-12% db in replicates I, II, and III .

Table A2: Moisture ratio with time for test at Temp = 36.2°C, RH=27%

Cumulative	Moisture ratio								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	H1†	M1	L1	H2	M2	L2	H3	M3	L3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.65	0.70	0.71	0.84	0.74	0.76	0.78	0.64	0.68	0.77
1.65	0.49	0.55	0.73	0.53	0.59	0.68	0.46	0.53	0.65
2.65	0.39	0.45	0.66	0.42	0.49	0.61	0.37	0.44	0.61
3.67	0.31	0.39	0.58	0.33	0.41	0.55	0.29	0.37	0.54
4.62	0.27	0.33	0.52	0.29	0.37	0.51	0.25	0.33	0.50
18.77	0.09	0.12	0.26	0.09	0.13	0.23	0.08	0.12	0.24
26.70	0.06	0.09	0.20	0.06	0.09	0.17	0.06	0.09	0.18
42.72	0.04	0.04	0.11	0.03	0.05	0.10	0.03	0.04	0.10
50.78	0.03	0.03	0.08	0.03	0.03	0.08	0.02	0.03	0.08
66.73	0.01	0.01	0.05	0.01	0.02	0.03	0.01	0.01	0.05
74.83	0.01	0.01	0.04	0.01	0.01	0.02	0.01	0.01	0.04
90.75	0.01	0.00	0.02	0.01	0.01	0.02	0.00	0.01	0.01
98.70	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.01
116.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
121.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
136.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
141.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A3 Moisture content (% db) with time for test at Temp = 26.8°C, RH=37%

Cumulative	Moisture content (% dry mass basis)								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	H1†	L1	H2	L2	M1	M2	H3	L3	M3
0.00	21.5	12.0	21.5	12.0	17.0	17.0	21.5	12.0	17.0
0.67	18.1	11.4	18.6	11.6	15.8	15.4	17.7	11.6	15.2
1.67	16.3	11.3	16.7	11.5	14.7	14.4	16.0	11.4	14.4
2.67	15.3	11.3	15.6	11.4	14.1	13.9	15.1	11.4	13.8
3.67	14.6	11.2	14.8	11.3	13.7	13.5	14.4	11.3	13.4
4.67	14.0	11.1	14.2	11.3	13.3	13.1	13.9	11.2	13.1
5.67	13.6	11.1	13.8	11.2	13.0	12.9	13.5	11.2	12.9
6.67	13.3	11.0	13.4	11.2	12.8	12.7	13.2	11.2	12.7
21.00	11.5	10.8	11.5	10.9	11.6	11.6	11.5	10.9	11.6
29.00	11.2	10.8	11.2	10.8	11.3	11.4	11.2	10.9	11.4
45.00	10.9	10.7	10.9	10.8	11.1	11.2	10.9	10.8	11.2
53.00	10.9	10.7	10.9	10.8	11.1	11.1	10.9	10.8	11.1
69.00	10.8	10.7	10.8	10.8	11.0	11.0	10.8	10.8	11.0
77.00	10.8	10.7	10.7	10.7	11.0	11.0	10.8	10.8	11.0
93.00	10.7	10.7	10.7	10.7	10.9	11.0	10.7	10.8	11.0
101.00	10.7	10.7	10.7	10.7	10.9	11.0	10.7	10.8	11.0
117.00	10.6	10.6	10.6	10.7	10.9	10.9	10.6	10.8	10.9
125.00	10.6	10.6	10.6	10.7	10.9	10.9	10.6	10.7	10.9
141.00	10.6	10.6	10.5	10.7	10.8	10.9	10.6	10.7	10.9
149.00	10.5	10.6	10.5	10.6	10.8	10.9	10.6	10.7	10.9
165.00	10.5	10.5	10.4	10.6	10.7	10.8	10.5	10.7	10.8
173.00	10.5	10.5	10.4	10.6	10.7	10.8	10.5	10.6	10.8
190.00	10.5	10.5	10.4	10.6	10.7	10.8	10.5	10.6	10.8
197.00	10.5	10.5	10.4	10.6	10.7	10.8	10.5	10.6	10.8

† Refer to Table A1 for explanation of the code.

Table A4: Moisture ratio with time for test at Temp = 26.8°C, RH=37%

Cumulative	Moisture ratio								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	H1†	L1	H2	L2	M1	M2	H3	L3	M3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.67	0.69	0.65	0.74	0.76	0.81	0.74	0.65	0.70	0.72
1.67	0.52	0.55	0.56	0.66	0.64	0.59	0.50	0.60	0.58
2.67	0.43	0.51	0.46	0.59	0.54	0.50	0.42	0.56	0.49
3.67	0.37	0.46	0.39	0.54	0.47	0.44	0.36	0.50	0.43
4.67	0.32	0.41	0.34	0.50	0.42	0.38	0.31	0.45	0.38
5.67	0.28	0.39	0.30	0.46	0.37	0.35	0.28	0.43	0.34
6.67	0.25	0.36	0.27	0.43	0.34	0.32	0.25	0.40	0.31
21.00	0.09	0.19	0.10	0.24	0.14	0.13	0.09	0.21	0.13
29.00	0.07	0.17	0.07	0.20	0.11	0.10	0.06	0.18	0.10
45.00	0.04	0.12	0.04	0.15	0.07	0.06	0.04	0.14	0.07
53.00	0.04	0.12	0.04	0.15	0.06	0.06	0.04	0.14	0.06
69.00	0.03	0.11	0.03	0.13	0.05	0.04	0.03	0.13	0.04
77.00	0.03	0.11	0.03	0.12	0.05	0.04	0.03	0.13	0.04
93.00	0.02	0.09	0.02	0.11	0.04	0.04	0.02	0.12	0.04
101.00	0.02	0.09	0.02	0.11	0.03	0.03	0.02	0.12	0.03
117.00	0.02	0.07	0.02	0.10	0.03	0.03	0.02	0.09	0.02
125.00	0.01	0.06	0.01	0.09	0.03	0.02	0.01	0.08	0.02
141.00	0.01	0.04	0.01	0.07	0.02	0.02	0.01	0.05	0.02
149.00	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.03	0.01
165.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.00
173.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
190.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
197.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A5 Moisture content (% db) with time for test at Temp = 15.2°C, RH=48%

Cumulative	Moisture content (% dry mass basis)								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	M1†	H1	M2	H2	L1	L2	M3	H3	L3
0.00	16.9	22.3	16.9	22.3	12.2	12.2	16.9	22.3	12.2
0.67	16.3	20.6	16.4	20.9	12.2	12.2	16.1	20.0	12.2
1.67	15.8	19.3	15.9	19.6	12.2	12.3	15.7	18.9	12.2
2.67	15.5	18.6	15.6	18.7	12.3	12.3	15.4	18.3	12.3
3.67	15.3	18.0	15.4	18.1	12.3	12.3	15.2	17.7	12.3
4.67	15.1	17.6	15.1	17.7	12.3	12.3	15.1	17.3	12.3
5.67	15.0	17.3	15.0	17.3	12.3	12.3	14.9	17.0	12.3
6.67	14.8	17.0	14.8	17.0	12.3	12.3	14.8	16.7	12.3
22.67	14.0	15.1	14.0	15.1	12.4	12.4	14.0	15.0	12.4
30.67	13.9	14.9	13.9	14.8	12.4	12.5	13.9	14.8	12.4
46.67	13.8	14.7	13.7	14.5	12.5	12.5	13.8	14.5	12.5
54.67	13.7	14.6	13.6	14.5	12.5	12.5	13.7	14.5	12.5
70.67	13.3	14.4	13.3	14.2	12.5	12.6	13.4	14.2	12.5
78.67	13.2	14.2	13.3	14.1	12.5	12.6	13.3	14.2	12.5
94.67	13.1	14.0	13.2	13.9	12.6	12.6	13.2	13.9	12.5
102.67	13.0	13.9	13.2	13.8	12.6	12.6	13.1	13.7	12.5
118.67	12.9	13.5	13.1	13.7	12.6	12.6	13.1	13.6	12.6
126.67	12.9	13.4	13.1	13.7	12.6	12.6	13.0	13.6	12.6
142.67	12.9	13.4	13.1	13.7	12.6	12.6	13.0	13.6	12.6

† Refer to Table A1 for explanation of the code.

Table A6: Moisture ratio with time for test at Temp = 15.2°C, RH=48%

Cumulative	Moisture ratio								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	M1†	H1	M2	H2	L1	L2	M3	H3	L3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.67	0.86	0.81	0.87	0.83	1.00	1.00	0.80	0.73	1.00
1.67	0.73	0.67	0.73	0.68	1.00	0.94	0.70	0.61	1.00
2.67	0.65	0.58	0.65	0.59	0.91	0.86	0.62	0.54	0.90
3.67	0.60	0.52	0.59	0.52	0.85	0.86	0.57	0.47	0.83
4.67	0.56	0.47	0.54	0.46	0.85	0.77	0.53	0.43	0.80
5.67	0.51	0.44	0.50	0.42	0.85	0.77	0.49	0.39	0.80
6.67	0.47	0.40	0.45	0.38	0.79	0.71	0.45	0.35	0.80
22.67	0.26	0.20	0.22	0.16	0.56	0.49	0.24	0.16	0.53
30.67	0.25	0.17	0.20	0.13	0.44	0.37	0.23	0.13	0.40
46.67	0.21	0.15	0.16	0.10	0.35	0.23	0.20	0.11	0.27
54.67	0.20	0.14	0.14	0.09	0.32	0.20	0.18	0.10	0.23
70.67	0.09	0.11	0.06	0.07	0.24	0.14	0.09	0.07	0.17
78.67	0.07	0.10	0.05	0.06	0.21	0.11	0.08	0.06	0.13
94.67	0.04	0.07	0.02	0.03	0.09	0.06	0.04	0.03	0.07
102.67	0.03	0.06	0.02	0.02	0.06	0.00	0.02	0.02	0.07
118.67	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.03
126.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
142.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A7 Moisture content (% db) with time for test at Temp = 35.4°C, RH=61%

Cumulative time (h)	Moisture content (% dry mass basis)								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	L1†	M1	H1	H2	M2	H3	L2	L3	M3
0.00	11.4	16.3	21.0	21.0	16.3	21.0	11.4	11.4	16.3
0.75	12.0	15.6	19.4	19.5	16.2	18.5	12.0	12.0	15.6
1.82	12.4	15.0	17.7	17.8	15.6	17.0	12.5	12.4	15.1
2.82	12.6	14.8	16.8	16.9	15.3	16.3	12.7	12.7	14.9
3.82	12.8	14.7	16.2	16.3	15.1	15.8	12.9	12.9	14.8
4.82	12.9	14.6	15.8	15.9	14.9	15.6	13.0	13.0	14.7
19.42	13.5	14.2	14.8	14.8	14.5	14.8	13.5	13.5	14.4
27.42	13.5	14.2	14.7	14.8	14.4	14.7	13.6	13.6	14.4
43.42	13.5	14.1	14.6	14.8	14.4	14.7	13.6	13.6	14.4
51.42	13.5	14.1	14.6	14.7	14.4	14.6	13.6	13.6	14.4
67.42	13.5	14.1	14.6	14.7	14.4	14.6	13.6	13.6	14.4
78.22	13.5	14.1	14.6	14.7	14.4	14.6	13.6	13.6	14.4

† Refer to Table A1 for explanation of the code.

Table A8 : Moisture ratio with time for test at Temp = 35.4°C, RH=61%

Cumulative time (h)	Moisture ratio								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	L1†	M1	H1	H2	M2	H3	L2	L3	M3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.75	0.71	0.68	0.75	0.76	0.94	0.61	0.72	0.73	0.62
1.82	0.54	0.42	0.48	0.48	0.64	0.36	0.52	0.54	0.40
2.82	0.42	0.32	0.34	0.34	0.47	0.26	0.41	0.42	0.29
3.82	0.33	0.26	0.25	0.26	0.35	0.19	0.32	0.34	0.21
4.82	0.28	0.21	0.19	0.19	0.23	0.15	0.27	0.28	0.17
19.42	0.02	0.06	0.03	0.02	0.03	0.02	0.02	0.04	0.03
27.42	0.00	0.03	0.01	0.02	0.00	0.01	0.00	0.01	0.01
43.42	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01
51.42	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
67.42	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
78.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A9 Moisture content (% db) with time for test at Temp = 25.8°C, RH=68%

Cumulative time (h)	Moisture content (% dry mass basis)								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	L1†	M1	L2	M2	H1	H2	M3	L3	H3
0.00	12.0	16.9	12.0	16.9	21.5	21.5	16.9	12.0	21.5
0.67	12.4	16.5	12.5	16.8	20.7	19.8	16.5	12.4	19.3
1.67	12.9	16.4	12.9	16.5	19.6	18.8	16.4	12.9	18.5
2.67	13.3	16.3	13.2	16.3	18.8	18.2	16.3	13.3	18.0
3.67	13.6	16.2	13.5	16.3	18.4	17.9	16.3	13.6	17.7
4.67	13.8	16.2	13.7	16.2	18.0	17.7	16.3	13.8	17.5
5.67	14.0	16.2	13.9	16.2	17.8	17.5	16.2	14.0	17.4
6.67	14.2	16.2	14.3	16.1	17.6	17.4	16.2	14.2	17.3
21.00	15.3	16.1	15.1	16.0	16.8	16.8	16.1	15.2	16.7
29.00	15.3	16.1	15.2	16.0	16.7	16.8	16.1	15.3	16.7
45.00	15.4	16.1	15.4	16.0	16.6	16.6	16.0	15.4	16.6
53.00	15.5	16.1	15.4	16.0	16.5	16.6	16.0	15.4	16.6
69.00	15.5	16.0	15.4	16.0	16.5	16.6	16.0	15.4	16.5
77.00	15.5	16.0	15.4	15.9	16.5	16.5	16.0	15.4	16.5
93.00	15.5	16.0	15.4	15.9	16.4	16.5	16.0	15.4	16.5
101.00	15.5	16.0	15.4	15.9	16.4	16.5	16.0	15.5	16.5
119.67	15.5	16.0	15.4	15.9	16.4	16.5	16.0	15.5	16.5

† Refer to Table A1 for explanation of the code.

Table A10 : Moisture ratio with time for test at Temp = 25.8°C, RH=68%

Cumulative	Moisture ratio								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	L1†	M1	L2	M2	H1	H2	M3	L3	H3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.67	0.89	0.59	0.86	0.95	0.85	0.65	0.61	0.89	0.56
1.67	0.75	0.40	0.74	0.63	0.61	0.45	0.44	0.74	0.40
2.67	0.64	0.29	0.64	0.46	0.47	0.34	0.36	0.63	0.30
3.67	0.56	0.26	0.57	0.38	0.39	0.28	0.31	0.55	0.25
4.67	0.49	0.23	0.51	0.32	0.31	0.23	0.27	0.48	0.21
5.67	0.43	0.17	0.45	0.27	0.26	0.21	0.26	0.42	0.18
6.67	0.38	0.17	0.34	0.24	0.22	0.18	0.23	0.36	0.16
21.00	0.07	0.09	0.09	0.11	0.06	0.07	0.14	0.06	0.05
29.00	0.05	0.06	0.08	0.06	0.05	0.06	0.09	0.04	0.04
45.00	0.03	0.04	0.03	0.06	0.03	0.04	0.01	0.02	0.02
53.00	0.02	0.03	0.02	0.06	0.01	0.03	0.01	0.02	0.02
69.00	0.01	0.01	0.01	0.03	0.01	0.02	0.00	0.01	0.01
77.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.01
93.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
101.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
119.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A11 Moisture content (% db) with time for test at Temp = 15.5°C, RH=69%

Cumulative	Moisture content (% dry mass basis)								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	H1†	M1	M2	L1	H2	L2	M3	L3	H3
0.00	21.4	16.7	16.7	11.9	21.4	11.9	16.7	11.9	21.4
0.72	20.1	16.7	16.7	12.2	20.6	12.3	16.7	12.3	20.5
1.72	19.6	16.7	16.7	12.6	19.9	12.7	16.7	12.7	19.8
2.72	19.3	16.7	16.7	12.8	19.5	13.0	16.8	13.1	19.5
3.72	19.2	16.8	16.7	13.0	19.3	13.3	16.8	13.3	19.3
4.72	19.1	16.8	16.7	13.3	19.1	13.5	16.9	13.5	19.1
5.72	19.0	16.8	16.7	13.5	19.0	13.7	17.0	13.8	19.0
6.72	18.9	16.8	16.7	13.6	18.9	13.9	17.0	13.9	19.0
20.98	18.7	17.1	16.9	15.2	18.4	15.6	17.2	15.6	18.7
28.98	18.6	17.2	17.0	15.6	18.3	15.9	17.3	16.0	18.5
44.98	18.5	17.3	17.1	15.9	18.1	16.2	17.4	16.3	18.4
52.98	18.5	17.4	17.2	15.9	18.1	16.3	17.5	16.3	18.4
69.83	18.5	17.4	17.2	16.0	18.1	16.4	17.5	16.4	18.4
76.68	18.5	17.4	17.2	16.1	18.1	16.5	17.5	16.5	18.4
92.68	18.5	17.4	17.2	16.6	18.1	16.9	17.5	16.9	18.4
100.68	18.5	17.4	17.2	16.8	18.1	17.1	17.5	17.2	18.4
116.68	18.5	17.4	17.2	16.9	18.1	17.2	17.5	17.2	18.4
124.68	18.5	17.4	17.2	16.9	18.1	17.2	17.5	17.2	18.4

† Refer to Table A1 for explanation of the code.

Table A12 : Moisture ratio with time for test at Temp = 15.5°C, RH=69%

Cumulative time (h)	Moisture ratio								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	H1†	M1	M2	L1	H2	L2	M3	L3	H3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.72	0.57	1.00	1.00	0.93	0.76	0.93	0.97	0.93	0.70
1.72	0.40	0.99	1.00	0.87	0.55	0.85	0.91	0.85	0.47
2.72	0.30	0.94	1.00	0.81	0.44	0.79	0.83	0.78	0.36
3.72	0.26	0.88	1.00	0.77	0.36	0.74	0.79	0.74	0.29
4.72	0.22	0.82	1.00	0.73	0.31	0.70	0.72	0.69	0.25
5.72	0.20	0.79	0.94	0.69	0.27	0.66	0.67	0.64	0.22
6.72	0.16	0.76	0.90	0.66	0.24	0.62	0.63	0.61	0.20
20.98	0.08	0.46	0.52	0.34	0.11	0.31	0.35	0.29	0.11
28.98	0.03	0.33	0.33	0.27	0.06	0.24	0.24	0.23	0.05
44.98	0.01	0.15	0.17	0.20	0.00	0.18	0.15	0.17	0.02
52.98	0.00	0.09	0.10	0.19	0.00	0.17	0.08	0.16	0.01
69.83	0.00	0.04	0.04	0.17	0.00	0.16	0.05	0.15	0.00
76.68	0.00	0.01	0.02	0.16	0.00	0.14	0.01	0.13	0.00
92.68	0.00	0.00	0.00	0.07	0.00	0.05	0.00	0.05	0.00
100.68	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00
116.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
124.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A13 Moisture content (% db) with time for test at Temp = 35.5°C, RH=75%

Cumulative	Moisture content (% dry mass basis)								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	H1†	M1	M2	H2	L1	L2	L3	M3	H3
0.00	21.4	16.4	16.4	21.4	11.5	11.5	11.5	16.4	21.4
0.68	20.4	16.9	17.3	21.0	12.7	13.0	13.0	16.9	20.0
1.68	19.5	17.1	17.4	20.2	13.8	14.3	14.4	17.1	19.4
2.68	19.0	17.3	17.5	19.7	14.6	15.1	15.3	17.3	19.1
3.68	18.8	17.3	17.6	19.3	15.3	15.7	15.9	17.4	18.9
4.68	18.6	17.4	17.6	19.1	15.7	16.1	16.3	17.5	18.8
5.68	18.6	17.4	17.7	19.0	16.1	16.4	16.6	17.5	18.7
6.68	18.5	17.5	17.7	18.8	16.3	16.6	16.8	17.5	18.6
24.25	18.2	17.5	17.7	18.3	17.4	17.3	17.3	17.6	18.4
32.25	18.2	17.5	17.7	18.3	17.4	17.3	17.4	17.6	18.4
50.25	18.1	17.5	17.7	18.3	17.5	17.3	17.4	17.6	18.3
57.33	18.1	17.5	17.7	18.3	17.5	17.3	17.4	17.6	18.3
74.42	18.1	17.5	17.7	18.3	17.5	17.3	17.4	17.6	18.3

† Refer to Table A1 for explanation of the code.

Table A14: Moisture ratio with time for test at Temp = 35.5°C, RH=75%

Cumulative time (h)	Moisture ratio								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	H1†	M1	M2	H2	L1	L2	L3	M3	H3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.68	0.72	0.54	0.34	0.89	0.80	0.75	0.74	0.62	0.57
1.68	0.42	0.36	0.26	0.62	0.62	0.53	0.51	0.40	0.35
2.68	0.29	0.23	0.16	0.45	0.48	0.38	0.36	0.26	0.25
3.68	0.22	0.16	0.14	0.34	0.37	0.27	0.26	0.20	0.20
4.68	0.18	0.10	0.09	0.28	0.30	0.21	0.19	0.12	0.17
5.68	0.15	0.06	0.05	0.23	0.24	0.15	0.13	0.09	0.13
6.68	0.12	0.04	0.03	0.18	0.19	0.11	0.10	0.07	0.11
24.25	0.04	0.00	0.03	0.00	0.02	0.00	0.01	0.06	0.03
32.25	0.03	0.00	0.03	0.00	0.02	0.00	-0.00	0.00	0.02
50.25	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
57.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
74.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A15 Moisture content (% db) with time for test at Temp = 15.4°C, RH=88%

Cumulative time (h)	Moisture content (% dry mass basis)								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	L1†	H1	H2	M1	L2	M2	L3	M3	H3
0.00	12.1	21.8	21.8	16.9	12.1	16.9	12.1	16.9	21.8
0.70	13.4	22.4	22.2	17.5	13.0	17.9	13.6	18.1	22.3
1.70	14.9	22.9	22.4	18.2	13.9	19.1	15.4	19.3	22.7
2.70	16.1	23.2	22.5	18.8	14.7	19.8	16.6	20.1	23.0
3.70	17.2	23.6	22.7	19.3	15.5	20.6	17.7	20.9	23.2
4.70	18.0	23.7	22.8	19.6	16.1	21.1	18.5	21.4	23.4
5.70	18.7	23.9	22.9	20.0	16.6	21.5	19.2	21.8	23.5
6.70	19.3	24.1	23.0	20.3	17.1	21.8	19.8	22.2	23.6
19.70	23.7	25.6	24.2	23.1	21.4	24.5	23.9	24.7	24.7
27.70	24.9	26.2	24.7	24.0	22.7	25.4	25.0	25.5	25.3
43.70	25.7	26.6	25.3	24.9	24.0	25.9	25.7	25.9	25.7
51.70	25.4	26.2	25.0	24.7	24.0	25.5	25.4	25.5	25.2
67.70	25.2	25.8	24.5	24.3	23.7	25.1	25.1	25.2	24.8
75.70	25.1	25.6	24.4	24.2	23.6	25.0	25.0	25.0	24.7
91.70	25.0	25.6	24.3	24.0	23.6	24.9	24.9	25.0	24.6
99.70	25.3	25.9	24.5	24.2	23.7	25.2	25.2	25.2	24.9
116.70	25.0	25.6	24.3	24.1	23.6	24.9	24.9	24.9	24.6
123.70	24.9	25.5	24.2	24.0	23.5	24.8	24.8	24.8	24.5
139.70	24.8	25.3	24.1	23.8	23.4	24.7	24.7	24.7	24.4
146.70	25.1	25.6	24.3	24.1	23.6	25.0	25.0	25.0	24.7
164.70	24.5	25.0	23.8	23.6	23.1	24.4	24.4	24.4	24.1
171.70	24.5	25.0	23.8	23.6	23.1	24.4	24.5	24.5	24.1
189.70	24.5	25.0	23.8	23.6	23.1	24.4	24.5	24.5	24.1

† Refer to Table A1 for explanation of the code.

Table A16 : Moisture ratio with time for test at Temp = 15.4°C, RH=88%

Cumulative	Moisture ratio								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	L1†	H1	H2	M1	L2	M2	L3	M3	H3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.70	0.89	0.82	0.80	0.91	0.92	0.87	0.87	0.84	0.78
1.70	0.77	0.66	0.71	0.80	0.83	0.71	0.73	0.68	0.61
2.70	0.67	0.55	0.62	0.72	0.76	0.61	0.63	0.57	0.48
3.70	0.58	0.45	0.52	0.65	0.69	0.51	0.54	0.48	0.37
4.70	0.52	0.40	0.48	0.59	0.64	0.44	0.48	0.41	0.31
5.70	0.47	0.35	0.43	0.54	0.59	0.39	0.42	0.35	0.27
6.70	0.42	0.30	0.39	0.49	0.55	0.34	0.38	0.31	0.22
19.70	0.06	-0.17	-0.20	0.07	0.16	-0.02	0.05	-0.03	-0.26
27.70	-0.03	-0.37	-0.48	-0.06	0.04	-0.13	-0.04	-0.14	-0.53
43.70	-0.10	-0.48	-0.76	-0.19	-0.08	-0.19	-0.10	-0.19	-0.67
51.70	-0.07	-0.35	-0.60	-0.15	-0.07	-0.14	-0.07	-0.14	-0.47
67.70	-0.05	-0.25	-0.38	-0.10	-0.05	-0.10	-0.05	-0.09	-0.31
75.70	-0.04	-0.19	-0.32	-0.08	-0.04	-0.07	-0.04	-0.07	-0.23
91.70	-0.04	-0.18	-0.26	-0.06	-0.04	-0.07	-0.04	-0.07	-0.22
99.70	-0.06	-0.26	-0.35	-0.09	-0.05	-0.10	-0.06	-0.10	-0.33
116.70	-0.04	-0.17	-0.25	-0.07	-0.04	-0.07	-0.04	-0.06	-0.19
123.70	-0.03	-0.13	-0.20	-0.05	-0.03	-0.05	-0.03	-0.05	-0.15
139.70	-0.02	-0.10	-0.14	-0.03	-0.02	-0.04	-0.02	-0.03	-0.11
146.70	-0.04	-0.19	-0.27	-0.07	-0.04	-0.08	-0.04	-0.07	-0.24
164.70	0.00	0.00	-0.01	0.01	0.00	0.00	0.00	0.01	0.02
171.70	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.01
189.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A17 Moisture content (% db) with time for test at Temp = 25.7°C, RH=93%

Cumulative	Moisture content (% dry mass basis)								
time	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
(h)	M1†	H1	M2	L1	H2	L2	L3	H3	M3
0.00	16.7	21.7	16.7	12.0	21.7	12.0	12.0	21.7	16.7
0.63	19.1	23.3	18.2	13.5	22.5	14.5	14.9	23.5	19.5
1.63	20.9	24.4	19.5	15.4	23.1	17.4	18.1	24.8	21.7
2.63	22.4	25.4	20.5	17.2	23.6	19.4	20.2	25.8	23.1
3.63	23.7	26.3	21.4	18.1	24.1	21.1	22.0	26.7	24.4
4.63	24.6	27.0	22.2	19.2	24.5	22.5	23.3	27.4	25.5
5.63	25.4	27.6	22.9	20.2	25.0	23.7	24.5	28.1	26.4
6.63	26.1	28.0	23.5	21.0	25.3	24.5	25.4	28.5	27.0
17.63	29.6	30.2	27.7	26.6	28.5	29.3	29.7	30.5	29.5
25.63	30.2	30.6	28.8	28.1	29.7	30.1	30.3	30.7	30.4
41.63	30.3	30.6	29.9	29.2	30.8	30.3	30.4	30.7	30.7
49.63	30.5	30.7	30.1	29.8	30.9	30.5	30.4	30.8	30.9
65.63	30.6	30.7	30.5	30.2	31.0	30.5	30.4	30.8	30.9
73.63	30.7	30.7	30.8	30.3	31.0	30.6	30.4	30.9	30.9
89.63	30.7	30.7	30.8	30.3	31.0	30.6	30.4	30.9	30.9
97.63	30.7	30.7	30.8	30.4	31.0	30.6	30.4	30.9	30.9
113.63	30.7	30.7	30.8	30.4	31.0	30.6	30.5	30.9	30.9

† Refer to Table A1 for explanation of the code.

Table A18 : Moisture ratio with time for test at Temp = 25.7°C, RH=93%

Cumulative time (h)	Moisture ratio								
	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
	M1†	H1	M2	L1	H2	L2	L3	H3	M3
0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.63	0.82	0.83	0.89	0.92	0.91	0.86	0.84	0.81	0.80
1.63	0.70	0.70	0.80	0.81	0.85	0.71	0.67	0.66	0.64
2.63	0.59	0.59	0.73	0.71	0.80	0.60	0.56	0.55	0.55
3.63	0.50	0.49	0.66	0.67	0.74	0.51	0.46	0.45	0.46
4.63	0.44	0.42	0.61	0.61	0.70	0.44	0.39	0.38	0.38
5.63	0.37	0.35	0.56	0.55	0.65	0.37	0.32	0.31	0.32
6.63	0.33	0.31	0.52	0.51	0.61	0.33	0.27	0.26	0.27
17.63	0.08	0.06	0.22	0.21	0.28	0.07	0.04	0.04	0.10
25.63	0.04	0.01	0.14	0.13	0.14	0.02	0.01	0.03	0.03
41.63	0.03	0.01	0.07	0.06	0.03	0.01	0.01	0.02	0.01
49.63	0.01	0.01	0.05	0.03	0.01	0.01	0.00	0.01	0.00
65.63	0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.01	0.00
73.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
89.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
97.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
113.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† Refer to Table A1 for explanation of the code.

Table A19. Mean air velocities (m/s) in nine trays of thin-layer drying equipment in nine experimental tests.

RH	Mean air velocity m/s								
(%)	Tray 1	Tray 2	Tray 3	Tray4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9
27	0.09	0.09	0.32	0.11	0.97	0.40	0.07	0.12	0.30
37	0.16	0.07	0.20	0.05	0.07	0.21	0.13	0.06	0.27
48	0.15	0.08	0.36	0.14	0.07	0.32	0.08	0.14	0.31
61	0.16	0.24	0.34	0.16	0.20	0.48	0.15	0.50	0.49
68	0.15	0.31	0.43	0.18	0.21	0.47	0.17	0.18	0.44
69	0.20	0.19	0.48	0.17	0.14	0.48	0.20	0.28	0.49
75	0.17	0.18	0.48	0.14	0.12	0.50	0.13	0.28	0.49
88	0.16	0.15	0.50	0.19	0.29	0.45	0.17	0.13	0.45
93	0.18	0.21	0.52	0.24	0.14	0.49	0.23	0.27	0.49

Appendix B

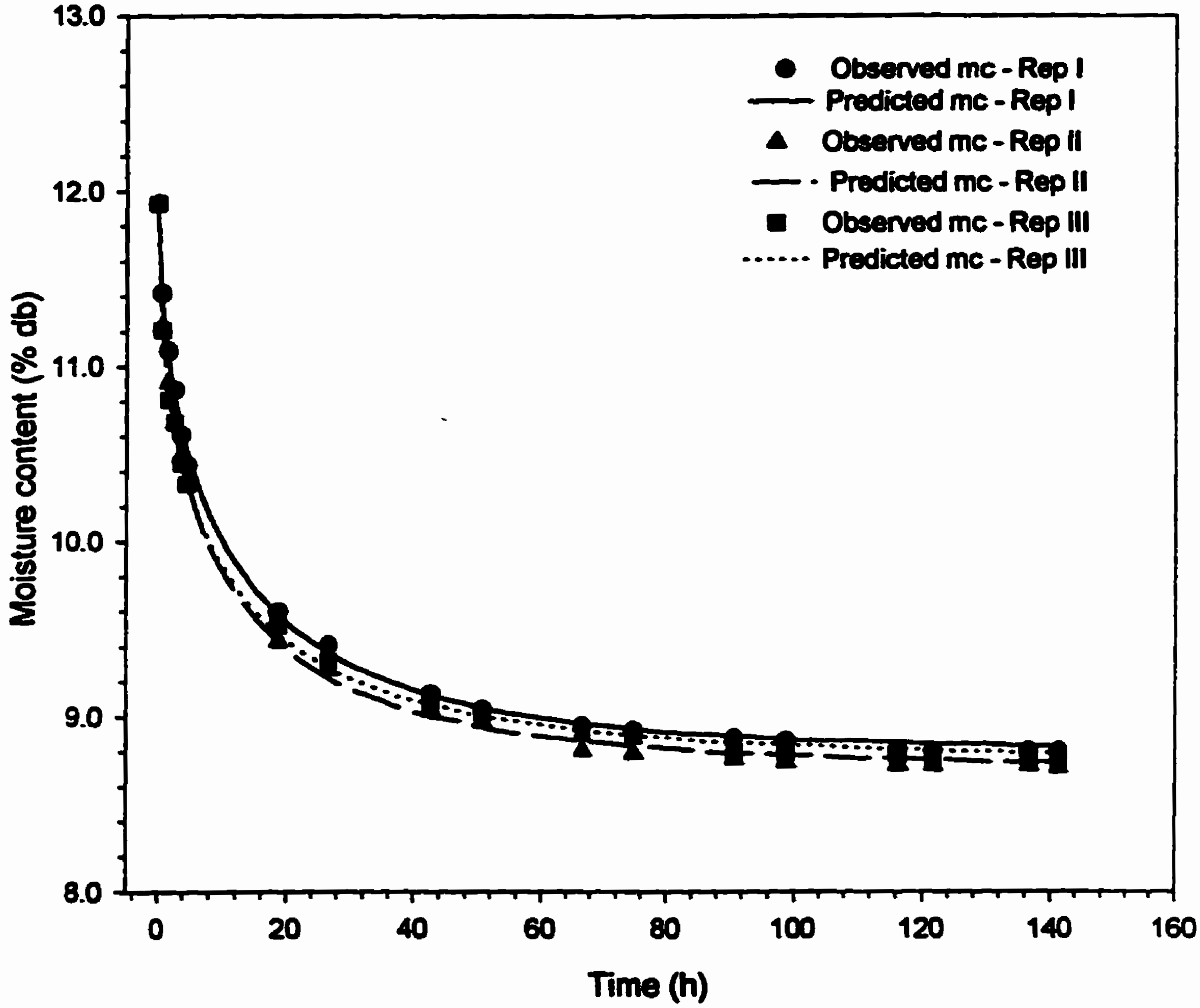

Fig. B1 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 27%, initial mc = 11.9% db for three replicates.

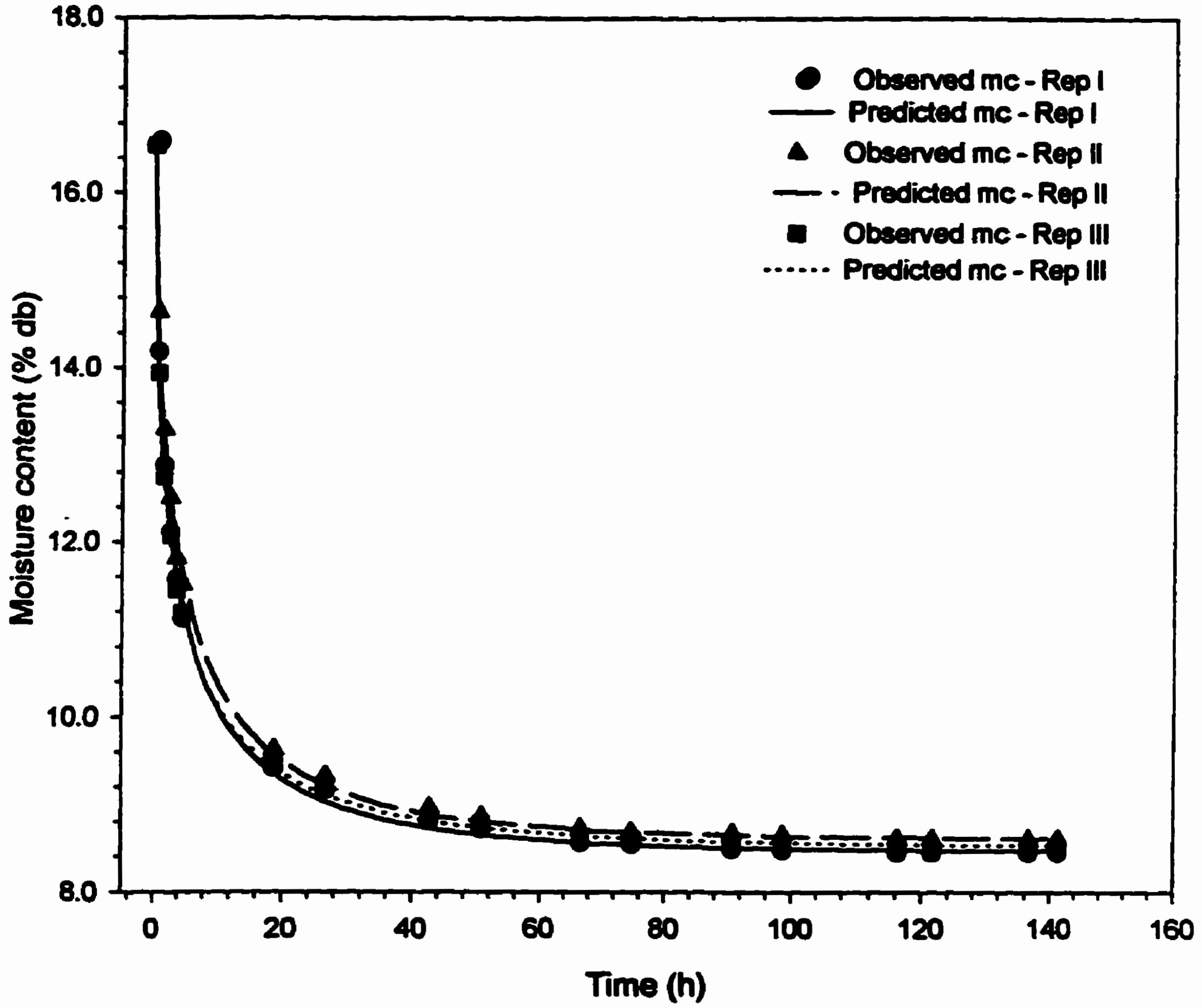

Fig. B2 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 27%, initial mc = 16.5% db for three replicates.

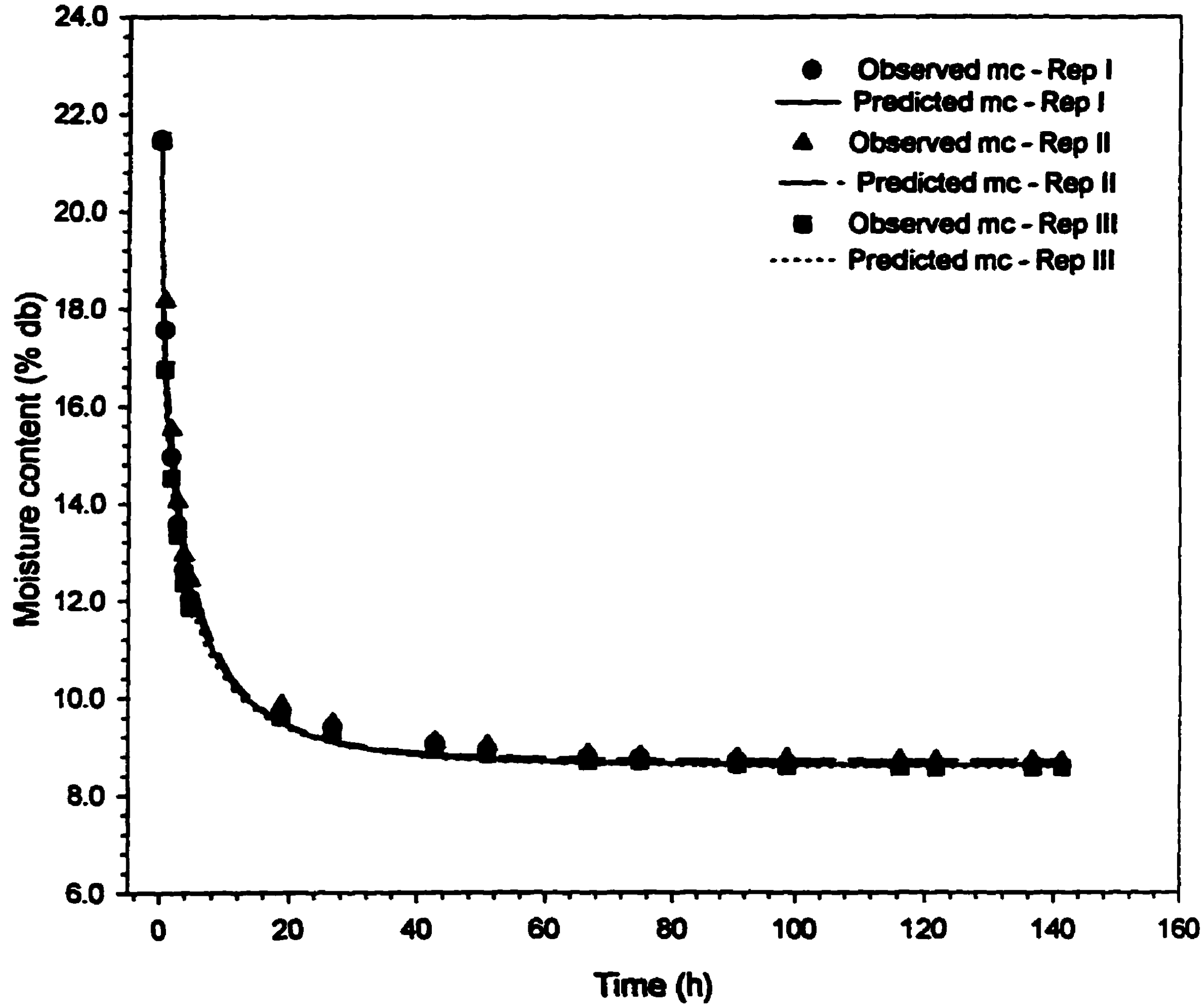

Fig. B3 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 27%, initial mc = 21.5% db for three replicates.

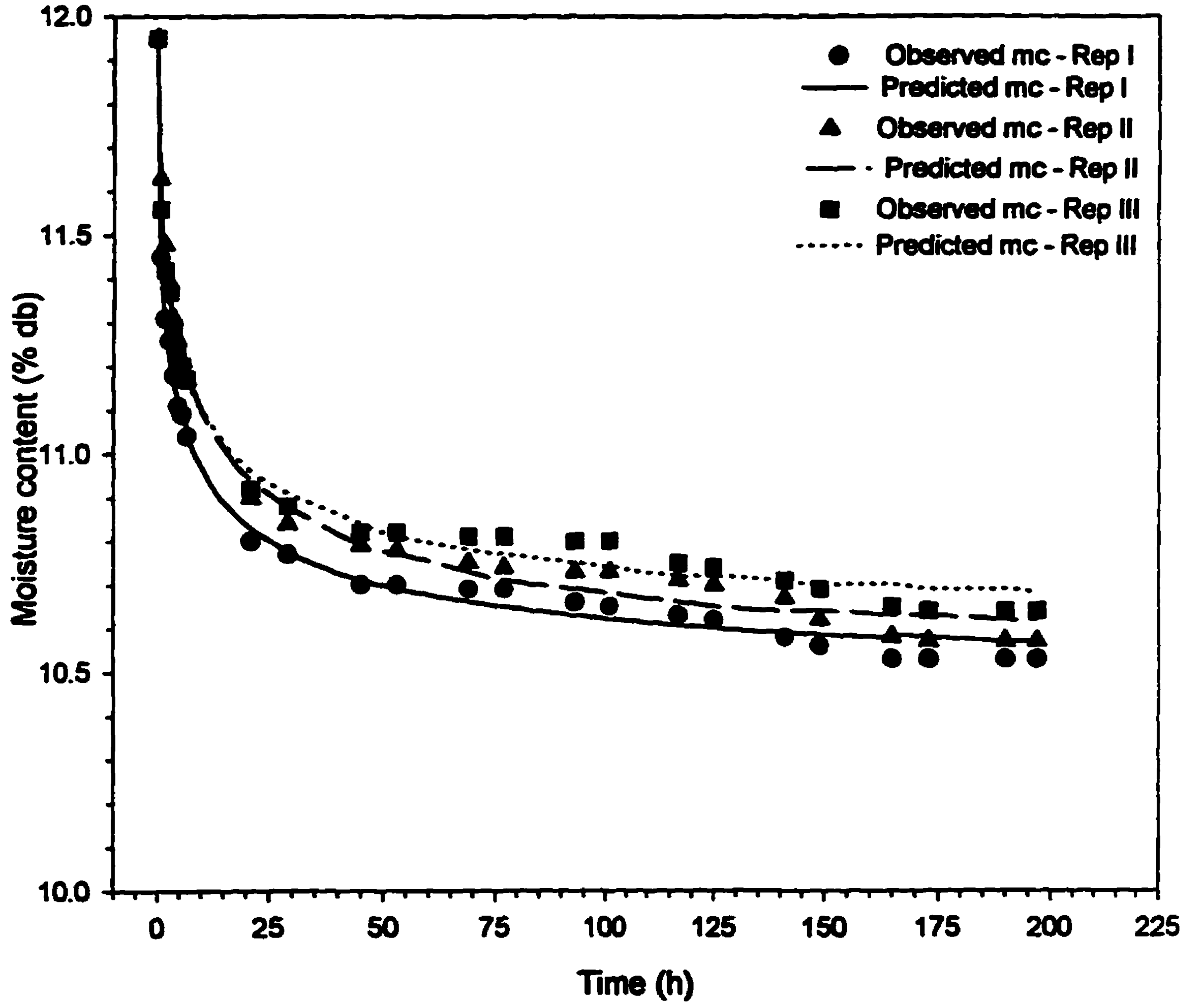

Fig. B4 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 37%, initial mc = 12.0% db for three replicates.

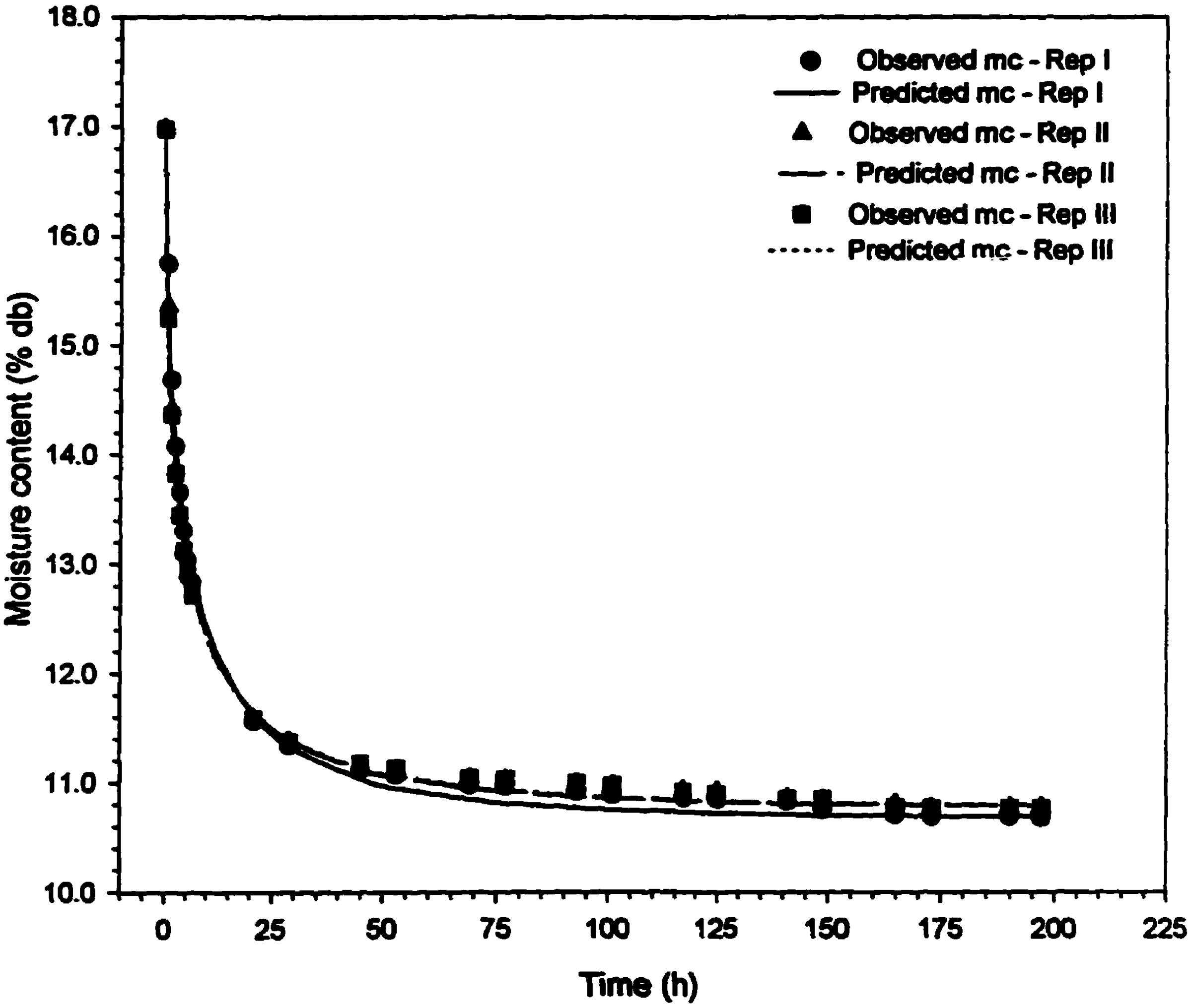

Fig. B5 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 37%, initial mc = 17.0% db for three replicates.

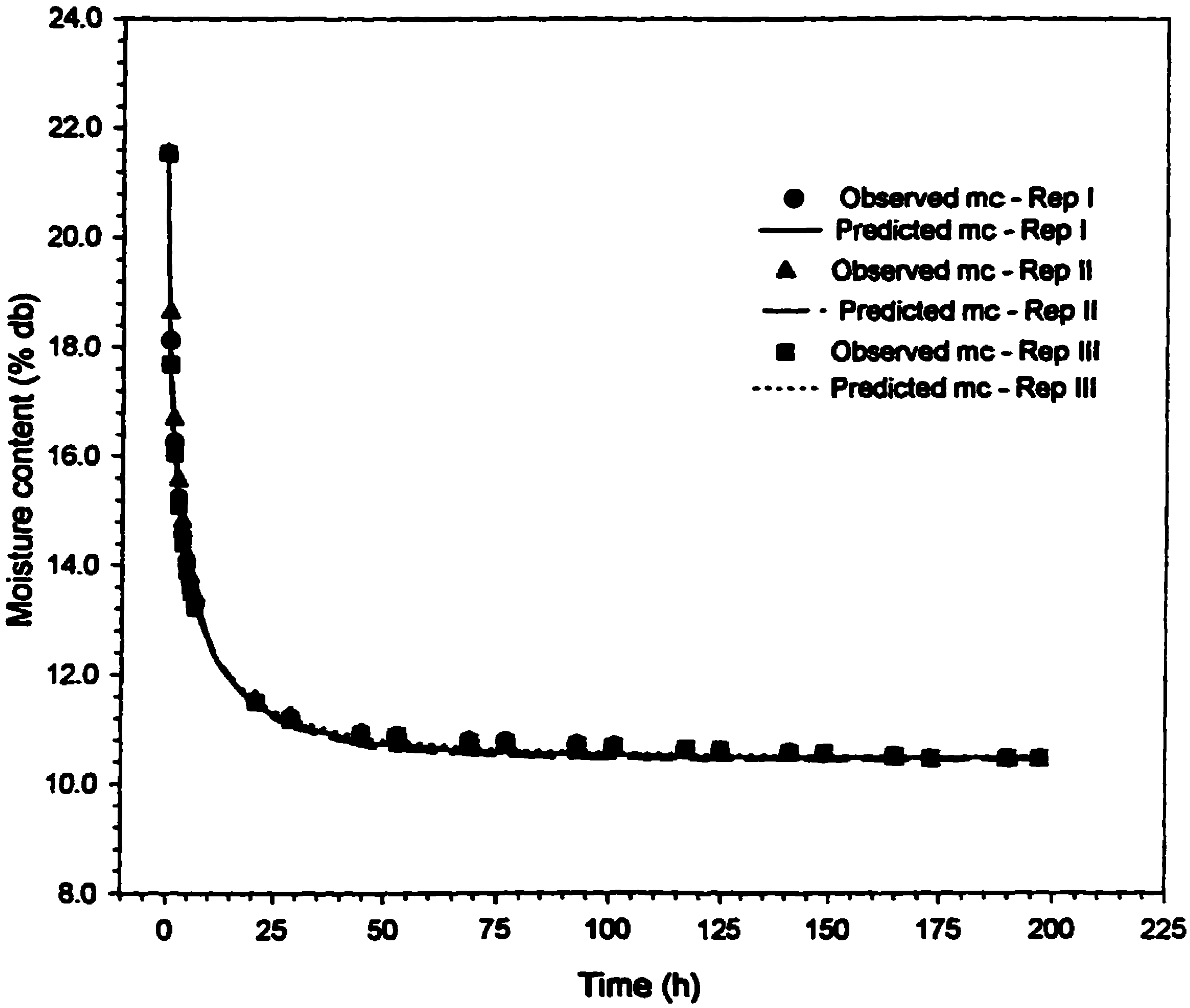

Fig. B6 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 37%, initial mc = 21.5% db for three replicates.

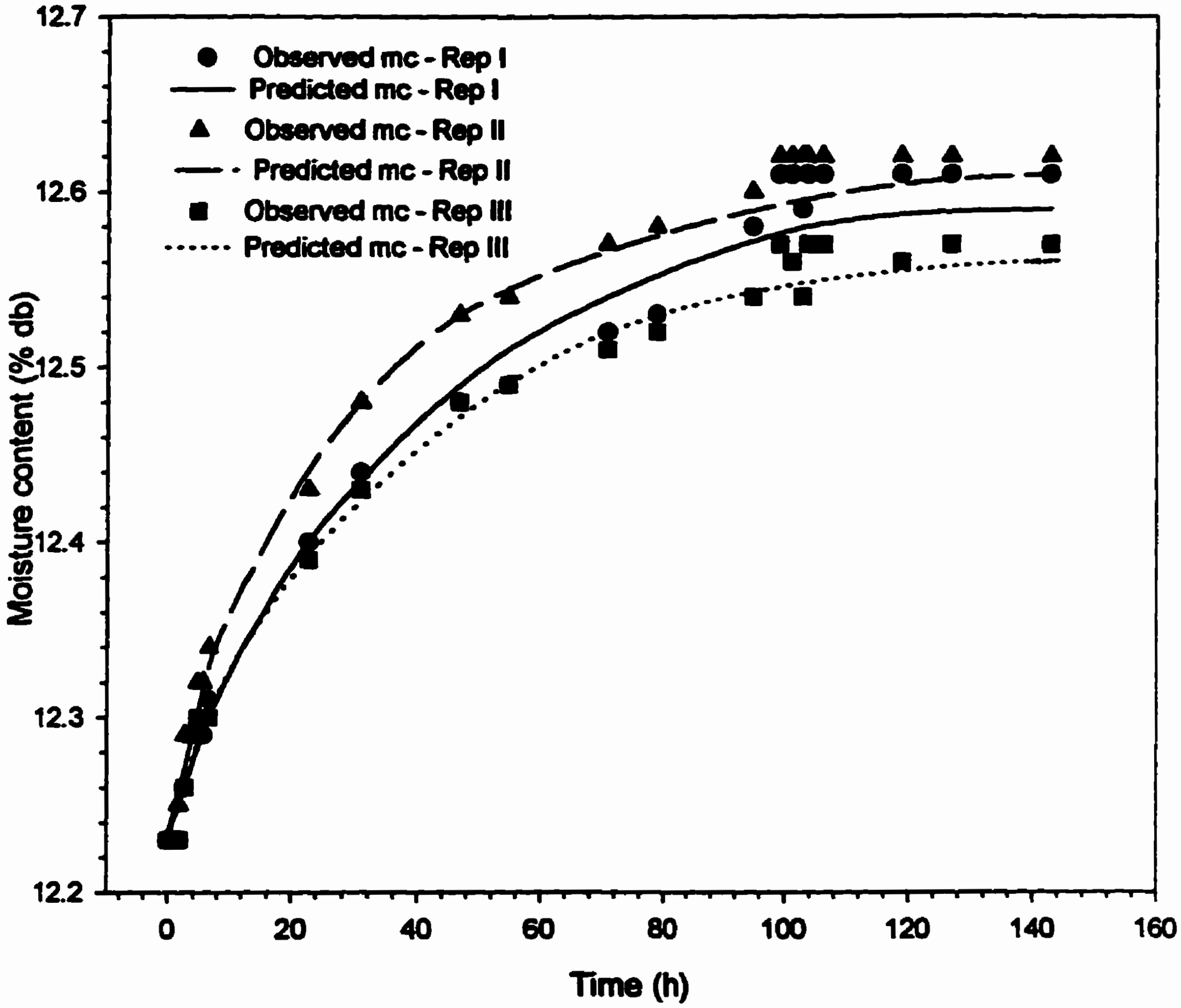

Fig. B7 - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 48%, initial mc = 12.2% db for three replicates.

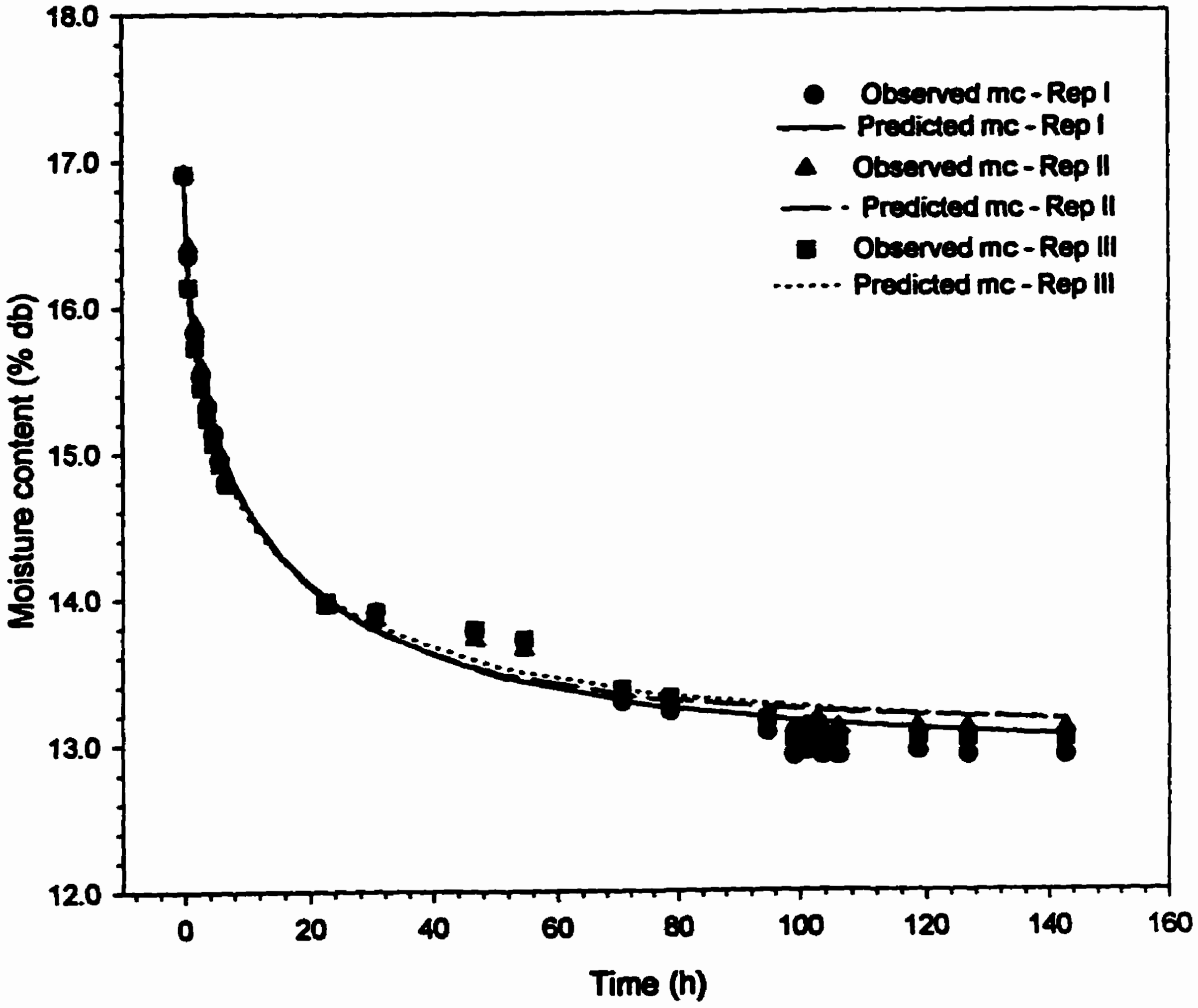

Fig. B8 - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 48%, initial mc = 16.9% db for three replicates.

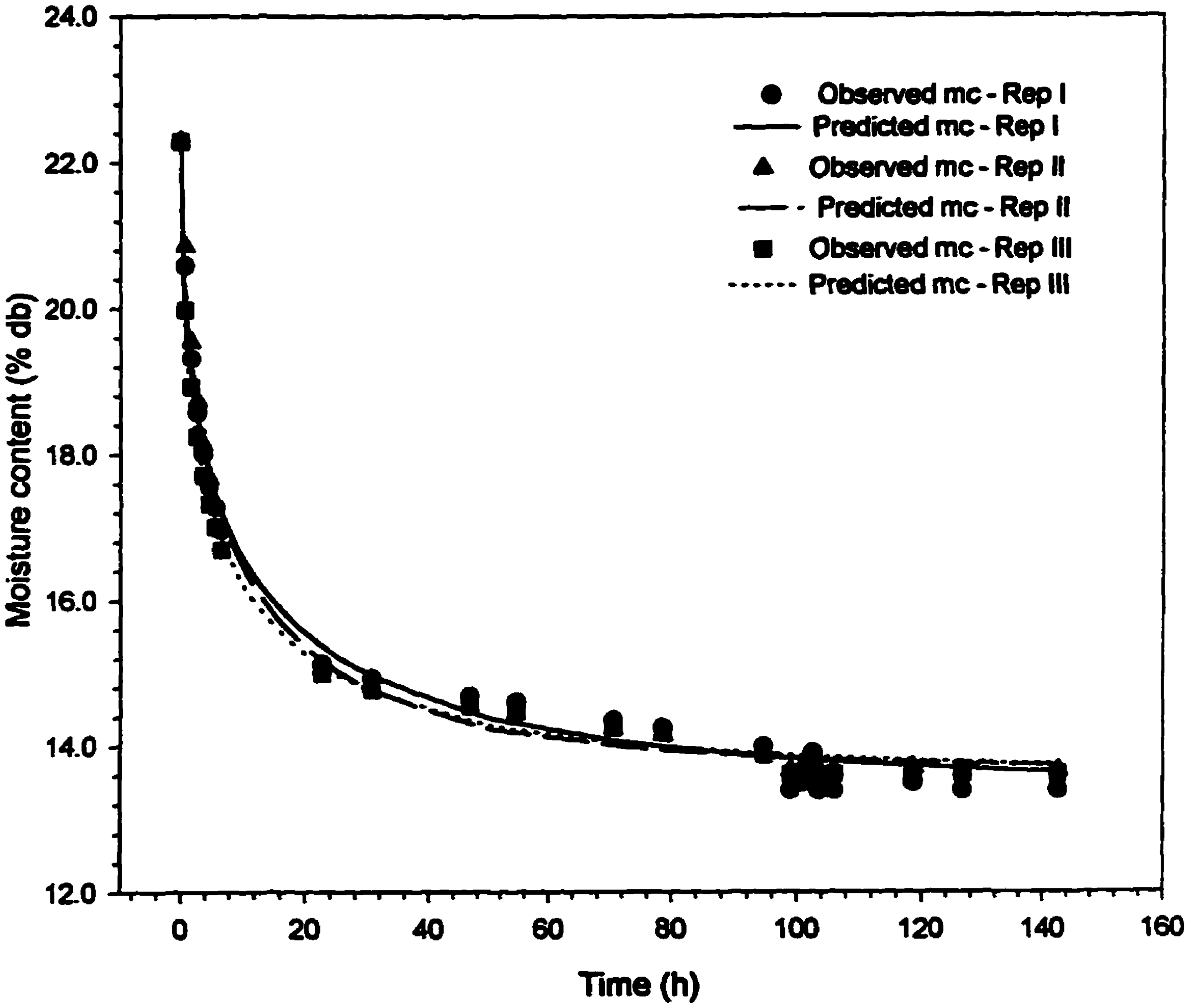

Fig. B9 - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 61%, initial mc = 22.3% db for three replicates.

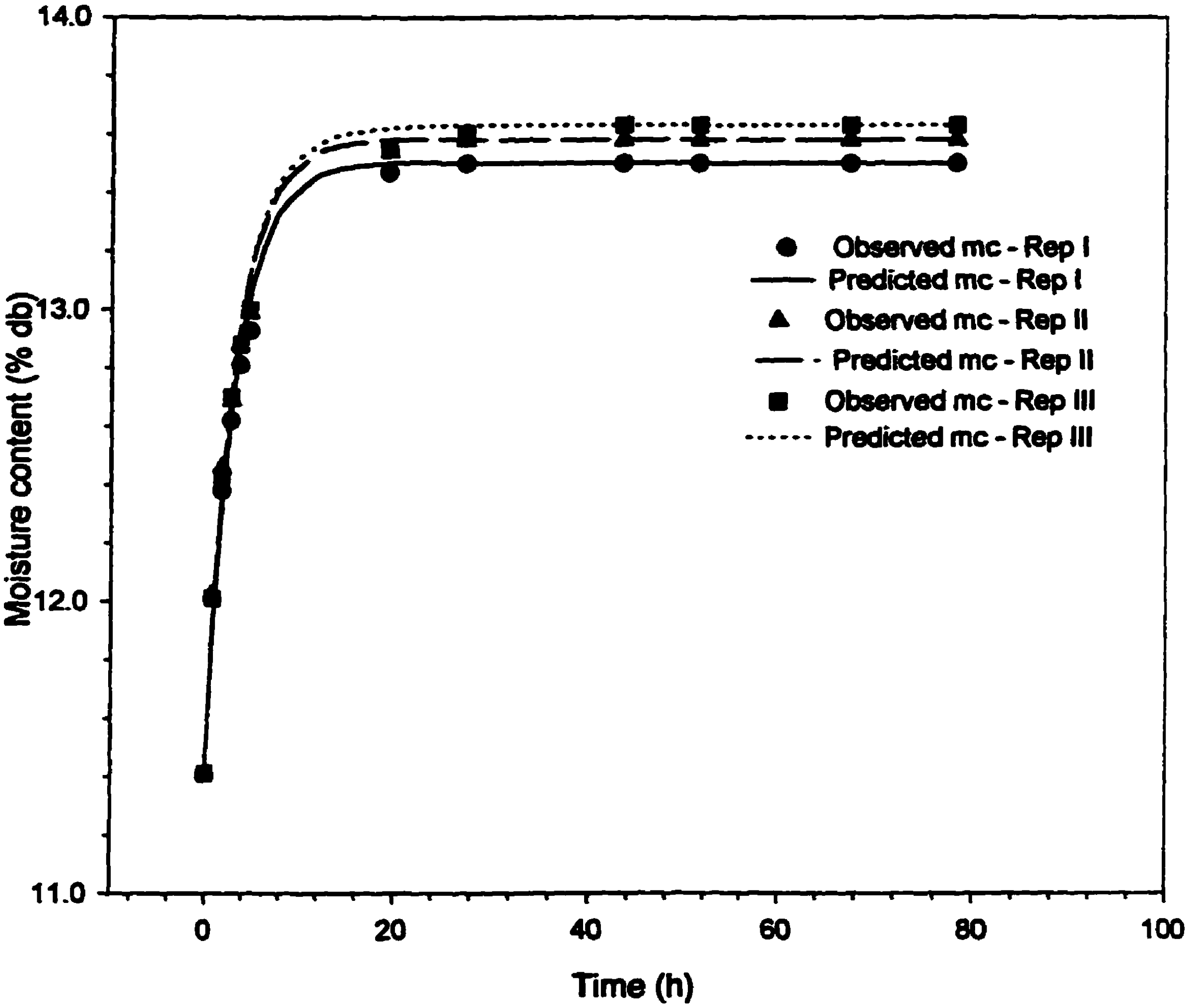

Fig. B10 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 61%, initial mc = 11.4% db for three replicates.

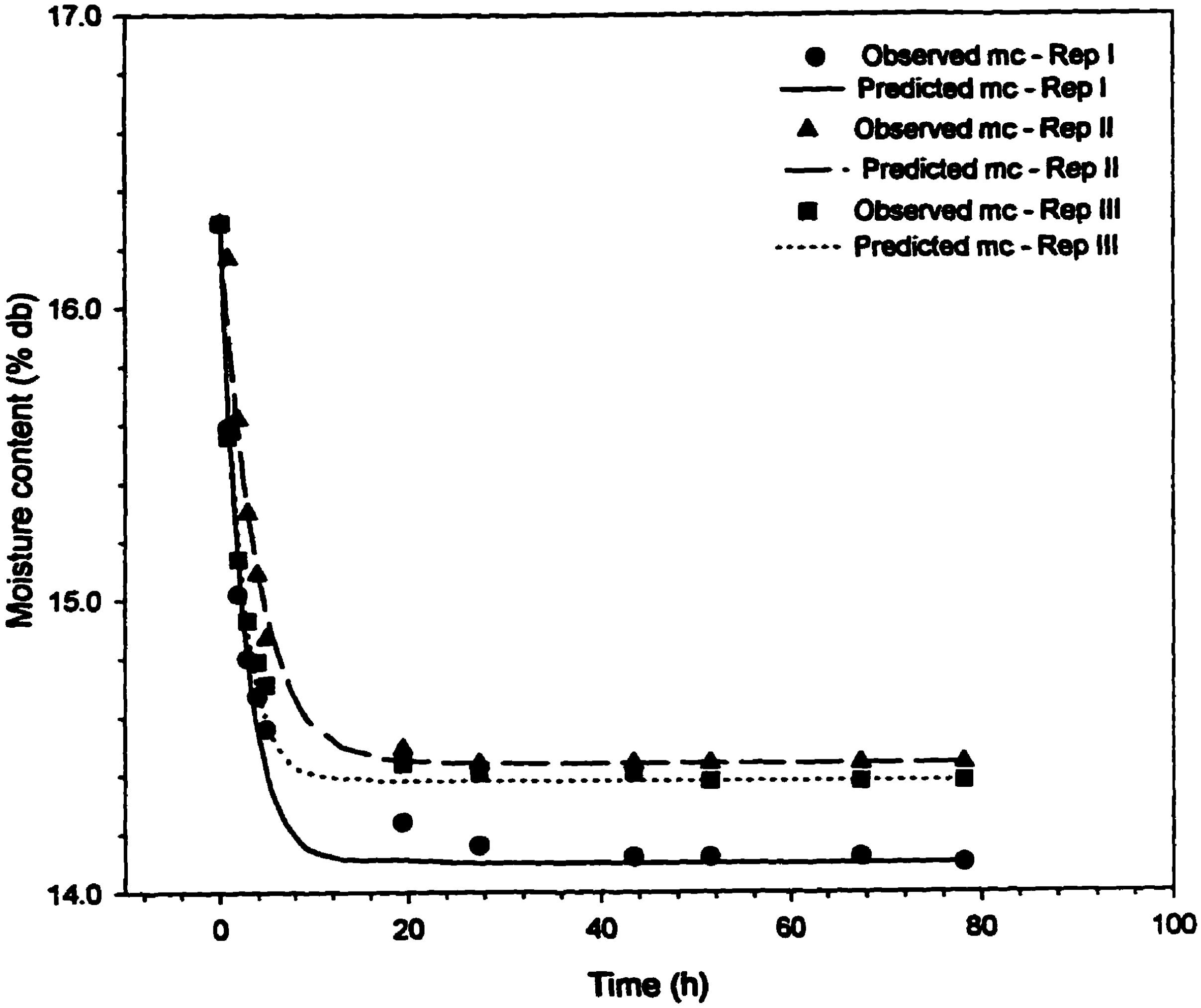

Fig. B11 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 61%, initial mc = 16.3% db for three replicates.

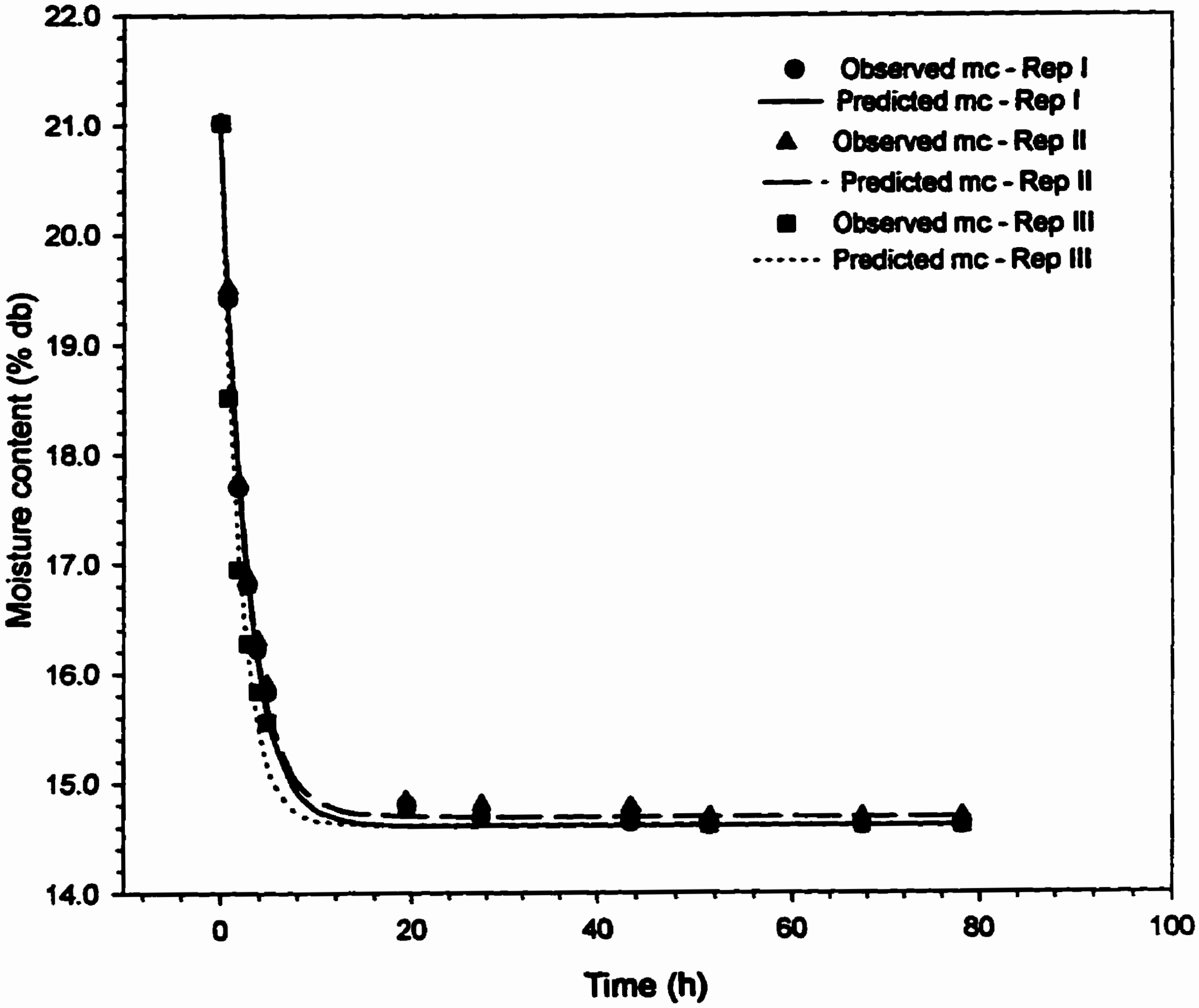

Fig. B12 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 61%, initial mc = 21.0% db for three replicates.

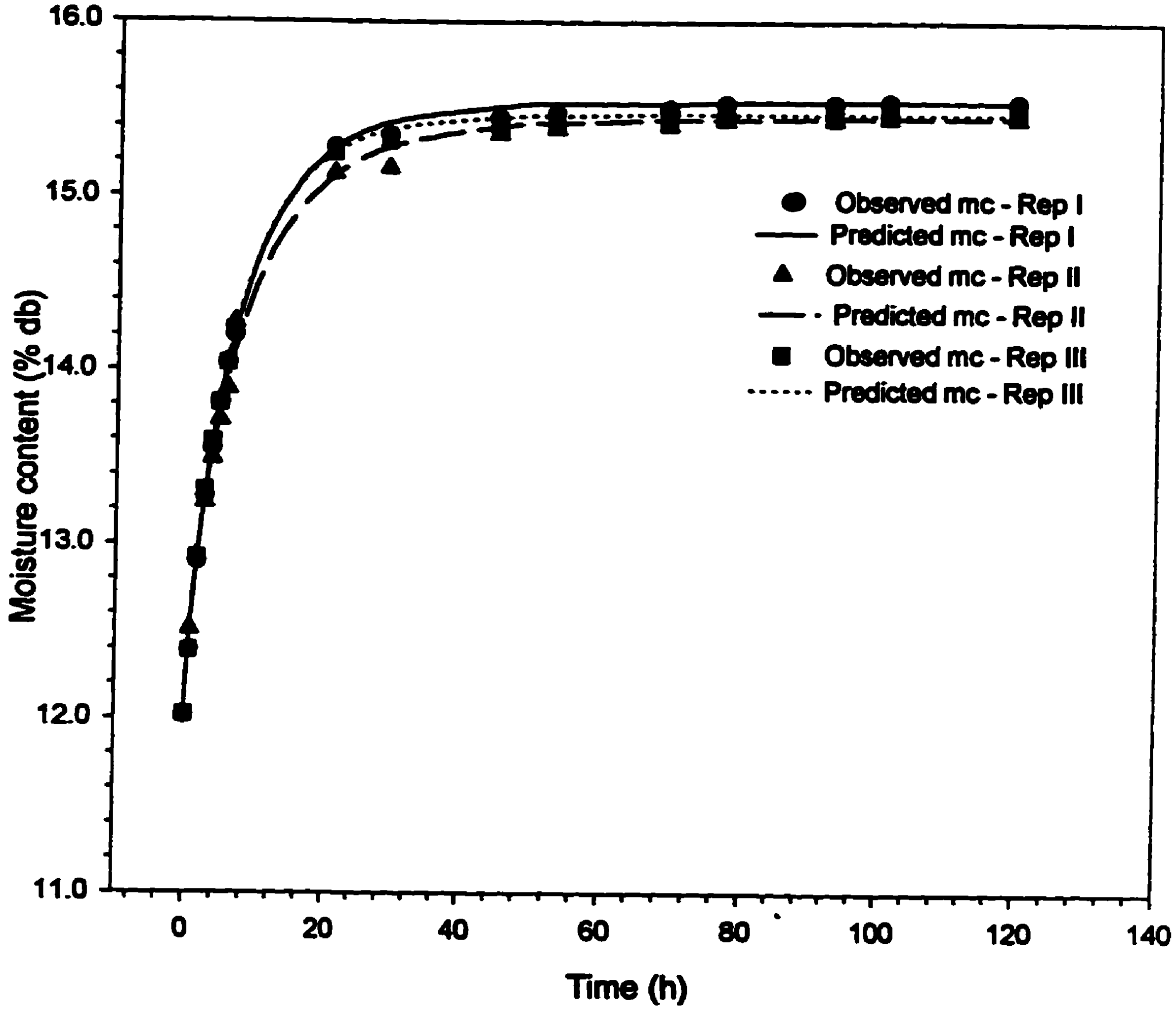

Fig. B13 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 68%, initial mc = 12.0% db for three replicates.

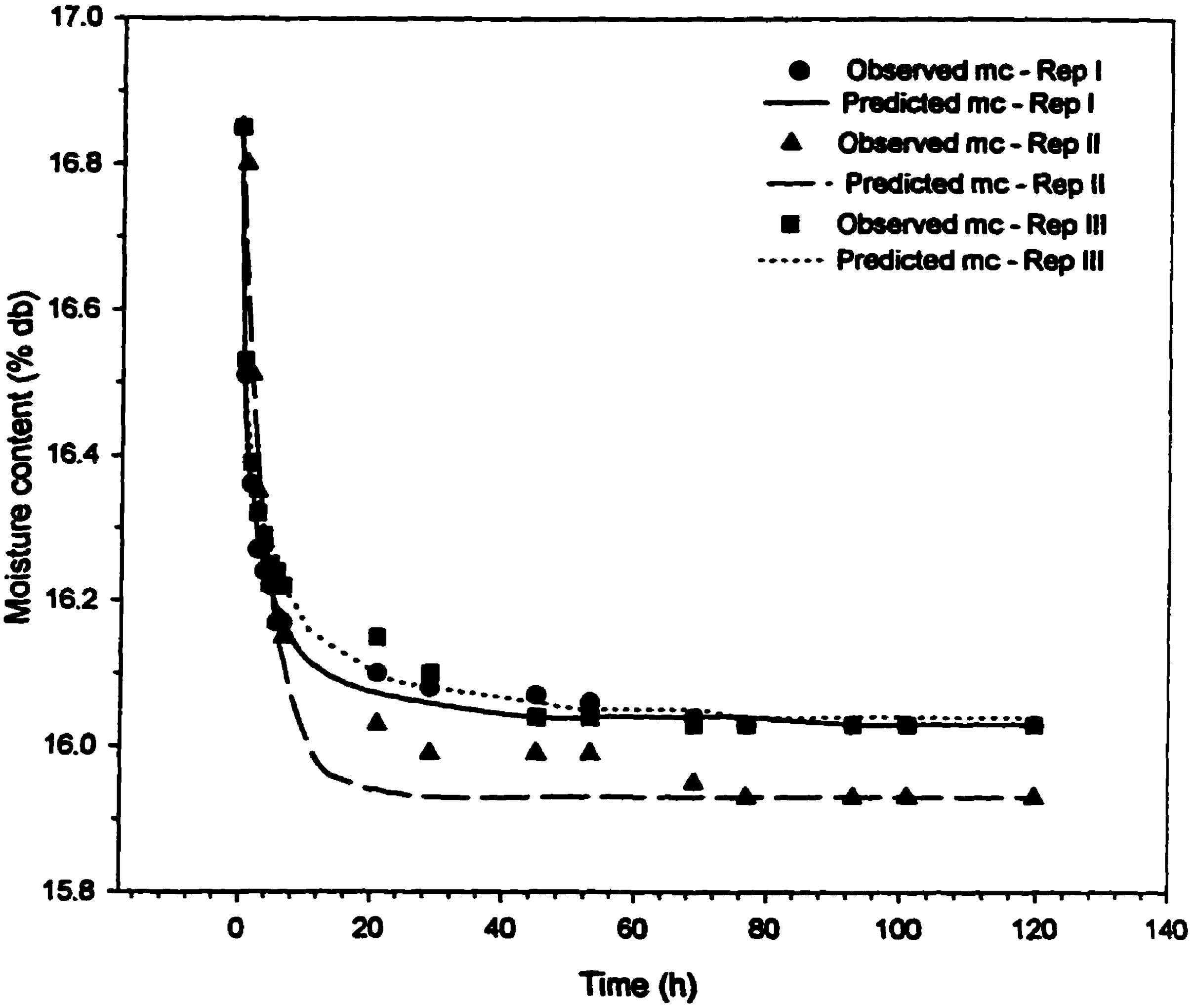

Fig. B14 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 68%, initial mc = 16.9% db for three replicates.

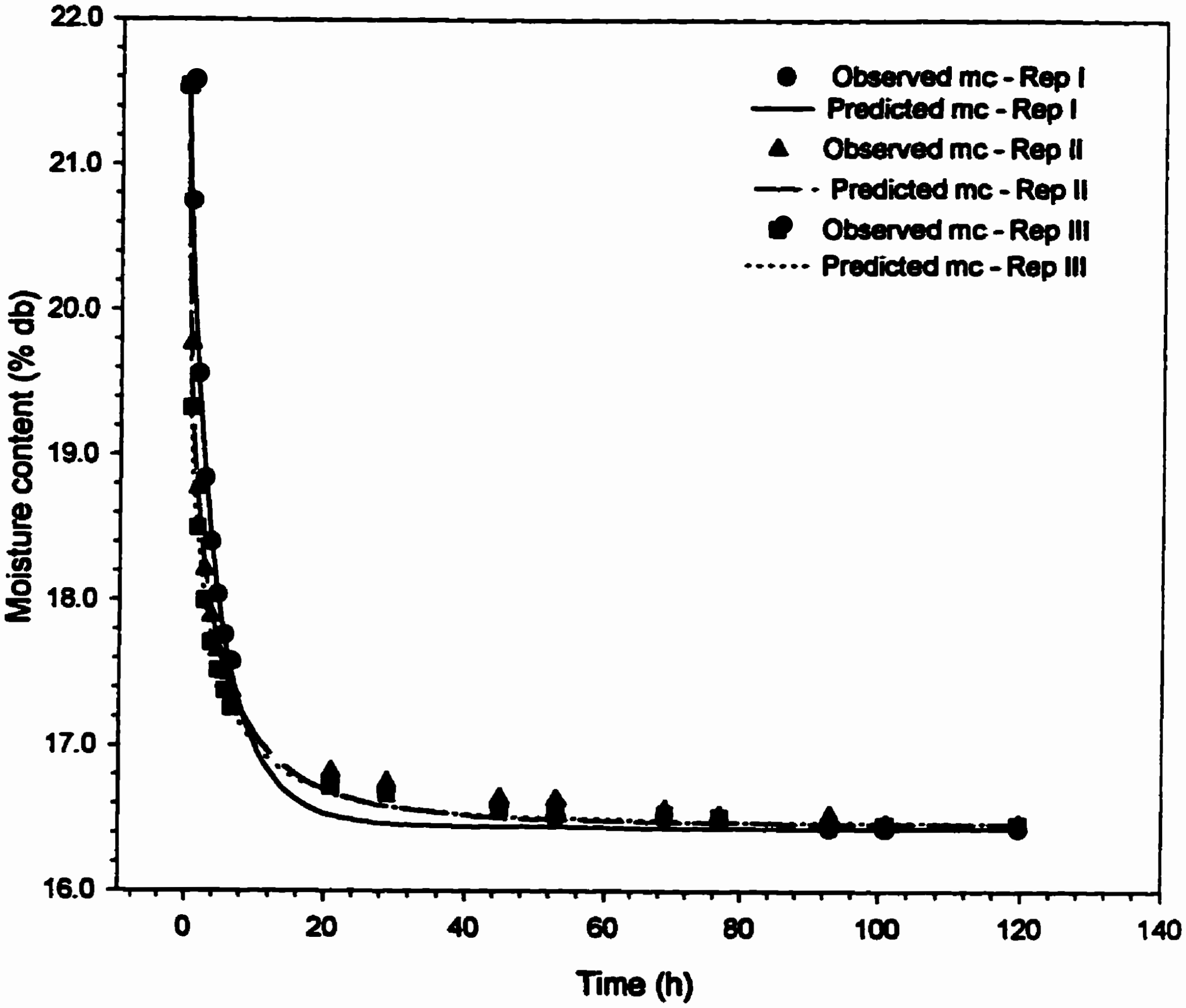

Fig. B15 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 68%, initial mc = 21.5% db for three replicates.

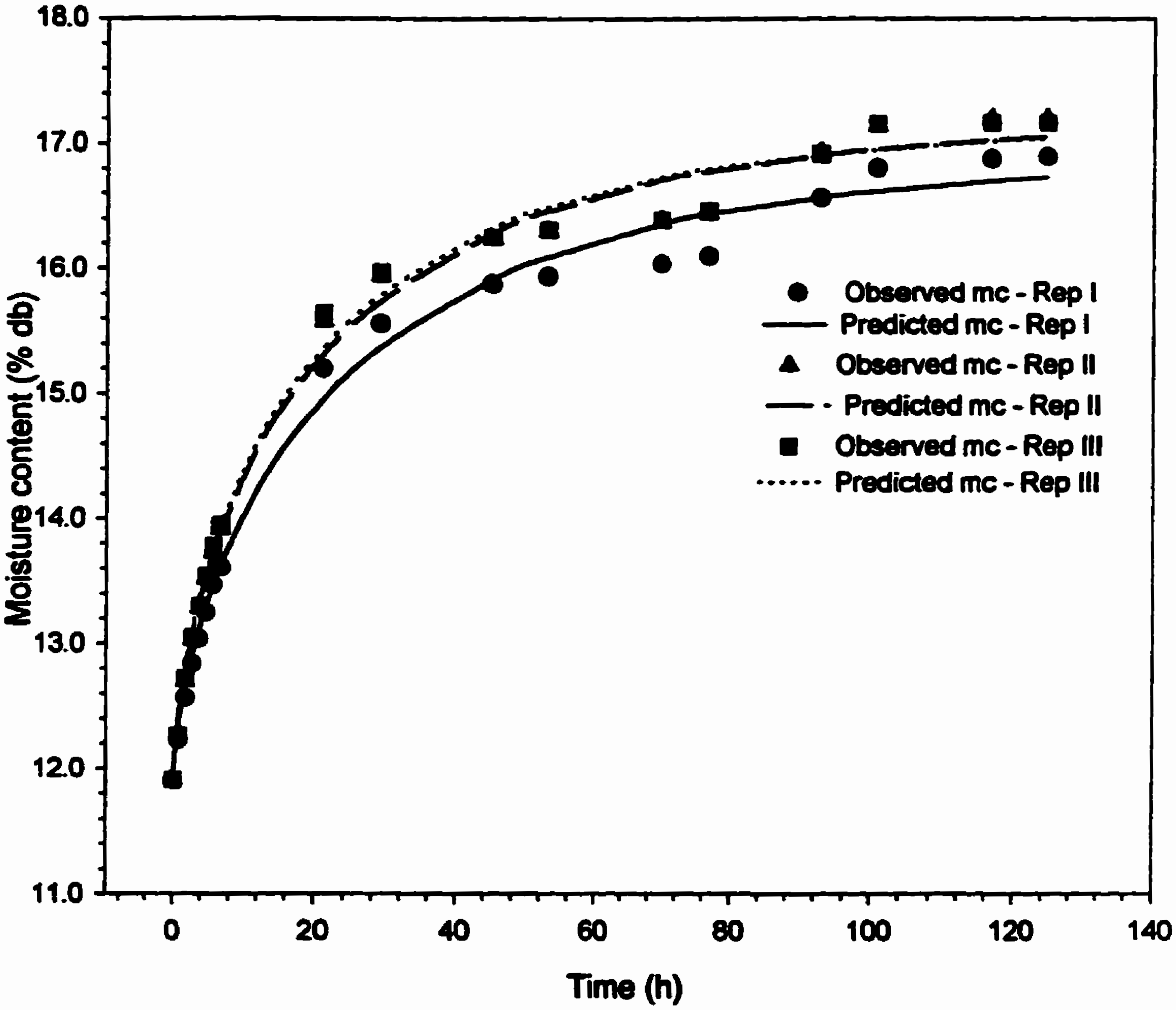

Fig. B16 - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 69%, initial mc = 11.9% db for three replicates.

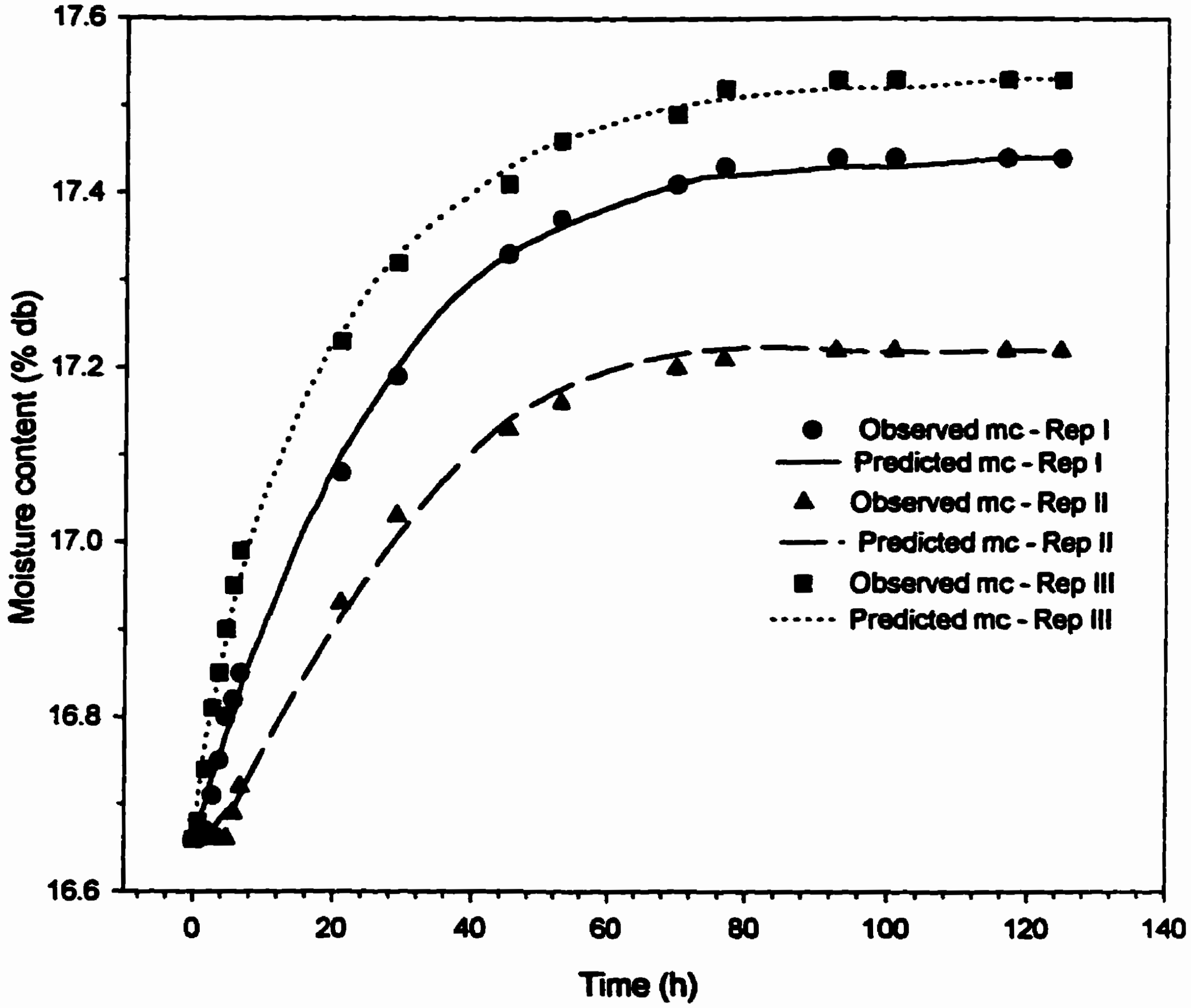

Fig. B17 - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 69%, initial mc = 16.7% db for three replicates.

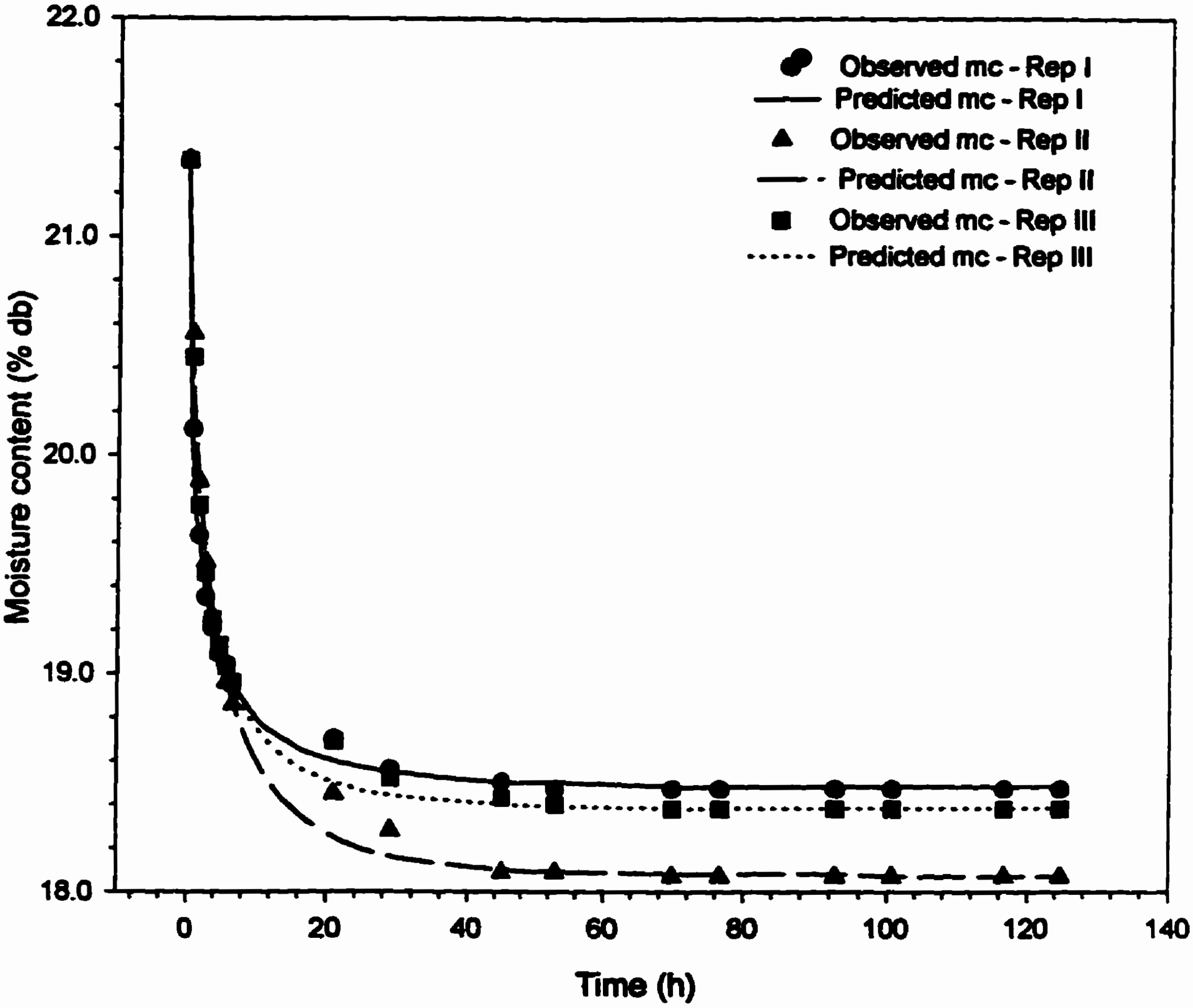

Fig. B18 - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 69%, initial mc = 21.4% db for three replicates.

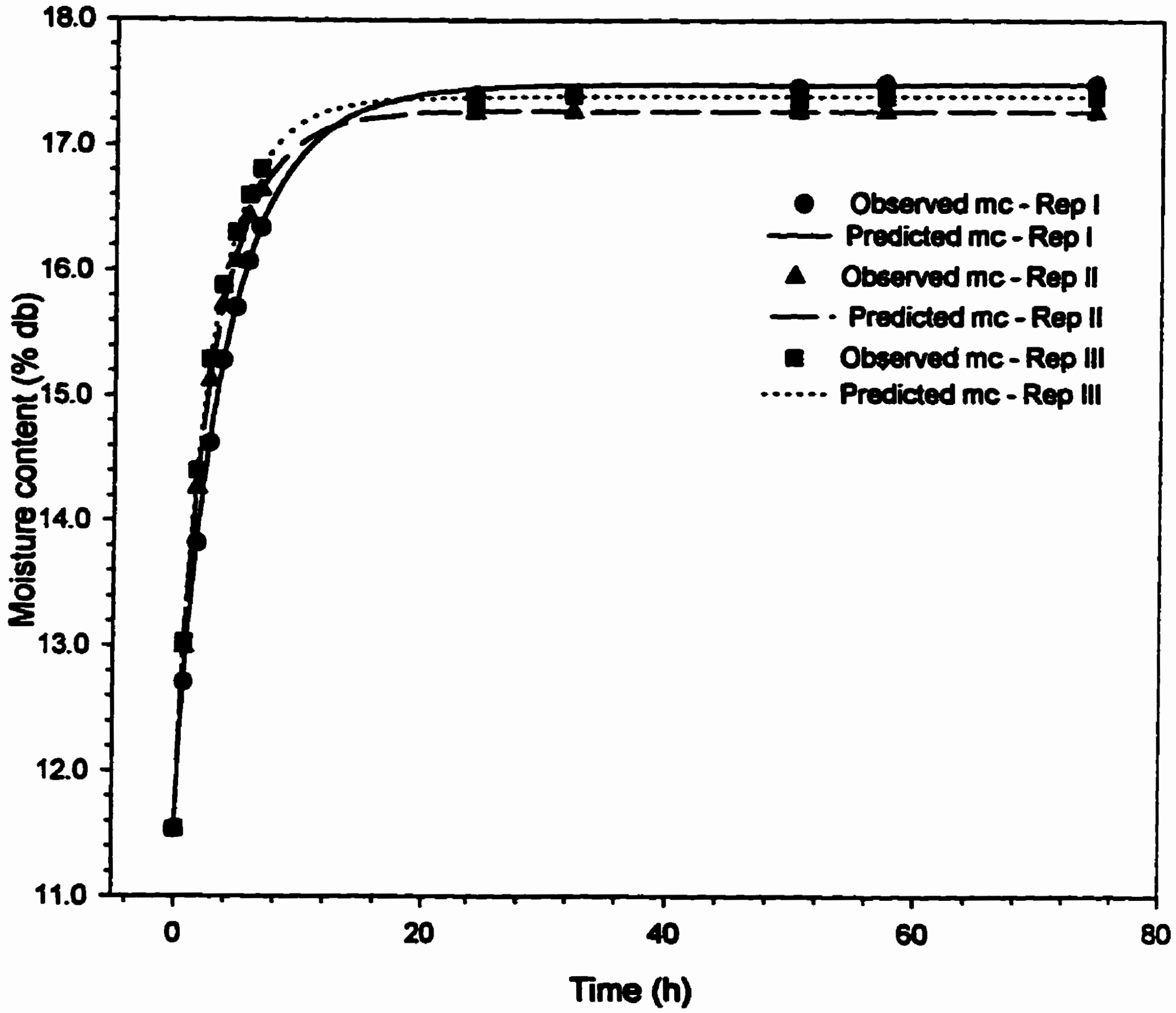

Fig. B19 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 75%, initial mc = 11.5% db for three replicates.

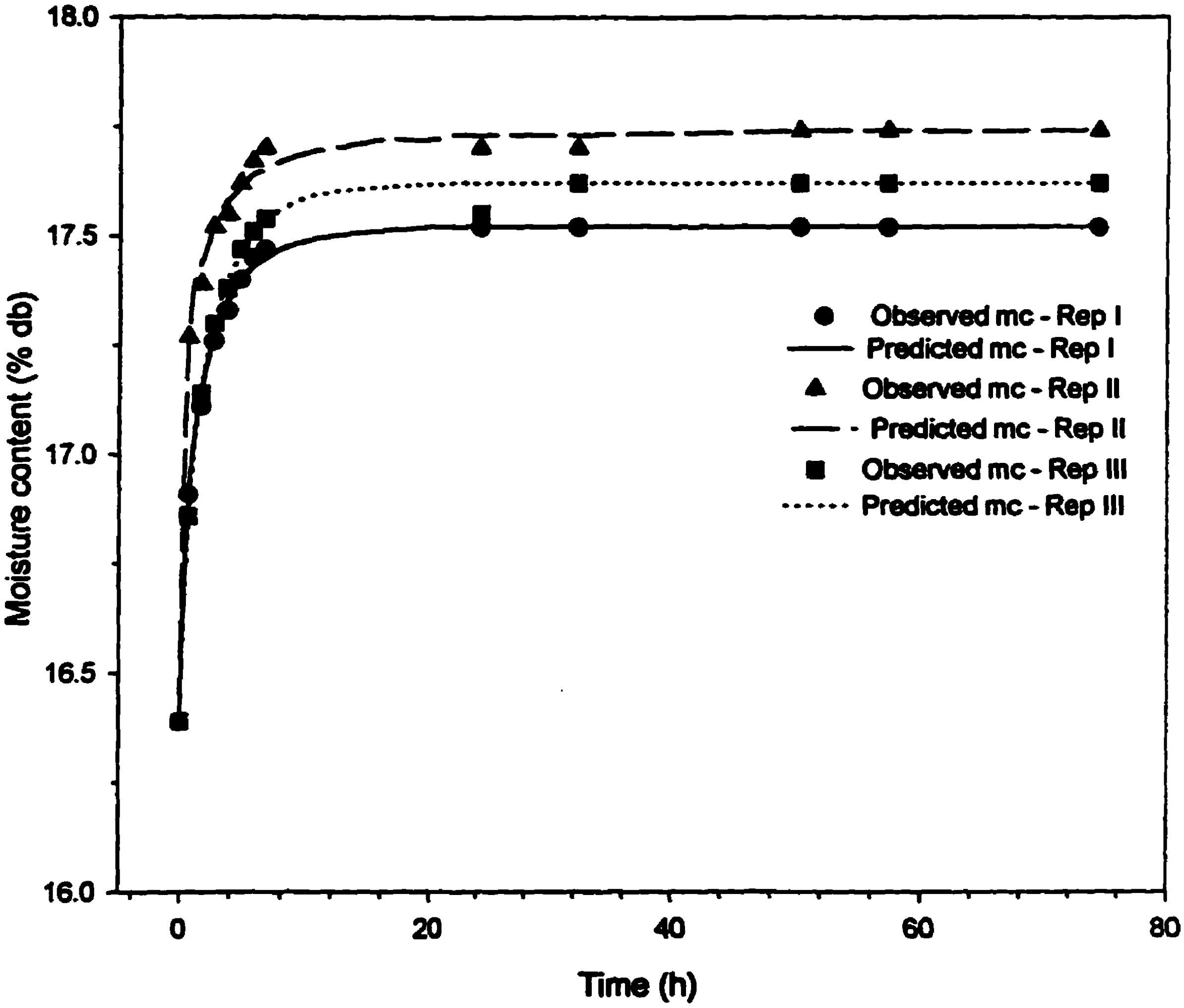

Fig. B20 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 75%, initial mc = 16.4% db for three replicates.

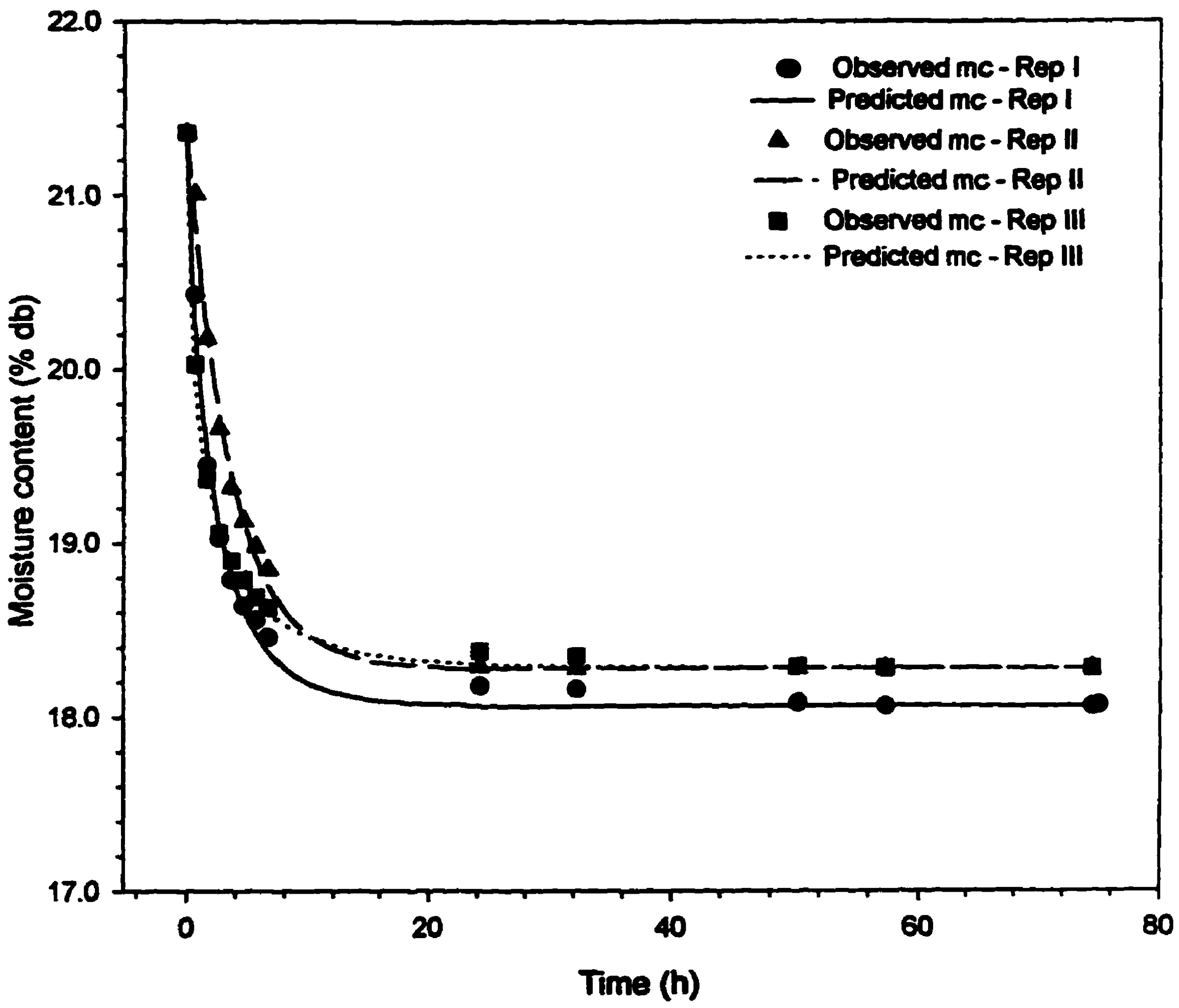

Fig. B21 - Experimental and predicted by Page's equation moisture content at temperature = 36°C, RH = 75%, initial mc = 21.4% db for three replicates.

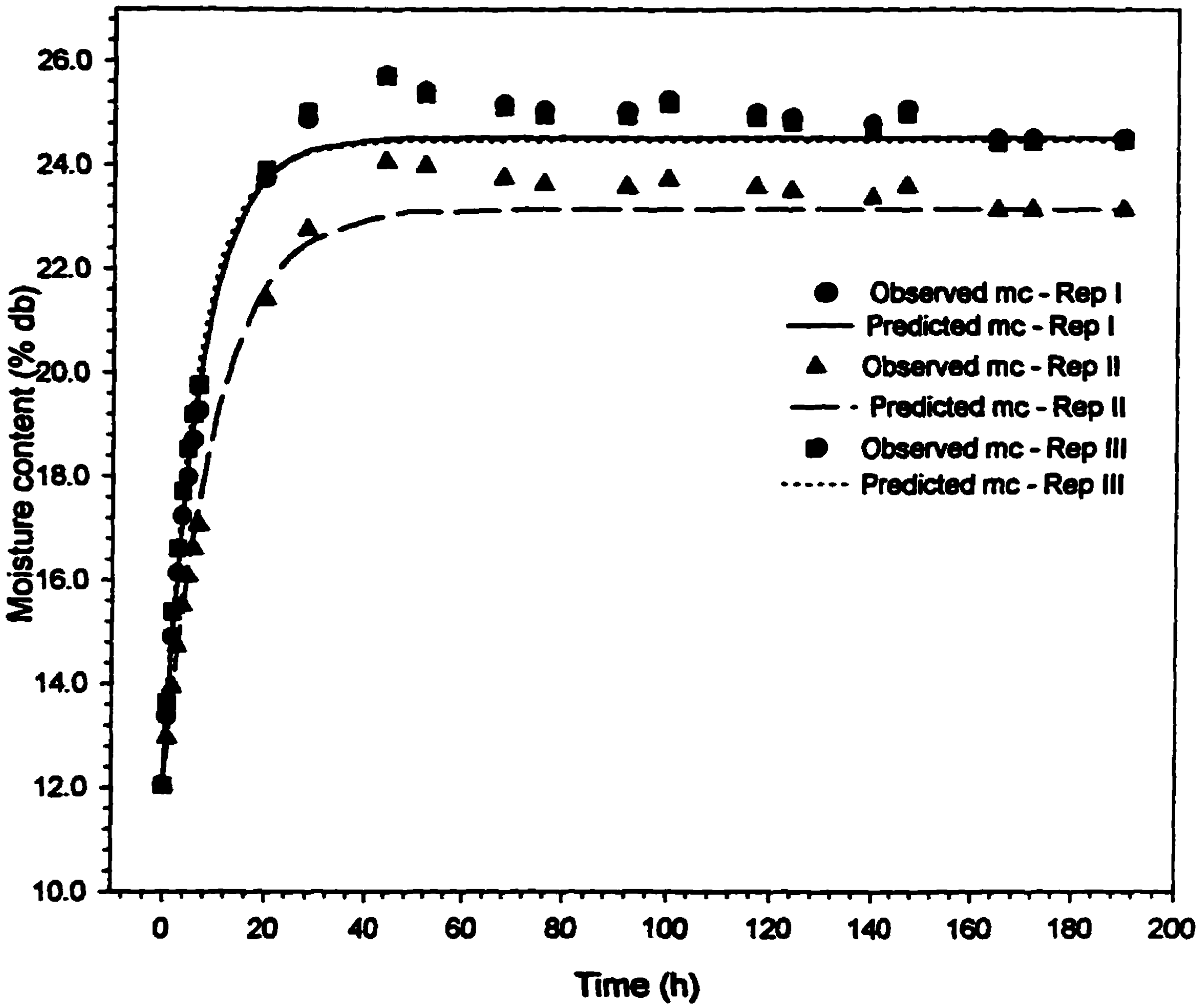

Fig. B22a - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 88%, initial mc = 12.1% db for three replicates.

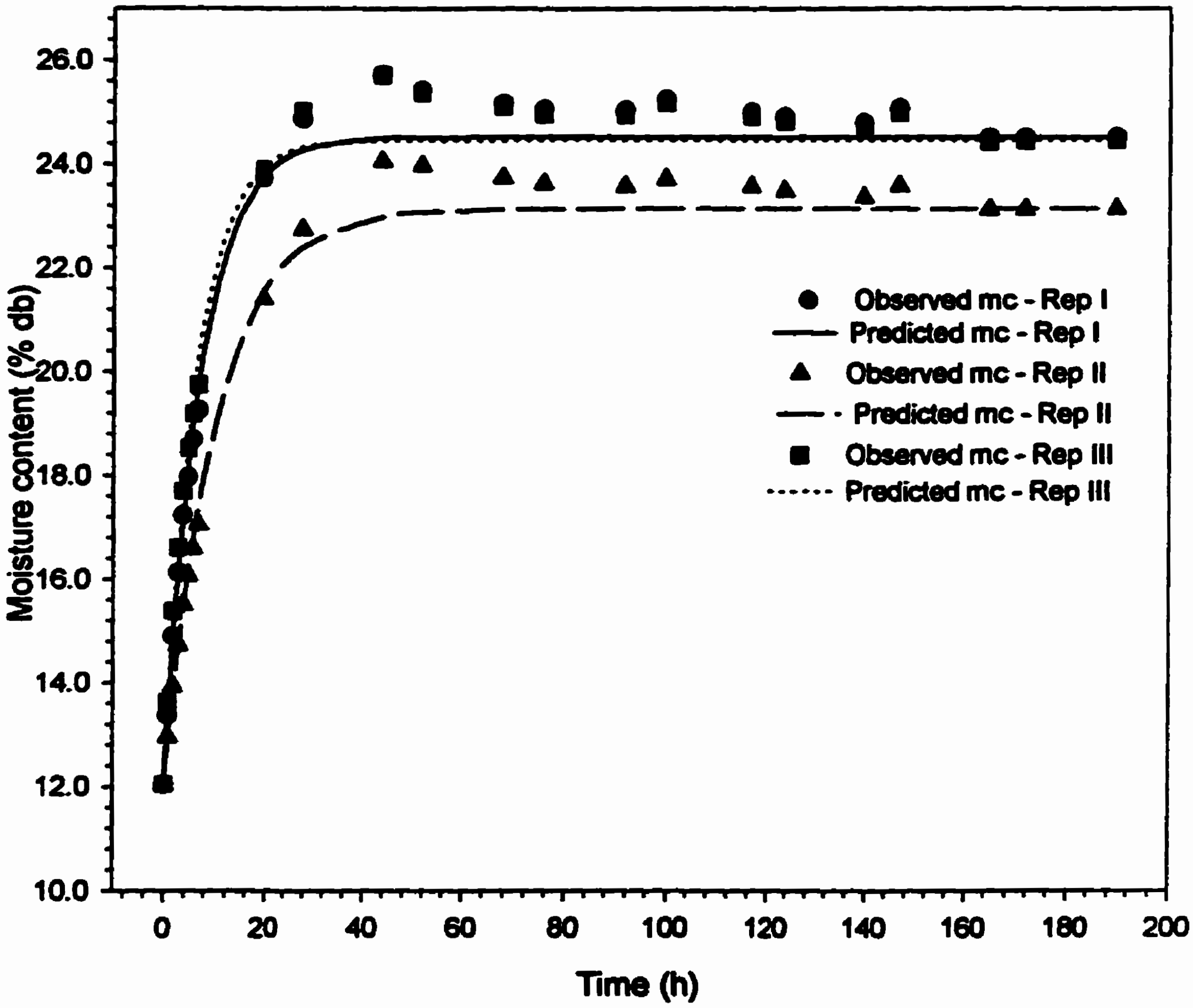

Fig. B22b - Experimental and predicted by Lewis' equation moisture content at temperature = 15°C, RH = 88%, initial mc = 12.1% db for three replicates.

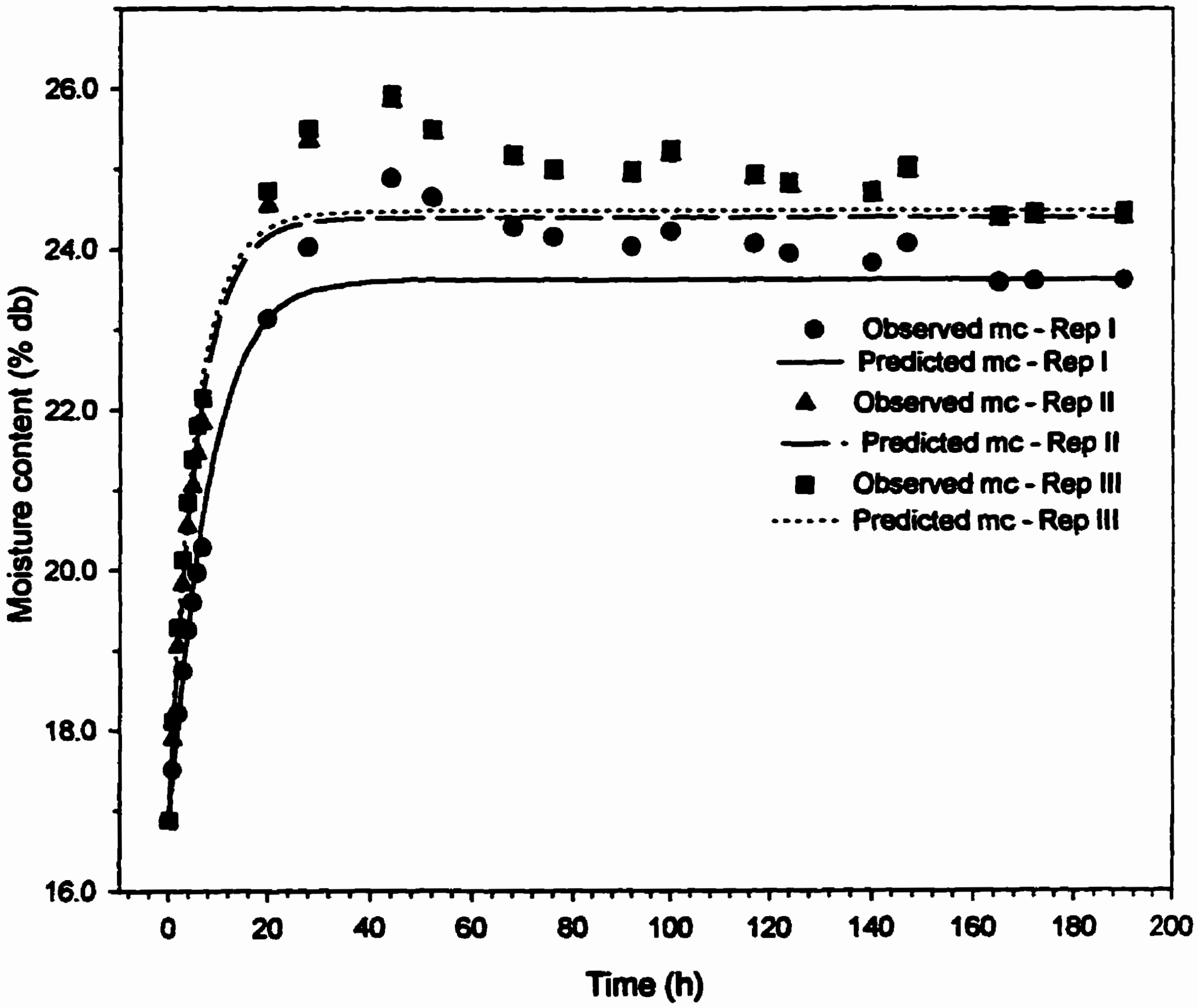

Fig. B23a - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 88%, initial mc = 16.9% db for three replicates.

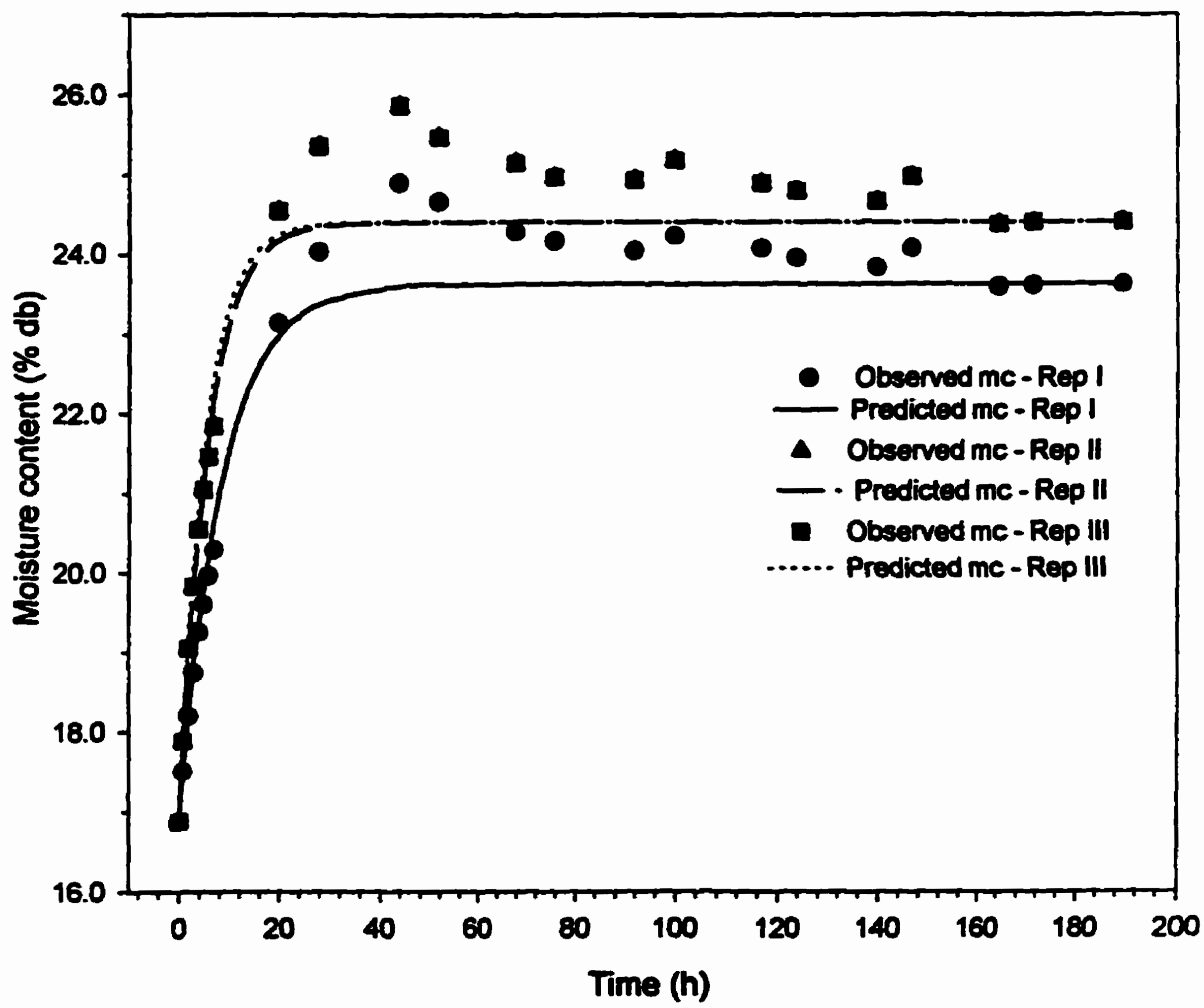

Fig. B23b - Experimental and predicted by Lewis' equation moisture content at temperature = 15°C, RH = 88%, initial mc = 16.9% db for three replicates.

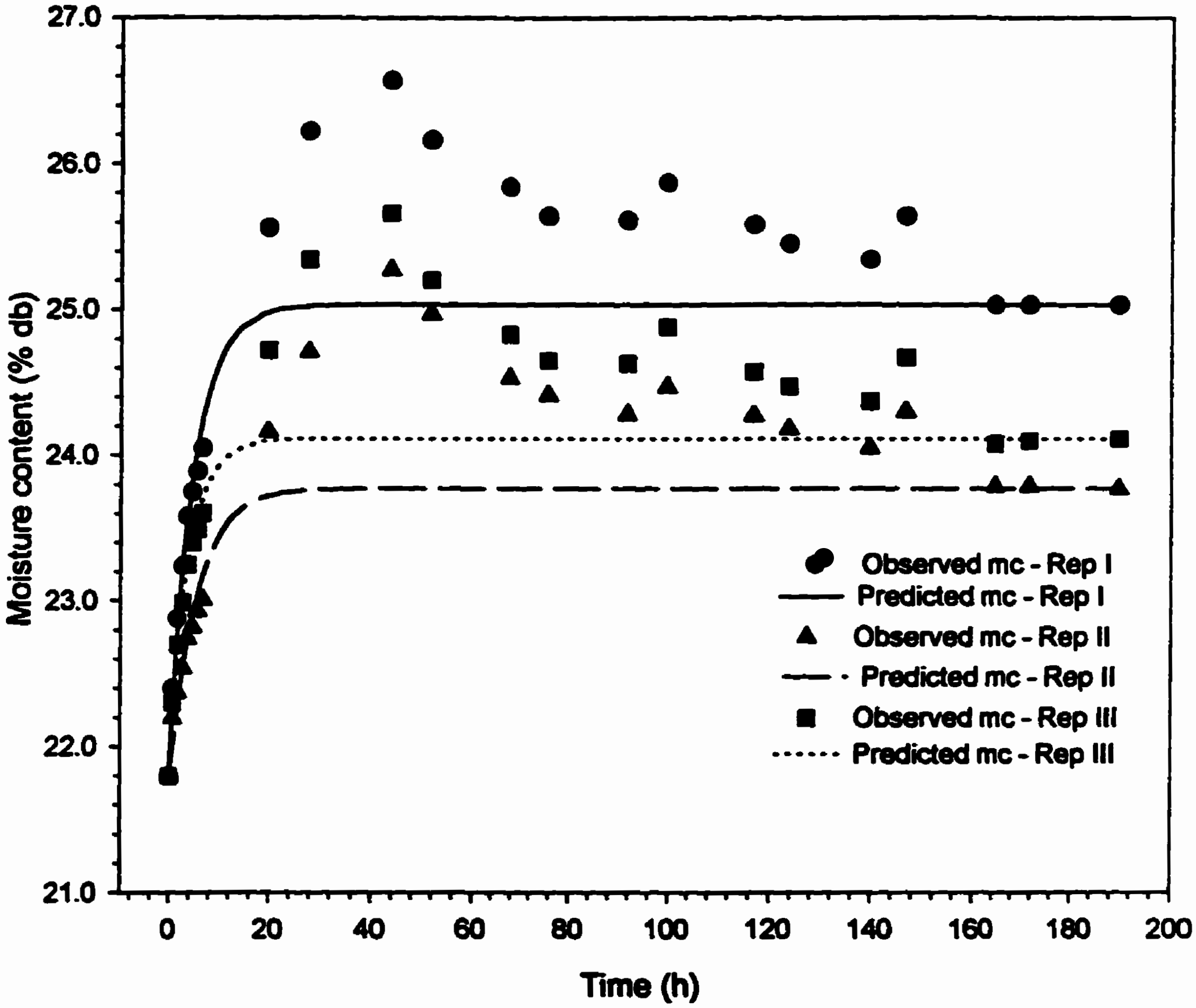

Fig. B24a - Experimental and predicted by Page's equation moisture content at temperature = 15°C, RH = 88%, initial mc = 21.8% db for three replicates.

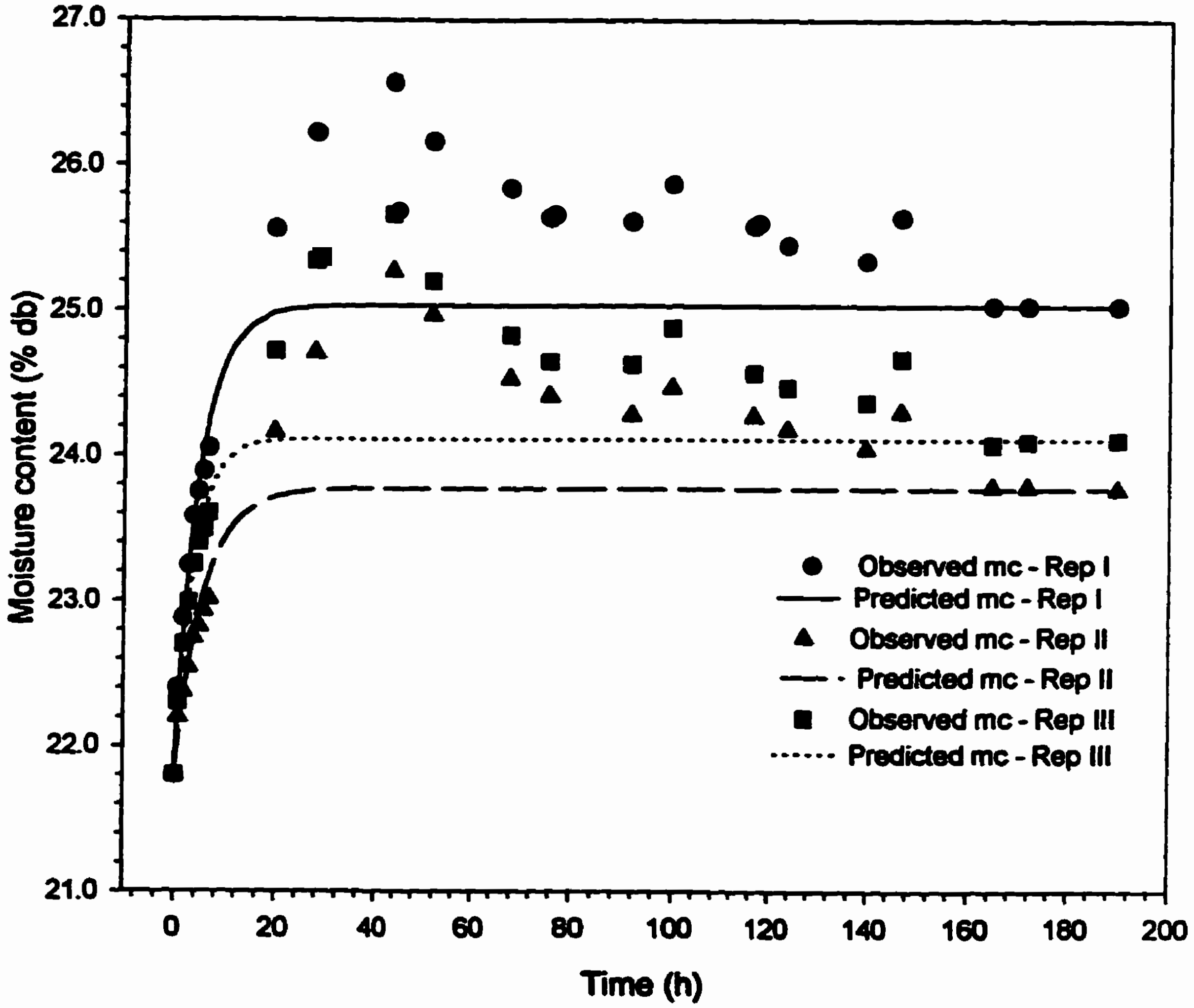

Fig. B24b - Experimental and predicted by Lewis' equation moisture content at temperature = 15°C, RH = 88%, initial mc = 21.8% db for three replicates.

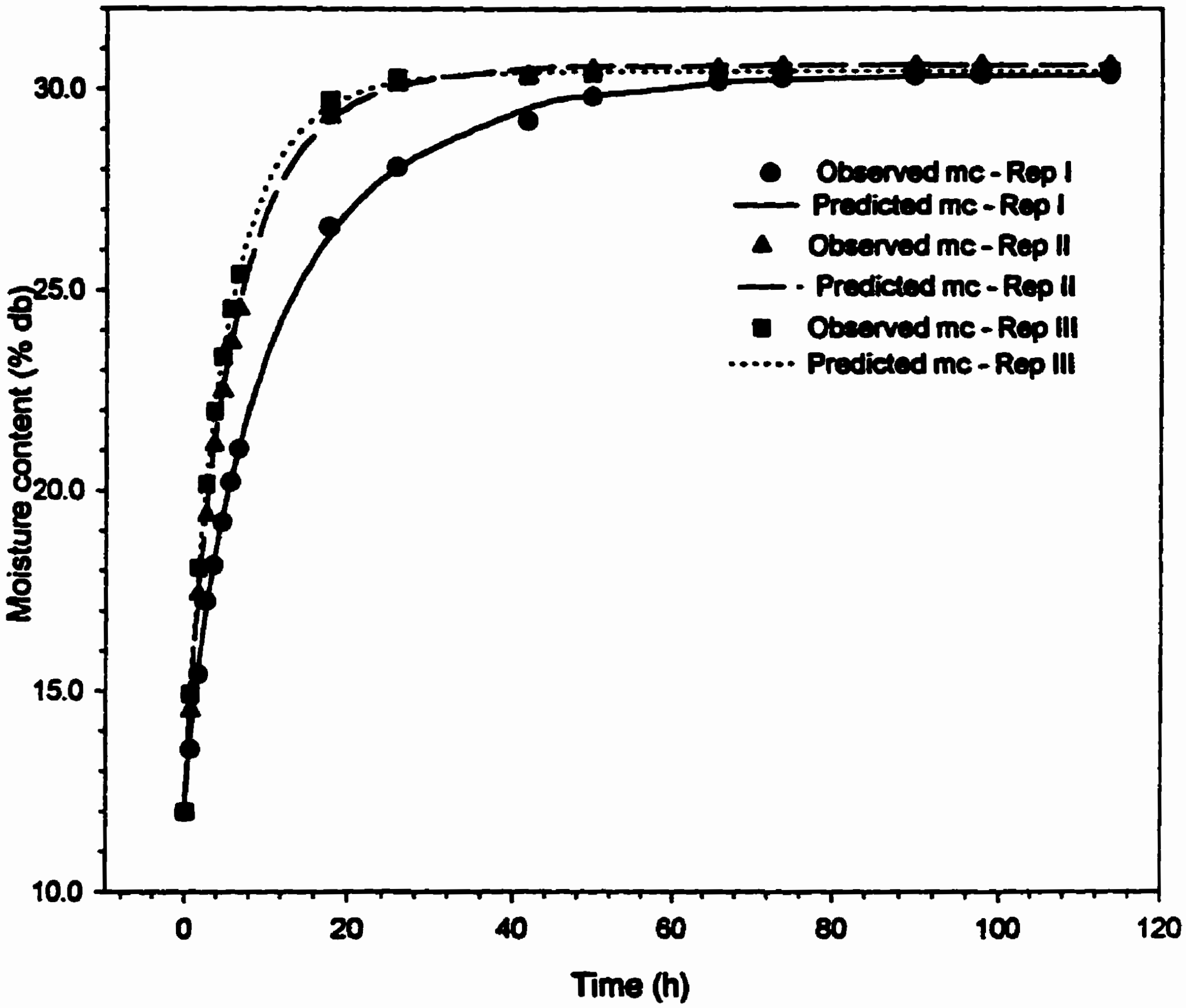

Fig. B25 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 93%, initial mc = 12.0% db for three replicates.

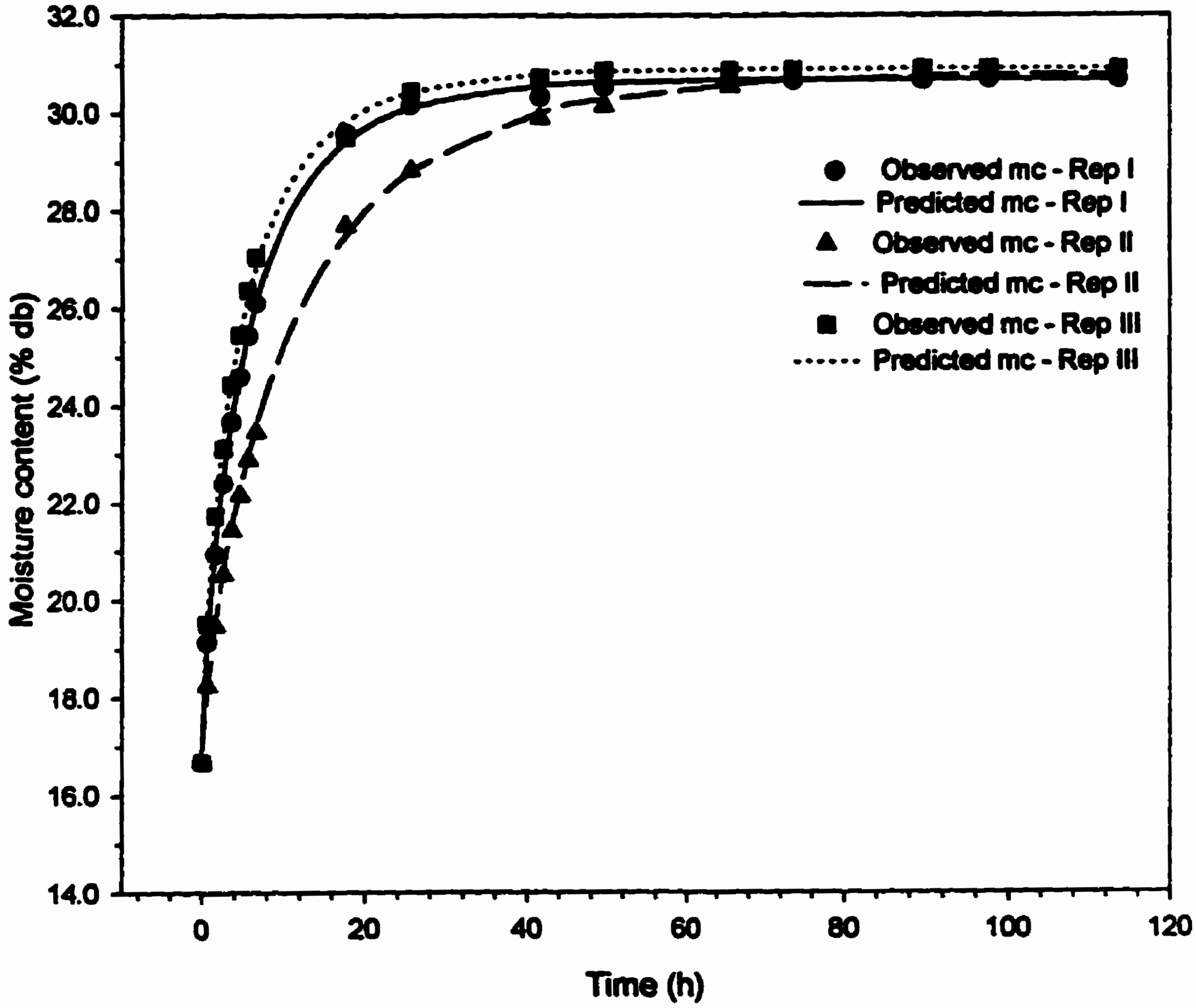

Fig. B26 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 93%, initial mc = 16.7% db for three replicates.

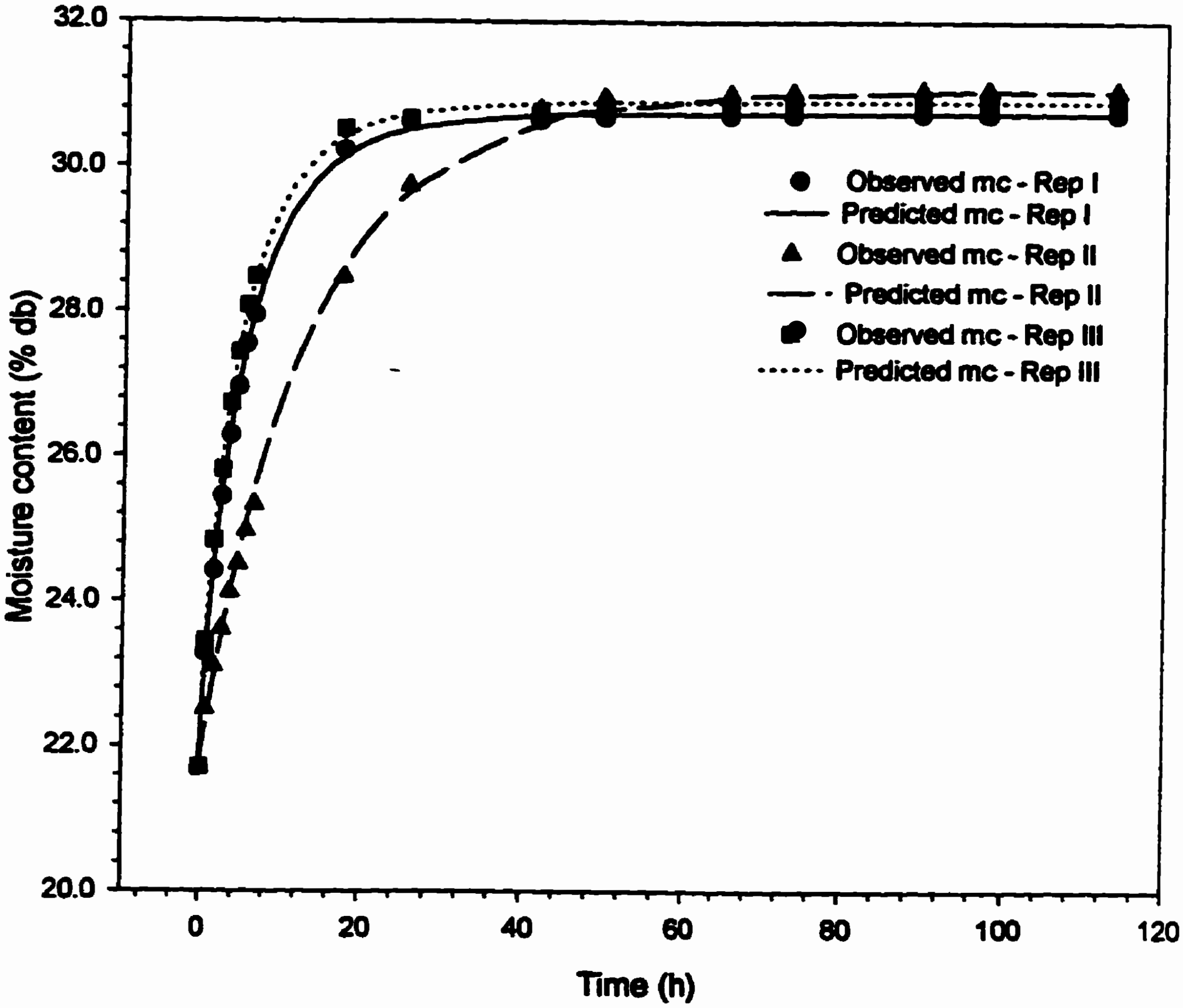

Fig. B27 - Experimental and predicted by Page's equation moisture content at temperature = 25°C, RH = 93%, initial mc = 21.7% db for three replicates.

Appendix C

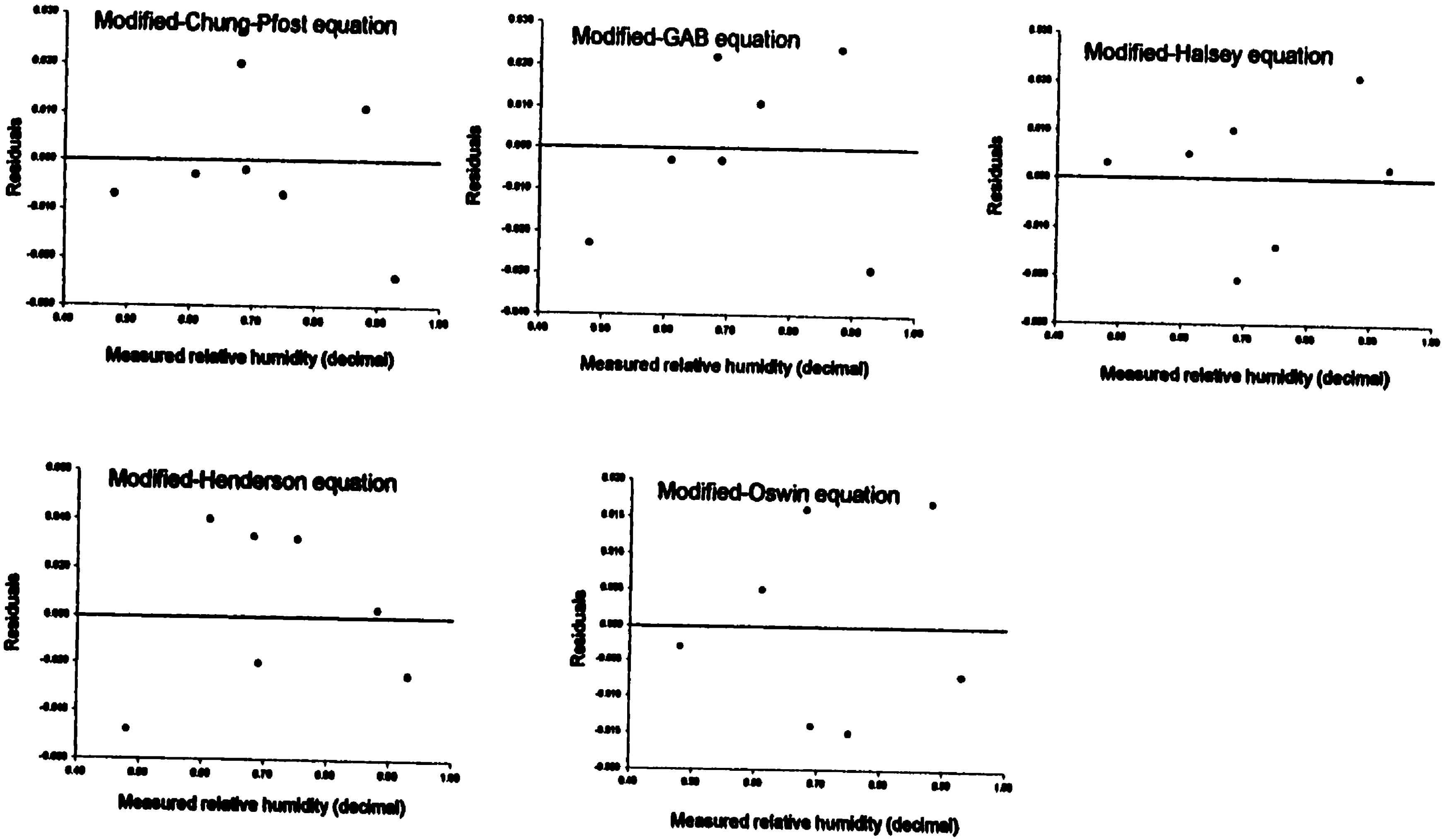

Fig. C1 - Comparison of residuals of measured equilibrium relative humidity for the five equation for sorption at various relative humidities and temperatures

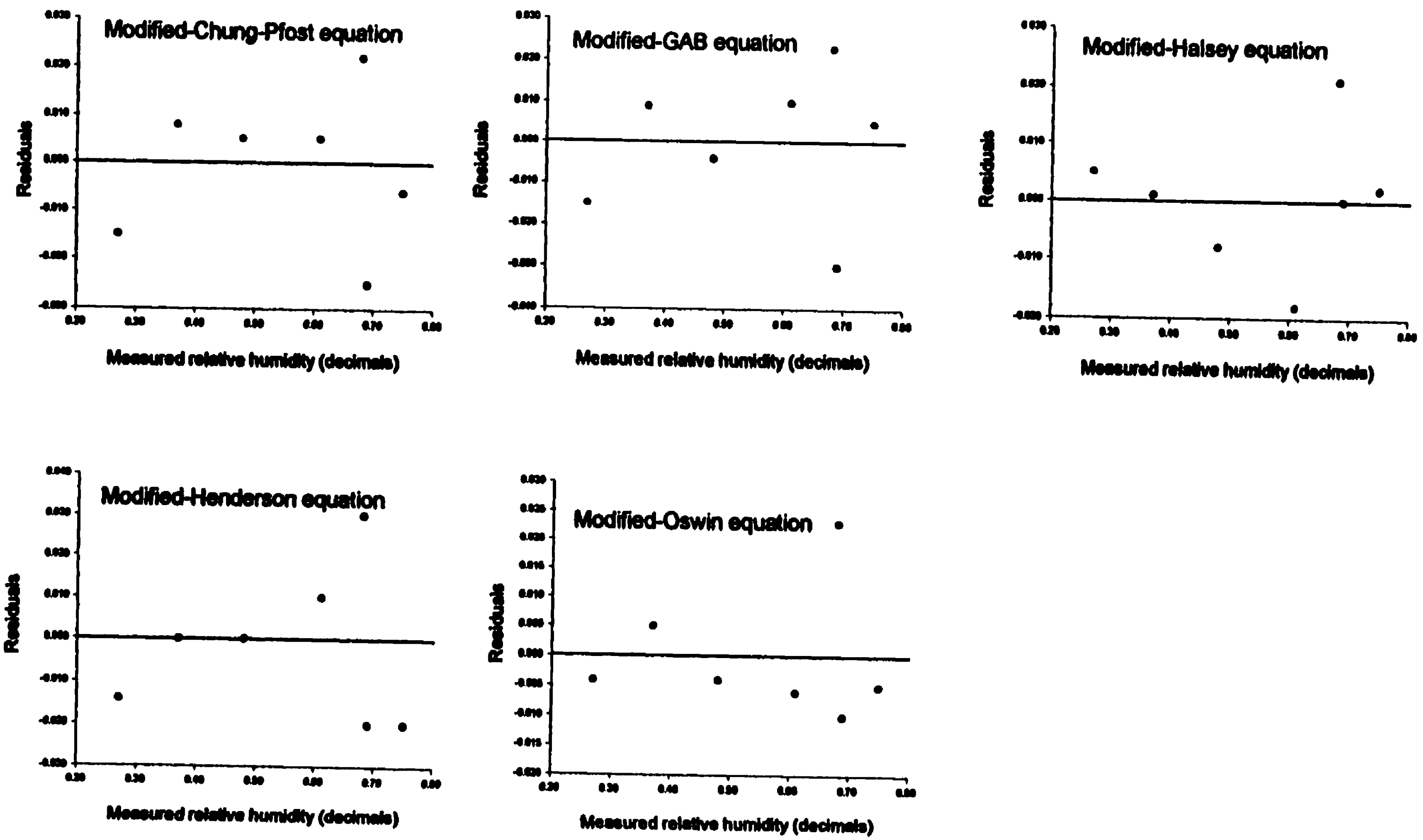

Fig. C2 - Comparison of residuals of measured equilibrium relative humidity for the five equation for desorption at various relative humidities and temperatures

Table C3 Mean equivalent radius of a sphere for 'AC Belmont' hulles oat kernels determined by air comparison pycnometer.

IMC (%db)	Volumetric reading for 800 kernels (mL)	Mean Volume of 800 kernels (mL)	Volume per kernel (mL)	Equivalent radius of sphere (mm)	Mean Equivalent radius of sphere (m)
21.95	19.66				
21.95	19.65	19.66	0.0246	1.803	
21.95	19.66				
16.28	18.18				
16.28	18.20	18.19	0.0227	1.757	0.00176
16.28	18.19				
11.11	17.25				
11.11	17.25	17.23	0.0215	1.726	
11.11	17.19				