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THE PREDICTION OF DRYING TIME OF EXPANDED POLYSTYRENE BLOCKS

**A thesis presented in partial fulfilment of the requirements for the degree of
Master of Technology in Production Technology at
Massey University**

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FOR MY MOTHER

Abstract

A study of methods to predict the drying time of expanded polystyrene was made with the aim of optimizing the drying conditions of the drying kiln at Lanwood Industries.

Experiments were carried out in both a laboratory and Lanwood Industries factory. The drying rate was found to decrease with increasing product thickness and to increase with increasing drying temperature. Drying temperature between 50 and 60 °C has a stronger influence on the EPS drying process than between 40 and 50 °C.

A simplified theoretical method can be used to predict the drying time in the industrial environment when quick computation is needed. Newton's model can fit the full-scale drying process, but it did not fit the laboratory drying processes well. Page's model has an excellent fit to the three dimensional EPS drying process and it is also able to scale up the laboratory drying results. It supplies a powerful tool to describe the drying process and predict the drying time of the EPS product.

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Chapter 1 Introduction

This project, which has been done in conjunction with Lanwood Industries of Palmerston North, was supervised by Mr. Phil Collins from the Production Technology Department at Massey University. The research intends to improve the drying quality of expanded polystyrene (EPS) blocks used as insulation by the construction industry.

The processing of the EPS product employs a pre-expansion stage where steam is blown through raw polystyrene beads which contain a small amount of pentane. The partly expanded beads from this stage are called "prefoam". Before moulding the prefoamed beads are put into large hoppers to dry. After drying, the material is then blown into a mould and treated again with steam to soften the prefoamed bead for final fusing. Blocks of EPS leaving the moulder contain both pentane (the expanding agent) and up to 10 % moisture from the steam injected during moulding. Before hot wires cut the blocks into slabs, the blocks are dried in warm air chambers to allow the pentane and moisture to disperse. Residual pentane can cause a fire hazard during cutting. If too much moisture remains in the block, the cutting wires cool down which causes an uneven cut surface, drag marks or "picture framing". Moisture also has other adverse effects, such as detaching the outer layer of composite panels and reducing the insulation efficiency.

The purpose of this project is to determine the optimum conditions for drying moisture from moulded EPS, in order to minimise the drying time while also maintaining acceptable product surface quality during the hot-wire cutting. Both laboratory drying tests and full-scale drying tests were carried out to study the drying process of the EPS product.

In EPS block (3.6m×1.2m×0.65m) drying, moisture movement occurs along the length, width and height of the block which involves three dimensional drying. In order to simulate the full-scale drying process, drying samples were cut into a cubic shape

from fresh moulded EPS blocks and dried in a laboratory drying cabinet. These results together with drying theory were used to scale up the laboratory experimental data to the full-scale drying operation. The capillary theoretical method, Newton's model and Page's model were used for the drying time calculation.

Some limitations encountered during the data collection and analysis were: the varying drying conditions during the full-scale tests, the limited experimental data, and the large gap in dimensions of drying materials between the laboratory tests and the full-scale tests. The scale-up procedures are by no means straight forward. However, Page's equation was found to give a better fit for the experimental data of both the laboratory and the full-scale tests. Page's model is able to describe the three dimensional drying process of the EPS product. It also provides a method to scale up the laboratory results for the optimization of the drying conditions.

Chapter 2 Review of Existing Knowledge and Background Theory

Solids drying is one of the oldest, most common and perhaps the most important unit operations in the industrial sector. Drying also is extremely energy inefficient in many industrial processes. The developments in drying have led to mainly improvement of the efficiency of technology on the market in this century, and may lead to better industry-academia interaction in the future.

It is rarely possible to carry out a thorough process design of a dryer on a theoretical basis alone (Pakowski and Mujumdar, 1995). Generally previous knowledge comes from industrial experience for the given material and the type of dryer. Different products require different types of dryer systems for the final water removal. In order to design and operate dryers, it is necessary to have a mathematical model capable of describing the drying process quantitatively.

The development of mathematical models to describe drying processes has been a topic of many research studies for several decades. The complexity of the drying phenomenon causes difficulty in predicting or designing a drying process with mathematical accuracy. It is for these reasons that drying is often called an art as much as a science (Malhotra and Okazaki, 1992).

The purpose of this chapter is to review the basic knowledge of drying principles, the internal and external conditions which affect the drying processes and the mathematical models proposed for describing the drying process. Because relatively little information is available on the drying of EPS blocks, the characteristics of EPS are discussed so that EPS blocks drying can be studied and simulated. Some fundamental equations have been developed to estimate the drying processes. Theoretical, semitheoretical and empirical equations are analyzed for calculating and designing the drying processes.

2.1 Basic theory

2.1.1 General principles

Drying is a process of simultaneous heat and moisture transfer. The heat is required to evaporate the moisture which is removed from the drying product surface by the external drying medium, usually air. Drying operations usually involve the removal of water by passing air over the drying material, and the water must diffuse through the various resistance from inside of the drying product to escape. Two processes occur simultaneously during drying; (1) heat (usually from hot air) transfers from the surrounding environment to evaporate the surface moisture; (2) internal moisture transfers to the surface of the material and subsequently evaporates on the surface. The rate of water movement is determined by the rate of mass and heat transfer. Under a constant drying condition, the material will lose water until an equilibrium condition is established. The equilibrium moisture content varies widely with the air temperature, air humidity and the properties of the material. The drying principles are well described in fundamental chemical engineering books (McCabe et al, 1993, Perry and Green, 1984, Peters, 1984).

2.1.2 Drying rates and drying curves

In basic drying theory, the drying process is determined by the drying temperature, time and the moisture content distribution of the drying material. The drying processes can be represented by a drying curve. The drying curve represents the drying-rate and the moisture content during the drying process. The drying-rate is expressed as kilogrammes of water removed per hour. Drying curves are based on experimental data of moisture content at different times during the course of a drying operation. The drying curve can be divided into three different periods: one constant-rate period and two falling-rate periods (McCabe et al, 1993, Perry and Green, 1984, Peters, 1984). Figure 2.1 illustrates the drying curves.

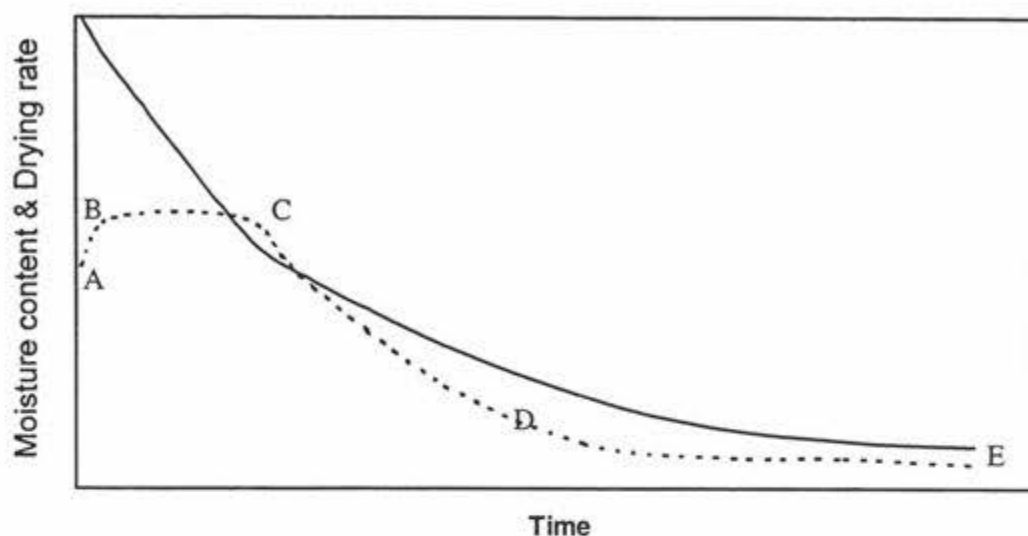


Figure 2.1 The solid line is moisture content versus time. The dashed line is drying rate versus time. The period of drying: AB, a warming-up period; BC, the constant-rate period; C, the critical moisture content; CD, the first falling-rate period; DE, the second falling-rate period.

1. *The first period is the constant-rate period (period BC) during which moisture evaporates at the surface and free water continues to move to the surface. External conditions control the drying rate in this period. When the drying temperature is high, the drying rate is fast and the constant-rate period is short. When the drying temperature is low, the length of constant-rate period increases (Strahm and Flores, 1994). The drying rate in the constant-rate period is determined by the rate of surface evaporation (Mujumdar and Menon, 1995). When the surface moisture falls below the critical moisture content, the falling-rate period begins.*

2. *The falling-rate period is divided into two stages*

a) *The first is the surface drying period (period CD) during which the moisture content on the surface decreases significantly. At this stage, the entire evaporating surface can no longer be maintained and saturated by moisture movement from within the drying material. Resistance opposing the movement of vapour to the surface*

becomes greater, and internal resistance becomes more critical in controlling drying rate.

b) The second is the period of penetrating evaporation front (period DE) which is when the wet line recedes to the centre of the drying material until no more free water remains in the drying material. This drying stage is controlled by internal resistance. Under constant external conditions, the drying material will continue to dry until an equilibrium moisture content has been reached. The point which is from the first falling-rate period to the second falling-rate period is called the second critical moisture content (McCabe et al, 1993).

The falling-rate period usually predominates in determining the overall drying time to lower moisture content (Perry and Green, 1984). This period begins at the critical moisture content when the constant-rate period ends. If the initial moisture content is below the critical moisture content, the entire drying process will occur in the falling-rate period. The drying-rate curve in the falling-rate period varies from one type of material to another (McCabe et al, 1993). McCabe et al (1993) emphasised the shape of the curve depends on the thickness of the material and on the external variables. The rate of drying becomes zero at the equilibrium moisture content (Perry and Green, 1984).

Mujumdar and Menon (1995) defined the characteristic drying curve. When the drying-rate curves are determined over a range of conditions for a given solid, the curves appear to be geometrically similar and are simply a function of the extent to which drying has occurred. However, this characteristic curve must satisfy two restrictive criteria: 1) when the critical moisture content is invariant and independent of initial moisture content and external conditions; 2) all drying curves for a specific substance could often be approximated to a single curve so that the shape of the curve is unique and independent of external conditions. This curve is called the 'characteristic' drying curve of a particular substance. The characteristic drying-rate curve represents the drying process of the particular substance.

2.1.3 Critical moisture content

Critical moisture content (point C) is the free moisture content of the material at the end of the constant-rate period. The critical moisture content varies with the thickness of the material and with the rate of drying. It must be determined experimentally for each material and for each drying condition.

It is necessary to know values of critical moisture content, if the drying curve is used for a drying process calculation or a predicting equation is used for estimating drying times in the falling-rate period. The values of critical moisture content are difficult to obtain without making actual drying tests (Perry and Green, 1984; Suzuki, 1980). However, when drying tests are not feasible, some estimate of critical moisture content must be made. It appears that the constant-rate period ends when the moisture content at the surface reaches a specific value. That is the point that the drying rate begins to fall. If the initial moisture content of the solid is below the critical point, the constant-rate period does not occur. The critical moisture content is best determined experimentally although some approximate data are available (McCabe et al, 1993). Since the critical moisture content is an averaged value through the material, its value depends on the rate of drying, the thickness of the material, and the factors influencing moisture movement and resulting gradients within the solid, so it is not a specific property for a given material. As a result, the critical moisture content increases with increased drying rate and with increased thickness of the material being dried (Suzuki et al, 1977; Perry and Green, 1984).

Drying-rate curves are used for the calculation of critical moisture content (Mazza and Lemaguer, 1980; Mowlah et al, 1983; Igene et al, 1990). The value of the critical moisture content can be obtained from the drying-rate curves corresponding to the end of the constant-rate period. Suzuki (1980) introduced a simple and approximate, but powerful estimation method of the critical moisture content. When a solid is dried experimentally, data are usually obtained relating moisture content to time. These data are then differentiated numerically or graphically and plotted as drying rate and moisture content. As the differentiation process is very sensitive to a fluctuation or

noise in the original data, the calculated drying rate usually shows fairly large scatter. However, by smoothing the data, the constant-rate period can generally be observed after a short warming up period. The falling-rate period can also be observed when the moisture content decreases. The actual drying rate curve changes gradually from the constant-rate period to the falling-rate period.

The critical moisture content has been estimated by solving a nonlinear moisture diffusion equation by Suzuki (1980) with the following criteria: the surface moisture content is assumed to be zero at the critical moisture content; the apparent evaporating zone locates very close to the surface if moisture is uniformly distributed within porous material; the apparent mass transfer coefficient over the drying material surface remains virtually constant even when the fraction of the wet surface area decreases. Peters (1984) determined the free moisture content of the solid at the end of the constant-rate period is designated as the critical free moisture content.

2.1.4 Equilibrium moisture content

Equilibrium moisture content is when a hygroscopic material attains a definite moisture content at specified conditions. That is, the vaporization of moisture in the drying material is condensed, and the drying material is maintained equilibrium with its contacted air temperature and humidity. The value of equilibrium moisture content depends on temperature and humidity. The drying rate becomes zero at equilibrium moisture content.

Equilibrium moisture content depends greatly on the nature of the drying material, air temperature and humidity. Marinos-Kouris and Maroulis (1995) commented that equilibrium moisture content depends upon many factors, among which are the chemical composition, the physical structure, and the surrounding air conditions.

Equilibrium moisture content of the solid is particularly important in drying because it represents the limiting moisture content for given conditions of humidity and

temperature. If the material is dried to moisture content less than it normally possesses in equilibrium with atmospheric air, it will return to its equilibrium value on storage unless special precautions are taken. Perry and Green (1984) stated when a hygroscopic material is maintained in contact with air at constant temperature and humidity until equilibrium is reached, the material will attain a definite moisture content. This moisture is termed the equilibrium content for the specified conditions. At zero humidity the equilibrium moisture content of all materials is zero. Equilibrium moisture content of a hygroscopic material may be determined in a number of ways, the only requirement being a source of constant-temperature and constant-humidity air. The methods of the equilibrium moisture content measurements procedure were well described by Perry and Green (1984), Sun and Woods (1994).

It is widely accepted that an increase in temperature results in decrease equilibrium moisture content (Zhang et al, 1996). However, Banaszek and Siebenmorgen (1990) argued for a given air condition, equilibrium moisture content varied linearly with initial moisture content. Equations were developed to relate equilibrium moisture content to initial moisture content, temperature and relative humidity. A large number of equations (theoretical, semiempirical, empirical) have been proposed in the literature (Madamba et al, 1994; Bala and Woods, 1991; Diamante and Munro, 1990). Very little is said in the literature concerning the determination of equilibrium moisture content in a given saturated atmosphere.

Because of the long time required to obtain equilibrium conditions for a certain material, a constant weight is generally implied by the term equilibrium moisture content (Neuber, 1980). Zuritz et al (1979) suggested weighing the samples until there was no weight change as measured to the second decimal place (0.01 g). Ferrel et al (1966) recorded weight change with time until a change in weight corresponding to less than 0.05 % change in the moisture content was observed. Labuza (1984) suggests recording the change in weight until the change in moisture content is less than 0.001 kg/kg drying solids. Lomauro et al (1985) defined equilibrium to be reached when the moisture content (kg/kg dry basis) did not change by more than 0.5 % for three

consecutive sampling periods of not less than 7 days. The equilibrium moisture content was considered to be the first in the series of consecutive readings.

2.2 Factors affecting the air drying

2.2.1 External conditions

External drying condition are especially important during the initial stages of drying when unbound surface moisture is being removed. Mujumdar and Menon (1995) described the drying rate as being governed by the rate at which the two processes proceed. The removal of water as vapor from the material surface is the first process. The second process is the movement of moisture internally within the material which is a function of the properties of the material, the temperature and its moisture content. The first process depends on the external conditions of temperature, air humidity and flow, area of exposed surface and pressure.

2.2.1.1 Temperature

In general, drying rates were found to be strong influenced by air temperature (Chakraverty and Jain, 1984; Li and Morey, 1987; Kiranoudis et al, 1992). The observed increase in drying rate with temperature can be explained in terms of an Arrhenius type function of temperature (Cobbinah et al, 1984; Chungu and Jindal, 1993). The higher the drying temperature, the lower the air humidity and the faster the drying rate. However, if drying temperature is too high, the initial drying rate is too fast which will cause not only damage to the properties of drying materials but also increase the critical moisture content, subsequently reducing the later stage drying rate. There is a maximum permissible temperature, beyond which the product undergoes undesirable changes (Vagenas and Marinos-Kouris, 1991; Mujumdar and Menon, 1995).

2.2.1.2 Relative humidity

If a hygroscopic material is maintained in contact with air at constant humidity and temperature until equilibrium is reached, the material will attain a definite moisture content. So the given conditions of humidity and temperature represent the limiting moisture content of the drying solid-equilibrium moisture content. If the material is dried to a moisture content less than it normally possesses in equilibrium with atmospheric air, it will return to its equilibrium value on storage (Perry and Green, 1984, Peters, 1984). Some experimentation found that the air humidity does not significantly alter the drying characteristics (Cobbinah et al, 1984; Kiranoudis et al, 1992). However, Vagenas and Marinos-Kouris (1991) found an increase in air humidity decreases the required thermal load. McCabe et al (1993) considered the drying rate was controlled most readily by controlling the air humidity of drying, because at low temperature, relative humidity controls the rate of water vapour transport from the drying material surface to air. An increase in relative humidity decreases the drying rate (Misra and Brooker, 1980; Farmer et al, 1983)

2.2.1.3 Air velocity

Alzamora et al (1980) verified that the air velocity does not influence the falling drying rate for any of the various thickness of material studied. However, Lebert and Bimbenet (1991) commented that the drying rate increases with air velocity, but this influence is less at higher air flow velocity. Van Arsdell and Copley (1964) defined that for air velocities higher than 4 m/s the effect of velocity on the drying rate is eliminated. Mujumdar and Menon (1995) considered variables such as air quality, which normally enhance the rate of surface evaporation, become of decreasing importance except to promote higher heat transfer rates. When the dimensions of the moist solid are large or the moisture diffusivity in the solid is low and when moisture from inside the body is being removed, drying is internally controlled. In this case any intensification of heat and mass transfer condition on the gas side by increasing gas

velocity or turbulence does not help reduce the drying time. Researchers in drying simulation generally agree that the air flow rate has no significant effect on drying rate (Pabis and Henderson, 1962; Hutchinson and Otten, 1983; Chakraverty and Jain, 1984; Li and Morey, 1987; Kiranoudis et al, 1992).

2.2.2 Internal conditions

The movement of moisture internally within the solid, is a function of the physical nature of the solid, the temperature and its moisture content. Mujumdar and Menon (1995) discussed the drying process of mass and heat transfer for a wet solid. A temperature gradient develops within the solid while moisture evaporation occurs from the surface. This produces a migration of moisture from within the solid to the surface, which occurs through diffusion, capillary flow, internal pressures set up by shrinkage during drying, and in conduction dryers, through a repeated and progressive occurring vaporization and recondensation of moisture to the exposed surface. This internal movement of moisture is important when it is the controlling factor in a drying operation carried to final moisture contents, after the critical moisture content.

2.2.2.1 Physical properties of solids

There are some important properties of EPS which can influence the drying process. To analyse and simulate EPS drying, it is essential to have accurate information on EPS physical and thermal properties such as density, void fraction, cell structure, thermal conductivity and moisture resistance. Physical dimensions of EPS, such as length, width and thickness, environmental conditions, temperature, and moisture content are the important data for EPS drying. The process of moisture movement in EPS is complicated by several factors that make mathematical analysis difficult.

- 1) density of EPS
- 2) porosity of EPS foams
- 3) cell structure of EPS foams

4) dimensions of EPS blocks

5) thermal conductivity of EPS

1) Density. Density is a guide to other physical quantities. Density and porosity are related to the resistance to airflow through a known product depth, which is essential in heated air dryer (Madamba et al, 1994). The thermal resistivity of EPS increases with density over a certain range, so the moisture movement during drying is influenced by density (BASF TI-032/3e, 1975). The permeability to water vapour in EPS decreases with an increase of EPS density. The value of density depends on the moisture content. Because true density is moisture dependent, its values are sometimes presented as a function of moisture content. EPS blocks may be weighed as a check on average density and water content. In this project the density is expressed on a bone dry basis (samples have reached the equilibrium moisture content at a certain condition).

2) Cell structure. Another important characteristic is the cell structure which is the extent of communication between the foamed cells. When many cells are interconnected, the foam has a large fraction of open cells and is termed an open-cell foam. In contrast, numerous noninterconnecting cells result in a large fraction of closed cells and a closed-cell foam (Klempner and Frisch, 1991). Because of the moulding condition, the pre-expanded polystyrene beads produce a smooth-skinned closed-cell foam. The permeability of closed-cell foams is relatively low. This characteristic determines the high internal moisture resistance within the EPS block. Near the side faces of a block the cells tend to become flattened during moulding, because of internal pressures in the block and the cell count tends to decrease from the face to the centre. The conductivity of the EPS near the face is less than that of near the centre (BASF TI-088/1e, 1975). Expanded polystyrene foams are light, closed-cell foams with low thermal conductivity and excellent water resistance. Figure 2.2 shows the pre-expanded beads have fused into each other to form moulded expanded polystyrene.

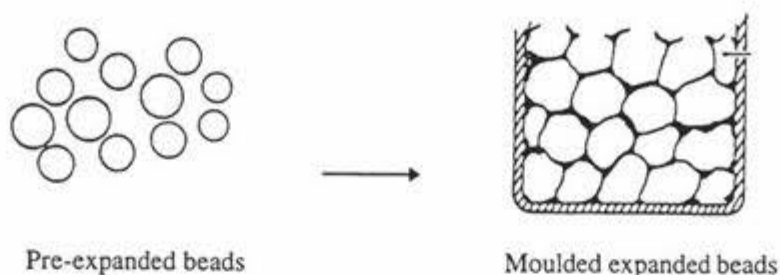


Figure 2.2 The pre-expanded beads and final moulded polystyrene beads.

3) *Porosity*. Expanded polystyrene takes up liquid water extremely slowly, but is moderately permeable to water vapour (BASF TI-042/2e, 1975). Connor (1992) found that free water cannot easily migrate through the expanded polystyrene. EPS is a porous material composed of foamed cells bound together by fusing of the cell walls with the cells remaining discrete. The porosity decreases with an increase of EPS density. Because of the cellular structure, the skin of closed-cell foamed EPS prevents moisture from moving through the individual cells. After moulding, it is assumed that most moisture exists in EPS as free water in the voids between the cells. As the polystyrene foamed beads appear to be water proof and remain as discrete bubbles the contained water remains in the interstices between the beads - increased interstices sizes allow more water to be held in the polystyrene (Connor, 1992). As EPS dries, moisture can migrate through the voids between the cells. These voids are the main path for moisture escaping.

4) *Dimensions of EPS blocks*. The characteristic dimension of drying samples proved to influence the drying rates in a negative way (Kiranoudis et al, 1992; Madamba et al, 1994). The length, width and thickness of EPS influence the moisture movement. Moisture in the zone near a surface escapes first, and later in the deeper zones. Therefore, the thicker the block, the longer it will take to establish equilibrium moisture content. When the free water is removed from the EPS, internal moisture transfer is the controlling mechanism for EPS drying. The moisture moves to the EPS surface by several mechanisms: by capillary attraction, by diffusing water vapour, by vapour convection in gas flow, etc. Keey (1978) describes the moisture movement in drying a porous material as four stages (Figure 2.3). In the first stage, the moisture is distributed continuously through the free spaces between the touching particles. The

moisture flows as liquid in the pores by capillary motion. In the second stage, the moisture is replaced by air and shrinks into rings at the waists of pores. The capillary motion ceases and the moisture becomes successive evaporation and condensation between liquid bridges. The onset of the second stage is defined as the critical point of transition at which the falling-rate period of drying begins. In the third stage, these liquid bridges evaporate entirely which only leave adsorbed moisture behind and moisture moves by unhindered vapour diffusion. The final stage is one of desorption-adsorption which the moisture in the drying material is maintained equilibrium with its environment.

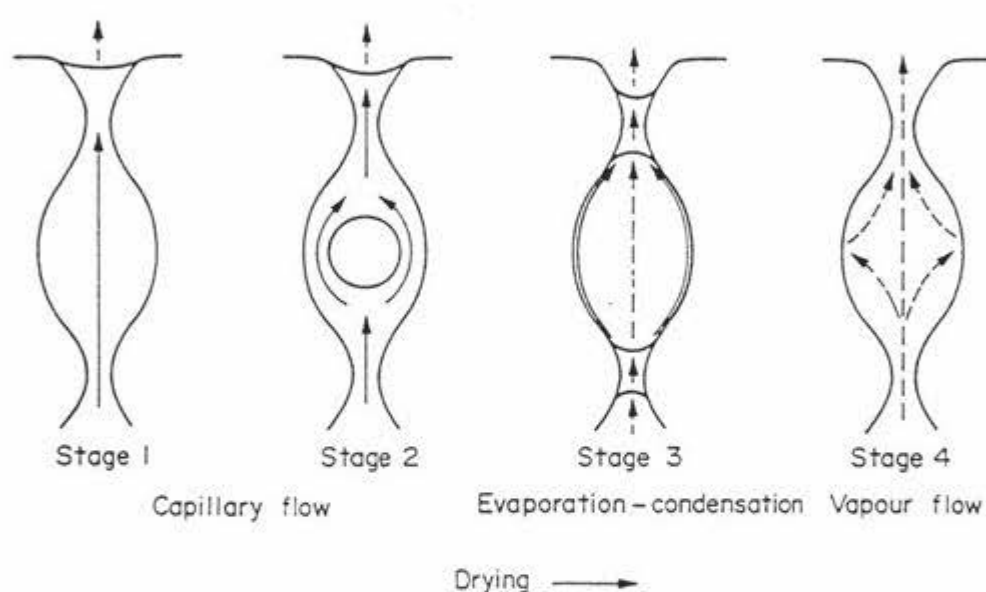


Figure 2.3 Four stages of moisture migration in the drying of a porous material.

The drying process is the mass and heat transfer through the drying body. The moisture movement through the dimensions of the drying body controls the drying time. The flow of moisture appears as moisture gradient through the EPS block. The dependency of drying rate on material thickness must be established experimentally (Perry and Green, 1984).

A small amount of shrinkage occurs when EPS blocks are dried in practice. The shrinkage is roughly the same in all three dimensions-length, width and thickness, about 1 % (BASF TI-056/2e, 1985). Comparing to the dimensions of EPS blocks, the

shrinkage is very small during drying (less than 1 %). In this project, the influence of shrinkage on the moisture transfer is negligible. The length, width and height dimensions of EPS blocks in Lanwood Industries are considered as $3.6\text{m} \times 1.2\text{m} \times 0.65\text{m}$, respectively. The volume of shrinkage is ignored during the drying process.

5) *Thermal conductivity*. Expanded polystyrene has a low thermal conductivity, the value of which depends on its density and the temperature. The function of thermal conductivity of EPS at any given temperature with variable density is explained by Klempner and Frisch (1991) as follows: at low density product, the conductivity begins to rise rapidly with decreasing density. The properties of foamed EPS depend on the size of closeness foamed cells (foamed cells are noninterconnected) which is the large the size of foamed cells, the lower the density. The coefficient of thermal conductivity of foams always increases when the cell size increases, because a porous solid consisting of a large number of small foamed cells will transfer less heat than a solid comprising a small number of large foamed cells (under similar conditions). Thus, when density is low, cell size is large and conditions are favourable for heat transfer.

The thermal conductivity of EPS also depends on the sample thickness, but the effect of thickness is small compared with that of density. "For material of density about 15 kg/m^3 the measured thermal conductivity is almost constant at thickness greater than about 40 mm, but at lesser thickness it increases steadily with thickness." (BASF TI-088/1e, 1975)

Another variable affecting the thermal conductivity of EPS is the moisture. Klempner and Frisch (1991) stated that even small amounts of moisture have a considerable deleterious effect on the heat insulating capacity of a foam. Paljak (1973) found the nearly parabolic relationship between thermal conductivity and moisture contents for the cellular polystyrene especially at the region of higher moisture content.

2.2.2.2 Temperature

As a result of heat transfer, a temperature gradient develops in the solid while moisture evaporation occurs from the surface (Mujumdar and Menon, 1995). The temperature gradient set up in the solid will also create a vapor pressure gradient, which will in turn result in moisture vapor diffusion to the surface; this will occur simultaneously with liquid moisture movement.

2.2.2.3 Moisture content

Drying is the movement of moisture from higher moisture potential to lower. Moisture content is one of the function of the moisture transfer coefficient (Koponen, 1987; Suzuki and Maeda, 1978; McCabe et al, 1993). The coefficient increases with moisture content up to a certain level (Cobbinah et al, 1984; Kiranoudis et al, 1993). Li and Morey (1987) commented that initial moisture content has little effect on drying rates. Mujumdar and Menon (1995) considered the moisture contained in a wet solid exerts a vapor pressure to an extent depending upon the nature of solid, and the temperature. A wet solid exposed to a continuous supply of hot air continues to lose moisture until the vapor pressure of the moisture in the solid is equal to the partial pressure of the vapor in the air. The solid and air are then said to be in equilibrium, and the moisture content of the solid is called the equilibrium moisture content under the prevailing conditions. Further exposure to this air for indefinitely long periods will not bring about any additional loss of moisture. The moisture content in the solid could reduced further by exposing it to air with lower relative humidity.

Since a wet solid is usually swollen compared with its condition when free of moisture and its volume changes during the drying process, it is not convenient to express moisture content in terms of volume (Mujumdar and Menon, 1995). The moisture content of a solid is usually expressed as the moisture content by weight of bone-dry material in the solid, X . Sometimes a wet basis moisture content W , which is the

moisture-solid ratio based on the total mass of wet material, is used. The two moisture contents are related by the following expression, $X = \frac{W}{1 - W}$.

2.3 Drying models and calculations

It has become feasible to develop models describing drying processes. These models can aid in the reduction of the number and type of experiments required to understand the influence of drying condition factors during drying process. The parameters of the mathematical models are necessary to predict the moisture content with time. The design of a dryer is based on a suitable mathematical model and the empirical knowledge of the drying process (Vagenas and Marinos-Kouris, 1991). In most of the drying modeling studies, it is assumed that the surface of drying product reaches equilibrium instantaneously. This is necessary because of the lack of availability of mass transfer prediction equations for the drying products exposed to almost zero air velocity. Thus, the drying parameters are calculated based on the assumption which account for both internal and external resistance to moisture transfer (Lomauro et al, 1985).

2.3.1 Pure diffusion model

In most cases the internal solid resistance to mass transfer is much higher than to heat transfer. In this situation moisture diffusion is the process that controls the drying rate in the falling-rate period.

Diffusivity can be defined by Fick's first law of diffusion (Crank, 1956):

$$F = -D \frac{\partial C}{\partial z} \quad (2.1)$$

where, F is the moisture flux ($\text{kg/m}^2 \cdot \text{s}$), C is the local moisture concentration (kg/m^3), z is the space coordinate (m), and the D is the moisture diffusivity (m^2/s).

The well known Fick's second law which is the fundamental differential equation of diffusion, derived from Equation (2.1) for an isotropic medium (Crank, 1956):

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} \quad (2.2)$$

where, C is the local moisture concentration (kg/m^3), t is the time(s), D is the moisture diffusivity (m^2/s) which is taken to be independent of concentration.

Equation (2.2) can be derived to Equation (2.3), which considers diffusivity depending on concentration, by introducing the local concentration of dry solids ($\rho \text{ kg/m}^3$). The local concentration (ρ), equals the mass of dry solids divided by the volume of the moist material, which varies with moisture content as in the case of shrinkage caused by dehydration (Zogzas et al, 1994).

$$\frac{\partial(\rho X)}{\partial t} = D \frac{\partial^2(\rho X)}{\partial z^2} \quad (2.3)$$

where X is the local moisture content (dry basis) of the amount of water per unit weight of the dry solid (kg/kg).

An analogous form of Equation (2.3), neglecting shrinkage and using the moisture content, X (kg/kg dry basis), is as:

$$\frac{\partial X}{\partial t} = D \frac{\partial^2 X}{\partial z^2} \quad (2.4)$$

Pakowski and Mujumdar (1995) described the situation where moisture diffusion is the process that controls the drying rate in the falling rate period. Equation (2.4) can be used to calculate the drying rate under these conditions. For a given boundary conditions this equation can be solved for any given geometry.

Marinos-Kouris and Maroulis (1995) pointed out diffusion in a solid during drying is a complex process that may involve molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion. Combining all these phenomenon into one, the effective diffusivity can be defined from Fick's second law. Equation (2.4) shows the time change of the material moisture distribution, this equation can be used for design purposes in cases in which the controlling mechanism of drying is the diffusion of moisture.

Pakowski and Mujumdar (1995) described the use of Equation (2.4) for the calculation of the drying rate, while Strumillo and Kudra (1986) described its use in calculating the drying time. Solutions of the Fickian equation for a variety of initial and boundary conditions are entirely described by Crank (1956).

The effective moisture diffusivity is estimated from the drying data (Saravacos et al, 1989). The ratio of actual moisture content at any time in excess of the equilibrium moisture content (X_e) to the difference between X_o and X_e is defined as the moisture ratio (MR), where $MR = (X - X_e) / (X_o - X_e)$, and X_o is the initial moisture content (Rangroo and Rao, 1992). The drying data can be plotted as moisture ratio (MR) versus time (t). If the initial moisture content of the samples is relatively low, the internal diffusion of moisture controls the drying process, and all the experimental data are obtained in the falling-rate period.

The analytical solution of Equation (2.4) for an infinite slab, assuming undimensional moisture movement without volume change, constant diffusivity, uniform initial moisture distribution and negligible external resistance, is:

$$MR = \frac{\bar{X} - X_e}{X_o - X_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \frac{\pi^2 Dt}{4L^2}\right] \quad (2.5)$$

where, MR is the dimensionless moisture ratio, $\bar{X}$ is the average moisture content of the wet material (kg/kg dry basis), X_o is the initial moisture content (kg/kg dry basis),

X_e is the equilibrium moisture content (kg/kg dry basis) and L is the one half-thickness of the slab (m).

Chungu and Jindal (1993) addressed another assumption on Equation (2.5) that during the falling-rate period all exposed surfaces are at the equilibrium moisture content and offer no resistance to moisture transfer. The apparent moisture diffusion coefficient is function of temperature, relative humidity and initial moisture content. The equilibrium moisture content of materials in drying processes can be determined by linear extrapolation of the drying data (Saravacos et al, 1989).

A simplified diffusivity coefficient measurement was described as Equation (2.6) in which all terms except the first in the summation series in Equation (2.5) are small, and can be omitted. In this case, the diffusion coefficient D can be measured from the slope of the plot of $\ln(MR)$ against time t or t/L^2 (Hawlder et al, 1991; Gekas and Lamberg, 1991).

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 Dt}{4L^2} \quad (2.6)$$

Alzamora et al (1980) stated the falling rate period was studied by plotting the experimental data as $\log(X-X_e)/(X_o-X_e)$ versus time; if the data fell on a straight line the moisture diffusivity was calculated from its slope. Lomauro et al (1985) introduced the equation $D = -(4L^2/\pi^2) * \text{slope}$ in determining effective or apparent diffusion coefficient, where the slope is obtained from a plot of $\ln(MR)$ versus time. The method is especially useful when a break in the MR versus time plot is observed. A diffusion coefficient can be obtained for each portion of the curve.

Equation (2.7) is used for calculating the drying time which is derived from Equation (2.6), when Dt/L^2 is greater than 0.1 (Brooker et al, c1992).

$$t = \frac{L^2}{\pi^2 D} \ln \frac{8\pi^2 (X_o - X_e)}{\bar{X} - X_e} = \frac{4L^2}{\pi^2 D} \ln \frac{8\pi^2}{MR} \quad (2.7)$$

Equation (2.7) is for materials in which moisture movement is controlled by diffusion, where t is the drying time in the falling-rate period. For the falling-rate period, differentiating Equation (2.7) with respect to time and rearranging gives (Perry and Green, 1984):

$$-\frac{dX}{dt} = \frac{\pi^2 D}{4L^2} (X - X_e) \quad (2.8)$$

Equation (2.8) shows that when diffusion controls the drying process, the rate of drying is directly proportional to free-moisture content and inversely proportional to the square of the thickness; and that if time is plotted against the logarithm of the free-moisture content, a straight line should be obtained from the slope which D can be calculated.

If the porous size of a granular material is suitable, moisture may move from a region of high to one of low concentration as the result of capillary action rather than by diffusion. A porous material contains a complicated network of interconnecting pores and channels. The capillary forces provide the driving force for the movement of water through the pores toward the surface (Perry and Green, 1984; McCabe et al, 1993).

For drying under constant conditions, the drying time can be determined from the drying-rate curve. The drying rate during the falling-rate period can be expressed as a function of the free moisture content of the material as follows:

$$R = -\frac{m_s}{A} \frac{dX}{dt} \quad (2.9)$$

where R is the drying rate ($\text{kg/m}^2 \cdot \text{hour}$), m_s is the drying solid mass (kg), X is the free moisture content (% kg/kg dry basis), t is the drying time (hour).

The total drying time can be expressed as:

$$t = \frac{m_s}{A} \int_{x_e}^{x_s} \frac{dX}{R} \quad (2.10)$$

Chien et al (1971) stated most of the equations and theories on the mechanism of moisture flow have been set up for thin layer drying. By making use of several simplifying assumptions, (that is considering that a deep bed is composed of a group of thin layers based on the heat and mass balance analysis in a thin layer, and developing calculation formulas by layers), they considered an approach to the investigation of the moisture movement in deep bed drying which includes the use of dimensional analysis.

Roman et al (1979) emphasised Equation (2.5) can be used in three different fashions, which do not necessarily yield the same results. By assuming that when the term n equals to zero, a good approximation to the results D can be obtained numerically or graphically from a semilogarithmic plot of $\log(X-X_e)$ versus time (t). Bluestein and Labuza (1972) discussed that effective diffusion coefficients which are calculated from each data point, represent the integral of the instantaneous effective diffusion coefficient starting from time zero by taking more terms of the series.

Some good results were obtained by using two-term exponential model (Equation 2.11) to describe drying behaviour (White et al, 1973; Sharaf-Eldeen et al, 1980; Syarief et al, 1984).

$$MR = A_1 \exp(-k_1 t) + A_2 \exp(-k_2 t) \quad (2.11)$$

where A_1 , A_2 , k_1 and k_2 are empirical drying parameters.

Lebert and Bimbenet (1991) noted that adjusting with 2 or 3 exponential terms gives a better prediction for the product moisture evolution versus time than adjusting with only one exponential term.

2.3.2 Semitheoretical drying equations

A simplification of the solution to the diffusion equation (2.5) has frequently been used to predict the drying rate (Brooker et al, c1992). Instead of an infinite number of terms, only the first term of Equation (2.5) is employed to calculate the drying rate. The following expression results:

$$MR = \frac{X - X_e}{X_o - X_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D t}{4L^2}\right) = \frac{8}{\pi^2} \exp(-Kt) \quad (2.12)$$

where K is the drying constant.

Perry and Green (1984) assumed for long drying times, Equation (2.5) simplifies to limiting form of the diffusion equation as Equation (2.12) when D is constant. Chien et al (1971) stated the similar equation (2.13):

$$MR = \frac{X - X_e}{X_o - X_e} = a \exp(-kt) \quad (2.13)$$

where a is the coefficient intercept on the ordinate of semilogarithmic graphs, k is the drying constant.

Xiong et al (1991) determined effective diffusivities from drying curves. The value of D at different moisture contents was evaluated from the slope by employing Equation (2.12). The effective diffusivity is fairly constant at sufficiently high moisture levels and decreases at lower moisture contents as can be seen from typical variation of D with moisture. This drop in the effective diffusivity as moisture content decreases may be thought of as a result of a decrease in the availability of water molecules for diffusion.

A very similar relationship to Equation (2.12) that is analogous to Newton's law of cooling is often used in drying analyses, Equation (2.14) (Brooker et al, c1992; Sun and Woods, 1994).

$$MR = \frac{X - X_e}{X_o - X_e} = \exp(-kt) \quad (2.14)$$

Equation (2.12) and (2.14) are both called the "semitheoretical drying equations" and K and k the "drying constants". The units of K and k are hour^{-1} . For constant air velocity and relative humidity, k may be a function of temperature, moisture content and moisture ratio (MR) (Dung et al, 1981).

Equation (2.12) may be differentiated to give the drying rate as Equation (2.8), where dX/dt is the drying rate, kg/hour (Perry and Green, 1984). The drying rate of a solid material is proportional to the difference between moisture content at any time and the equilibrium moisture content (X_e) (Lewis, 1921; Chien et al, 1971; Dung et al, 1981), that is stated as Equation (2.15).

$$\frac{dX}{dt} = -k(X - X_e) \quad (2.15)$$

When Equation (2.5) is plotted on semilogarithmic graph paper, a straight line is obtained when the value of $(X - X_e)/(X_o - X_e)$ is less than 0.6. Equation (2.5), (2.7), (2.8) and (2.15) hold only for a slab-sheet solid whose thickness is small relative to the other two dimensions. Crank (1956) stated the mathematical solutions for other shapes.

Chakraverty and Dey (1981) indicated the plot of moisture ratio (MR) versus drying time (t) on semilogarithmic graph paper yields straight line. Accordingly, the slope of the straight line is the drying constant k . The drying constant, k was the calculated by the graphical method. The results show that the air temperature has a significant effect on k and the airflow rate has no significant effect on k . That is, the rate of drying

increased with the increase of air temperature and the variation in air velocity has no significant effect on rate of drying.

Henderson and Perry (1976) analysed moisture content data using the Newton drying Equation (2.14). In order to get a better fitting of the drying curve, Equation (2.14) is rearranged as Equation (2.16) (Banaszek and Siebenmorgen, 1993; Sun and Woods, 1994).

$$X = (X_o - X_e) \exp(-kt) + X_e \quad (2.16)$$

2.3.3 Empirical drying equations

Several purely empirical drying equations have been developed. Some researchers have used a modification of the Newton drying equation that is commonly referred to as Page's equation (2.17). This modification consists of including an additional parameter to the Newton's equation (2.14), resulting in better agreement with experimental data. The thin-layer drying process is customarily characterised by moisture ratio (MR) and time (t) of drying by the Page's equation (2.17) (Page, 1949; Sabbah, 1968).

$$MR = \frac{X - X_e}{X_o - X_e} = \exp(-kt^N) \quad (2.17)$$

where k is the drying constant, N is the exponent parameter.

Taking natural logs on both sides of Equation (2.17) above and rearranging, the general procedure for the determination of k and N of Page's equation (2.17) is as Equation (2.18) (Overhults et al, 1973; Hutchinson and Otten, 1983; Ramesh and Srinivasa, 1996).

$$\ln(-\ln(MR)) = \ln(k) + N \ln(t) \quad (2.18)$$

Diamante and Munro (1991) modified Page's equation (2.17) to include the same dependence on samples thickness as the Fick diffusion equation to give the modified Page's equation (2.19).

$$MR = \frac{X - X_e}{X_o - X_e} = \exp\left[-k\left(\frac{t}{L}\right)^2\right] \quad (2.19)$$

Li and Morey (1987) used Page's equation (2.17) to describe thin-layer drying rates. Linear regression was employed to find the drying parameters k and N for each run. The results show that drying air temperature has a significant effect on both k and N . The dimension has little effect on k but some effect on N . Li and Morey (1987) plotted the values for k and N versus airflow rate. The results show that airflow rate has no significant effect on drying rates. Li and Morey (1987) studied a linear regression analysis between drying parameters k and N and initial moisture content. The correlation coefficients between k and N and initial moisture content (X_o) suggest that initial moisture content has little effect on drying rates. However, Banaszek and Siebenmorgen (1993) argued that the drying constant was found to be a function of initial moisture content. The experimental data were fitted from different initial moisture contents to the moisture transfer equation given by Page (Banaszek and Siebenmorgen, 1990). Overhults et al (1973) described preliminary studies with several other drying equations which indicated that a model similar to that used by Page (1949) and later by Sabbah (1968) would adequately describe the experimental data. The model (Equation 2.17) drying constants k and N were estimated from the data by using a computerized least squares technique.

Chandra and Singh (1984) found the values of the coefficients k and N were related to initial moisture content, relative humidity and air temperature. Misra and Brooker (1980) concluded that the drying temperature and air velocity significantly affected k , and relative humidity of air and the initial moisture content affected N . Syarif et al (1984) found the final coefficients for Page's equation were a function of drying temperature only. Bruce (1985) showed the superiority of Page's equation (2.17) to Newton's equation (2.14) with respect to time. That is, Page's equation (2.17)

describes the observed drying curve more closely and is a significant improvement over the Newton's equation (2.14). Bruce (1985) found the initial drying rate which is predicted by Page's equation (2.17) is normally too high. The Page's equation (2.17) is effective where accurate modeling of initial drying behaviour is not important.

Overhults et al.(1973) considered no theoretical relationship between the exponent, N , and the various test conditions was known. Plots were made with several different variables and the most consistent relationship was found to be between N and the drying air temperature. The change in N over the range of initial moisture contents was very small as compared with its change over the range of experimental temperatures. The results of regression analysis indicate that k does vary slightly with the initial moisture content.

The model (Equation 2.17) was transformed to a linear equation of the form Equation (2.20).

$$X = (X_o - X_e) \exp(-kt^N) + X_e \quad (2.20)$$

Values of k and N of Equation (2.20) for each test were then determined by regression methods (Overhaults et al, 1973; Misra and Brooker, 1980; Syarief et al, 1984; Banaszek and Siebenmorgen, 1990; Ramesh and Srinivasa Rao, 1996). The regression coefficient for fitting the foregoing model to the data was greater than 0.98 for all tests (Overhults et al, 1973).

White et al (1973) found that the following modified Equation (2.21) fitted the drying curve better than Equation (2.17) in some case.

$$MR = \exp[-(kt)^N] \quad (2.21)$$

The two-term exponential equation (2.11) and Newton's equation (2.14) are exponential in nature and have some theoretical background. Page's equation (2.17) is

a pure empirical equation which is better to fit the experimental data. These mathematical models have been developed to predict drying processes.

Chapter 3 Materials and Experimental Work

The drying of EPS product is perhaps the longest operation in the manufacturing process, and is carried prior to cutting the EPS block by hot wires. The research studied the drying process of the EPS product in the existing drying kiln. The aim of this project was to set up a model to predict the drying time of the EPS product which can lead to the optimization of the drying result. This chapter describes the EPS product producing and drying process, the cutting problem which is caused by moisture in the EPS product, and the drying equipment and measurement in the laboratory and the drying kiln.

Experiments were carried out in a laboratory (Production Technology Department, Massey University) and in the manufacturing company (Lanwood Industries, Palmerston North, New Zealand) for samples and the full-scale product drying tests, respectively. In the laboratory tests, drying samples were cut from fresh moulded EPS blocks, then dried in a drying cabinet and weighed at known time intervals on electronic balances. Full-scale tests were set up in a drying kiln during the current production operation at Lanwood Industries. Fresh moulded EPS blocks were weighed during drying on a weighing scale which was connected with a computer. Air temperature, humidity and air velocity were recorded during the EPS product drying in both laboratory tests and full-scale tests.

In this research, the equilibrium moisture content was assumed to have been reached when the EPS product weight changed less than 0.002 g/g over a 24 hour interval. Laboratory tests were designed to scale up the drying results from the laboratory to the factory which involved three temperatures (40, 50 and 60 °C) and three cubic samples (100, 200 and 250 mm cube). There was little difference of the drying curves between 40 and 50 °C. Drying rate increased a lot at 60 °C. The drying rate decreased with

increasing of the sample cubic size. Only the falling drying-rate period was observed in laboratory drying tests.

3.1 EPS products

3.1.1 Materials

Expanded polystyrene contains a blowing agent, pentane, which can convert polystyrene raw beads into foams. To foam a polystyrene block, raw polystyrene beads are first expanded by contact with steam at atmospheric pressure. The degree of expansion obtained in this step determines the density of the final moulded polystyrene block (BASF TI-038/1e, 1974). If producing very low density blocks, two-stage pre-expansion may be required.

Starex EPS (SF-160, Cheil Industries INC, Made in Korea) is used for industrial EPS blocks making. The EPS blocks made by Lanwood Industries are for the insulation construction industry with the length, width and height of dimensions 3.6m×1.2m×0.65m, respectively.

3.1.2 EPS production processes

At Lanwood Industries, the EPS production processes include expansion (pre-expansion and moulding), drying and cutting, etc.

3.1.2.1 Expansion

Raw polystyrene beads should be pre-expanded to expanded foam beads first according to the required density of the EPS product. To produce pre-expanded polystyrene of constant density it is necessary to provide a steady supply of steam. During the pre-expansion of beads, the cells are filled with mixture of pentane vapour

and water vapour. Polystyrene beads are moist after being pre-expanded in live steam. When the beads cool down, the water vapour condenses and the residual pentane redissolves in the polystyrene. Since moist beads are not suitable for moulding, they must dry out before the end of the normal aging period (BASF TI-083/1e, 1977). The pre-expanded material should be stored for at least 5 to 8 hours depending on its density. The intermediate storage of pre-expanded polystyrene in silos also diffuses out the residual blowing agent. This reduces the blowing agent to the extent necessary for further processing. At Lanwood Industries, mesh storage silos are used for intermediate storage of pre-expanded beads allowing air to flow freely through the beads.

The final expansion involves the conversion of the loose mass of pre-expanded polystyrene into foamed blocks. In this stage, dry steam is fed to the mass of beads, causing the polymer structure to soften, at the same time increasing the vapour pressure of the residual blowing agent and consequently causing the further expansion of the beads. This process is carried out in a confined space with gas-permeable walls which are nevertheless firm and do not allow any increase in volume; polystyrene can only expand to take up the free space between the beads. These voids are closed, causing the touching surfaces to fuse together. The overall density of moulded EPS is approximately the same as the bulk density of pre-expanded beads. The degree of pre-expansion is controlled by varying the time that the beads are exposed to steam.

The density is not uniform throughout the EPS blocks moulded at Lanwood Industries. It is assumed that the uneven density in a moulded block is due to the uneven steam during moulding and the steam passing the polystyrene beads unequally. The polystyrene beads which are first in contact with steam expand and fuse together. There is no more room for the expansion of the beads which are later applied with steam. The beads in the centre of the block fuse together by the steam but can not expand as much as the beads near the end faces of the block, thus causing the density within the block to be uneven. Appendix A shows the measurement of uneven density distribution in an EPS moulded block. The difference in density causes differences in

internal physical properties in EPS blocks, such as compressive stress, strength and thermal conductivity, etc.

3.1.2.2 Drying

The EPS block needs to be dried to allow the pentane and moisture to disperse before being cut into slabs by hot wires. At Lanwood Industries, the EPS block must be dried at about 50 °C for more than a week to be free from internal moisture and residual pentane. The EPS block drying is presumed to proceed as follows: after moulding, the block is taken out of the moulder and moved into the drying kiln. The surface moisture evaporation starts when the moulding pressure is released, which is the initial drying stage. Moisture on the surface of the EPS moulding skin escapes very quickly. Once the surface dries out, moisture from inside of the block starts to move to the surface, this moisture movement controls the total drying rate. At Lanwood Industries, when the EPS block warms up in the drying kiln, heat flows to the outer surfaces and then into the interior of the block. Mass is transferred as liquid and vapour within the EPS block and as vapour from the surface. This movement results from the combined effects of the moisture and temperature gradients of the heat and mass transfer. The temperature gradient creates a moisture gradient and thus causes moisture migration. When the moisture migrates away from the EPS surface, the drying front moves into the EPS block.

During the moulding, pre-expanded polystyrene beads are fused together with closed-cell foam which is noninterconnected (Klempner and Frisch, 1991). The skinned pre-expanded beads have low water vapour permeability which resist the moulding steam penetrating through the expanded polystyrene cell walls to the cores (Connor, 1992). That is, most free moisture will exist in the interstices between the cells after moulding, and these interstices provide the passageway for the moisture movement. During drying, the moisture flows as liquid in the voids by capillary motion. When the capillary motion ceases, the moisture becomes successive evaporation between liquid bridges. When the moisture is insufficient to supply the liquid bridges, it is moved out by

diffusion (Keey, 1978). The voids between cells extend the moisture diffusion distance in the EPS block. The drying rate therefore decreases with increasing thickness of the porous material. In EPS block drying, moisture gradients occur along the length, width and height of the block which involve three dimensional drying.

The moisture in a fresh EPS block comes from the moulding steam. Moist board has a higher apparent density than dry board, and unless it is dried before being used there is a risk of passing board that does not satisfy minimum requirements when the density measurement is used for quality control purposes (BASF TI-032/3e, 1975).

There are also a number of undesirable consequences of the moisture in the EPS product. Moisture lets the hot wire cool down resulting in inaccurate cutting of the EPS block. In flat roofs the water vapour can blister the membrane; in cold stores wall tiles may spring; in sandwich units the facing may part from the core (BASF TI-032/3e, 1975); and moisture will condense within the panel depending on the temperature and reduce the insulation effect (Connor, 1992).

It is necessary for reducing drying time that the prefoamed beads are evenly dried and matured, and that moulding conditions are optimized to minimise the amount of moisture held in the block.

3.1.2.3 Cutting expanded polystyrene

A number of techniques are used to cut blocks of expanded polystyrene. The principal ones are: power saws, routers and electric wire cutters (Shell Plastics). Where a moulded block has simply to be cut into sheets, the most widely used techniques is cutting by electrically heated resistance wires. The method is simple and electrically safe provided low voltages are used, and the equipment is relatively cheap. At Lanwood Industries, most of the EPS blocks are cut by multiple cutting hot wires. Hot wire cutting is slower than sawing. To offset this disadvantage, multiple wires are

stretched across a frame so that the block is cut into a large number of sheets in one pass.

Expanded polystyrene blocks are cut for required uniformity of thickness and smoothness of the slabs. In practice, variations in the moisture content and moisture distribution occur within the block which cause uneven marks to be made by the hot wires. This is because if there is water within the block, the hot wire will encounter the wet patch during the cutting, which results in the wire cooling down, this produces slight ripple marks on the cut sheet. These faint marks can be minimised by ensuring that EPS block has been given time to dry out properly. Due to the additional hazard created by the exposed hot wire, it is particularly important that residual pentane diffuses out of the cutting block. The moisture content of EPS blocks should be tested after drying for the cutting requirement. Good cutting results are characterized by closed, low-gloss or only slightly grained cut surfaces.

3.2 Drying experiments

3.2.1 Drying samples

In this research, drying samples were collected from the manufacturing company (Lanwood Industries). Drying samples were cut from fresh moulded blocks with density in the range of 15 to 24 kg/m³. In order to study the relationship of the drying rate and the thickness of the drying material, EPS drying samples were cut into a cubic shape to simulate the full-scale drying process.

The uneven steam distribution within the mould and uneven density within the block cause the uneven moisture content distribution within the block during the moulding. Therefore, drying samples taken from one EPS block in each test run had initial moisture content which were quite different. Appendix B illustrates experimental data of the uneven moisture distribution in the EPS block.

3.2.2 Equipment

Experiments were done for the EPS drying on both laboratory and factory scales. They were the laboratory drying cabinet tests and full-scale Lanwood Industry drying kiln tests. A drying cabinet was constructed for the EPS sample drying. All the experiments were carried out at atmosphere pressure.

3.2.2.1 Drying cabinet

The drying cabinet in this project is reconstructed from a domestic clothes drying cabinet. It contains two shelves which are made of expanded metal. There is an electrical heating element in the bottom of the cabinet. The heating element can be adjusted to the required temperature. One temperature sensor is installed on a draught-hole close to the heater which is used for the temperature control. Under the heater, a fan is installed that can blow the heated air up, and the hot air is distributed evenly by a layer with draught-holes before passing the two shelves. This is to ensure an even air flow passing over the samples area and to obtain a uniform temperature profile in the air flow in the drying cabinet. The dimensions of the dryer cabinet are: length, 550 mm; breath, 470 mm; lower shelf thickness, 245 mm; upper shelf thickness, 260 mm. Two temperature sensors were installed to record the drying air temperature which can be read on two electronic thermometers. One is on the upper shelf (Dick Smith Electronic Q-1424, ± 0.1 °C, Made in Taiwan), the another is installed under the lower shelf (Lutron TM-902C, ± 1 °C, Made in Taiwan). A thermometer (maximum 110 °C, ± 0.1 °C) is installed on the top air outlet channel which can directly show the outlet air temperature. The aperture of the outlet channel on the top of the cabinet can be adjusted to control the air flow. The walls of drying cabinet are insulated with 15 mm thick expanded polystyrene slabs to minimise the effect of heat loss to the surroundings. Figure 3.1 shows the structure of the drying cabinet.

The drying conditions were measured manually during the laboratory experiment. Relative humidity was measured at air outlet channel by Rotronic A1 Hygrometer

instrument with the humidity sensor type CK 90 (± 0.1 % RH) and a silicon diode temperature sensor (± 0.1 °C) which permit accurate measurement of humidity and temperature. Air flow rate was monitored at air outlet channel by a wind speed indicator (Turbo Meter, Davis Instruments, Made in USA, ± 0.1 m/s). The relative humidity was about 10 to 12 % RH at the drying temperature 50 °C. The air flow rate was about 1.6 to 2.2 m/s.

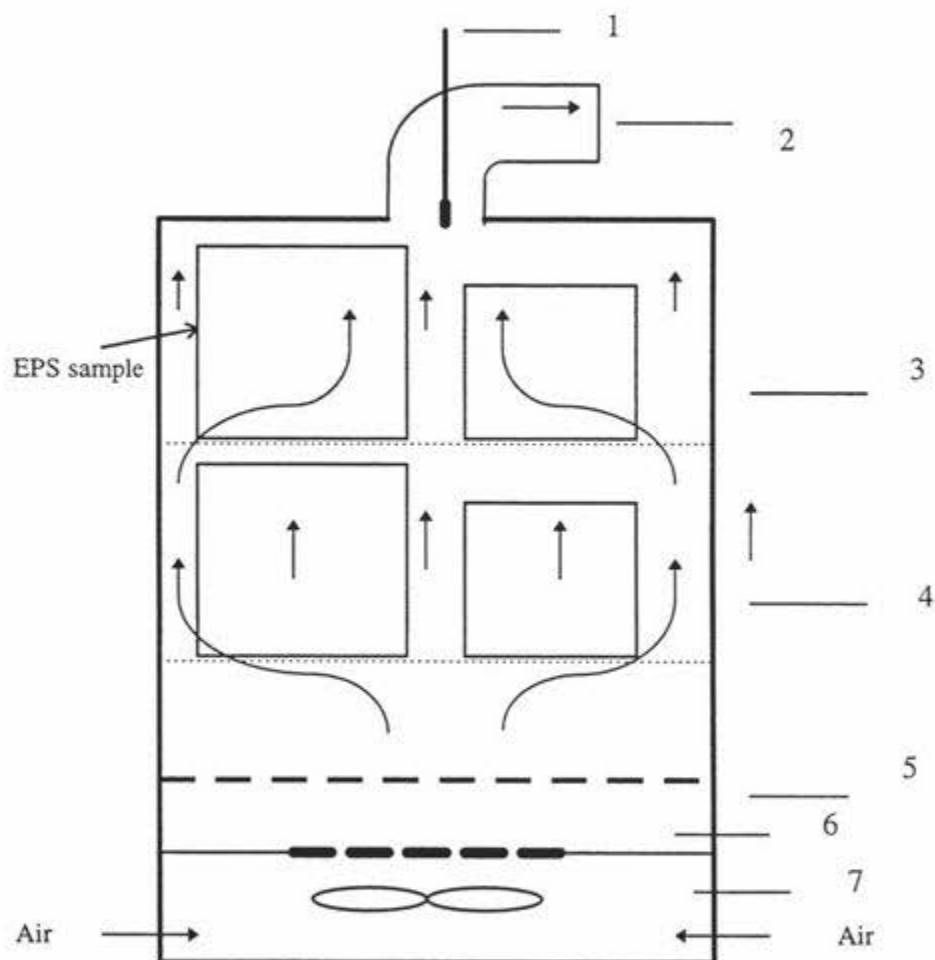


Figure 3.1 The drying cabinet. 1, thermometer; 2, air outlet channel; 3, upper shelf; 4, lower shelf; 5, air distributor holes; 6, heater; 7, air fan.

The weighing system consists of two electronic balances: a Mettler P162 (Mettler CH-8606 Greifensee-Zurich, Made in Switzerland) and a Mettler PE6000 (Mettler CH-8606 Greifensee-Zurich, Made in Switzerland). During the test, drying samples were taken out of the drying cabinet and weighed at known time intervals. Sample weights

less than 160 g were weighed by the electronic balance Mettler P162, which has a maximum weight limit of 160 g and accuracy of ± 0.001 g. Sample weights more than 160 g were weighed by Mettler PE6000 which has a maximum weight limit of 6000 g and accuracy of ± 0.01 g. The sample weight loss was converted to a moisture content (kg/kg dry basis) which was represented as a function of drying time at known time intervals. The accuracy of moisture content was ± 0.002 g/g (dry basis).

3.2.2.2 Drying kiln

EPS blocks are dried in a drying kiln at Lanwood Industries. The drying kiln has three chambers which can contain a total capacity of 142 EPS blocks (Figure 3.2). EPS blocks are placed vertically with about a 10 mm gap between each other.

In the drying kiln, hot air is supplied by a recirculating air blower through the air ducts on the floor level on which the EPS block stands (Figure 3.3). Air blows out through air ducts from the bottom of the drying chambers to the roof. The air movement pattern is shown in Figure 3.4. The air flow rate was found to increase from the end of the chambers to the door. Hot air passes over the surface of the EPS block and this provides both the source of the heat and the removal of the vapour.

The most difficult measurement in the drying kiln is the moisture content of the drying material which is the weight loss of the EPS product during the drying. A weighing scale (Sauter EB60 Weighscale, D-7470 Albstadt 1-Ebingen, Made in Germany) which connected to a computer (PC 286) was placed at the end of a drying chamber. The maximum weight of the weighscale is 60 kg at which accuracy is ± 20 g. The weight of the EPS block was recorded at successive time intervals on the computer during the drying (Figure 3.5). The EPS block and its surrounding temperatures were measured by seven temperature sensors (Dallas, DS1820) which connected to an interface which was powered by a 9V, 500mA adaptor. Two temperature sensors were placed within the EPS block; one at the middle and one halfway to the middle. The others that measured the air temperature were around the block from bottom to the top and one

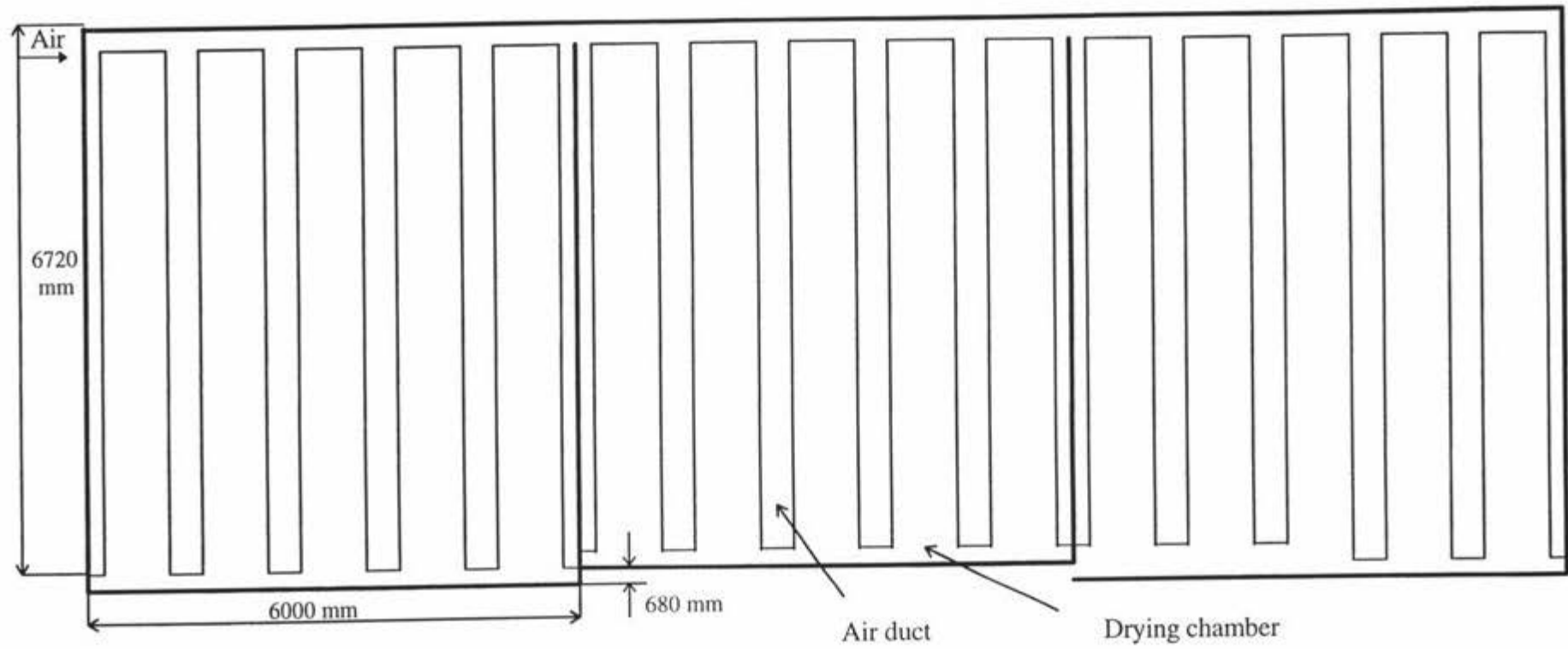


Figure 3.2 The Lanwood kiln ductwork.

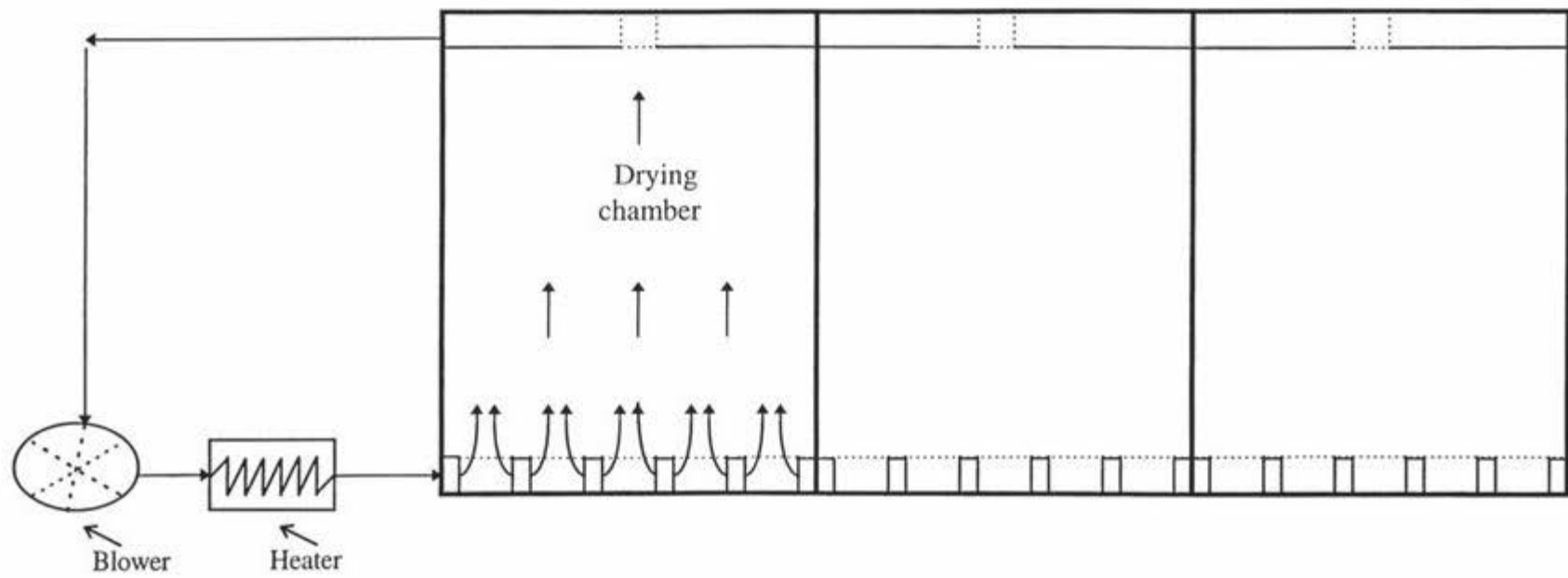
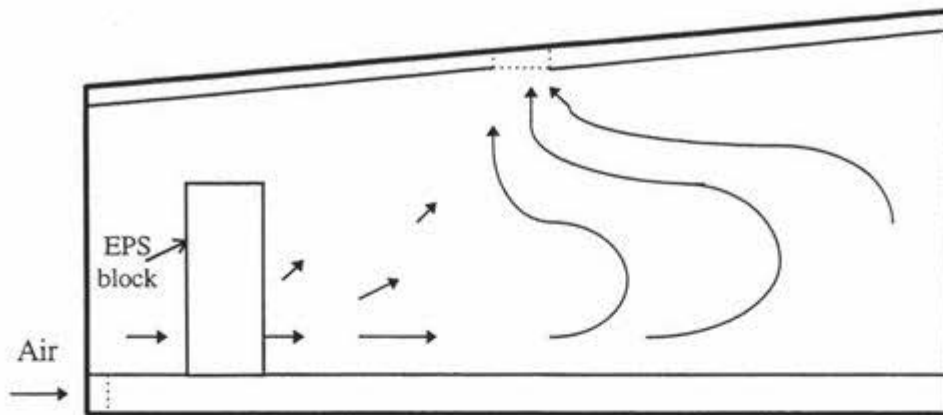
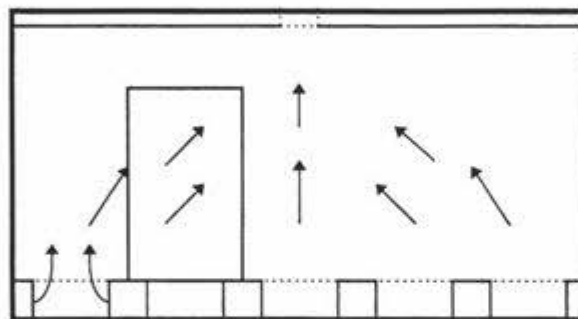


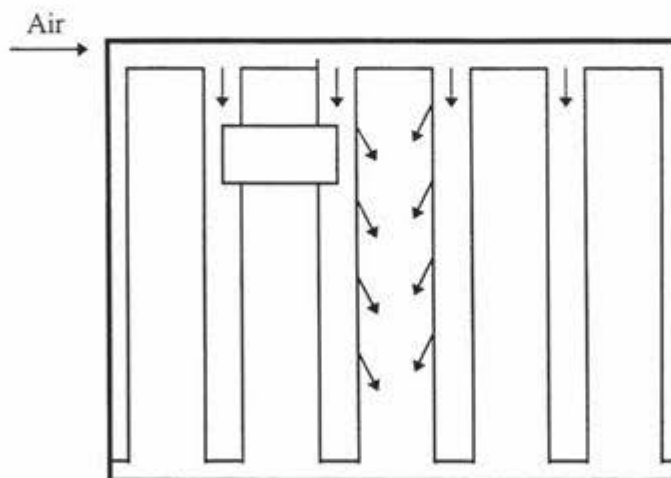
Figure 3.3 Diagram of the air flow in Lanwood drying kiln.



a: side view



b: front view



c: top view

Figure 3.4 Air flow in a drying chamber. a: side view, b: front view, c: top view.

was adjacent to the inlet air duct. The experimental data - temperature and weight recording were realised through the code written in Pascal Language. An Uninterruptable Power Supply (UPS-300, Optronix, New Zealand) system was set up to avoid data record interruptions because of the power cuts.

The drying kiln is maintained at atmospheric pressure with air circulated at a temperature of about 50 °C in the current drying operation. Relative humidity was measured by Rotronic (Hygroskop A1) portable instruments with type CK90 humidity sensor (± 0.1 % RH) and a silicon diode (± 0.1 °C) for the measurements of humidity and temperature, respectively. Air flow rate was recorded using an anemometer (Airflow, DVA 30VT) with an accuracy of ± 0.01 m/s in different position of the drying chamber. The measured relative humidity was about 14 to 16 % RH which was apparently higher than the laboratory tests (10 to 12 % RH). The measured air flow rate distribution was quite different in the drying kiln. The air flow rate varied from 0.7 m/s to 1.8 m/s at different points of the air duct level in the drying kiln.

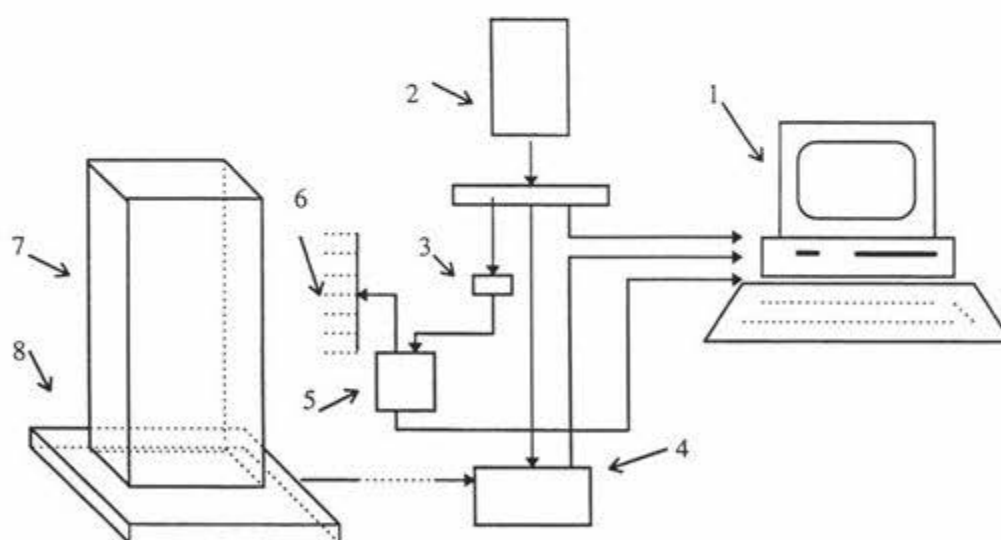


Figure 3.5 A schematic diagram of the full-scale experimental apparatus. 1, computer 286; 2, UPS-300; 3, adaptor; 4, Sauter 1200 recorder; 5, temperature interface; 6, temperature sensors Dallas; 7, EPS block; 8, weighing scale EB60.

3.2.3 Measurements

A number of variables are measured in the drying cabinet and the drying kiln. They are:

- air temperature
- air relative humidity
- air flow rate
- sample weights at known time intervals
- sample dimensions (length, width and thickness)
- sample center and surface temperature (full-scale experiments)

In laboratory experiments, sample weights were measured off-line by electronic balances. In full scale experiments, the block weight and temperature were recorded on-line by a computer. All air conditions were measured on-line throughout these experiments.

3.2.3.1 Laboratory drying measurements

After preliminary tests involving weighing samples from the drying cabinet at various intervals, the following procedure was adopted for the laboratory experiments in this research.

A total of 9 experimental runs lasting from 1 to 3 weeks each were performed. Five runs were used for the data analysis. The drying cabinet was set to the required conditions of air temperature and air flow rate. The drying temperature and the air flow rate were kept constant during drying. The temperature, relative humidity and air flow rate were measured at the end of the air outlet channel. For each run the drying cabinet was allowed to stabilize at least half an hour at the specified air temperature before the test began.

In laboratory experiments, EPS samples were cut from the fresh moulded EPS blocks with fresh surfaces in the factory by a band saw or hot wires for required cubic sizes. Because residual volatile blowing agent in expanded polystyrene blocks can be ignited by hot wire cutting equipment, when samples were cut by hot wires a dry power extinguisher was kept close to the cutting machine in the event of emergencies. Each cubic size had a duplicated sample for accurate measurement. After cutting, samples were wrapped in plastic film then taken to the drying laboratory as soon as possible to avoid moisture loss. In the laboratory, samples were weighed at ambient temperature by electronic balances (Mettler P162 and Mettler PE6000) immediately after the plastic film was opened, which were the initial weights of samples. Then samples were placed in the drying cabinet to start drying at the specified temperature and weighed at known time intervals. After the last weighing, the sample dimensions were accurately measured and the sample density was calculated.

The moisture content is obtained from the following procedure: during drying, the EPS sample is taken out of the cabinet at known time intervals and weighed on electronic balances; this is the wet weight of the sample, m_w (g). After weighing, the sample is taken back to the cabinet; the final measurement of weight is considered at which the EPS product has reached the equilibrium moisture content, m_d (g); the moisture content is obtained from the equation as follows:

$$X = \frac{m_w - m_d}{m_d} \quad (3.1)$$

where X is the dry basis moisture content (%). The accuracy of moisture content was ± 0.002 g/g (dry basis).

It is well known that the drying curve is used to represent the drying process. The drying curve is based on experimental data of the moisture content at known time intervals during the course of a drying operation, which is plotted as the moisture content versus time. The slope of this curve at any point represents the instantaneous drying rate corresponding to one particular moisture content. In one of the preliminary

tests a total number of thirty samples (about 50 mm cube) were dried at 50 °C in 200 hours. Figure 3.6 is the drying curve of the mean moisture content of thirty samples versus time at 50 °C. Figure 3.7 is the drying rate versus moisture content which is the mean value of the drying results. It is obvious from the drying curve that the moisture content drops very quickly in the first few hours, then the drying curve becomes flat (Figure 3.6). Figure 3.7 shows the drying process of these samples starts at the falling drying-rate period, and the constant drying-rate period does not appear.

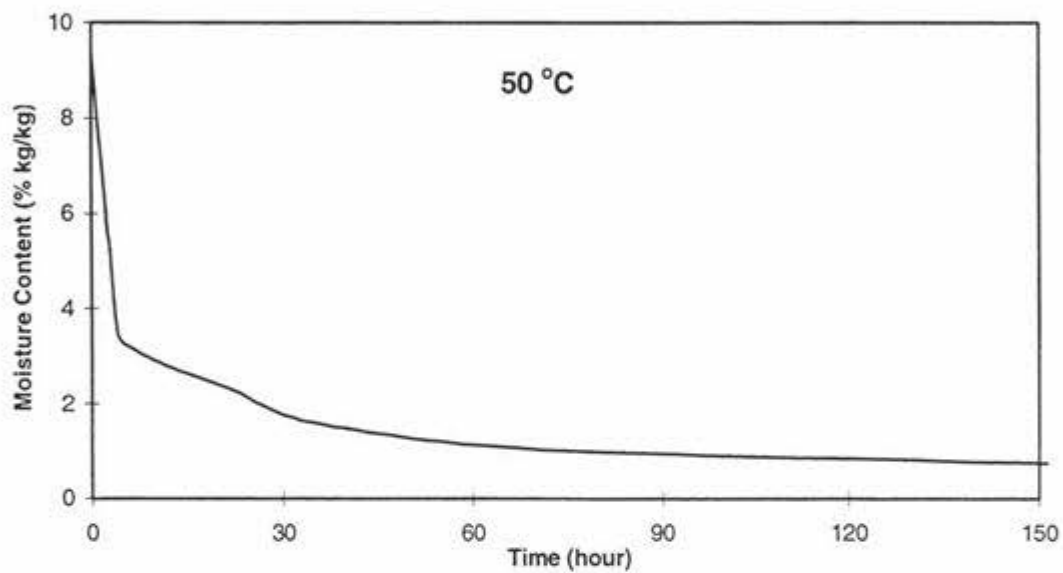


Figure 3.6 Mean moisture content of thirty, 50 mm cubic EPS samples versus time.

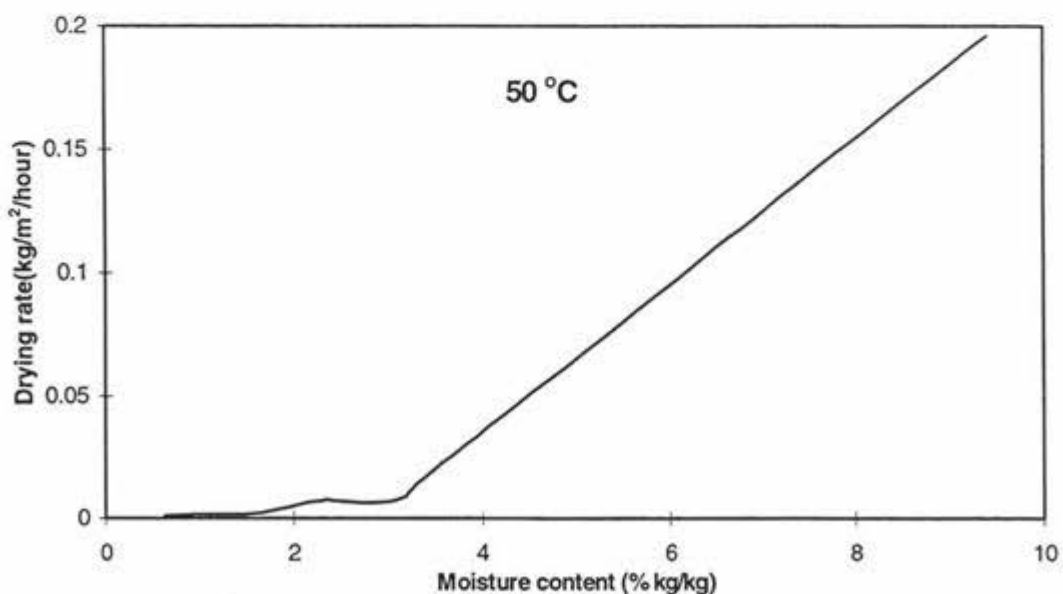


Figure 3.7 Mean drying rate of thirty, 50 mm cubic EPS samples versus moisture content.

Drying time intervals of 2, 4, 6, 12, 18, 24, 36, 48 and 50 hours were used in this run. The accuracy of electric balances was checked before each weighing. The relative humidity and air velocity which were recorded before each weighing were at 10 to 12 % RH and 1.6 to 2.2 m/s, respectively. During the test, EPS samples were moved from the drying cabinet to take the weight measurement, and taken back immediately after the weighing test to keep the constant drying experiment. The accuracy of the electric balances was checked again after weighing. This experiment finished when sample weights indicated that the samples had dried to about 0.2 % (kg/kg dry basis) moisture content. The mean dry weight of the thirty samples in this run was 8.50 g, the mean initial moisture content was 9.41 % (kg/kg dry basis) and the mean density was 15.71 kg/m³.

It was difficult to obtain precise information about the initial stage of drying, since the weights of the samples fell very rapidly. However, in the initial drying stage, the drying rate can be considered as reducing to a linear function of the moisture content. As it can be seen in Figure 3.7, the portion of the drying-rate curve between 9.4 % and 3.7 % of the moisture content appears to give a straight line. During this period, most of the moisture was escaping by vaporization at the surfaces of EPS samples. When the free moisture content decreased, the available wetted surfaces decreased resulting in a steady reduction of the drying rate. When the moisture vaporization has become entirely subsurface, the vapour reaches the surfaces by molecular diffusion through each dimension, and this moisture diffusion movement controls the drying rate. The drying curve levels off in this stage (Figure 3.6). This period dominates the overall drying time which depends on the thickness of the EPS sample.

Experimental tests for the determination of the equilibrium moisture content were tried in preliminary test runs. Six different cubic samples which were about 75, 100, 125, 150, 200 and 250 mm cube were dried in one run. Each size had duplicate samples which were cut from a fresh moulded block in the symmetry position with similar dimensions. For each size, the duplicate samples were accurately weighed on electronic scales then each placed on a different drying cabinet shelf to get the average drying

results. This drying test was carried out at 50 °C air temperature. The relative humidity and the air flow rate were at 10 to 12 % RH and 1.6 to 2.2 m/s, respectively. Samples were weighed at short time intervals in the initial stage then at longer time intervals. That is at about 0.25, 0.5, 0.75, 1, 1.5, 2.5, 5, 10, 24, 24, 48, 48 and 72 hours. This experiment lasted more than 300 hours.

In this test, samples (75 to 250 mm cube) were found to still slightly lose weight even though they had been dried about 300 hours. From the Technical Literature of Styropor (BASF, 1991), the heat distortion temperature of EPS is higher than 80 °C. The drying temperature at 50 °C is quite safe for EPS products. After the long drying time, we can only consider the weight loss is the movement of the remaining moisture in the form of vapour by diffusion. Figure 3.8 is a semilogarithmic chart which illustrates the drying curves of the series cubic sized samples at 50 °C. In the first 10 hours the moisture loss rate decreases with sample size increasing. Then the difference among each cubic sized sample becomes very small in the following drying period and the drying curves turn to nearly merge to each other.

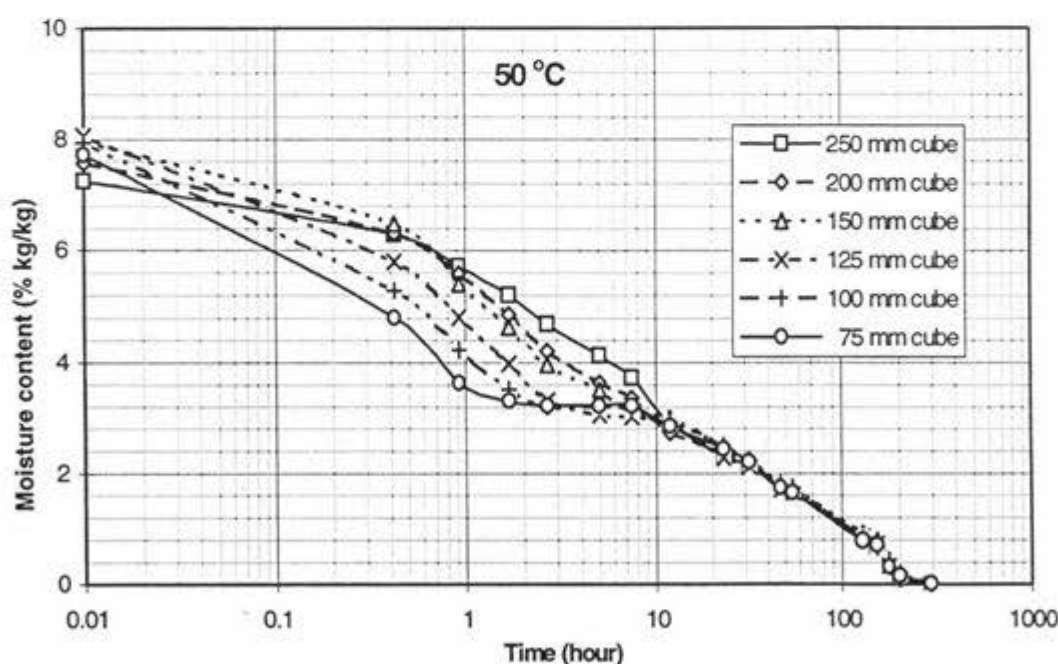


Figure 3.8 Moisture contents of different cubic sized samples versus time at 50 °C.

It is not worth running all the experiments for such a long time. To avoid excessive experimental time, the moisture content at 0.4 % (kg/kg dry basis) was assumed to be the equilibrium moisture content where all the drying curves of these cubic samples had already become flat. The final weighing of the following drying tests was determined when the sample weight changed less than 0.002 g/g over a 24 hour period.

Further drying experiments were done to find out the effect of air temperature on the drying rate. Duplicated samples of 100, 200 and 250 mm cube were dried in three runs at the drying temperatures 40, 50 and 60 °C which the relative humidity was at 15 to 18 % RH, 10 to 12 % RH and 8 to 9 % RH, respectively. The air flow rate was about 1.6 to 2.2 m/s in all these runs. The measurements of drying conditions and sample weights were the same as the methods mentioned above. Samples were dried in the drying cabinet for at least 5 days. In order to compare different experimental runs, we selected known time intervals to organize the experimental data which is moisture loss at time intervals of 0.25, 0.5, 0.75, 1, 1, 1, 1.5, 2, 10, 12, 24, 48 and 48 hours approximately. The test run at 40 °C had additional weighing intervals which lasted 7 days from the start of drying to reach the assumed equilibrium moisture content.

Figures 3.9, 3.10 and 3.11 represent these three test runs which are the drying curves of three different cubic sized samples (100, 200 and 250 mm cube) at three air temperature (40, 50 and 60 °C). The drying curves changed more sharply from the first falling-rate period to the second falling-rate period as the sample size decreased.

Figures 3.12, 3.13 and 3.14 are drying-rate curves versus moisture content corresponding to Figure 3.9, 3.10 and 3.11, respectively. Only the falling drying-rate period was found in these drying-rate curves.

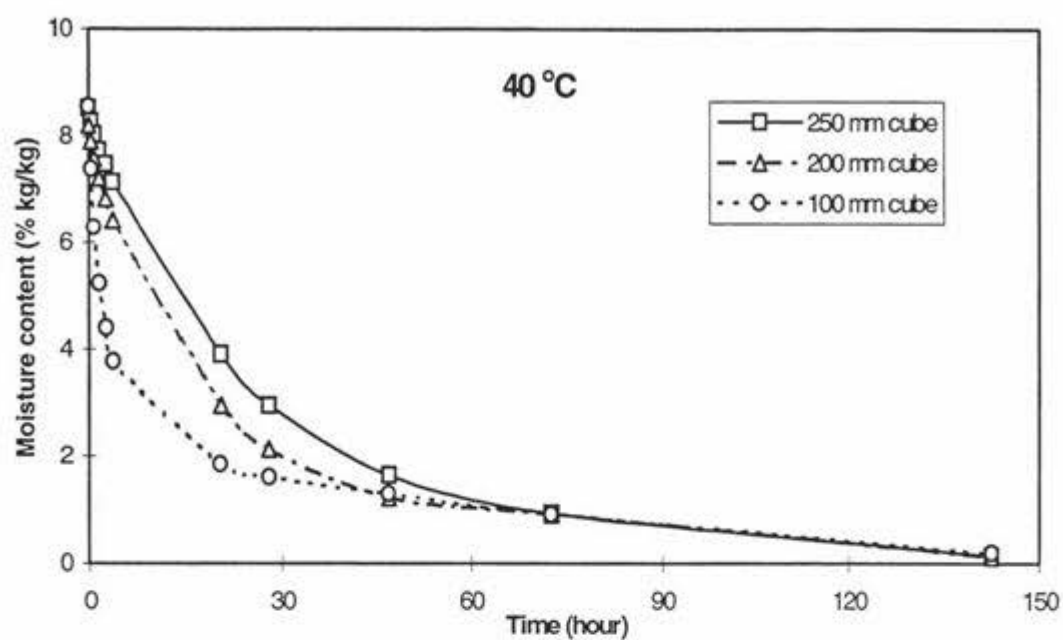


Figure 3.9 Moisture contents of three cubic sized samples versus time at 40 °C.

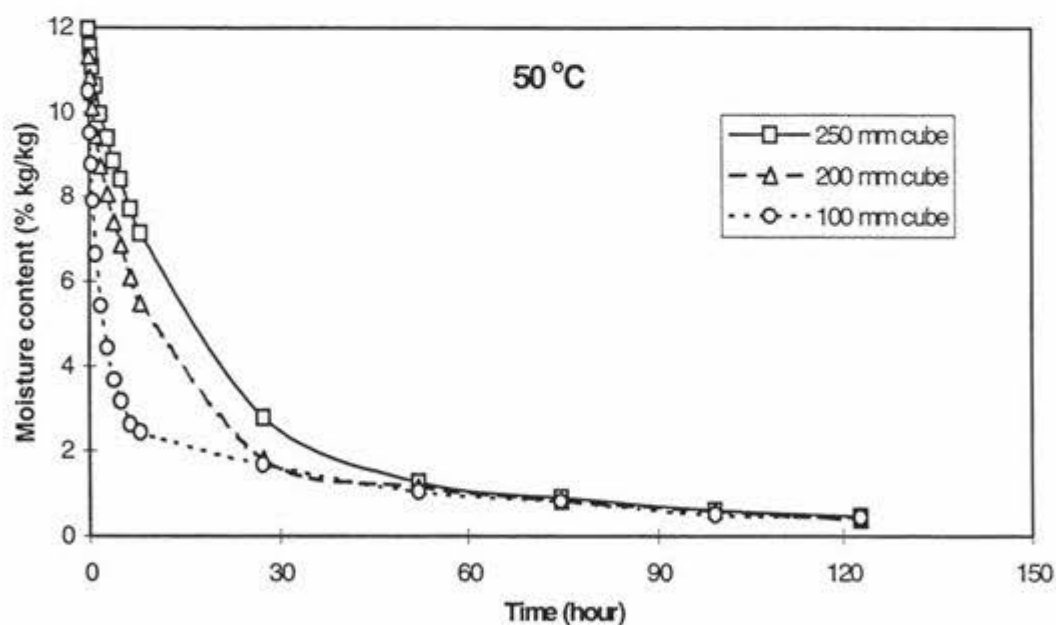


Figure 3.10 Moisture contents of three cubic sized samples versus time at 50 °C.

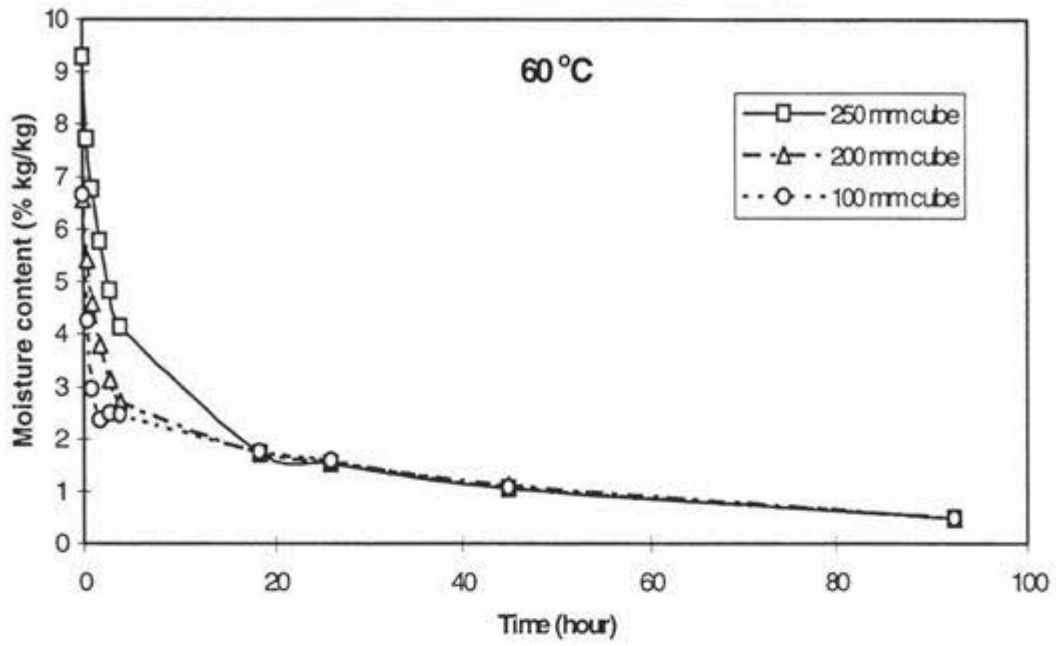


Figure 3.11 Moisture contents of three cubic sized samples versus time at 60 °C.

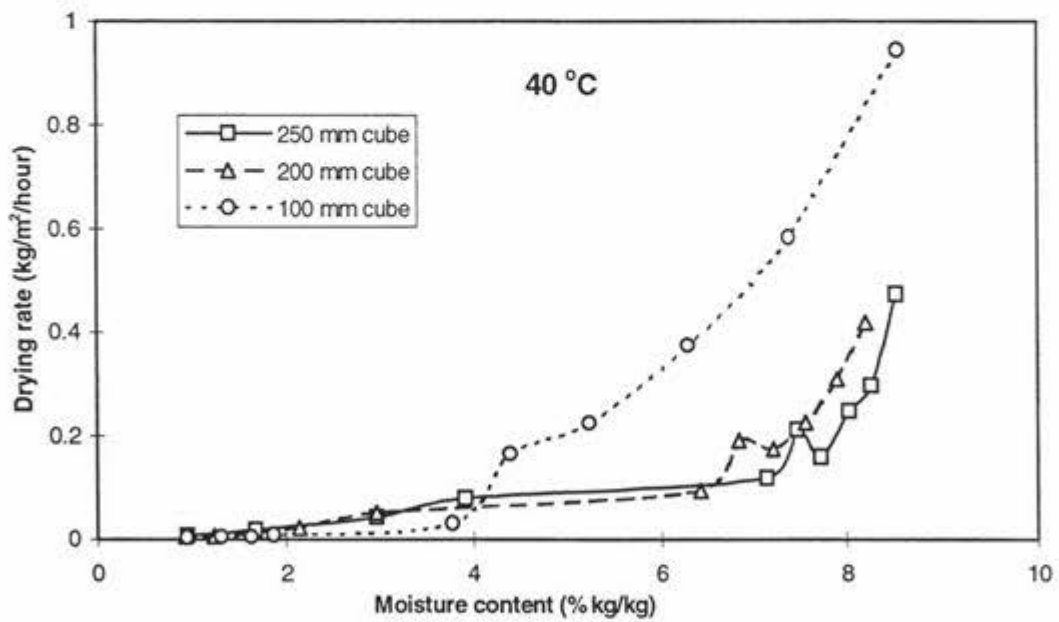


Figure 3.12 Drying rate of three cubic sized samples versus moisture content at 40 °C.

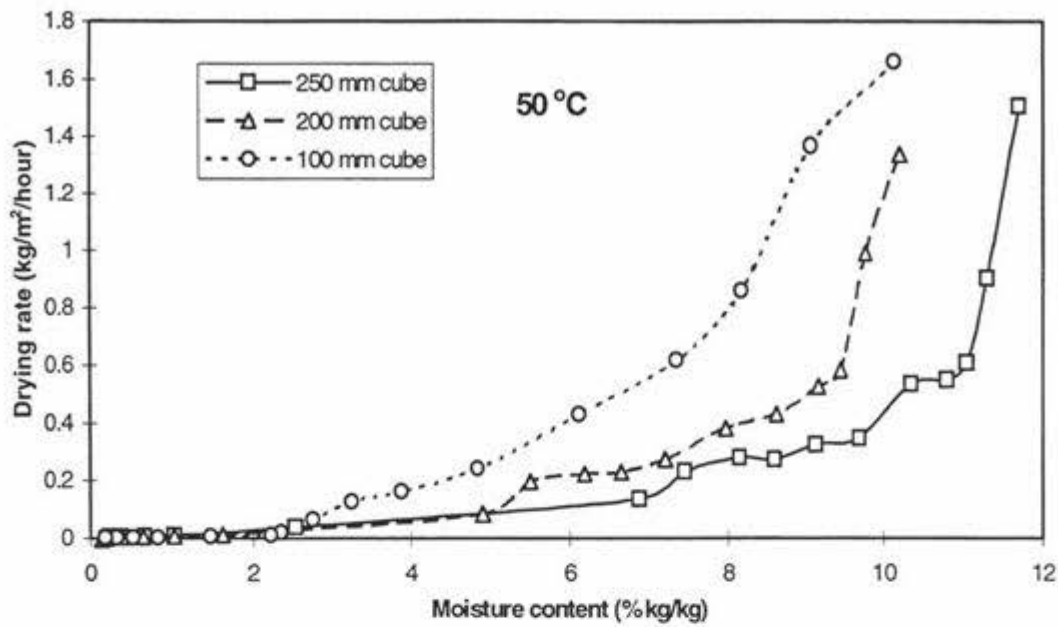


Figure 3.13 Drying rate of three cubic sized samples versus moisture content at 50 °C.

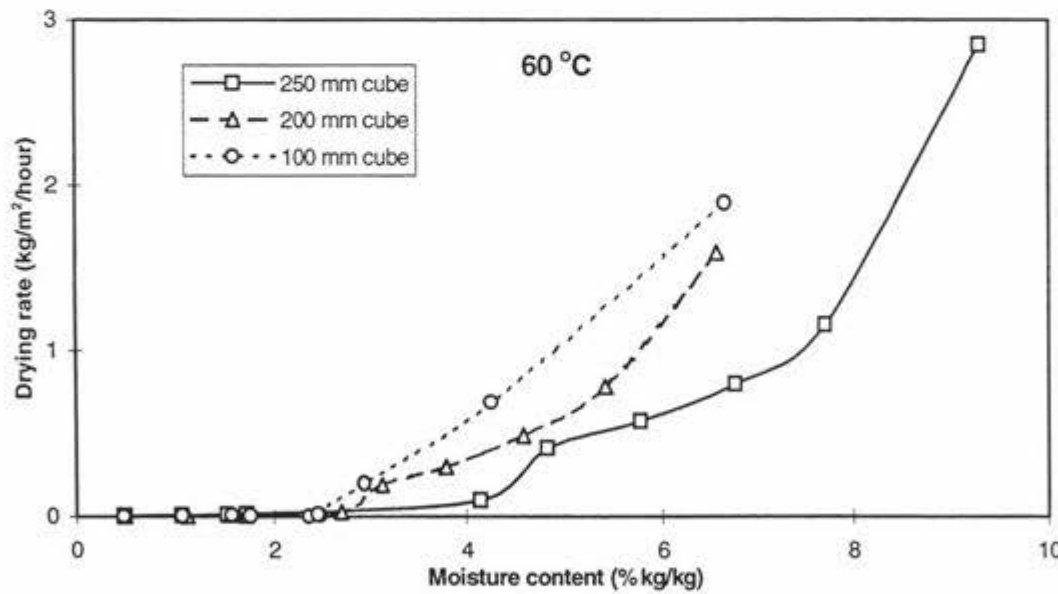


Figure 3.14 Drying rate of three cubic sized samples versus moisture content at 60 °C.

In order to find the effect of the drying temperature, Figures 3.9, 3.10 and 3.11 were rearranged to Figure 3.15, 3.16 and 3.17 which are the drying curves of same cubic sized sample at the different temperatures. In Figure 3.15, 3.16 and 3.17, it is obvious that a fairly steep moisture loss rate occurs at 60 °C. The drying curve at 60 °C shows

a faster moisture loss rate than at 40 and 50 °C. There is very little difference in the drying curves between 40 and 50 °C except the initial moisture content.

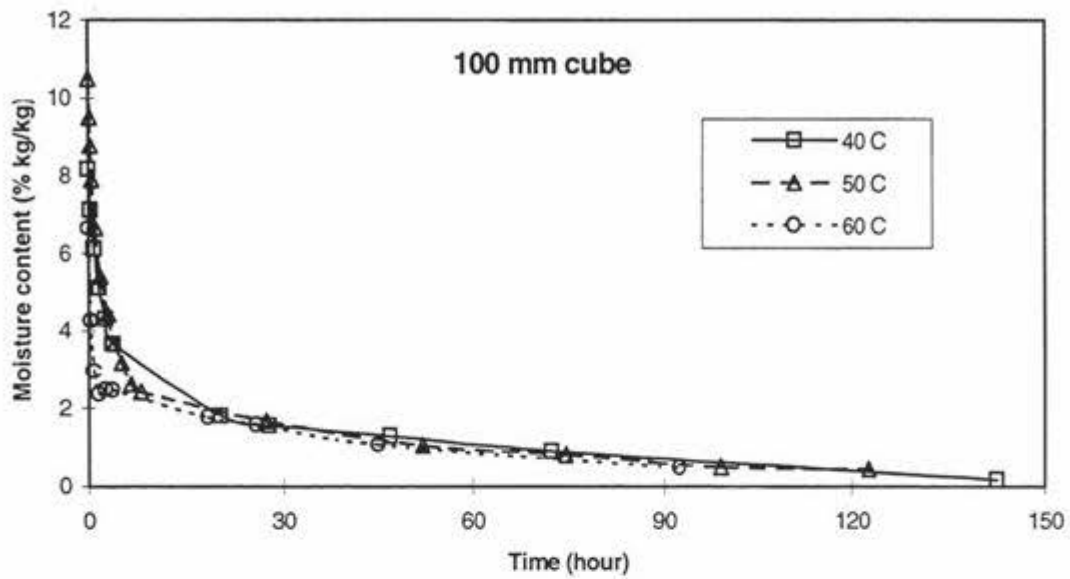


Figure 3.15 Moisture contents of 100 mm cube samples versus time at 40, 50 and 60 °C.

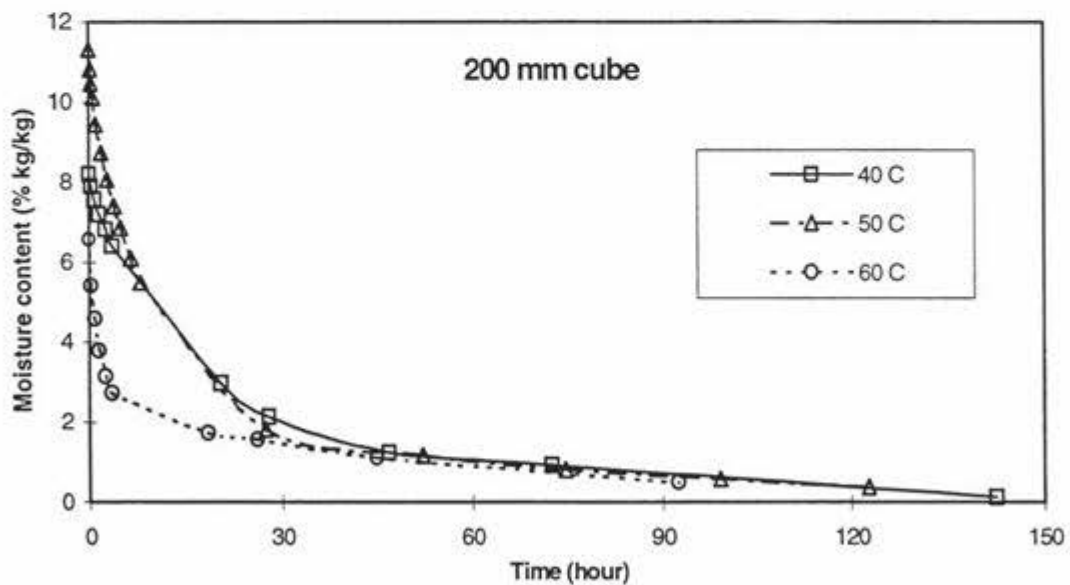


Figure 3.16 Moisture contents of 200 mm cube samples versus time at 40, 50 and 60 °C.

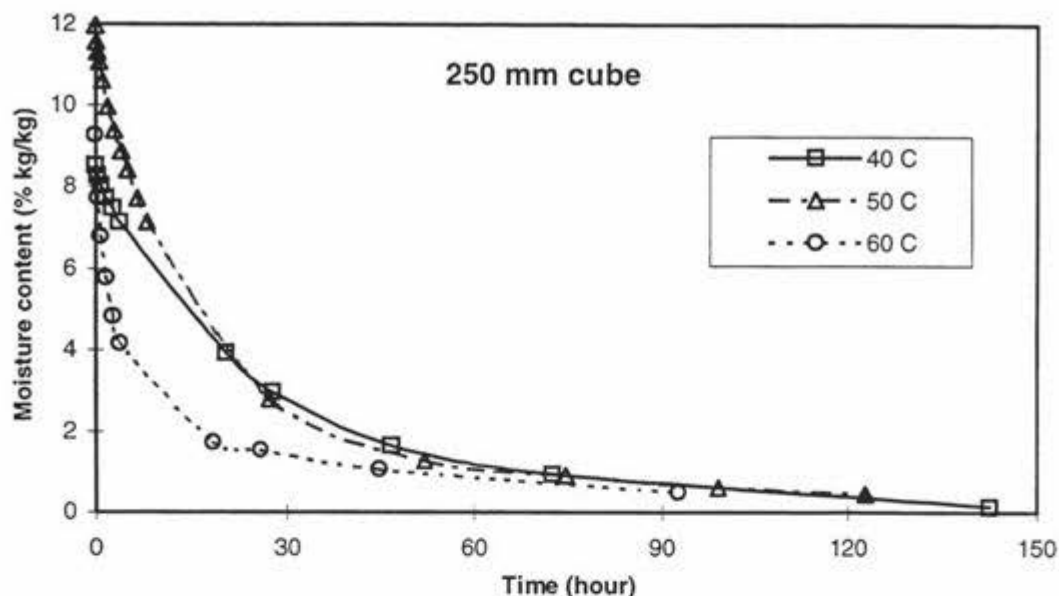


Figure 3.17 Moisture contents of 250 mm cube samples versus time at 40, 50 and 60 °C.

The moisture loss rate decreases with increasing sample size, and the drying curve of big samples is flatter than small samples (Figure 3.9, 3.10 and 3.11). All the drying-rate curves show that no constant-rate period was found in these test runs (Figure 3.12, 3.13 and 3.14). In laboratory tests, we considered that EPS samples were dried under falling-rate period only. The temperature at 60 °C has a strong effect on the EPS drying process, the drying curve changes more sharply at 60 °C than 40 and 50 °C (Figure 3.15, 3.16 and 3.17). If we neglect the different initial moisture content, there is little difference in the drying process between 40 and 50 °C.

3.2.3.2 Full-scale drying measurements

Three full-scale drying tests were carried out at Lanwood Industries. One run was used for data analysis. As described in Section (3.2.2.2), full-scale drying tests were assisted by a computer, with which the EPS block weights and the temperatures were recorded at regular time intervals. From the experiments which have been done, it appears that usually the moisture content of the EPS block before drying is around 8 to 10 % (kg/kg dry basis) at the block density 15 to 24 kg/m³, and the corresponding dry weight of EPS block is approximately 42 to 68 kg. The relative humidity and the air

flow rate were measured manually. The relative humidity was about 14 to 16 % RH at about 50 °C drying temperature. In this full-scale test, the experiment was terminated when the block weight changed less than 0.002 kg/kg (dry basis) over a 24 hour period. The EPS block weight and temperatures were recorded directly by the computer every 5 minutes in this test run.

The full-scale drying test is the one way to illustrate the industrial drying process. It is useful to adjust laboratory test results for setting up mathematical models to determine the drying time in the current industrial operation. However, during factory operation, the drying kiln has to be opened quite often to deliver and remove EPS blocks. The drying conditions change with cold air entering the drying kiln while the door is opened, and the weight of EPS block changes with the changing air buoyancy. That is, when the EPS block is moved into the drying kiln, cold air enters the drying kiln and causes the temperature to drop. When the door of the drying kiln is closed, the air temperature starts to increase to the pre-set temperature. Because the cold air density is higher than hot air, the air buoyancy decreases with increasing of the air temperature. As the air around the block changes its temperature, so the air density changes and hence the buoyancy effect changes. For the polystyrene material with large volume (2.808 m³) and low density (about 15 kg/m³), this effect is significant. Appendix C shows the value of the weight changing with the air buoyancy. The weight and temperature data that were recorded by the computer fluctuated for this reason, resulting in calculated drying-rate data which were fairly scattered. Figure 3.18 shows the original data of an EPS block weight versus time during the drying test which was recorded by the computer.

Because the changed drying conditions caused the fluctuated experimental data, the full-scale experimental data had to be modified to get the ordinary data curves. By deleting the junk data and using the moving average method, the EPS product drying-rate curve shows trend of the drying process. Figure 3.19 shows a drying curve of the moisture content of a EPS block against time. Figure 3.20 shows the curve of the drying rate versus moisture content. The dry weight of the EPS block in this test was

49.98 kg. The EPS block density was 17.80 kg/m^3 . The calculated initial moisture content was 7.2 % (kg/kg dry basis).

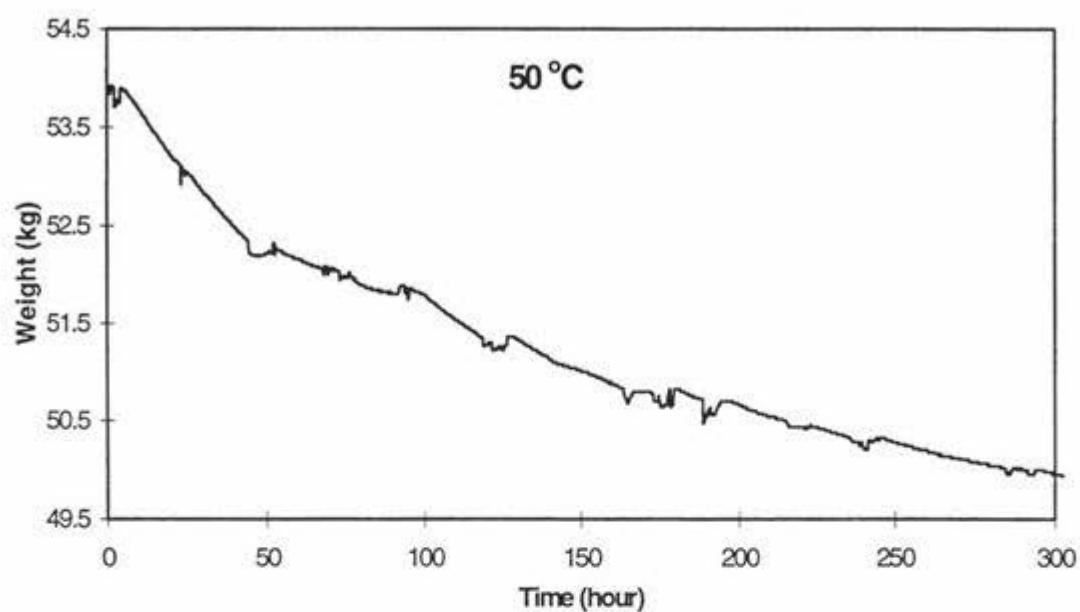


Figure 3.18 The weight of an EPS block versus time in the full-scale test.

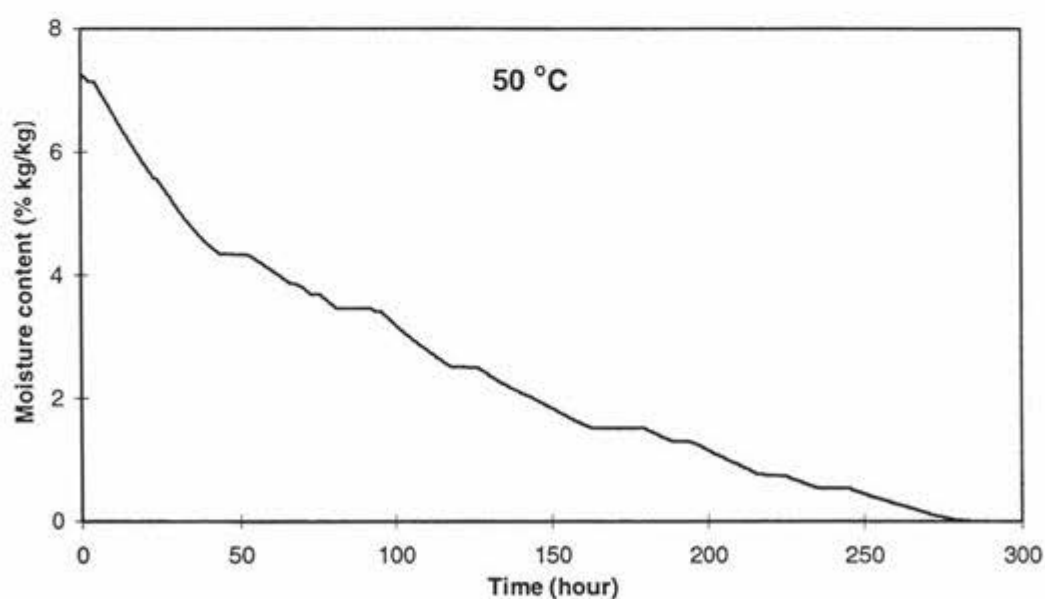


Figure 3.19 Moisture content of an EPS block versus time in the full-scale test.

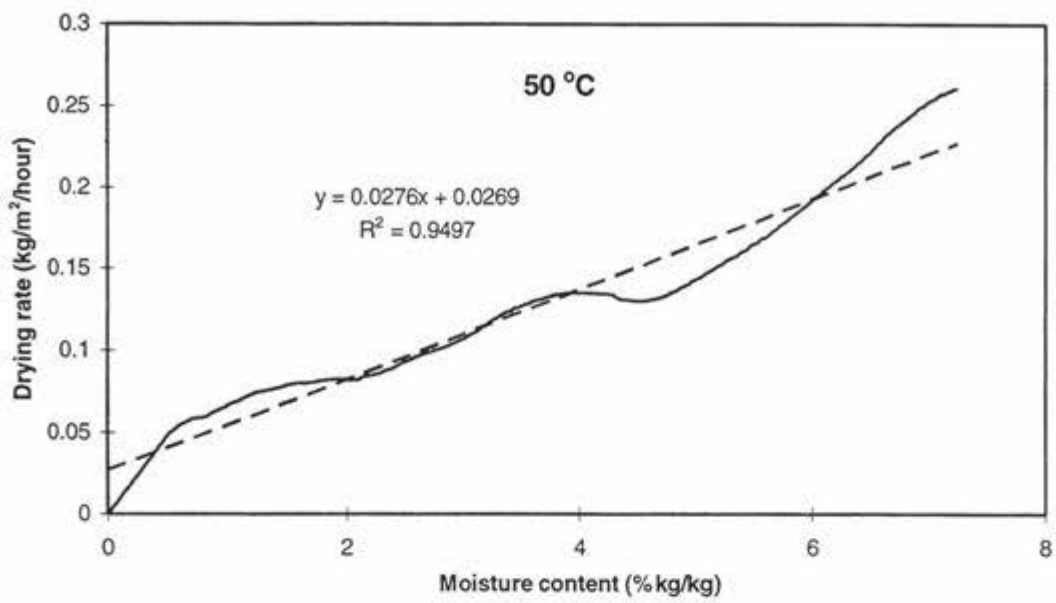


Figure 3.20 The drying rate of an EPS block versus moisture content in the full-scale test. The solid line is the experimental data. The dash line is the linear regression.

The moving average method has to use an average value of the experimental data in a periodic time interval. It is unavoidable that the information of the initial drying period will be lost. The constant-rate period cannot be detected from Figure 3.20. The drying-rate changes fluctuated in the falling-rate period. Figure 3.20 shows the unusual drying rate curve which is caused by production operation. However, if the trend of the drying-rate is considered to be linear, then the relationship of the drying-rate and the moisture content can be obtained by introducing the linear regression method. The curve fitting function and its least square are shown in Figure 3.20.

In full-scale tests, the EPS block dimensions were measured before and after drying. Table 3.1 shows the measurement of the EPS product dimensions before and after drying.

Dimension (mm)	Before drying	After drying	Shrinkage (%)
Length	3610	3600	0.3
Breadth	1215	1212	0.3
Thickness	630	625	0.8

Table 3.1 The shrinkage of an EPS block after drying.

The shrinkage of the EPS block was less than 1 % in all dimensions during the drying. For such small volume changes, the shrinkage is considered to be negligible compared to size of the large cuboid EPS block.

3.2.4 Discussion of experimental results

The effect of the sample thickness and the drying temperature on the drying rate were tested in three experiments of three cubic sized samples (100, 200 and 250 mm cube) and three drying temperatures (40, 50, and 60 °C).

In drying theory, the critical moisture content depends on the thickness of the drying material and the rate of drying. If the initial moisture content of the solid is below the critical point, the constant-rate period does not occur. In the laboratory tests, the moisture loss rate was very fast in the initial drying stage, and the constant drying-rate period was not observed even though samples were weighed at small time intervals in the initial stage. In laboratory tests, EPS sample drying process is considered to start at the falling drying-rate period and this period dominates the drying time (Figure 3.12, 3.13 and 3.14). The shape of the drying curve in the falling-rate period was found to depend on the thickness of the sample (Figure 3.9, 3.10 and 3.11). The drying curve of big cubic sized samples is flatter than small samples. In the full-scale tests, because of using the moving average method, the constant-rate period cannot be detected on the drying-rate curve. If the drying process is considered to start at the falling-rate period, the trend of the full-scale drying-rate curve can be assumed to be a straight line using the linear regression method (Figure 3.20).

Figure 3.9, 3.10 and 3.11 were rearranged to Figure 3.15, 3.16 and 3.17 which were used to study the effect of the drying temperature. Neglecting the different initial moisture content, the drying temperature at 60 °C has a strong effect on the drying process, such that the moisture loss rate is much faster than at 40 and 50 °C. The drying curves at 40 and 50 °C show very little difference in the drying process.

From these results, we can consider that the moisture loss rate of the EPS product decreases with increasing sample size, and the effect of drying temperature at 50 to 60 °C is stronger than at 40 to 50 °C.

In this research, the equilibrium moisture content was assumed to have been reached when the EPS product weight changed less than 0.002 g/g over a 24 hours interval (0.4 % dry basis). In the series test runs of three cubic sized samples and three temperatures, drying times were limited to 170 hours at 40 °C, 150 hours at 50 °C and 120 hours at 60 °C. Figure 3.9 to 3.11 shows the differences in final moisture content in each run suggesting that equilibrium had not been reached to the same level. However, an error of several fractional percentage points in equilibrium moisture content has a relatively small effect on the calculated value of the moisture content in this case, since the initial moisture content is about 8 to 10 % (kg/kg dry basis) and final moisture content is about 0.4 % (kg/kg dry basis). The moisture content at the time when the test was terminated was assumed to be the equilibrium moisture content. This was due to no separate equilibrium moisture content information of the EPS product being available. We recognize the shortcoming of lacking such information; however, a separate equilibrium moisture content study was beyond the scope of this project and might be not necessary.

Duplicated samples in each tests were obtained from the same block which were cut from the symmetry position with similar dimensions. The uneven moisture content distribution within the EPS block might cause the different initial moisture content in the two duplicated samples. During drying, they were placed in different shelves to get average drying results and the weighing test was carried out simultaneously for the duplicate samples to eliminate the operation error. The average value of the duplicate samples was used for further data analysis.

It is worth mentioning that moisture is easy to evaporate through the cut surfaces of EPS samples. Moisture may have been lost while samples were cut, wrapped with plastic film by hand and delivered from the factory to the laboratory, even though methods were used to keep the moisture in.

The walls of the drying cabinet are insulated by EPS slabs (15 mm thick). Most of the heat loss happened when the door of drying cabinet was opened for weighing samples. It can be ignored when compared to the total drying time.

Most drying tests were used to evaluate the effect of the air temperature and material dimensions on the EPS product drying process. It would be time consuming and expensive to obtain experimental data for small temperature intervals and for a large range of sample sizes extending from very small to full-scale products. Also our drying cabinet is unable to take samples which are larger than 250 mm cube. Due to the constraint of volume capacity of the drying cabinet, it is difficult to scale up drying results from laboratory tests to the full-scale test because of the large difference in block size.

Because of the production operation, the full-scale test was not carried out at constant drying conditions as in the drying cabinet. Experimental data of the full-scale test had to be modified by the moving average method to get smooth curves. In the extrapolation of drying results from laboratory tests to the full-scale test, error is unavoidable.

Theoretically, increasing air velocity does not influence the drying rate for slow drying materials. In this research, the influence of air speed is not studied to improve the drying performance of the EPS product.

Chapter 4 Analysis and Modelling of the Drying Process

The EPS product drying values were determined by the drying curve and the drying-rate curve in each test run which comprised laboratory tests at three temperatures (40, 50 and 60 °C) with three sample dimensions (100, 200 and 250 mm cube) and a full-scale test. The falling-rate period was only found in the laboratory tests. In the full-scale test, the information from the initial drying period was lost by using the moving average method. Compared the entire drying process, the constant-rate period of the full-scale test can be neglected for the total drying time calculation. The final moisture content for the Lanwood Industries EPS product needs to be low enough to result in a smooth surface when cut by hot wires. An approximate value of the final moisture content (2 % dry basis) was inferred from the laboratory tests for the full-scale drying time calculation. Theoretical, semitheoretical and empirical methods were used for the drying time calculation.

A simplified method based on capillary theory was used for the full-scale drying time calculation. This theory gave a linear relationship between the drying rate and moisture content. Newton's and Page's equations were used to fit the experimental data curves. Newton's equation was found to lack the ability to describe the laboratory drying tests of the EPS product where samples are at high temperature and in small dimensions. Page's equation results in better agreement with the experimental data for both the laboratory and the full-scale tests, and it can be developed for the optimization of the EPS product drying process. The drying parameters k and N of Page's equation were generalized as functions of the drying temperature and the sample dimensions.

4.1 Drying process analysis

The drying curve is the basic description of the drying process, and the most important factor in drying calculation is the length of time required to dry a material from a given initial moisture content to a final moisture content. Under a constant drying condition, the drying time can be determined from the drying curve if it can be constructed. The drying curve can only be obtained from experiments on the material to be dried, and this gives the drying time directly. The drying curve for one set of conditions can be modified for other conditions, and then working back, the drying time can be taken from the drying curve.

The drying curves of the EPS product for different periods depend on the drying conditions and the properties of the drying sample. In this research, the drying process of EPS blocks has been studied to determine the industrial scale drying time.

4.1.1 Drying time in the constant-rate period

Theoretically, the constant drying rate is a function of three drying parameters: (1) air flow rate, (2) air temperature, and (3) air humidity. If the ambient conditions are constant, the drying rate will be constant. In this period, the external conditions control the drying rate. During the constant-rate period, moisture migrates from the interior to the surface and is vaporized. As long as the delivery of moisture from the interior to the surface is sufficient to keep the surface completely wet, the drying rate is constant. In the constant rate period, the drying rate is determined by the rate of surface evaporation.

The best methods of drying calculations are based on actual experimental data obtained under conditions of the drying material and the drying conditions. The time required for the constant-rate period can be determined directly from the drying curve of moisture content versus time. In order to calculate the drying time in the constant-rate period, the drying conditions have to be assumed constant. Drying time in the

constant-rate period can be calculated from Equation (4.1) which is derived from Equation (2.10):

$$t_c = \frac{m_d(X_o - X_c)}{AR_c} \quad (4.1)$$

where t_c is the drying time in the constant-rate period (hour), X_o is the initial moisture content (kg/kg dry basis), X_c is the critical moisture content (kg/kg dry basis), m_d is the dry solid mass (kg), A is the surface area of the drying solid (m^2) and R_c is drying rate in the constant period ($kg/m^2/hour$).

Critical moisture content is the moisture content at which the drying rate of a material changes from a constant-rate period to a falling-rate period. It varies with the thickness of the material and with the rate of drying. It must be determined experimentally for each material and for each drying condition.

To calculate the constant-rate period drying time, it is necessary to know the critical moisture content. However, these data are not easy to obtain even by experimental tests, especially the transition point. In this case, some estimate of critical moisture content must be made.

The drying rate increases with increasing drying temperature in the constant-rate period but the length of the constant-rate period decreases. However, if the constant-rate period is shorter then the overall drying time will increase. That is, the earlier the drying process changes to the falling-rate period, usually the longer required for the drying time. The drying temperature for the EPS block should be no higher than 60 °C. A higher temperature would not only have a harmful effect on the EPS product, but would also increase the critical moisture content and reduce the later drying rate. The drying temperature is limited to a range 40 to 60 °C in this research.

In this research, only the falling-rate period was observed in laboratory tests. EPS samples (less than 250 mm cube) did not display a constant-rate period because the

initial moisture content was below the critical moisture content. In the full-scale test, because the drying conditions were changed quite often by production operation, the original data were very fluctuating and noisy. The drying-rate curve had to be smoothed by the moving average method, so it is unavoidable that information from the initial drying period was lost. The constant-rate period is not detectable from the modified drying-rate curve (Figure 3.20).

In the full-scale test, the actual initial moisture content is 7.88 % (kg/kg dry basis) (The initial weight of the EPS block is 53.92 kg, the dry weight is 49.98 kg.). The average initial moisture content is 7.25 % at an initial drying rate of 0.26 kg/m²/hour, which is obtained by the moving average method (Figure 3.20). In Figure 3.20, the drying-rate curve starts from the falling-rate period. If the average initial moisture content is assumed to be the critical moisture content, the drying time of constant-rate period can be calculated by Equation (4.1). The area of the EPS block is a constant (14.88 m²), the time of the constant-rate period is about 8 hours. Compared to the entire drying time of the EPS product (nearly 300 hours), this constant-rate period is very short. Due to the limited importance of the constant-rate period in the EPS block drying, the constant-rate period will not be pursued further in this research.

4.1.2 Falling-rate period

The falling-rate begins at the critical moisture content where the constant-rate period ends. In a drying operation, the rate of drying during the falling-rate period is a function of moisture content of the material involved. As the moisture content decreases, the drying rate decreases. This period is usually divided into two stages. The first is the unsaturated surface drying period, the second is the internal moisture movement period. The shape of the falling-rate period is dependent on the sample thickness and the drying temperature. The point of change from the first falling-rate period to the second falling-rate period gradually becomes level and smooth from the small sample (100 mm cube) to the big sample (250 mm cube) (Figure 3.12, 3.13 and 3.14). There is no sharp change in the full-scale test (Figure 3.20).

Prediction of the drying rate of EPS product is more complicated during the falling-rate period than during the constant-rate period. Not only do the external heat and mass transfer have to be considered in the analysis, but also the heat and mass diffusion within the product. Many theories have been proposed for predicting solid drying behaviours in the falling-rate drying period, such as the diffusion theory and the capillary theory. Each theory can explain the drying process of certain materials. However, because of the complicated properties and structure of materials, every theory has its limitations. Usually, one has to go through experiments to determine the falling drying rate and the drying time which reaches a certain drying result. Semitheoretical and empirical models, such as Newton's and Page's equations, have been proved effective in describing the drying processes.

In our laboratory tests, the drying processes of the EPS samples started at the falling-rate period. It is believed that the initial moisture content was below the critical moisture content, and that the entire drying process occurs in the falling-rate period. In the full-scale test, the constant-rate period was not found in the drying curves since initial drying period information was lost by using the moving average method. However, due to the undetectable short constant-rate period, it can be ignored compared to the entire drying process. The falling-rate period dominates the total drying time of the EPS product. The drying time of the EPS products calculated in Section (4.2) only considered the falling drying rate period.

4.1.3 Final moisture content in industrial operation

The required final moisture content in the industrial drying of EPS is that which gives a smooth surface when the block is cut with hot wires. Excessive drying is wasteful and should be avoided. In the full-scale test, the drying process was considered to be complete when the moisture loss of the EPS block did not exceed 0.002 kg/kg (about 0.4 % kg/kg dry basis) in a 24 hour period. However, this drying result may be far

below that required for good cutting. The appropriate final moisture content should be studied in future work.

An unsatisfactory cut surface usually happens in the centre of the EPS block. This is because during drying, the heat is transferred through the material causing the moisture to move toward the surface, resulting in a moisture gradient. The amount of moisture is always higher in the centre of the block than near the surface and does not have enough time to evaporate, causing a cutting problem. The desired final moisture content for the industrial drying process is when the moisture content, even at the centre of the block, is below the moisture content which will influence the hot wire temperature during the cutting. The moisture distribution profile should be determined in order to obtain the moisture content in the centre of the block during drying. Controlling the final moisture content and evenness of moisture in EPS product should be studied with the aim of improving cutting quality and increasing productivity. However it is not easy to identify the point where the moisture content causes the change from a good cutting surface to a bad one. One reason is that there is no quantitative standard for the cutting surface. If the moulding steam is properly dried during the operation, there will be little moisture in the moulded block. A nearly fresh moulded block was cut by hot wires during the research, but the result was not obvious enough to distinguish the boundary of the cutting mark. Another reason is that it is both costly and time consuming to detect the moisture gradient profile in all the different drying stages. It needs lots of experiments and cutting of several EPS blocks to get the moisture distribution in different drying stages.

It may be convenient to assume that the drying of EPS blocks is a two-stage process. During the first stage the EPS product is more or less saturated, and the drying rate is determined by the rate of surface evaporation, which is influenced by the external drying conditions. This period is very short, it can be ignored during the calculation. Once the constant-rate period ends, the falling-rate period follows. In the falling-rate period, the rate of drying as well as the amount of wetted area at the surface decreases continuously. The drying process becomes controlled by diffusion of moisture within the foamed beads. As drying progresses, the surface moisture becomes very small

(virtually zero) and the drying zone moves deeper into the EPS product. The moisture gradient falls uniformly to the level of irreducible saturation, whereupon the surface dries out and the second falling-rate period begins. When the moisture content reached about 2 % kg/kg (dry basis) in the laboratory tests (Figure 3.9, 3.10 and 3.11), the moisture gradient became flat in the small samples, and the residual moisture was lost very slowly during the rest of drying. For the samples with 250 mm cubic size at 50 °C, 25 times more moisture was lost in the first 30 hours than in the following 90 hours (Figure 3.12). We assume the moisture gradient becomes flat during this stage. At this low level of moisture in EPS blocks, we suppose it will not significantly influence the hot wire temperature during cutting. The moisture content at this point is assumed to be the final drying moisture content of EPS blocks for the further calculation. However, this point should be defined experimentally for different thickness of EPS and different drying conditions in the industrial operation.

4.1.4 The results and discussion

In the laboratory drying tests, no constant-rate period was found in drying curves for samples smaller than 250 mm cubic. The drying process starts at the falling drying-rate period, even though some samples had an apparently high initial moisture content (more than 10 % kg/kg dry basis) (Figure 3.13). In the full-scale test, as the information of the initial drying period was lost by using the moving average method, the constant-rate period cannot be detected. However, an estimated calculation shows the constant-rate period is very short compared to the entire drying process, therefore it is neglected for the drying time calculation of the EPS product. The industrial drying process can be assumed to start at the falling-rate period.

In the full-scale test, the drying-rate curve showed fluctuations and it is not possible to distinguish the second critical point from this data curve. However, if the trend of the drying-rate curve is considered as a straight line, the relationship of the drying-rate and the moisture content can be obtained using the linear regression method (Figure 3.20).

Dimensions (mm cube)	Temperature (°C)	Initial moisture content (kg/kg dry baiss)	Initial drying rate (kg/m ² /hour)	Second critical moisture content (kg/kg dry basis)	Drying rate at the second critical point (kg/m ² /hour)
100	40	8.521	0.475	7.133	0.119
100	50	11.697	1.506	6.871	0.136
100	60	9.283	2.847	4.133	0.099
200	40	8.205	0.419	6.414	0.096
200	50	10.214	1.336	4.913	0.084
200	60	6.565	1.592	2.712	0.031
250	40	8.550	0.945	3.778	0.031
250	50	10.147	1.660	2.234	0.010
250	60	6.649	1.890	2.462	0.008

Table 4.1 Values of the drying curves in the laboratory tests.

The final moisture content for Lanwood Industries of the EPS product drying needs to be low enough to result in a smooth surface when cut by hot wires. Overdrying should be avoided. That is, an uneven cutting surface will not occur even though there is still an amount of moisture within the EPS block. However, as little research of the moisture gradient profile during the EPS drying has been conducted until now, it is suggested to study it in future work. In this research, the value for the drying time calculation is assumed to be at the moisture content of 2 % (kg/kg dry basis). This is the place where the drying curves of different samples level off in the laboratory tests. In the following drying period, the drying rate becomes very slow and extending the drying time will remove little moisture.

Theoretical, semitheoretical and empirical methods have been used to predict the drying time of EPS products in the following section. The drying values of the laboratory tests have been used for calculating the drying time (Table 4.1).

4.2 Drying time prediction

If experimental data are available to give the drying-rate curve during the falling-rate period, the drying time during this period can be determined by a direct graphical integration. The drying-rate curve depends on moisture content, temperature and the thickness of the drying solid. When the dimensions of the drying solid are large or when moisture from inside the body is being removed, drying is internally controlled.

Full-scale tests may be the only way to establish reliable data for the drying process. However, when a full-scale test is not available, mathematically approximate methods are employed to predict the drying processes. EPS is a kind of slow-drying material, most of the drying occurs in the falling-rate period. In this research, in order to predict the drying process of the EPS product at the range of 40 to 60 °C in the industrial drying kiln, a series of experiments with three cubic EPS samples at 40, 50 and 60 °C were carried out in the laboratory. The relationship that was to be established

experimentally for scaling up the drying process, was the dependency of the drying rate on the material thickness and the drying temperature.

Theoretical, semitheoretical and empirical models are used to predict the drying time of EPS product. These models are focused on the current industrial drying operation, however, the optimized drying condition was attempted to be defined by scale-up of the laboratory experimental data to the full scale operation.

4.2.1 Theoretical drying methods

The theoretical drying solutions for the average moisture content can be obtained directly from books on diffusion analysis, such as Crank (1956) which have been mentioned in Chapter 2.

4.2.1.1 The simplified method

The simplified method is Fick's second law approach where the moisture movement within the drying material is the process that controls the drying rate in the falling-rate period. Under constant conditions, the drying rate can be calculated using a model described by Fick's second law (Equation 2.4).

Expanded polystyrene is a porous material. The flow of liquid through the porous EPS block should conform to the capillary Equation (2.9). During drying, moisture flows through the interstices of the porous EPS product by capillary action. As water is moved by vaporization, a meniscus across each void is formed, which sets up capillary forces by the interfacial tension between the water and the solid. The capillary forces possess components in the direction perpendicular to the surface of the solid. It is these forces that provide the driving force for the movement of water through the voids toward the surface.

In the first falling-rate period, the vaporization zone is at or near the surface and the water in the voids of the EPS product is the continuous phase. The drying-rate curve is usually linear. As the water is progressively removed from the solid, an increasing fraction of the void volume is occupied by air. When the fraction reaches a certain limit, there is insufficient water left to maintain a continuous film on the void surface. The voids are filled with air which now becomes the continuous phase. Moisture can migrate either by creeping along the capillary walls or by successive evaporation between liquid bridges. On further drying, these liquids evaporate entirely leaving adsorbed moisture behind. When this stage appears, the drying rate becomes very slow. At this point, the drying curve tends to level off. In the final drying period, the water vapour must diffuse through the solid (McCabe et al, 1993).

In the falling-rate period, the drying time is given by Equation (2.10). In the porous EPS block drying process, the drying rate in the falling-rate period can be estimated as linear (Figure 3.20).

$$R = bX + c \quad (4.2)$$

where b and c are constants, and $dR = bdX$. Substitution for dX in Equation (2.10) gives, the time required in the falling-rate period,

$$t_f = \frac{m_d}{bA} \int_{R_2}^{R_1} \frac{dR}{R} = \frac{m_d}{bA} \ln \frac{R_1}{R_2} \quad (4.3)$$

where R_1 and R_2 are the initial and the final drying rates ($\text{kg/m}^2/\text{hour}$), respectively. The constant b is the slope of the drying rate in the first falling-rate period.

$$b = \frac{R_c - R_c'}{X_c - X_c'} \quad (4.4)$$

where R_c and R_c' are the drying rates at the first and the second critical points ($\text{kg/m}^2/\text{hour}$), respectively. X_c and X_c' are the moisture contents at the first and the second critical points (kg/kg dry basis), respectively.

Substitution of b from Equation (4.4) into Equation (4.3) gives

$$t_f = \frac{m_d(X_c - X'_c)}{A(R_c - R'_c)} \ln \frac{R_1}{R_2} \quad (4.5)$$

In the full-scale drying test, the trend of the drying-rate curve profile was found to be a straight line (Figure 3.20). If the constant-rate period is very short, also the equilibrium moisture content of the EPS product is very small, then these can be ignored, and Equation (4.5) can be simplified by noting that c , R'_c , X'_c drop out, that $R_c = R_1$, $X_c = X_o$, and that $R_1/R_2 = X_o/X_f$. The drying time can be calculated as follows:

$$t = \frac{m_d}{Ab} \ln \left(\frac{X_o}{X_f} \right) \quad (4.6)$$

where X_f is the dry basis final moisture content (% kg/kg).

The EPS block surface area and volume are 14.88 m^2 and 2.808 m^3 , respectively, at Lanwood Industries. The slope b is 0.028 which is obtained from the drying-rate curve by the regression method (Figure 3.20). Inserting data from the full-scale test, which the initial moisture content was 7.88 % (kg/kg dry basis), the drying weight of the EPS block was 49.98 kg and the assumed final moisture content was 2 % (kg/kg dry basis), into Equation (4.6), giving a drying time of 163.3 hours.

In the current industrial drying operation, the values of the EPS product area and volume are constants. The dry weight of the EPS product (m_d) and the initial moisture content can be calculated according to the density of the pre-expanded polystyrene, because the density of the moulded EPS block is nearly the same as the density of the pre-expanded polystyrene (BASF TI-038/1e, 1974). The dry weight of the EPS block is $m_d = \rho_m V$, where ρ_m is the density of the moulded EPS block (kg/m^3), V is the volume of the EPS product (m^3). If the density of the pre-expanded polystyrene is ρ_p (kg/m^3), then $\rho_m = \rho_p$, Equation (3.1) can be defined to calculate the initial moisture content,

$$X_o = \frac{m_w - \rho_p V}{\rho_p V} \quad (4.7)$$

where m_w is the wet weight of the drying material.

If the fresh moulded EPS block is weighed (m_w) and the final moisture content (X_f) is defined, when the slope b is 0.028, the drying time can be calculated as:

$$t = 4.493 \rho_p \ln \frac{m_w - 2.808 \rho_p}{2.808 \rho_p X_f} \quad (4.8)$$

The slope of the full-scale drying test and the slopes of the laboratory tests in the first falling-rate period (Figure 3.12, 3.13 and 3.14) are shown in Table 4.2. The slope of the drying-rate in the full-scale test was obtained by the linear regression method (Figure 3.20). The slope of the first falling-rate period in laboratory tests was calculated by Equation (4.4) from the drying-rate curve values. The second critical moisture content was taken from the average value of the transition area between the first falling-rate period and the second falling-rate period (Table 4.1). No obvious relationship has been found for scaling up the drying process by the dimensions of the EPS samples in the range of temperature 40 to 60 °C.

Dimension (mm cube)	Temperature (°C)	Slope b
100	40	0.192
100	50	0.059
100	60	0.449
200	40	0.180
200	50	0.236
200	60	0.405
250	40	0.999
250	50	0.316
250	60	0.534
3.6×1.2×0.65 (m ³)	50	0.028

Table 4.2 The slopes of drying-rate curves in the first falling-rate period.

4.2.1.2 Numerical method

Numerical techniques have become the usual methodology to evaluate the drying process. The numerical solution for complicated three dimensional problems has been developed in recent years (Zogzas et al, 1994). In the case where diffusivity is strongly dependent on moisture content, a proper numerical method may provide the best results. Despite the particular procedure used for the numerical calculations, the evaluation must be followed by a complete statistical analysis based on a significant number of experiments. A numerical approach may need a deep understanding of the drying processes. Numerical methods can be used to predict drying processes with amazing accuracy and speed. However, numerical methods are not simple to use and must take into account heat and mass transfer simultaneously.

Due to the complicated nature of simulating heat and mass transfer in solids, the solution of three dimensional EPS drying equation is not easily tackled. The numerical method can not be discussed here in detail.

4.2.2 Semitheoretical drying equation

A simplification of the solution to the diffusion equation can be used to describe the drying process. Instead of an infinite number of terms, only the first term of Equation (2.5) is employed to calculate the drying rate which is expressed as Equation (2.12)

A relationship very similar to Equation (2.12) is analogous to Newton's law of cooling can be used in EPS drying analysis (Equation 2.14). Because the drying curve is moisture dependent, for the better fitting of the drying curve this equation is rearranged as Equation (2.16).

The drying curves of three cubic samples at three drying temperatures and the drying curve of the full-scale test were fitted by Equation (2.16). The drying parameter k for the EPS product was determined from Figure C.1 to C.10 (Appendix C). The rearranged Newton's equation, drying parameter k , standard error and the correlation coefficient for each run are all shown in Appendix C. Newton's equation does not fit most of the drying curves well, it only fits the initial drying period of the laboratory tests, the later shape of Newton's model is far lower than the original data.. However, Newton's equation fits the drying curve of 250 mm cubic size samples at 40 °C and the full-scale test very well, it also has a good fit to the drying curve of 200 mm cubic size samples at 40 °C. Therefore, Newton's equation can be used to fit the EPS product at the slow drying conditions, which is where the EPS product is dried at a large volume or at a low temperature. If only the first falling-rate period is accounted for in the drying time calculation, Newton's equation is suggested to be used in the industrial scale where the computation needs to be minimized. However, the drying curve at high drying temperature might be overestimated and caution is needed when predicting the drying time. The value of the drying parameter k of Newton's equation for each run is shown in Table 4.3. When the final moisture content is 2 %, the drying time of this full-scale test is 160.1 hours, which is calculated by Equation (2.16).

Dimensions (mm cube)	Temperature (°C)	k
100	40	0.2643
100	50	0.3217
100	60	0.5468
200	40	0.0492
200	50	0.1019
200	60	0.2980
250	40	0.0375
250	50	0.0700
250	60	0.2615
3.6×1.2×0.65 (m ³)	50	0.0085

Table 4.3 The drying parameter k of Newton's equation in each test run.

In the industrial drying operation, when the equilibrium moisture content is very small and it can be ignored, the drying time can be calculated by Equation (4.9) which has the initial moisture content from Equation (4.7) substituted into Equation (2.16) as follows:

$$t = \frac{\ln \frac{m_w - \rho_p V}{X_f \rho_p V}}{k} \quad (4.9)$$

In the current production at Lanwood Industries, the drying parameter k is found to be 0.0085, so the drying time can be calculated as:

$$t = 117.647 \ln \frac{m_w - 2.808 \rho_p}{2.808 X_f \rho_p} \quad (4.10)$$

In this research, because of the cubic shape of the samples, the ratio V/A can represent the relative thickness of the samples, where A represents the surface area (m^2) and V is the volume of the drying material (m^3). However, it is more convenient to use the reciprocal A/V when showing the results on a graph (Brooker et al, c1992).

Figure 4.1 shows the Area/Volume versus drying parameter k of Newton's equation. If the drying volume is supposed to be infinitely large, the exponent of Newton's equation should be zero. A power function is reasonable to fit this relationship which passes through the origin. Figure 4.1 indicates that the drying parameter k has a larger difference at 50 to 60 °C than at 40 to 50 °C. The power function of the drying parameter k and its R-square at each temperature are shown in Figure 4.1.

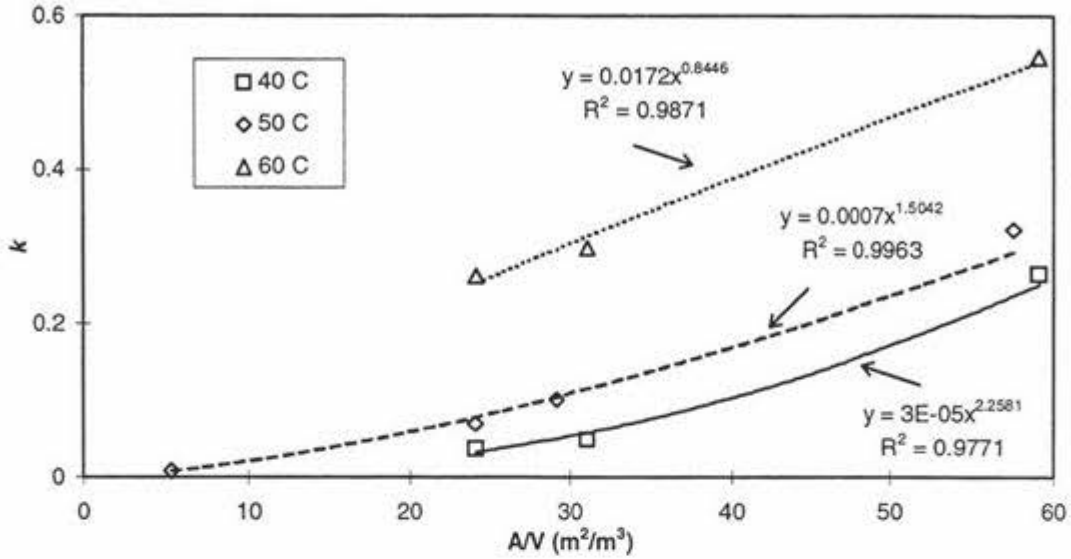


Figure 4.1 The drying parameter k of Newton's equation versus Area/Volume at different temperatures and the fitted power functions (— at 40 °C, - - at 50 °C and at 60 °C).

The drying parameter of k can be expressed as a function of drying temperature at 40 to 60 °C and the dimensions of the EPS product.

$$k = 6000e^{-0.318T} \left(\frac{A}{V}\right)^{0.071T-1.998} \quad (4.11)$$

Equation (4.11) is the relationship of the drying parameter k , the drying temperature and the EPS product dimension. However, because of the poor curve fitting of Newton's equation, it is not easy to scale up the drying process of the EPS product in this temperature range. In order to get an accurate prediction, experiments are suggested to be done with large samples which could get a good fit by Newton's equation. Also, it has to be adjusted by the full-scale experiment under the real drying conditions.

4.2.3 Empirical drying equation

A modified Newton's equation has been developed as Page's equation (2.17) for drying. Page (1949) introduced the exponent " N " to the time variable to better fit the experimental drying data. Due to the success of Page's equation in modeling the drying processes, Equation (2.17) was used to describe the experimental data obtained in this study. Equation (2.17) is transferred to Equation (2.20) to get a better fit of the drying curve. The drying parameters k and N were generalized as functions of drying air temperature and cubic size of the EPS product.

Appendix D shows the drying parameters k and N of Page's equation which fits the experimental data in each run (Figure D.1 to D.10). The rearranged Page's equation, standard error and the correlation coefficient for each run are also shown in Appendix D. Table 4.4 shows the values of the drying parameters k and N of Page's equation for each test run. In this full-scale test, at a final moisture content of 2 %, the drying time is 157.8 hours, which is calculated by Equation (2.20).

Dimensions (mm cube)	Temperature (°C)	k	N
100	40	0.3881	0.4453
100	50	0.4834	0.5841
100	60	0.7554	0.2345
200	40	0.0943	0.7808
200	50	0.1718	0.6862
200	60	0.4425	0.3897
250	40	0.0625	0.8432
250	50	0.1113	0.7730
250	60	0.3872	0.4878
3.6×1.2×0.65 (m ³)	50	0.0042	1.1421

Table 4.4 The drying parameters of k and N of Page's equation in each test run.

Page’s equation gives a better fit to the EPS samples and the full-scale drying curves. Only the drying curve of 100 mm cubic size samples at 50 °C has a slightly high standard error (Figure D.4, Appendix D). Figure 4.2 is the drying parameter k versus Area/Volume. As with the Newton’s equation mentioned before, the power function assumes that when the volume of the drying solid is infinitely large, the relationship of k and Area/volume will go through the origin. The power function of the drying parameter k and its R-square at each temperature are all shown in Figure 4.2. Figure 4.3 is the semilogarithmic plot of the drying parameter N versus Area/Volume, which can be considered a linear relationship between the drying parameter N and Area/Volume in each drying temperature. The linear function of the drying parameter N and its R-square at each temperature are shown in Figure 4.3. The drying temperature at 50 to 60 °C has more effect on the drying parameters k and N than at 40 to 50 °C.

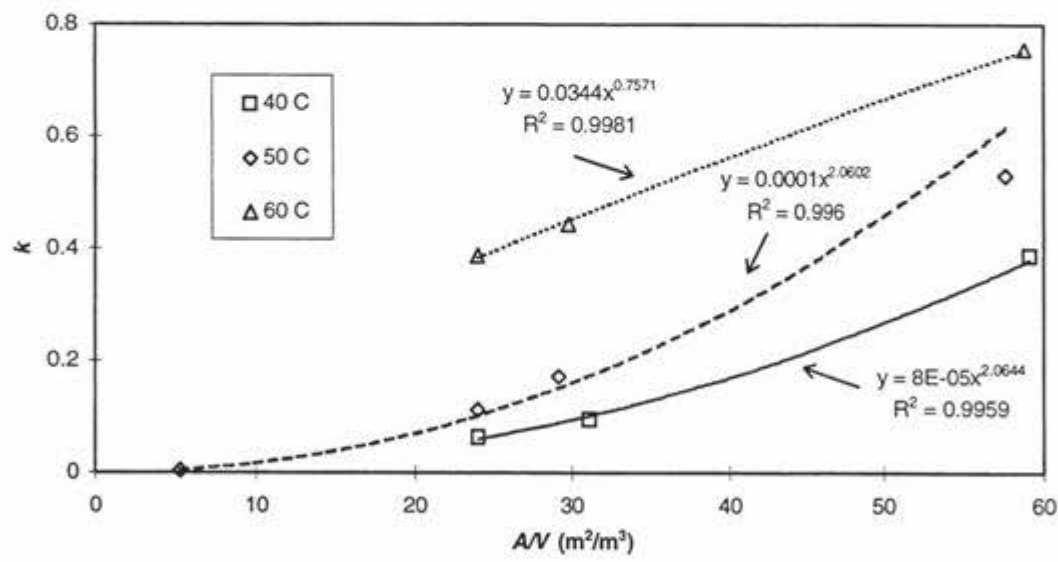


Figure 4.2 The drying parameter k of Page’s equation versus Area/Volume at different temperatures and the fitted power functions (— at 40 °C, – – at 50 °C and at 60 °C).

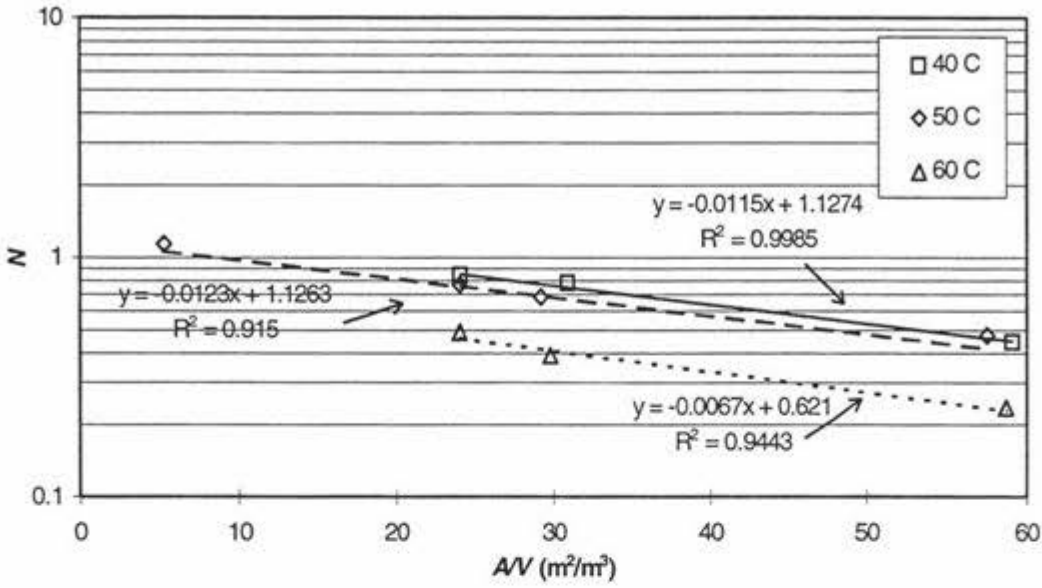


Figure 4.2 The drying parameter N of Page's equation versus Area/Volume at different temperatures and the fitted linear functions (— at 40 °C, -- at 50 °C and at 60 °C).

If the equilibrium moisture content is very small it can be ignored. Then Equation (2.20) can be rearranged to calculate the drying time by substituting the initial moisture content from Equation (4.7).

$$t = \exp\left(\frac{\ln\left(\ln\frac{m_w - \rho_p V}{X_f \rho_p V}\right) - \ln(k)}{N}\right) \quad (4.12)$$

In the current drying operation at Lanwood Industries, when k is 0.0042 and N is 1.1421, the drying time can be calculated as follows:

$$t = \exp\left(\frac{5.473 + \ln\left(\ln\frac{m_w - 2.808\rho_p}{2.808X_f \rho_p}\right)}{1.142}\right) \quad (4.13)$$

The drying parameters k and N can be defined as functions of the drying temperature and the dimensions of the EPS product.

$$k = 2000e^{-0.303T} \left(\frac{A}{V}\right)^{0.065T-1.641} \quad (4.14)$$

$$N = (0.000032T^2 - 0.003T + 0.056)\left(\frac{A}{V}\right) - 0.0025T^2 + 0.227T - 3.91 \quad (4.15)$$

Equation (4.13) derived from Page's model is complicated to use and should be simplified for the industrial calculation if possible. Equation (4.14) and (4.15) are useful for scaling up the drying process of the EPS product for the temperature between 40 to 60 °C. However, they should be verified by more experimental data, especially samples in the middle size of the EPS block and at smaller temperature intervals between 40 and 60 °C. As Page's model has given the best fit to the experimental data in both the laboratory and the full-scale tests, it appears suitable to optimize the drying temperature in future studies of the industrial drying operation.

4.2.4 The results and discussion

At Lanwood Industries, the dry weight of the EPS product can be obtained by substituting the pre-expanded polystyrene density in place of the EPS product density because they are nearly the same as each other (BASF TI-038/1e, 1974). The initial moisture content can be calculated from Equation (4.7) if the fresh moulded EPS block is weighed. To simplify the calculation, the equilibrium moisture content of the EPS product is neglected in the drying time calculation in view of its small value. It also has been discussed in previous sections that the constant-rate period of the full-scale drying can be ignored when the internal moisture movement controls the entire drying time. The drying process is considered to start at the falling-rate period. With these assumptions, theoretical, semitheoretical and empirical methods have been discussed to calculate the drying time of the EPS product.

To calculate the drying time, the simplified theoretical method used the simple linear regression technique to get the slope of the drying-rate curve of the full-scale test. The slopes of the laboratory drying-rate curves in the first falling-rate period were calculated using Equation (4.4) from the drying-rate curve values in Table 4.1. No relationship for these slopes was found between the laboratory and the full-scale tests. The drying time of this full-scale test was calculated by Equation (4.8) at 2 % (kg/kg dry basis) which is assumed as the final moisture content.

Newton's equation was fitted to the laboratory tests and the full-scale test (Figure C.1 to C.10, Appendix C). Newton's equation was found to fit better with the experimental data at a low temperature and the sample with the large volume. However, it did not fit to the data in the samples at a high temperature and small volume well. Therefore, it lacks the ability to scale up the laboratory experimental data. The drying parameter k , which is a function of the drying temperature and the sample dimension (Equation 4.11), is less reliable even though it has a reasonable physical meaning. The drying time of the full-scale test was calculated by Equation (4.10) with the final moisture content assumed to be 2 % (kg/kg dry basis).

Page's equation gave the better fit for the EPS product in both laboratory and the full-scale tests. The drying parameters k and N for Page's equation were found for each test run (Appendix D and Table 4.4). It supplies a reliable method to describe the drying process of the EPS product and it is a powerful tool for the optimization of drying conditions by scaling up laboratory tests. A power relationship was found for the drying parameter k versus Area/Volume in each temperature level (Equation 4.14) and a linear relationship was found for the drying parameter N versus sample Area/Volume (Equation 4.15) which is shown on a semilogarithmic chart (Figure 4.4). The drying parameter k increases as the drying temperature increases and decreases as the sample dimensions increase. The drying parameter N , on the contrary, decreases as the drying temperature increases and increases as the sample dimensions increase. The drying time of the full-scale test was calculated by Equation (4.13) with the final moisture content assumed to be 2 % (kg/kg dry basis).

In all these calculations, the drying process is considered to start at the falling-rate period, and the equilibrium moisture content is considered to be zero.

The three methods, Equation (4.8), (4.10) and (4.13), result in drying times of 163.3, 160.1 and 157.8 hours which is about six and half days. The simplified theoretical method results in a slightly higher value than the others. Page's equation gives the lowest value. Due to its better fit to the experimental data, Page's model is probably the more reliable method. However, the simplified theoretical method is useful for quick computation in the industrial area.

A numerical method is one way of fitting drying data to the equations for three dimensions. Theoretically, that is a precise method, however, during this procedure, there are a lot of physical properties which are difficult to obtain, and of course, a lot of calculations which relate to the heat and mass transfer. This method might be suggested to study three dimensional EPS drying in future research.

4.3 Evaluation of the drying models

Theoretical, semitheoretical and empirical methods have been used to describe the drying process of EPS. Each model is effective in describing the experimental data and has practical value, but also has limitations which are discussed below.

4.3.1 Limitations in accuracy and validity

The simplified theoretical model is easy to use in the industrial area. It assumes the drying-rate curve of the full-scale test is a straight line going through the origin. A regression method can be used to obtain the slope of the drying-rate curve. The approximate drying time can be calculated from Equation (4.8). However, because the fluctuating data had to be smoothed by the moving average method, the shape of the drying-rate curve is dependent on the interval of the moving average, therefore the slope of the regression line contains some inaccuracy. The calculated drying time can

only be seen as a rough estimate. In fact, the calculated drying time by the simplified method is higher than that calculated by Newton's and Page's equations. Also, the drying-rate curves of the EPS product in laboratory tests show two falling-rate periods (Figure 3.12, 3.13 and 3.14); the transition point from the first falling-rate period to the second falling-rate is difficult to determine. The judgment of this transition point will strongly influence the slope of the drying-rate curve. That is, the simplified method is not easily used to scale up the laboratory experimental data for the optimization of drying conditions. The simplified method seems only useful to estimate the drying time where speed of computation is more important than accuracy.

Newton's model has a good fit on the full-scale test and its equation is not very complicated. However, Newton's model also has the scale up problem. The poor fit for the laboratory experimental data by Newton's equation is unreliable for predicting the drying process of the industrial operation from the laboratory tests. It might be possible to test large volume samples which could get better data fitting by Newton's equation, but that requires large equipment. Newton's equation seems more suitable for the current industrial drying analysis, and it is more reliable than the simplified method.

Page's equation fits most of the drying curves including the laboratory tests and the full-scale test. Page's model can predict the current industrial drying process, and it also can scale up the laboratory data for the optimization of the drying conditions of the EPS product. In order to get more accurate drying parameters, it is suggested that more experiments should be done with an enlarged range of sample volumes and smaller intervals of drying temperatures. Also, the parameter functions of Page's equation need to be simplified if possible.

Theoretical and semitheoretical methods are derived from the thin-layer material drying analysis and do not directly apply to three dimensional material drying. The simplified theoretical method can be proposed for rapid calculation but this seems only useful in the full-scale operation. The limitation of the Newton's equation can be seen in

Appendix C: the agreement between the small sample experimental data and the fitted drying curves is not outstanding.

Page's equation fits the experimental data considerably better than Newton's equation. The drying parameters k and N were generalized as functions of drying air temperature and the sample Area/Volume. Since the EPS drying process is quite complex to calculate because it involves three dimensional drying, it is more practical to solve the drying process by an empirical method.

Because there is interference in production operations and the drying conditions are not constant, the industrial drying process cannot be scaled up from the laboratory drying results directly.

The gap in dimensions between laboratory tests and the full-scale test is large (250 mm cube to $3.6\text{m} \times 1.2\text{m} \times 0.65\text{m}$). This caused some inaccuracy in scaling up over such a large volume interval. Also, the shape of the EPS block is a cuboid ($3.6\text{m} \times 1.2\text{m} \times 0.65\text{m}$), whereas the samples for the laboratory tests were cut into cubes. The drying process differs along each of the dimensions of the EPS block because of their different lengths, so it is not as the equal lengths of the cubic sample. Due to these undesired factors of the difference between the laboratory tests and the full-scale test, the scale-up procedures are by no means straight forward. Caution must be taken when the drying parameter functions are used for the optimization of the EPS product in the industrial area.

The assumed final moisture content can only be used as an average moisture content in this research for the full-scale drying time calculation, as it was obtained from the laboratory drying tests. It cannot represent the moisture distribution within the full size EPS block. The moisture gradient within the block, for different drying conditions, should be investigated so that the moisture content at the centre of the block can be determined from the average moisture content. This would allow better prediction of the drying time needed to ensure a good cutting throughout the block.

4.3.2 The results and discussion

The simplified theoretical method has limited accuracy to predict the industrial drying process, but is still useful to estimate the drying time where the computation needs to be minimized. Newton's model described the full-scale drying process well and is simple to calculate, but it did not fit laboratory tests well. Page's model is superior to the other two methods and gave a much better prediction of the observed drying curve. Also, it is capable of scaling up the laboratory experiments.

Since Page's equation gives a good fit on both the laboratory and the full-scale tests, it will serve as a powerful tool for drying process optimization for commercial purposes such as process scaling and equipment design.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

To calculate the drying time, it is necessary to set up a mathematical model which can describe the drying process. Page's equation was found to give a better fit to the EPS product experimental data for both the laboratory and the full-scale tests. Page's equation is able to describe the three dimensional drying process of the EPS product. It supplies a powerful tool to scale up the laboratory drying results to the full-scale drying operation. The drying parameters k and N were expressed as functions of the temperature and the EPS product Area/Volume. The drying parameter k was found to increase with drying temperature and to decrease with drying product dimensions. The drying parameter N was found to decrease with air temperature and to increase with drying product dimensions. These functions (k and N) may be useful for the optimization of the drying conditions in future research.

Newton's equation was found to fit with the experimental data at a low drying temperature and the sample with the large volume. It did not fit well to the experimental data at a high temperature and the small volume. Newton's equation can describe the full-scale drying process, but it is unable to scale up the laboratory drying results to the industrial scale. It does involve simpler calculation than Page's equation.

The simplified theoretical method can be used to calculate the drying time in the industrial environment for quick computation. This assumes that the drying-rate is a linear function of moisture content. The slope can be obtained by the regression method for the drying time calculation. The simplified method has limited accuracy to calculate the full-scale drying time, but it is useful for estimations where the computation needs to be minimised.

At Lanwood Industries, the initial moisture content of the EPS product can be estimated by weighing the fresh moulded EPS block and measuring its volume. The dry weight of the EPS block can be obtained by substituting the density of the pre-expanded polystyrene in place of the density of the moulded EPS product because they are nearly the same as each other. The initial moisture content can be calculated by Equation (4.7), then it can be used in these above three methods to predict the drying time.

From the results of the laboratory tests, drying air temperature at 60 °C has a strong effect on the drying rate; the moisture loss rate at 60 °C is much faster than at 40 and 50 °C. There is little difference between the drying curves at 40 and 50 °C. The effect of the thickness of the EPS product on the drying rate was found to be that the moisture loss rate decreases as the EPS product dimensions increase.

To avoid excessive experimental time, an approximated equilibrium moisture content was determined at which the EPS product weight changed less than 0.002 g/g over a 24 hour period (about 0.4 % moisture content, dry basis). The drying experiment was not run to a bone-dry basis.

For the practical problem of changing drying conditions, the full-scale experimental data had to be modified by the moving average method to obtain smoothed drying curves. The information from the initial drying period was lost because the experimental data were averaged over the initial period. The smoothed drying-rate curve shows the trend of the drying process, but the constant-rate period cannot be detected. However, an estimated calculation shows the constant-rate period is very short compared to the entire drying process, therefore it is neglected for the drying time calculation. The industrial drying process is assumed to start at the falling-rate period.

It is more practical to simulate the three dimensional drying process by an empirical method rather than by theoretical and semitheoretical methods. Because the empirical model fits the experimental data well, it provides a method to predict the drying result

with changing drying conditions. However, it is not possible to scale up drying operations in any easy way. The laboratory drying results from such a small drying cabinet can not scale up to the full-scale drying operation directly. Also, the effect of the drying material thickness and the uncertainty of the full-scale drying conditions make it difficult to simulate the drying process.

5.2 Recommendations

In order to get accurate drying parameters, it is suggested that more experiments should be carried out with an enlarged range of sample volumes and smaller intervals of drying temperature. The drying parameters k and N of Page's model should be verified by full-scale experiments under real drying conditions. Also, the parameter functions (k and N) need to be simplified, if possible.

The final moisture content for the Lanwood Industries EPS product needs to be low enough to result in a smooth surface when cut by hot wires. The moisture distribution during the drying process should be studied in order to determine the best drying time for the EPS product cutting operation. That is, the moisture gradient profile within the block, for different drying conditions, should be investigated so that the moisture content at the centre of the block can be determined from the average moisture content. The moisture gradient profile can be used to determine an appropriate final moisture content to avoid excessive drying. It will improve cutting quality and increase productivity.

Some researchers suggested that a numerical method is a powerful tool to solve three dimensional drying problems accurately and speedily. It may be useful to describe the EPS product drying process by this method. It may also lead to better prediction of the drying time.

Because EPS properties depend on the product density, it is suggested that the effect of the EPS product density on the drying rate should be studied.

It is suggested that both the moulding steam and the drying of the pre-expanded polystyrene should be studied in future work even if it is beyond the topic in this thesis. Proper drying of pre-expanded polystyrene and controlling of the moisture in the moulding steam are necessary to minimise the amount of moisture held in the block. It not only can improve the production quality but also would reduce the drying time needed. It is also suggested that the production operation is arranged to reduce the drying kiln door open time and thus keep drying conditions constant.

Nomenclature

a	a coefficient intercept on the ordinate of a semilogarithmic graph
A_1, A_2	empirical drying parameters
b	a slope of the drying rate in the first falling-rate period
c	constant
C	local moisture concentration, kg/m^3
D	moisture diffusivity, m^2/s
F	moisture flux, $\text{kg/m}^2 \cdot \text{s}$
k_1, k_2	empirical drying parameters
k	drying constant, hour^{-1}
K	drying constant, hour^{-1}
L	one half-thickness of a slab, m
MR	moisture ratio
m_w	wet weight of a drying material, kg
m_d	dry weight of a drying material, kg
N	exponent parameter
R	drying rate, $\text{kg/m}^2 \cdot \text{hour}$
R_1	initial drying rate, $\text{kg/m}^2 \cdot \text{hour}$
R_2	final drying rate, $\text{kg/m}^2 \cdot \text{hour}$
R_c	drying rate at constant period, $\text{kg/m}^2/\text{hour}$
R_c'	drying rate at the second critical point, $\text{kg/m}^2 \cdot \text{hour}$
t	drying time, hour
t_c	drying time in constant-rate period, hour
X	moisture content of a drying material, kg/kg dry basis
$\bar{X}$	average moisture content, kg/kg dry basis
X_c	first critical moisture content, kg/kg dry basis
X_c'	moisture content at the second critical point, kg/kg dry basis
X_e	equilibrium moisture content, kg/kg dry basis
X_f	final moisture content, kg/kg dry basis

X_o	initial moisture content, kg/kg dry basis
W	moisture content of a drying material, kg/kg wet basis
z	space coordinate

Greek symbols

ρ_m	density of the moulded EPS block, kg/m ³
ρ_p	density of the pre-expanded polystyrene, kg/m ³

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Appendices

Appendix A Variation of the density distribution

Fifteen groups of samples at different positions of an EPS block, which are shown in Figure A, were analyzed by one-way analysis of variance in Minitab. For each position, two duplicated samples were measured to calculate the average density after drying.

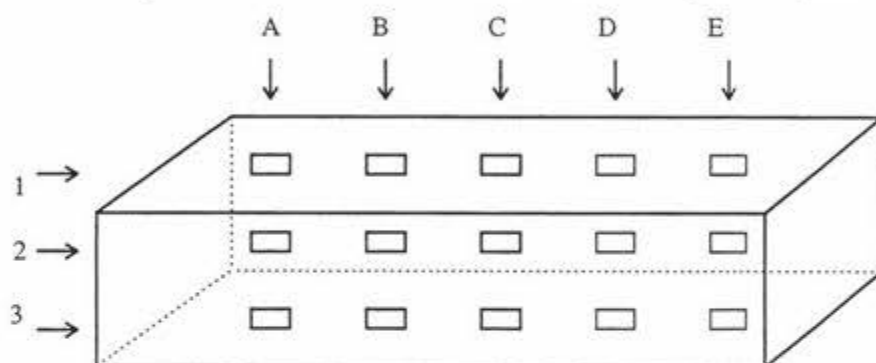


Figure A The sample position in an EPS block.

The mean density in each position and their differences are exhibited on the Minitab analysis table as follows:

One-Way Analysis of Variance

Analysis of Variance				
Source	DF	SS	MS	F
Factor	14	9.7681	0.6977	13.17
Error	15	0.7947	0.0530	
Total	29	10.5628		

				Individual 95% CIs For Mean (kg/m ³)	
				Based on Pooled StDev	
Level	N	Mean	StDev	-----+-----+-----+-----+-----	
A1	2	15.870	0.028	(-----*-----)	
A2	2	14.880	0.156	-----*-----	
A3	2	15.325	0.191	(-----*-----)	
B1	2	16.590	0.283	(-----*-----)	
B2	2	14.840	0.014	-----*-----	
B3	2	15.305	0.064	(-----*-----)	
C1	2	16.195	0.233	(-----*-----)	
C2	2	15.440	0.071	-----*-----	
C3	2	16.060	0.212	(-----*-----)	
D1	2	16.070	0.198	(-----*-----)	
D2	2	15.030	0.028	-----*-----	
D3	2	15.465	0.205	(-----*-----)	
E1	2	16.440	0.679	(-----*-----)	
E2	2	15.595	0.021	-----*-----	
E3	2	16.545	0.035	(-----*-----)	
Pooled StDev = 0.230				-----+-----+-----+-----+-----	
				14.70 15.40 16.10 16.80	

Here the p-value is 0.000. With such a small p-value, we have strong evidence that there are differences of the density in the EPS block. The density is non-uniform distributed in the EPS block.

Appendix B Variation of the moisture content

The variations of the moisture content was obtained from the same samples which were used for the density analysis in Appendix A. The moisture content is the mean value of two duplicated samples in each position which is shown in Figure A. The mean of moisture content in each position and their differences are exhibited on the Minitab analysis table as follows

One-Way Analysis of Variance

Analysis of Variance				
Source	DF	SS	MS	F
Factor	14	28.392	2.028	4.72
Error	15	6.444	0.430	
Total	29	34.836		

Individual 95% CIs For Mean (% w/w)			
Based on Pooled StDev			
Level	N	Mean	StDev
A1	2	7.575	0.686
A2	2	8.190	0.707
A3	2	7.445	0.530
B1	2	9.835	0.163
B2	2	9.225	1.379
B3	2	8.850	0.283
C1	2	9.945	0.092
C2	2	10.665	0.389
C3	2	9.695	0.658
D1	2	10.740	0.226
D2	2	10.350	0.721
D3	2	9.040	0.354
E1	2	9.495	0.516
E2	2	9.910	1.259
E3	2	9.280	0.212

Pooled StDev =	0.655
----------------	-------

7.5	9.0	10.5
-----	-----	------

The p-value is 0.003. Thus, for the significance level at 0.05 or even 0.01, we have evidence that there are differences of moisture content in the EPS block.

Appendix C Buoyancy effects on the EPS block weight during drying

As the air around the EPS block changes its temperature, so its density changes and hence the buoyancy effect changes.

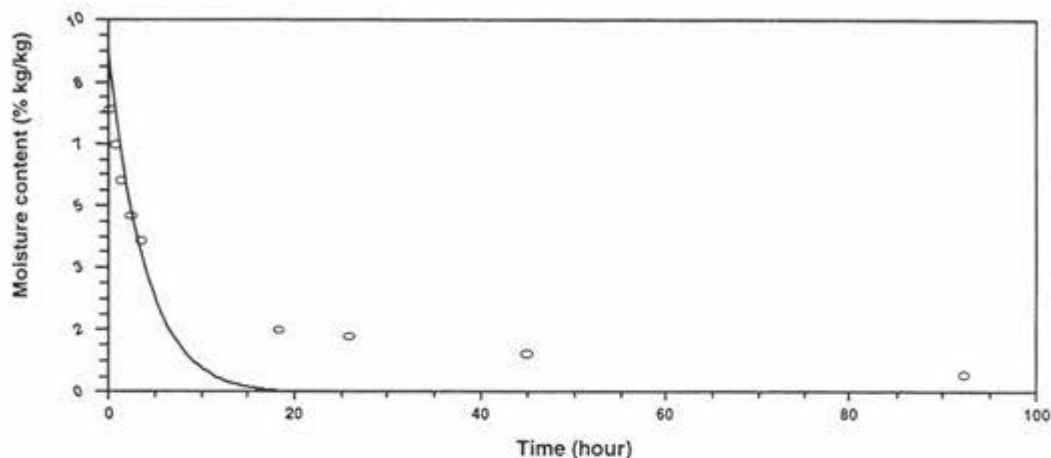
Air at 20 °C (and 1 atmosphere pressure) has a density of 1.20 kg/m³.

When heated to 50 °C its density is reduced by the ratio $\frac{273+20}{273+50} = 0.907$, that is to 1.089 kg/m³. The change in density is 0.111 kg/m³, in the volume of an EPS block (2.808 m³), amounts to 0.312 kg difference in buoyancy. So the block is expected to weigh about 300 g less when weighed in air at 20 °C than at 50 °C.

This would account for the drop in observed weights when the kiln doors are opened and the air temperature decreases. It would also account for the initial increase in observed weight. The first readings were in cold air, then as the air in the kiln slowly recovered to the higher temperature. The buoyancy became less, giving an apparent increase in the weight of the block.

Appendix D Comparison of experimental data and Newton's equation

250 mm cubic sample at 60 °C



D.1 Comparison of experimental data of 250 mm cubic sample at 60 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

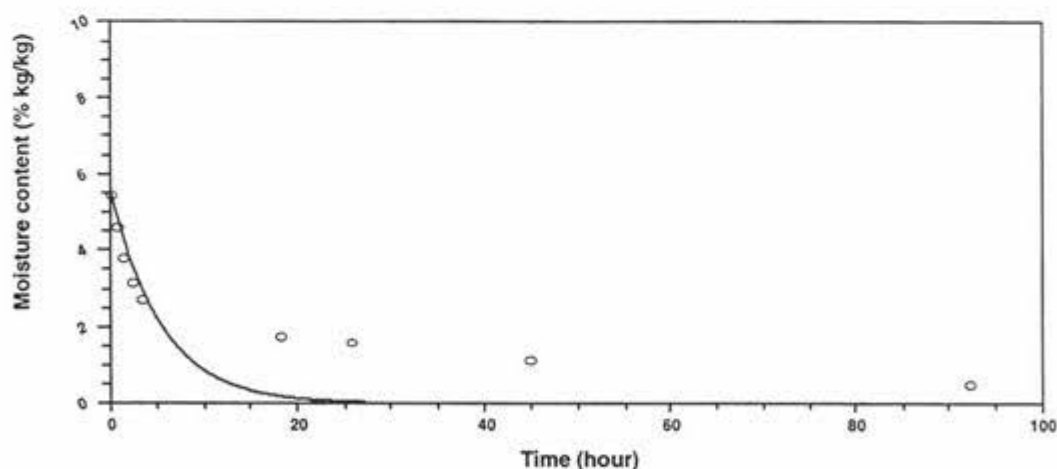
Newton's Model: $X = 9.283 \exp(-kt)$

$k=0.26149032$

Standard Error: 0.9364510

Correlation Coefficient: 0.9520787

200 mm cubic sample at 60 °C



D.2 Comparison of experimental data of 200 mm cubic sample at 60 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

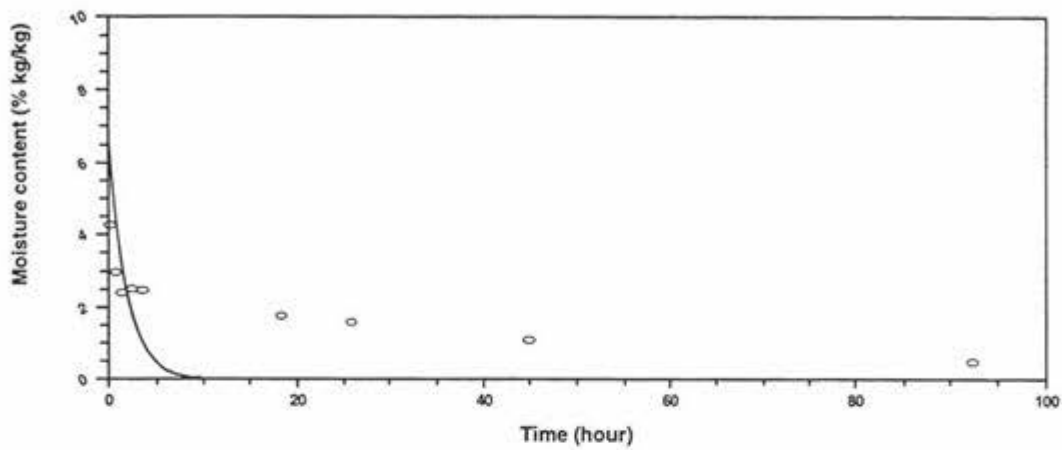
Newton's Model: $X = 6.565 \exp(-kt)$

$k=0.29896949$

Standard Error: 0.9229854

Correlation Coefficient: 0.8843371

100 mm cubic sample at 60 °C



D.3 Comparison of experimental data of 100 mm cubic sample at 60 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

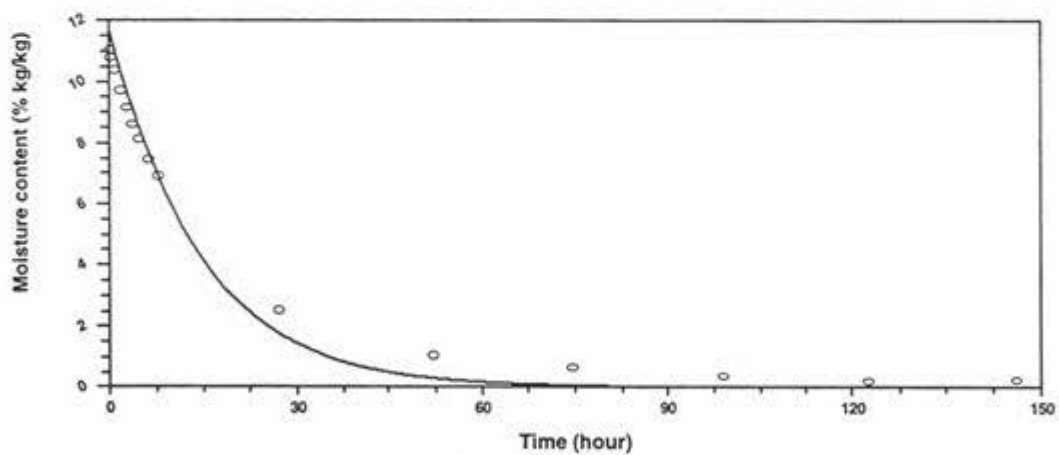
Newton's Model: $X = 6.649 \exp(-kt)$

$k=0.54675762$

Standard Error: 1.2265389

Correlation Coefficient: 0.7172514

250 mm cubic sample at 50 °C



D.4 Comparison of experimental data of 250 mm cubic sample at 50 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

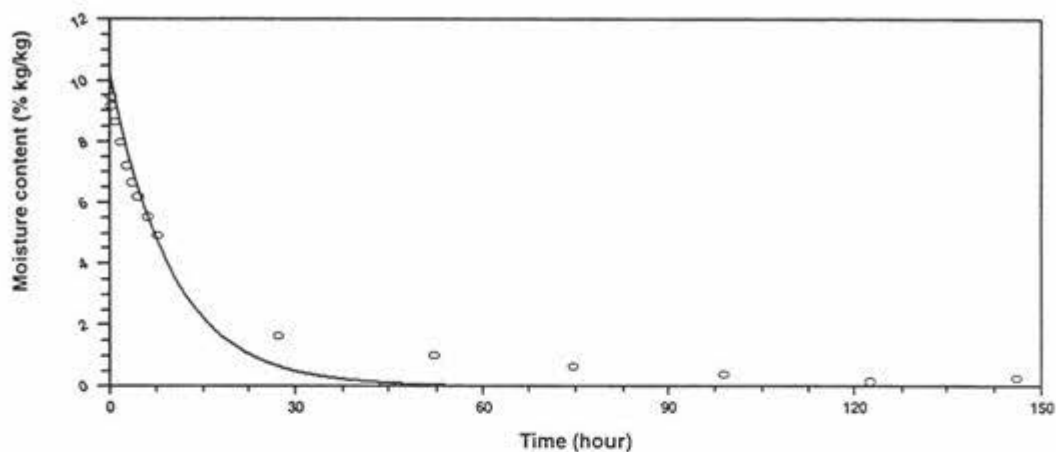
Newton's Model: $X = 11.697 \exp(-kt)$

$k=0.069968528$

Standard Error: 0.4453892

Correlation Coefficient: 0.9951083

200 mm cubic sample at 50 °C



D.5 Comparison of experimental data of 200 mm cubic sample at 50 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

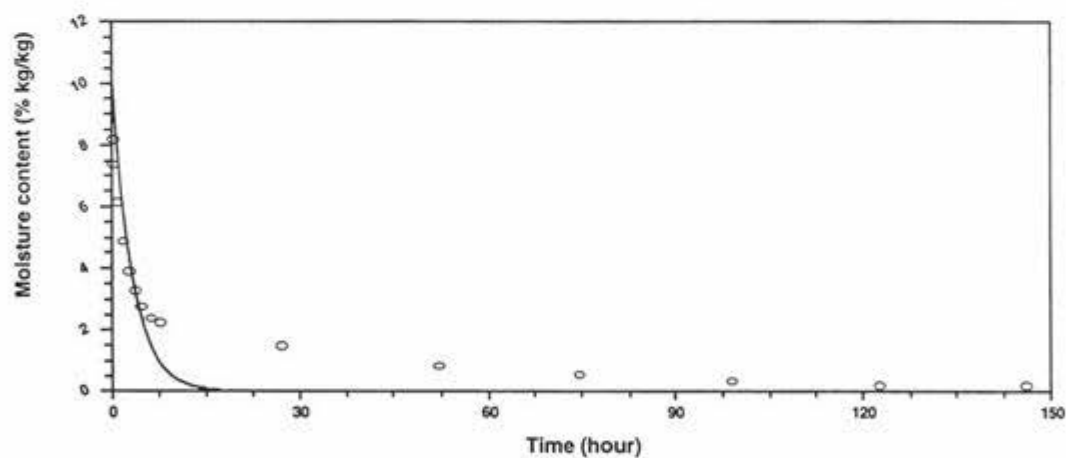
Newton's Model: $X = 10.214 \exp(-kt)$

$k=0.10191544$

Standard Error: 0.4981858

Correlation Coefficient: 0.9913575

100 mm cubic sample at 50 °C



D.6 Comparison of experimental data of 100 mm cubic sample at 50 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

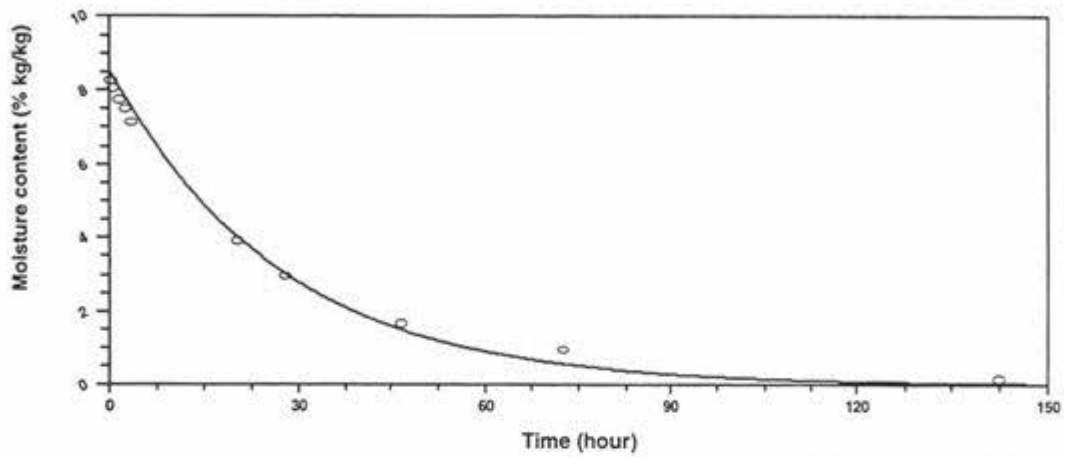
Newton's Model: $X = 10.147 \exp(-kt)$

$k=0.32167585$

Standard Error: 0.8255594

Correlation Coefficient: 0.9683913

250 mm cubic sample at 40 °C



D.7 Comparison of experimental data of 250 mm cubic sample at 40 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

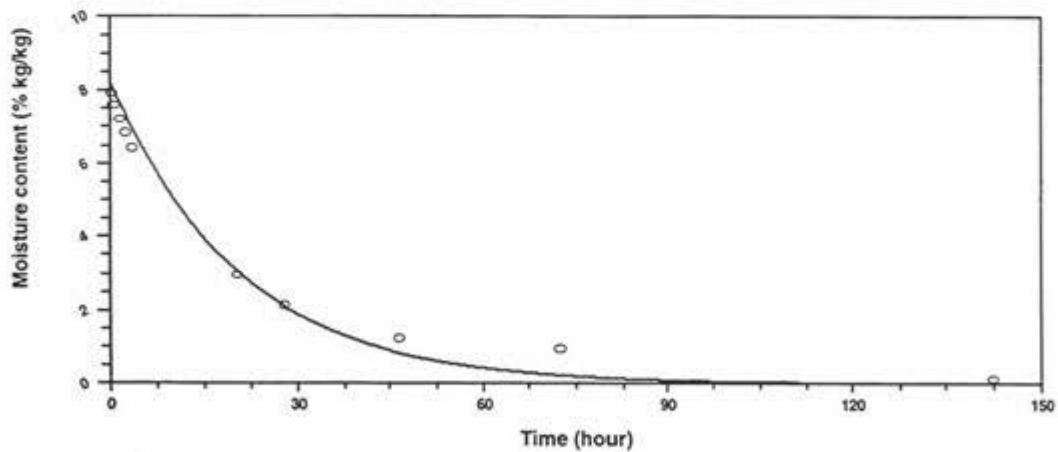
Newton's Model: $X = 8.521 \exp(-kt)$

$k=0.037465897$

Standard Error: 0.2295783

Correlation Coefficient: 0.9975248

200 mm cubic sample at 40 °C



D.8 Comparison of experimental data of 200 mm cubic sample at 40 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

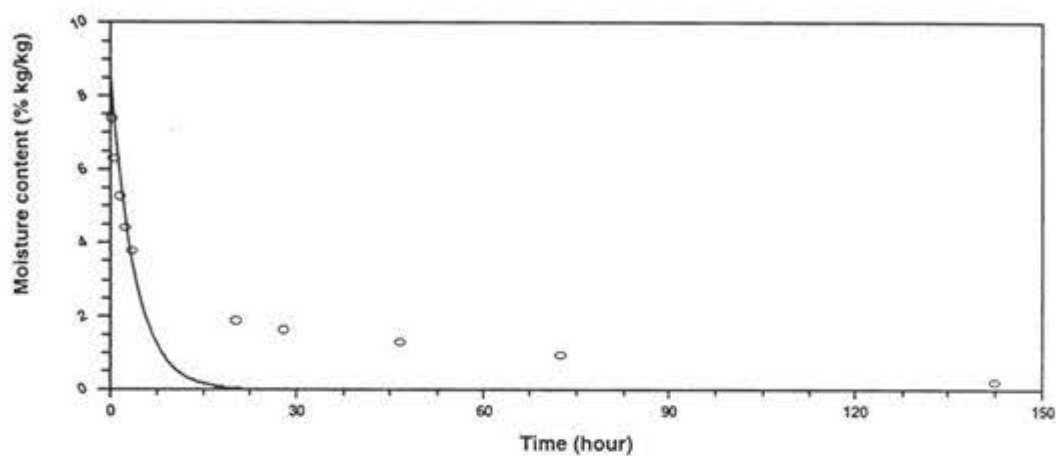
Newton's Model: $X = 8.205 \exp(-kt)$

$k=0.049175428$

Standard Error: 0.3615496

Correlation Coefficient: 0.9935305

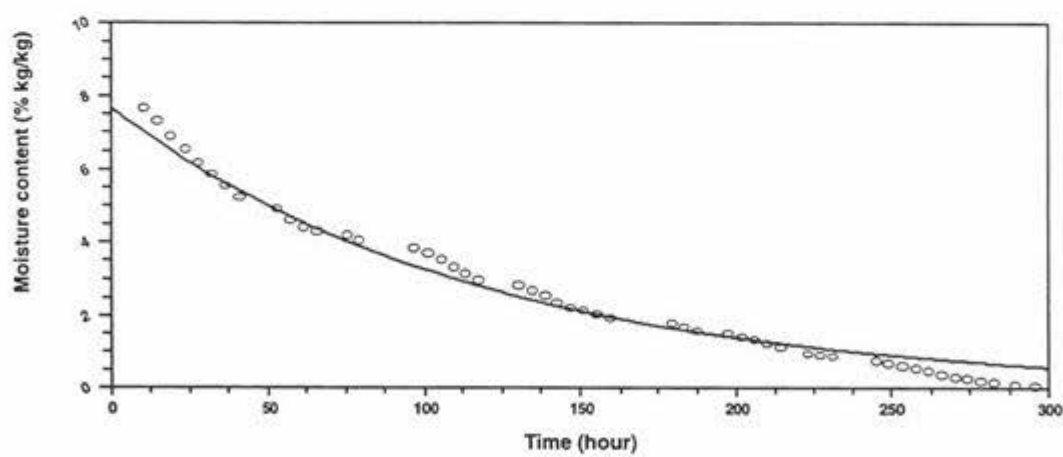
100 mm cubic sample at 40 °C



D.9 Comparison of experimental data of 100 mm cubic sample at 40 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

Newton's Model: $X = 8.55 \exp(-kt)$
 $k=0.26427508$
Standard Error: 0.9693525
Correlation Coefficient: 0.9394591

Full-scale test at 50 °C

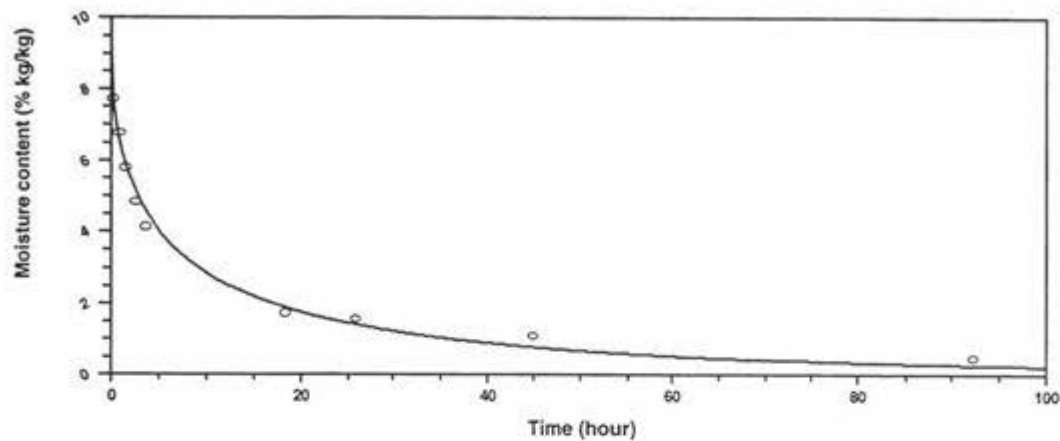


D.10 Comparison of the full-scale experimental data at 50 °C and Newton's equation. The circles are experimental data, the solid line is Newton's model.

Newton's Model: $X = 7.652 \exp(-kt)$
 $k=0.0085271976$
Standard Error: 0.3073975
Correlation Coefficient: 0.9895587

Appendix E Comparison of experimental data and Page's equation

250 mm cubic sample at 60 °C



E.1 Comparison of experimental data of 250 mm cubic sample at 60 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 9.283 \exp(-kt^N)$

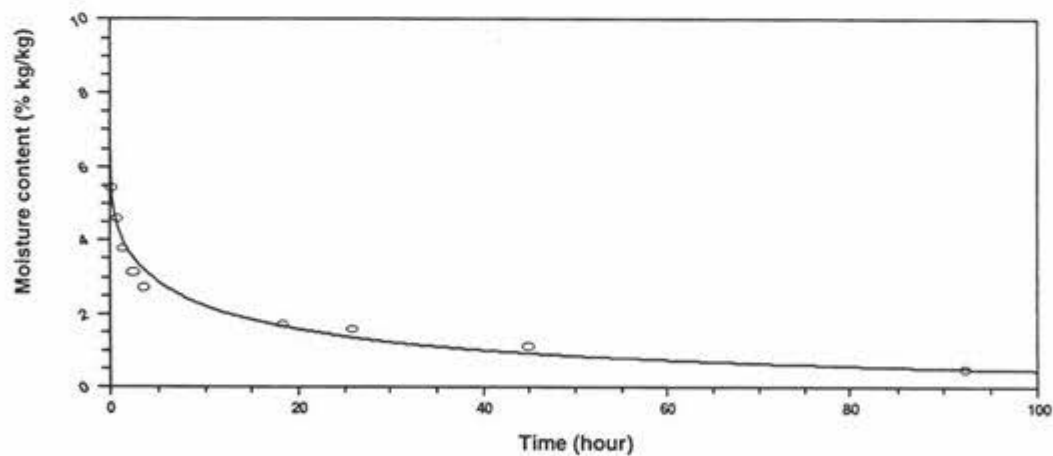
$k=0.38723235$

$N=0.48775633$

Standard Error: 0.2519665

Correlation Coefficient: 0.9969855

200 mm cubic sample at 60 °C



E.2 Comparison of experimental data of 200 mm cubic sample at 60 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 6.565 \exp(-kt^N)$

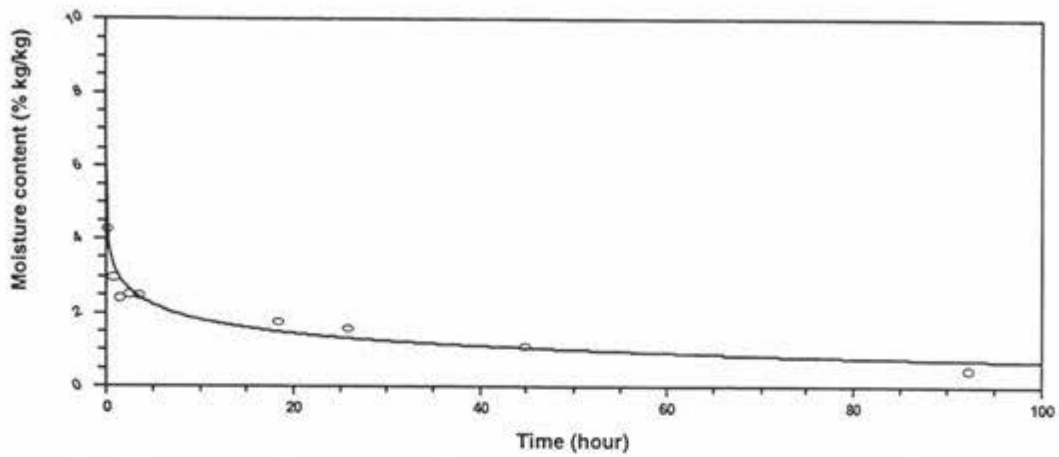
$k=0.44252738$

$N=0.38968786$

Standard Error: 0.2956892

Correlation Coefficient: 0.9900086

100 mm cubic sample at 60 °C



E.3 Comparison of experimental data of 100 mm cubic sample at 60 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 6.649 \exp(-kt^N)$

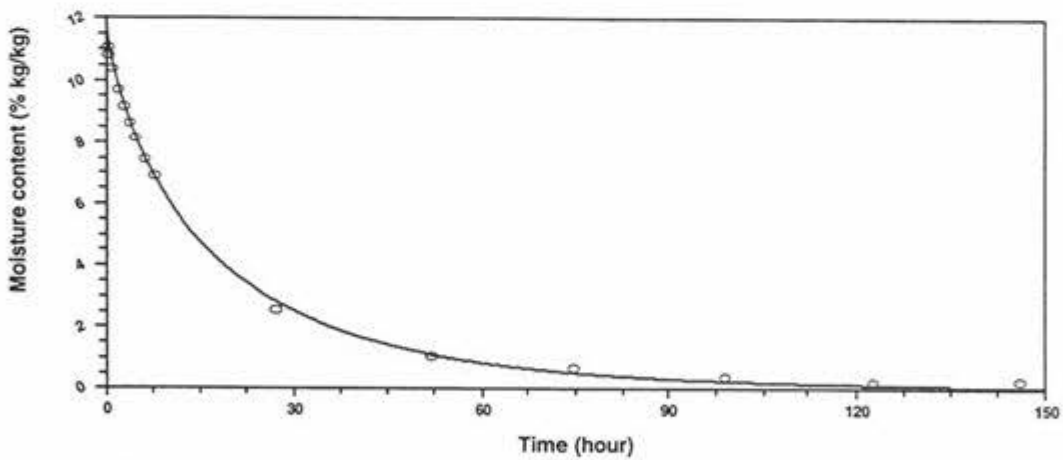
$k=0.75542233$

$N=0.23448891$

Standard Error: 0.3252413

Correlation Coefficient: 0.9847091

250 mm cubic sample at 50 °C



E.4 Comparison of experimental data of 250 mm cubic sample at 50 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 11.697 \exp(-kt^N)$

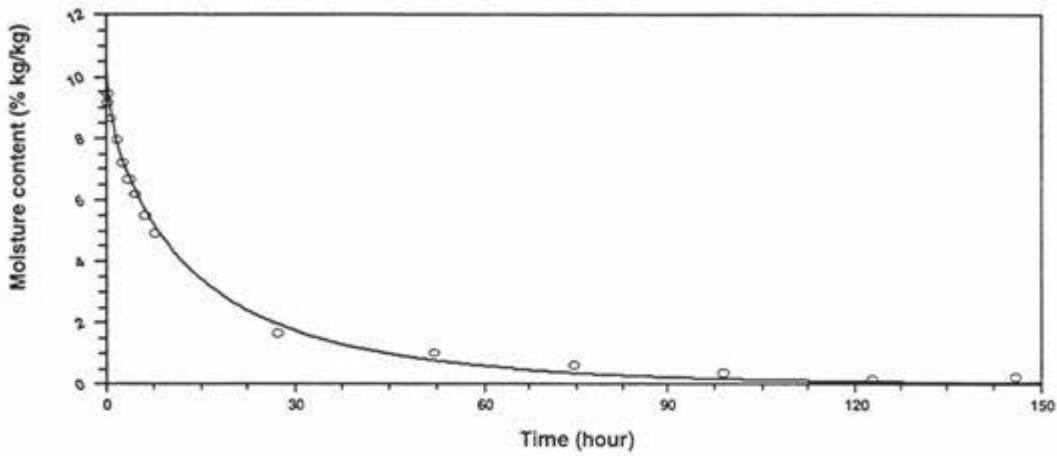
$k=0.11134288$

$N=0.77300379$

Standard Error: 0.1191225

Correlation Coefficient: 0.9996727

200 mm cubic sample at 50 °C



E.5 Comparison of experimental data of 200 mm cubic sample at 50 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 10.214 \exp(-kt^N)$

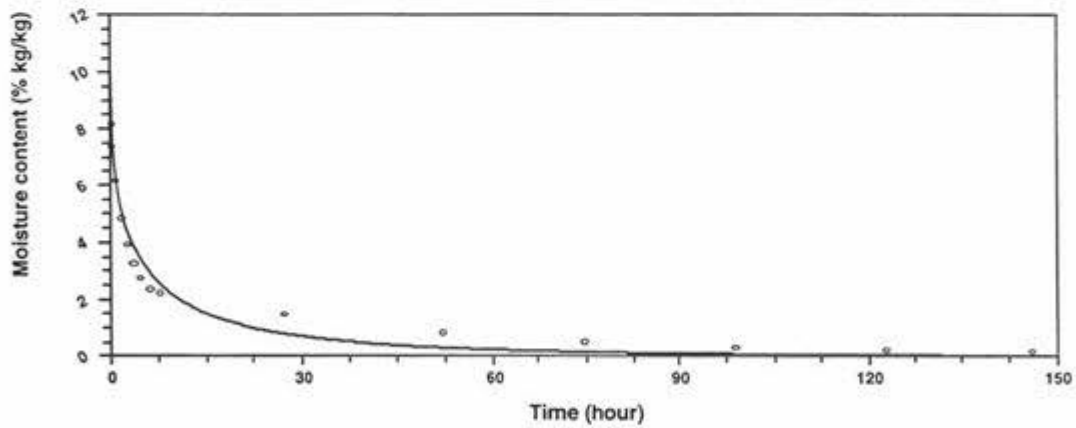
$k=0.17177046$

$N=0.68616507$

Standard Error: 0.1519747

Correlation Coefficient: 0.9992490

100 mm cubic sample at 50 °C



E.6 Comparison of experimental data of 100 mm cubic sample at 50 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 10.147 \exp(-kt^N)$

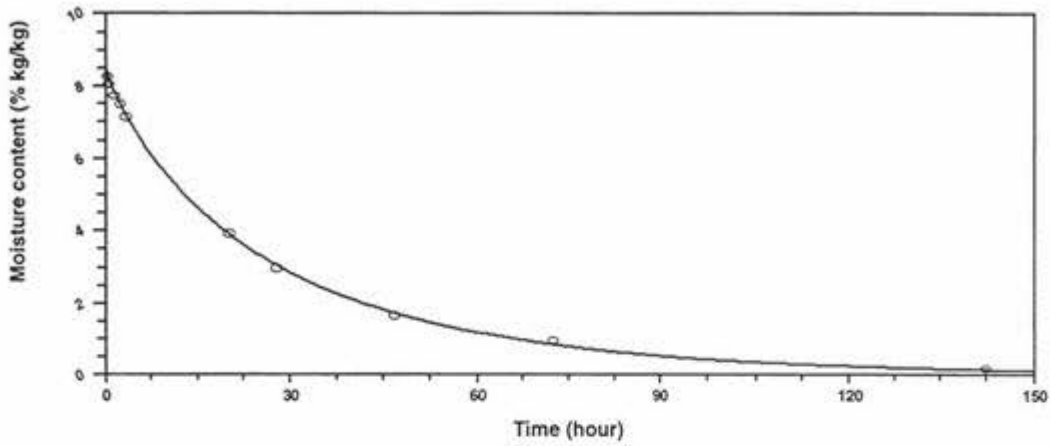
$k=0.52971926$

$N=0.475$

Standard Error: 0.4917246

Correlation Coefficient: 0.9889018

250 mm cubic sample at 40 °C



E.7 Comparison of experimental data of 250 mm cubic sample at 40 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 8.521 \exp(-kt^N)$

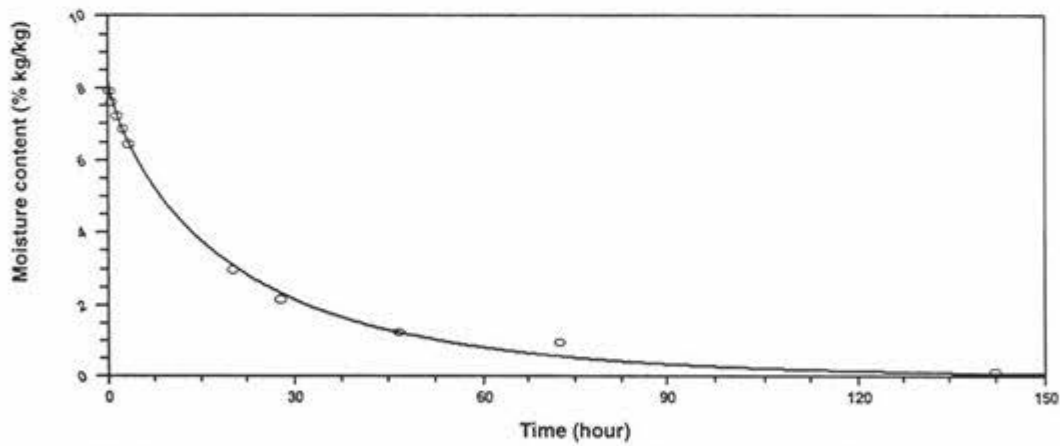
$k=0.062485769$

$N=0.84323149$

Standard Error: 0.0612499

Correlation Coefficient: 0.9998416

200 mm cubic sample at 40 °C



E.8 Comparison of experimental data of 200 mm cubic sample at 40 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 8.205 \exp(-kt^N)$

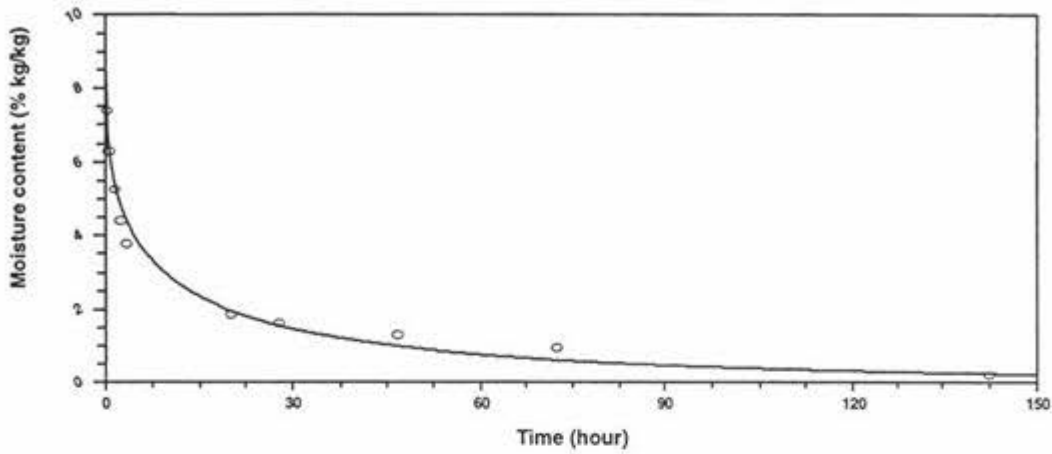
$k=0.094272381$

$N=0.78079399$

Standard Error: 0.1418375

Correlation Coefficient: 0.9991064

100 mm cubic sample at 40 °C



E.9 Comparison of experimental data of 100 mm cubic sample at 40 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 8.55 \exp(-kt^N)$

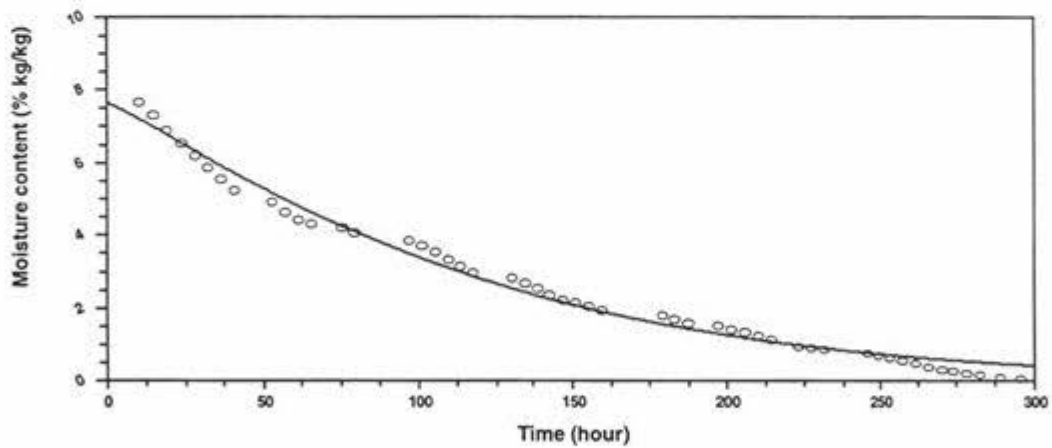
$k=0.38814752$

$N=0.44530551$

Standard Error: 0.3480951

Correlation Coefficient: 0.9931631

Full-scale test at 50 °C



E.10 Comparison of the full-scale experimental data at 50 °C and Page's equation. The circles are the experimental data, the solid is the Page's model.

Page's Model: $X = 7.652 \exp(-kt^N)$

$k=0.0042369712$

$N=1.1421295$

Standard Error: 0.2523557

Correlation Coefficient: 0.9931134