Moisture movement in concrete during drying

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Doctoral Thesis Presented by:
Chartered Engineer

August 2009
DECLARATION

The author hereby declares that this thesis, in whole or in part, has not been submitted to any other University as an exercise for a degree. Except where reference has been given in the text, it is entirely the author’s own work.

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__________________________
Niall Holmes
Chartered Engineer

August 2009
DEDICATION

This thesis is dedicated to the memory of my father Jim who passed away on the 6th December 2005. I miss you every day. I know how much you wanted me to finish this work.
ACKNOWLEDGEMENTS

During the course of my research, I have received a lot of help from a variety of people. I would like to take this opportunity to mention and thank all those who have made a substantial contribution in helping me complete this work.

Firstly, I have would like to sincerely thank my supervisor Dr. Roger P. West for all his help over the years. I know that this is a much better thesis as a result of his input.

For the technical support offered by all the technicians in the Civil Engineering Department must also be noted for helping me prepare the experimental side of this work and to Alan Rynhart and Sean Fallon of Tramex Ltd, for their technical support and advice.

To my parents Jim and Sally, who have given me un-ending support during all my endeavours. Thank you so much for everything.

To my wonderful wife Jennifer who has provided me with the will, encouragement, support and dedication to fulfil my dream and finish this work.
The prediction of moisture distribution within concrete slabs has considerable practical importance as it affects the time at which coverings can be safely applied. Moisture in concrete affects creep, shrinkage, strength development, durability and must be present in sufficient quantities for full hydration to occur and for workability on site. However, an excess of moisture in concrete at the point of covering particularly can lead to a number of problems such as delamination and blistering of vinyl, buckling of timber floors and rising of tiles. Moisture migrates in concrete slabs as a diffusion-type process during drying and is lost to the ambient air via evaporation from exposed surfaces. Drying will continue until equilibrium is reached between the humidity in the concrete and in the ambient air. The measured relative humidity (rh) profiles indicate that non-linear profiles exist early on as drying was more rapid near the surface, particularly during accelerated drying. Over time, however, the moisture movement became more uniform through the slab.

This thesis presents the results from a series of rh measurements taken at the surface and through the depth in a number of concrete slabs with varying thicknesses (100, 150 and 200mm) and w/c ratios (0.4, 0.5 and 0.6) and allowed to dry in two different ambient drying environments; naturally in a laboratory and artificially in a control room where drying was accelerated using a heater and dehumidifier. These properties were chosen as they represent typical ranges of slab thicknesses and w/c ratios used in practice for most ground bearing slab applications. From these results, a commercial finite element model (FEM) (DIANA) has been set up to predict the changing rh over time using calibrated material properties, namely the diffusion coefficients and evaporation rates. The FEM demonstrated that it could be used to predict the rh over time.

When the surface reached 75% rh, the point specified by the British Standard to be achieved before any covering should be applied, an impervious floor covering (vinyl) was applied and the rh continued to be monitored through the depth as the residual moisture redistributed. For the concrete to reach a surface rh of 75%, it may take several months or even years, particularly for very thick slabs. It is common on many construction sites to speed up the process by accelerating drying by using dehumidifiers and heaters. However, it has been shown here that this only leads to rapid drying near the surface with large residues of moisture remaining deep in the concrete. As a consequence, when an
impervious covering is applied, this residue of moisture will slowly re-distribute due to the humidity gradient between the top and bottom of the slab and slowly builds-up under the covering. To model this, the FEM was again set up to suit the new initial and boundary conditions with the impervious covering now applied and the \( rh \) through the depth. Again, the results compared well with those measured. Along with this, a vapour pressure is created and this combines with the moisture build-up to cause the problems above. This thesis presents measurement of this pressure as well as a number of pull-off tests that physically assess what forces are required to lift sealed vinyls from concrete surfaces.

Heavily influenced by this work and the results, the ASTM in America are developing a new standard method (ASTM F 2170-02, 2002) which specifies that the \( rh \) should be measured at 20 or 40% of the depth for 1 or 2-face drying respectively using humidity probes like those used here. These results were presented to the ASTM committee when this new standard was being discussed as the results show that indeed the \( rh \) at 40% of the depth at the point of covering is a good indicator of the long-term \( rh \) after sealing.

Although accelerated drying methods have largely been responsible for damages to floor coverings, this thesis proposes that accelerated drying can be used so that the long-term \( rh \) in the concrete leads to fewer instances of problems after sealing. It has been proposed that if the slab was allowed to dry until it achieves a surface \( rh \) of between 67-72% (for the w/c ratios here) using artificial drying methods, the long-term \( rh \) would fall within the known long-term ‘safe’ humidity range of 75-80%, where the chances of future damage to the covering would be significantly reduced. It is shown that by continuing to use these artificial drying methods until a surface \( rh \) of 67% is achieved, significant time savings can still be made, (as much as 30-40 days here) particularly when compared to natural drying.

The conclusions from this work add significantly to the current knowledge. It presents new experimental techniques and a calibrated finite element model based on these results to predict the \( rh \) through the depth of drying concrete slabs, before and after application of impermeable coverings which has also been shown to compare well with previous experimental results. It also proposes that artificial drying methods can be employed so that coverings can be applied much sooner while safe in the knowledge that long-term problems are minimised. Furthermore, results from this work have been used to develop new standards for the measurement of the \( rh \) in the USA.
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The following is a list of principal notations. All of the following are defined in the text where they are first used and are listed here solely for clarity.

\[ \text{rh} \quad \text{Relative Humidity (\%)} \]
\[ D(h) \quad \text{Diffusion coefficient as a function of the pore rh (m}^2/\text{sec)} \]
\[ S \quad \text{Sorptivity (mm/min}^{0.5} \text{)} \]
\[ K \quad \text{Permeability (m/sec)} \]
\[ t \quad \text{Time (sec)} \]
\[ D \quad \text{Diffusion coefficient (m}^2/\text{sec)} \]
\[ J \quad \text{Rate of moisture transfer or flux (g/m}^2.\text{sec)} \]
\[ h_s \quad \text{Surface rh (\%)} \]
\[ P \quad \text{Vapour pressure of the air (Pa)} \]
\[ P_s \quad \text{Saturated vapour pressure (at the same temperature) (Pa)} \]
\[ \text{OPC} \quad \text{Ordinary Portland Cement} \]
\[ f_c \quad \text{Compressive strength (N/mm}^2 \text{)} \]
\[ w/c \quad \text{Water/Cement ratio} \]
\[ w_E \quad \text{Evaporable water content (kg/m}^3 \text{)} \]
\[ D_1 \quad \text{Diffusion coefficient at 100% rh (m}^2/\text{sec)} \]
\[ K_V \quad \text{Vapour water transport coefficient (m}^2/\text{sec)} \]
\[ K_L \quad \text{Liquid water transport coefficient (m}^2/\text{sec)} \]
\[ f_{cu} \quad \text{Mean compressive strength (N/mm}^2 \text{)} \]

**Greek Symbols**

\[ \theta \quad \text{Term used to signify Euler backward and forward method, Galerkin method and mid-difference method (1, 0, } \frac{2}{3} \text{ and } \frac{1}{2} \text{ respectively).} \]
\[ \eta \quad \text{Concrete Porosity (\%)} \]
\[ \rho \quad \text{Density (kg/m}^3 \text{)} \]
\[ c \quad \text{Specific heat (J/kg}^0\text{C).} \]
\[ \rho c \quad \text{Heat capacity per unit volume (J/m}^3.0\text{C).} \]
## Notation

### Anagrams

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<td>Damp-proof membrane</td>
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<tr>
<td>DPC</td>
<td>Damp-proof course</td>
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<td>BS</td>
<td>British Standard</td>
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<td>VET</td>
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1. INTRODUCTION

1.1 PREAMBLE

Concrete, like any other wet porous material, will dry when exposed to the ambient air through exposed surfaces. Moisture profiles in concrete are non-linear during drying, particularly early on, as the moisture near the surface is lost faster than that deep in the concrete. The early drying is led by evaporation of moisture from the exposed surfaces, which creates a relative humidity (\(\text{rh}\)) gradient near the surface initially and through the depth over time. The moisture movement during drying is a diffusion process through the concrete, which is defined as the migration of moisture, in a liquid or vapour form, from a region of high concentration to a region of lower concentration and its rate is a function of the internal pore \(\text{rh}\). Diffusion and evaporation of moisture depends on a number of properties such as the ambient conditions (temperature and humidity), w/c ratio, hydration (particularly early on) and the concrete pore structure which is related to the hydration process. All of these properties combine to make the general drying of concrete a complex non-linear process.

In most concrete slabs on grade, there is only one face exposed to the surrounding air as the remaining sides and base are insulated against moisture loss by the use of damp-roof membranes (DPM) or damp-proof courses (DPC). Therefore, drying is most commonly one-dimensional as the top of the concrete is the only face exposed to the surrounding air.

One area that moisture movement in concrete affects is the point in time when impermeable coverings (tiles, vinyl, etc.) can be safely applied to the surface without future damage due to excessive residues of moisture remaining in the concrete after covering. The current British Standard (BS 8203, 1996) recommends that a concrete floor can be covered when the surface reaches 75% \(\text{rh}\), established using a surface hygrometer test. However, substantial residual moisture can remain in the concrete, particularly if rapid drying practices are used to achieve this 75% \(\text{rh}\) threshold faster, a common practice on site using heaters and dehumidifiers. This residual moisture, on covering, will then slowly equilibrate within the slab resulting in a higher \(\text{rh}\) on the surface. The combination of moisture redistributing and the accompanying increase in vapour pressure under the
covering may cause a number of problems, such as blistering of paint, delamination of vinyl, buckling of timber boards and rising tiles from the concrete surface. This problem has increased recently due to the promotion of fast track construction projects and the requirement to cover the floor as soon as possible. However, this thesis presents a way to continue to use accelerated drying methods so that these problems can be reduced and allowing the covering to be laid sooner. The method allows artificial drying to continue for longer, past the 75% $rh$ point so that the long-term equilibrated $rh$ in the concrete falls within an accepted ‘safe’ range were problems like these are minimised.

This thesis presents the results of experimental tests to monitor both the $rh$ profiles at the surface and through the depth and the surface moisture content using hand-held instruments before and after application of an impermeable floor covering. It also presents vapour pressure measurements under the covering as well as pull-off tests that measure the tensile force required to lift a sealed vinyl from a concrete surface. Further, a commercial Finite Element (FE) model (DIANA) has been set-up using suitable physical and calibrated material properties that can be used to predict the $rh$ profiles in concrete slabs both during drying and after an impermeable covering is applied for normal OPC concretes in similar drying environments.

Heavily influenced by this work and its results, the ASTM in America are developing a new standard method (ASTM F 2170-02, 2002) which specifies that the $rh$ should be measured at 20 or 40% of the depth for 1 or 2-face drying respectively using humidity probes like those used here. These results were presented to the ASTM committee when this new standard was being discussed as the results show that indeed the $rh$ at 40% of the depth at the point of covering is a good indicator of the long-term $rh$ after sealing.

1.2 EXPERIMENTAL WORK

In order to monitor the $rh$ profiles in concrete during drying, a number of slabs were poured with varying dimensions (500x500x100mm deep, 500x500x200mm deep and 700x700x150mm deep) and w/c ratios (0.4, 0.5 and 0.6). They were allowed to dry in a natural (in a laboratory) and accelerated (in a control room) drying environments with elevated temperatures and reduced humidities using a heater and dehumidifier. The $rh$ was
measured at the surface using a surface hygrometer and a number of new experimental apparatuses at various depths in the concrete using humidity probes inserted into plastic tubes drilled into the concrete after curing. This resulted in the measurement of the \( rh \) profile through the depth of the slab at various times. The probes were attached to hand-held meters, which give a digital display of the \( rh \). The surface moisture content was measured using another type of hand-held meter by pressing it onto the surface giving a reading of the near surface moisture content in percentage terms.

An impermeable floor covering (a vinyl) was applied to the 150mm thick slabs when they reached a surface \( rh \) of 75\%, the point specified in the British Standard (BS 8203, 1996) before any covering can be applied. After the covering was applied, the \( rh \) was continually monitored and the re-distribution of the residual moisture in the slab was observed along with the measurement of the vapour pressure that developed underneath the covering, using pore pressure probes. To assess the effects of the vapour pressures measured, a number of pull-off tests were carried out to determine the tensile force required to physically lift the vinyl off the concrete using a number of 150mm concrete cubes at various times with various w/c ratios.

In addition, a number of Vapour Emission Tests (VET) was also performed. This test measures the rate of moisture emissions from the concrete (in units of lbs/1000ft\(^2\)/24hrs) and is used in the United States of America (USA) to determine when a concrete slab can be covered with an impermeable covering (Vapour Emission Test, 1994) where an emission rate of between 3-5 lbs/1000ft\(^2\)/24hrs must be achieved before the concrete is sealed.

### 1.3 NUMERICAL MODELLING OF CONCRETE DRYING

In order to predict the \( rh \) profiles in concrete slabs during drying for normal OPC concretes, a well-known commercial FE package, DIANA, was used to model the changing \( rh \) in the concrete slab for the thicknesses, w/c ratios and in the two environments used here. DIANA was selected as it allows the user to input both linear and non-linear material properties, for both diffusion and evaporation. The physical model included a finer mesh for the top 40\% of the slab, based on the ASTM proposals. The material
properties (namely the evaporation and diffusion rates) were calibrated against the experimental results and compared well with previously published literature. The results from the analysis show, unsurprisingly, good comparisons with the experimental results. Furthermore, it also gave good comparisons (within 3-5%) with other published experimental results that demonstrated its robustness. The use of a model like this, to predict $rh$ profiles, during drying and after application of an impermeable floor covering, has not been developed to date, and represents new work.

1.4 AIMS AND OBJECTIVES

This work focuses on the study of the movement of moisture during drying in concrete slabs and the redistribution of moisture following application of an impermeable covering. For this, a number of experimental tests were undertaken which measured the $rh$ at the surface and through the depth during drying, with varying slab dimensions and w/c ratios, in a normal and an accelerated drying environment. Using these results, a finite element model has been set up and calibrated to predict these $rh$ profiles through the concrete slabs over time both during drying and after application of an impermeable covering. The main objectives of this work are outlined below.

- Review the current literature and present the current knowledge in the area of moisture migration in concrete during drying, theoretically and experimentally. This will help understand what experimental tests are required to fill the gaps in the knowledge and how to best set up and calibrate the finite element model to account for the physical and material properties respectively.
- Measure the movement of moisture during drying at various depths in a concrete slab over time using portable humidity probes and hand-held meters to gain an understanding of the effects the physical and material properties in the two drying environments have on the internal moisture condition.
- Analyse the effects of w/c ratio, slab thickness and drying environment on the $rh$ distributions in the concrete so as to accurately set up and calibrate the model.
- Use the calibrated model to predict the $rh$ profiles for the various slab thickness, w/c ratios and drying environments and compare the results with both the experimental results here and those from previously published literature to
demonstrate the model’s robustness and applicability.

- Study the effect of applying an impermeable floor covering to the surface of a concrete slab on the internal \( rh \) profiles by continuing to monitor the redistributed \( rh \) over time through the depth and the associated vapour pressure generated.

- Develop the previously calibrated finite element model further to account for the new boundary and initial conditions upon sealing so as to predict the redistributed \( rh \) profiles and compare these with the experimental results.

- Discuss how the results were used to influence a new standard in the USA to determine the depth at which the \( rh \) should be measured at, prior to covering, to give an indication of the long-term equilibrated \( rh \) after sealing.

- Give recommendations and new criteria that would allow the use of accelerated drying methods to continue so that the long-term \( rh \) in the concrete will not cause future problems to coverings.

### 1.5 STRUCTURE OF THESIS

The research strategy that was followed in order to achieve these objectives in the following Chapters is summarised below:

In Chapter 2, a review of the theoretical background behind moisture movement in porous media, like concrete, is presented. The aim is to better understand the results from the experimental tests and the effect of \( w/c \) ratios, slab thicknesses and drying environments. The theory behind the typical transport mechanisms in concrete and, in particular, during drying, namely diffusion and evaporation, are presented. The influence of the concrete pore structure on moisture movement is also discussed and how it contributes to moisture movement.

Chapter 3 presents a summary of the previous experimental and finite element analyses that have been carried out in the area of moisture movement during drying. This chapter also reviews previous work to determining equations and values for the diffusion coefficient, either as a function of the internal water content \( (w) \) or the pore \( rh \), and the rate of evaporation. Following the review, the make up of the material properties in the finite element model will be better understood to best predict the actual drying. At the end of the
Chapter 4 deals with the first stage of the experimental tests that were carried out, and describes how the changing $rh$ distribution and surface moisture content was monitored over time, using a variety of moisture probes, instruments and newly developed apparatus. The slabs, with thickness of 100, 150 and 200mm and w/c ratios of 0.4, 0.5 and 0.6 were allowed to dry in a laboratory and a control room using a heater and dehumidifier raise the ambient temperatures and reduce the ambient humidity respectively. To monitor the changing $rh$ in the concrete, a number of plastic tubes were placed in drilled holes at various depths and probes inserted to read the $rh$ that were attached to hand-held meters that display the result. The humidity at the surface was monitored using the established surface hygrometer test and a number of newly developed plastic tent apparatuses sealed onto the concrete. In addition, a number of Vapour Emission Tests were also carried out to measure the rate of vapour emission from the concrete surface.

Chapter 5 presents the results from the experimental work. The results are separated into various sections to discuss the effects of the various properties separately in the experimental stage, namely the drying environment, w/c ratio and the slab thickness using a base slab thickness or w/c ratio for the discussions. By doing this, the sensitivity of each property in terms of drying time, $rh$ profile and trends can be seen in its own right. Each section presents the $rh$ profiles and the surface moisture content results. In addition, the results from the vapour emission tests are discussed.

Chapter 6 presents the setting up of the finite element model in terms of the physical model and calibration of the material models to predict the $rh$ profiles for the various slabs in the two drying environments. The model is capable of using non-linear material properties as a function of $rh$ (for diffusion) and time (for evaporation) and are calibrated using the results from the experimental work. The non-linear diffusion coefficient used for this study was derived using a previously published and widely accepted empirical equation that varies with the internal $rh$ and accounts for the w/c ratio by using different initial rates of diffusion when the $rh$ is 100%. The evaporation rate was calibrated from the $rh$ profiles and surface moisture results in the laboratory and control room. The results from this model compared well with the results both here and from previously published results.
using a similar approach.

Chapter 7 presents the results of the experimental monitoring and finite element analyses following application of an impermeable covering (vinyl) to the concrete surface after it reached a surface $rh$ of 75%. The $rh$ through the depth was continually monitored as the residual moisture slowly redistributed in the concrete. The increase in vapour pressure under the covering was also monitored as the moisture re-distributed. To assess the pressure from these tests, a number of pull-off tests was conducted on 150mm concrete cubes with a vinyl applied to one face. The results show that the vapour pressure alone is not enough, in this case, to lift vinyl from concrete surfaces and other factors such as glue insolubility, poor application and workmanship all contribute to ultimately cause the problems described earlier. Using the calibrated finite element model from the previous chapter, the effect of applying the impervious coverings was modelled and the results again compared well with the experimental results. The finite element analysis was further used to facilitate the continued use of rapid drying techniques so that the surface $rh$ could continue past the standard 75% surface $rh$ (to approximately 67% $rh$) so that the long-term equilibrated $rh$ in the concrete will not cause long-term delamination and other problems over time. By doing this, significant savings in waiting time can be made when sealing a concrete slab, safe in the knowledge that long-term problems are less likely to occur.

In Chapter 8, the conclusions drawn from the work are summarised and the implications of these results are presented with recommendations for future work.
2. THEORETICAL BACKGROUND TO MOISTURE MOVEMENT

2.1 INTRODUCTION

This chapter presents a review of the theoretical background to moisture movement in porous materials covering the general desorption (drying) of porous materials, including concrete. The aim, therefore, is to provide the reader with some background knowledge of the physical mechanisms involved in moisture movement. This is required to gain a good understanding of the experimental results presented later in Chapter 5. To achieve the main aims of this chapter, a classification of the various ways moisture moves through the material is presented in section 2.2, which includes sorption, permeability and diffusion. The various factors and driving forces behind each of these is discussed. In addition, the relationship between the different types of moisture movement through porous materials is also presented.

In section 2.3, the principles of diffusion, which are commonly accepted as the main transport mechanism in drying porous media, are presented. The theory behind the diffusion equation is discussed with its derivation in easy to follow steps. This equation is based on the principle that transport is caused by the existence of a concentration gradient in the material with the rate of this movement defined by the diffusion coefficient. The direct correlation of moisture diffusion theory to heat diffusion is also presented with the equations that represent both types of movement and the correlations that exist between the two phenomena given in detail. In addition, as with any type of drying, moisture is lost from the material via evaporation from the surface, which is exposed to the ambient air. The principles of evaporation, the equations that define it and the various physical and climatic factors that influence it are all presented.

In section 2.4, the physical mechanisms of moisture movement in concrete during drying are presented. This includes the various stages of moisture movement in porous media, which include liquid and vapour flow during drying. In addition, the influence of self-desiccation is also presented which is the loss of moisture from the concrete due to cement hydration before the material is exposed to ambient conditions.
In Section 2.5, the types of pores in concrete and how they influence moisture migration is discussed in detail. The pore structure development of concrete is greatly influenced by the hydration process over time as the products of hydration slowly fill the pores and affect the transport of moisture.

The main aim of this chapter therefore is to provide an insight into previous research/information on the general movements of moisture in concrete. Although there is relatively little which is new in this, it is important to present the general principles so that the reasons for the experimental programme and the results from those experimental tests can be readily understood.

2.2 TRANSPORT MECHANISMS IN POROUS MATERIALS

Within concrete, the principal ‘flow’ mechanisms are permeability, sorption and diffusion. These three processes describe the way that water (often pure or carrying aggressive ions), carbon dioxide and oxygen enter and move through the concrete under different driving regimes. Permeability is the movement of moisture under a hydraulic head, sorption is the absorption of water which is sucked into the empty pores due to surface tension and free energy and diffusion is the movement of moisture from an area of high concentration to an area of low concentration. Figure 2.1 shows the various factors that moisture movement is influenced by, namely the pore structure and environmental conditions. It also demonstrates that transport of moisture in concrete is a complicated process dependant on a number of factors.

The term ‘permeability’ is related to the flow of liquids or gases caused by a hydraulic head in a saturated medium. This flow follows Darcy’s law (Equation 2.1) for laminar liquid flow through a porous medium:

\[
\frac{dq}{dt} = \frac{K \rho g \Delta h}{\eta L}
\]

Equation 2.1

where \(dq/dt\) is the rate of liquid or gas flow (m³/sec), \(A\) is the cross-sectional area (m²), \(K\) is the permeability (m/sec), \(\eta\) is the dynamic viscosity of the fluid (N sec/m²), \(\rho\) is the density
of the fluid (kg/m³), $g$ is the gravity acceleration, $\Delta h$ is the drop in hydraulic head (m) and $L$ is the thickness of the sample.

However, in more general terms, Darcy’s law may be applied to any fluid flowing through a porous medium as shown in Equation 2.2,

$$v = -\frac{k}{\eta} \frac{dp}{dL}$$  \hspace{1cm} \text{Equation 2.2}

where $v$ is the apparent velocity of flow (m/sec) and $k$ is the intrinsic permeability (m²) of the porous medium. This is a more rational expression for permeability as it depends only
on the characteristics of the porous medium and not on the liquid through which it is passing (Dhir et al., 1989). The relationship between \( k \) and \( K \) is given in Equation 2.3.

\[
k = \frac{K \eta}{\rho g}
\]  

Equation 2.3

The sorptivity is an easily measured material property that characterizes the tendency of a porous material to absorb and transmit water by capillary action, mostly into an initially relatively unsaturated concrete. It was first introduced to building materials literature in the early 1980’s, particularly in the area of clay and aerated bricks and a few typical mortar mixes. The sorptivity rate \( S \) (mm/min\(^{0.5}\)) is obtained by considering the application of Equation 2.4 to one-dimensional cases of water absorption into an initially dry porous solid (Figure 2.2),

\[
S = \frac{i}{\sqrt{t}}
\]  

Equation 2.4

where the boundary condition at the wetted surface is moisture content, \( \theta = \theta_1 \) and the initial condition is \( \theta = \theta_0 \), where, for a dry material, the initial moisture content \( (\theta_0) \) is close to zero, \( i \) is the water absorption per unit area of the inflow surface (taken as mm in SI units) and \( t \) is time (min).

Typical sorptivity values for normal concretes range between 0.09 and 0.17 mm/min\(^{0.5}\) for w/c ratios between 0.4 and 0.6 respectively (Neville, 1995). The sorption value of concrete is influenced by the moisture content as the higher it is, the lower the measured sorptivity is, as the space for moisture ingress in the pores is decreased (Claesson, 1994). The sorptivity is, therefore, dependant on a number of factors such as the initial water content, the temperature and also the type of fluid that is being absorbed into the material.

Figure 2.3 shows typical results from tests on the absorption of water into an initially dry mortar bar over the length, x. The moisture content here is a ratio of the actual moisture content to the moisture content \( (\theta_r) \) in the reservoir, that is, \( \theta_r = 1 \) when completely saturated. The results show that the nearer the water reservoir, the more saturated the mortar is compared with that deeper in the bar. For example, after 38 minutes, the bar has a
Figure 2.2  One-dimensional water absorption into a sample of porous material from (a) a free-water reservoir (horizontally), (b) independent of gravity (infiltration) and (c) and capillary action (Hall, 1989).

Figure 2.3  Water content distributions into a mortar bar (Hall, 1989).

saturated value ($\theta_r$) of approximately 0.90 at 50mm in the mortar compared with a $\theta_r$ of 0.0 at approximately 75mm after the same time. The important characteristic here is that the absorption of the moisture is, as expected, higher at the surface that deeper in the concrete
and the validation of the distribution of moisture through the bar with time.

When the transport of a gas or a vapour through the material is the result of a concentration gradient (Figure 2.4) and not a pressure differential, movement of moisture takes place by diffusion, which is defined as:

“...the transfer of mass by a random motion of free molecules or ions in the pore solution resulting in a net flow from a region of higher concentration to a region (or regions) of lower concentration of the diffusing substance” (Crank, 1975).

Fick (1855) first studied diffusion and used the equation of heat conduction to mathematically quantify diffusion. The basis of diffusion is that the rate of transfer $J$ (g/m$^2$.sec) through a unit area $A$ (m$^2$) is proportional to the concentration gradient $C$ (g/m$^2$) measured over a distance $x$ (m) normal to the section, as described in Equation 2.5.

$$J = \frac{dC}{dx} \frac{1}{A}$$

Equation 2.5

This rate of transfer of mass through the unit area of a section is proportional to the concentration gradient $dC/dx$ and the diffusion coefficient, $D$ (m$^2$/sec), which is expressed in Equation 2.6 and is known as Fick’s first law of diffusion.

$$J = -D \frac{dC}{dx}$$

Equation 2.6

The negative term in Equation 2.6 arises because diffusion is occurring in the opposite direction to that of increasing concentration (Crank, 1975). In terms of $rh$ movement, Equation 2.7 shows how Fick’s first law can be used to describe the one-dimensional linear diffusion of humidity in concrete, where $h$ is the $rh$.

The transport of water vapour in the pore system of a porous material involves transport mechanisms and driving forces. For transient phenomena, such as one-dimensional drying of a cross-section of a porous material (such as concrete) over time, Fick’s second law of diffusion (Equation 2.8) is used and $D$ varies with the moisture concentration ($D(C)$).
Figure 2.4  Schematic representation of diffusional movement in porous materials

\[ J = -D \frac{dh}{dx} \]  
\[ \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left[ D(C) \frac{\partial C}{\partial x} \right] \]  
\[ \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left[ D(h) \frac{\partial h}{\partial x} \right] \]

However, a more convenient or appropriate approach in concrete drying involves the pore rh, h (where 0 < h < 100, as given in Equation 2.9, where D is a function of h (that is, \( D = D(h) \)).

2.2.1 Static and dynamic behaviour of water in pores

In terms of the static behaviour of moisture in concrete pores, the following assumptions are commonplace. Firstly, the moisture phases in concrete pores are liquid water and water vapour with the vapour (gas) phase assumed to follow the rules governing an ideal gas. Secondly, the overall moisture (liquid and vapour phases) behaviour can be modelled using one governing diffusion equation for drying, either in a micro or macroscopic state (Bazant and Najjar, 1971). The equilibrium between the liquid and water vapour in concrete pores is shown schematically in Figure 2.5, where the curvature of the meniscus between the vapour and the liquid water is a result of the pressures of the vapour and the liquid phases at their interface which are not equal.
**Figure 2.5** Equilibrated state of vapour and liquid water in pores (after Shimomura and Maekawa, 1997).

The mass conservation equations of vapour and liquid water in concrete (in microscopic terms) are given in Equations 2.10 and 2.11 respectively,

\[
\frac{\partial M_V}{\partial t} = -\frac{\partial J_V}{\partial x} + \nu \quad \text{Equation 2.10}
\]

\[
\frac{\partial M_L}{\partial t} = -\frac{\partial J_L}{\partial x} - \nu \quad \text{Equation 2.11}
\]

where \(M_V\) and \(M_L\) are the mass of vapour and liquid water per unit volume respectively (kg/m\(^3\)), \(t\) is the time (sec), \(J_V\) and \(J_L\) are the mass flux of vapour and liquid water respectively (kg/m\(^2\).sec) and \(\nu\) is the phase transition rate (kg/m\(^3\).sec), which, for concrete, is positive for evaporation from liquid water to vapour (Shimomura and Maekawa, 1997).

Transport of vapour within concrete is forced through narrow and tortuous paths and may not be easily transported within the pore structure as a bulk flow (Dalton, 1803). However, the dual diffusion of vapour and dry air will occur relatively easily in the pore structure of concrete because diffusion, by definition, is the random movement of molecules. However, the rate of water vapour diffusion in the pore structure is less than that in free air as the pores in concrete are not so effective for diffusion, due to narrower ‘flow’ paths. The mass flux of vapour in concrete can be described by Equation 2.12,
where $K_V$ is the material coefficient for the transport of vapour (which represents the effects of narrowness, linkage and tortuosity of the concrete pore structure, $0 < K \leq 1$), $V_G$ is the volume of the gas per unit volume ($m^3/m^3$), $D_V$ is the diffusion coefficient for the system of vapour and dry air ($m^2/sec$) and $p_V$ is the density of vapour ($kg/m^3$) (Shimomura and Maekawa, 1997).

### 2.3 PRINCIPLES OF DIFFUSION

As stated above, diffusion in porous materials, like concrete, is the movement of mass (moisture in this case in a liquid and/or vapour form) from a region of high concentration to a region of low concentration. Fick’s first and second laws of diffusion are commonly used in modelling diffusion. Here, the derivation of these equations is presented with a review of the various diffusion transport mechanisms that occur at isothermal conditions.

The diffusion process is very close to the analogy of heat flow and a wealth of literature is available that contain solutions to heat-conduction problems (Bazant and Najjar, 1971). The physics behind heat flow and diffusion are similar to moisture movement as they both follow a general Brownian motion. However, with diffusion not directly dependent on the temperature, as shown in Equations 2.7, 2.8 and 2.9, it must follow another type of physical motion because with an increase in temperature, the motion of the molecules would increase in a Brownian type motion. The following section will present the correlation between the two processes and the various equations that occur in both heat and diffusion problems.

#### 2.3.1 The diffusion equations

Figure 2.6 shows a rectangular shaped element subjected to the diffusion of a substance, where $J_x$ is the rate of transfer of the substance through a unit area in the $x$-direction (Crank, 1975), shown mathematically in Equation 2.13. This substance must also diffuse through the opposite face at a similar rate, shown in Equation 2.14. The contribution to the rate of increase of the diffusing substance in the element from the $dy$ face is shown in
Figure 2.6  Regular shaped element used to derive Fick’s Laws of Diffusion

\[ dy \left( J_x + \frac{\partial J_x}{\partial x} \, dx \right) \]

\[ dy \left( J_x - \frac{\partial J_x}{\partial x} \, dx \right) \]

Equation 2.13

Equation 2.14

Equation 2.15

Equation 2.16

Equation 2.14. However, considering Equation 2.6, the rate at which the concentration of the diffusing substance increases, or decreases, is given by Equations 2.15 and 2.16, where \( C \) is the concentration of the diffusing substance.

\[ -2dxdy \frac{\partial J_x}{\partial x} = 0 \]

Equation 2.15

\[ 2dxdy \frac{\partial C}{\partial t} = 0 \]

Equation 2.16

Combining Equations 2.14 and 2.15 yields Equation 2.17, where, from Equation 2.6, an equation for 1-dimensional diffusion is set-up, as shown in Equation 2.18, as diffusion is only occurring along the x-axis for isothermal conditions.
2.3.2 The analogy with heat flow

The equations commonly used to define heat flow are Equations 2.19 and 2.20, where \( J_H \) is the amount of heat flowing in one direction, \( T \) is the temperature, \( K \) is the heat conductivity, \( \rho \) is the density (kg/m\(^3\)) and \( c \) is the specific heat (J/kg \( ^0 \)C). The term \( \rho c \) is known as the heat capacity per unit volume (J/m\(^3\) \( ^0 \)C).

\[
J_H = -K \frac{dT}{dx}
\]

Equation 2.19

\[
\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \frac{K}{\rho c} \frac{\partial T}{\partial x} \right)
\]

Equation 2.20

On inspection of Equations 2.18 and 2.20, they correspond if one identifies the concentration \( C \) with the temperature \( T \) and taking \( D = K/\rho c \). By doing this, it is assumed that for diffusion, \( \rho c \) is equal to 1 as this factor is required to convert temperature to the amount of heat per unit volume and concentration. This is, by definition, the amount of diffusing substance per unit volume. Therefore, for diffusion, no conversion factor is needed (Crank, 1975) and it is usual to write \( K/\rho c = k \), the heat diffusivity, and so to convert into diffusion terms (Equation 2.21).

\[
D = k \quad \text{and} \quad \rho c = 1
\]

Equation 2.21

In terms of the boundary conditions for heat and diffusion, what is commonly referred to as a radiation boundary condition in heat flow (the heat flux across a unit area of the surface) is known as surface evaporation in diffusion. The rate of heat loss (\( H \)) from a unit area of the surface is usually given by Newton’s law of cooling (Equation 2.22),
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\[
\frac{\partial T}{\partial n} + H(T_S - T_O) = 0
\]

Equation 2.22

where \( T_S \) and \( T_O \) are the temperatures at the surface and that in the outside medium. In diffusion however, this rate of heat loss is known as the rate of evaporation through a unit area of the surface, \( \alpha \), shown in Equation 2.23,

\[
\frac{\partial C}{\partial n} + \alpha(C_S - C_O) = 0
\]

Equation 2.23

where \( C_S \) and \( C_O \) represent the concentrations at the surface and those in the outside medium.

2.3.3 Evaporation equations

The movement of water from building fabrics is often strongly influenced by evaporation into the surrounding air, and a complete analysis of water movement in and out of structures must embrace both diffusion and evaporation. To begin with, an understanding of evaporation physics is directly relevant to the drying of damp-affected buildings and control of fabric dampness by ventilation and/or heating; but it has wider significance. Almost all water entering porous building materials ultimately leaves by evaporation. Evaporation, therefore, plays a crucial role in controlling all water balances and rates of water exchange between the environment and the structure.

It is recognised that large amounts of water may be present in the fabric of newly constructed buildings and this water must be lost by evaporation before the building fabric may be regarded as satisfactorily ‘dry’. Although recommendations have been made in respect to the drying out of buildings, these only provide the most general guidelines and emphasise that drying periods may be very long. Various methods of reducing drying times are suggested including the use of dehumidifiers and heating systems, but there is a lack of quantitative data from which the critical factors that affect the drying process can be identified.

The physics of evaporation through a boundary layer is quite involved. It has been
suggested that the rate of evaporation may be represented by a constant flux boundary condition (CEB, 1992). However, it has been established, from surface moisture content readings and vapour emission tests (VET) presented in Chapter 5 here, that the evaporation rate is not constant but non-linear, varies over time and is dependent on the w/c ratio and drying environment.

Therefore, in order for a full analysis of concrete drying to be thorough and accurate, this process must be accounted for. In saturated concrete, diffusion is not the controlling process during drying early on as evaporation creates the initial \( rh \) gradient in the concrete so that diffusion develops in the slab. As drying continues, both evaporation and diffusion become equally involved in the drying process, as the moisture in the concrete develops an internal equilibrium and so drying is slower (Menzel, 1954).

To quantify the evaporation rate from porous structures, Menzel (1954) published a nomograph (Figure 2.7) that relates the rate of evaporation of the surface from the concrete to the air temperature and the wind speed. Equation 2.24 is used to quantify this nomograph,

\[
E_w = 0.0415(e_o - e_a)(0.253 + 0.215V)
\]

Equation 2.24

where \( E_w \) is the predicted rate of water evaporation (kg/m\(^2\)/h), \( e_o \) and \( e_a \) are the saturated water vapour pressure at the evaporating surface and air at the same temperature and \( V \) is the average horizontal wind speed measured 0.5m above the evaporating surface (m/sec).

The effect of temperature and humidity are accounted for in this equation by using the gas law to calculate saturated vapour pressures (\( e_o \) and \( e_a \)). However, several difficulties underlie this simplistic approach for quantifying evaporation. Firstly, Menzel’s nomograph is intended to predict the rate of water evaporation from a water-covered surface and not from a porous concrete surface (Kohler et al, 1955). Thus, the evaporation nomograph is not useful for predicting rate of water loss from concrete, unless the concrete surface is covered with, for example, bleed water. Secondly, it is difficult to take account of the large number of variables involved, such as the incident solar radiation, the air/concrete interface and the evaporative cooling from the surface. In addition, evaporation rates vary due to
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Figure 2.7 Menzel’s nomograph for predicting surface evaporation rates (Menzel, 1954).

Equation 2.25

\[ E_w = 0.0565(e_o - e_a) + 0.0485V - 0.305 \]

fluctuations in temperature, humidity and wind speed (Equation 2.25), coupled with spatial variations in microclimate induced by wind, sun and shade (Al-Fadhala and Hover, 2001). These are among the factors ignored by Menzel’s nomograph. Al-Fadhala and Hover (2001) developed a best-fit expression based on Equation 2.24 (Equation 2.25) to predict the surface evaporation from concrete in the Arabian Gulf region.

Crank (1975) referred to the surface evaporation as a ‘radiation boundary condition’ in heat flow where the heat flux across a unit area of the surface \( (J_h) \) was proportional to the difference between the surface temperature \( \theta_S \) and the temperature of the outside medium \( \theta_O \), i.e. given by \( H (\theta_S - \theta_O) \). This is sometimes referred to as Newton’s law of cooling and it corresponds to surface evaporation in diffusion,
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\[ J_S = K(C_S - C_A) \]  
Equation 2.26

where \( J_S \) is the flux across a unit area of the surface, \( K \) is the rate of evaporation from the surface and \( C_S \) and \( C_A \) are the concentrations just inside the concrete surface and the ambient air respectively. This relationship was also discussed by Shimomura and Maekawa (1997), where, in their paper into developing a micro-mechanical model for moisture diffusion in concrete and the associated shrinkage, they accepted that the moisture transfer through the surface exposed to the atmosphere is significant. The surface factor here is considered as the boundary condition in the drying shrinkage of concrete. It is treated in a similar manner to the heat transfer between a solid and a fluid and they assumed that the mass flux of water on the boundary surface is evaluated by Equation 2.27 below,

\[ J_B = \alpha_B (w_L - w_{LB}) \]  
Equation 2.27

where \( J_B \) is the mass flux of water at the boundary surface (kg/m\(^2\).sec), \( \alpha_B \) is the moisture transfer coefficient (m/sec), \( w_L \) is the water content of the concrete at the surface (kg/m\(^3\)) and \( w_{LB} \) is the water content in equilibrium with the atmosphere (kg/m\(^3\)). Following on from this, they assumed that the moisture transfer coefficient (\( \alpha_B \)) must be affected by the state of air-flow around the concrete surface, the pore structure of the concrete and the moisture state in the near surface pores. Considering these factors, the moisture transfer coefficient was determined using Equation 2.28,

\[ \alpha_B = \frac{D_{(wL)}}{d} \]  
Equation 2.28

where \( D_{(wL)} \) is the moisture diffusivity (m\(^2\)/sec) and \( d \) is a factor (with length dimensions in m) that represents an additional thickness of the specimen or the state of humidity distribution in the atmosphere near the surface or the thickness of the boundary film for moisture transport analysis. This equation was chosen in their model as it is applied directly on the basis of consideration of its physical mechanism and convenience for modelling purposes.

In a review of the impact of temperature and \( rh \) on the emission rates from common
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building materials (like concrete), Haghighat and de Bellis (1998) report that material emissions are the result of several mass transport processes. In their report, they discuss the fact that surface emissions occur between the material and the overlying air as a consequence of several mechanisms including evaporation and convection as shown in Equation 2.29,

\[ E_A = k_A (C_S - C_A) \]  

Equation 2.29

where \( E_A \) is the surface emission rate of compound \( A \) (mg/m²/hr), \( k_A \) is the mass transfer coefficient (m/hr) and \( C_S \) and \( C_A \) are the concentrations at the surface of the material and in the overlying air (mg/m³) respectively. This equation is identical in form to Equation 2.26 and 2.27 above. The mass transfer coefficient is dependent on the environment in which these processes are taking place, including the surface velocity and turbulence, surface characteristics and the properties of the overlying air.

de Freitas et al (1996) also stated that the evaporation process is extremely complex and the transfer coefficient is a function of a number of parameters which are difficult to measure. However, de Freitas argues that the coefficient can be established based on the difference between the concentration of water vapour at the material’s surface and that in the environment. In the first stage of drying, there is a flat gradient of constant ‘flow’ where the material is relatively saturated. Kim and Lee (1999) also assumed that the boundary condition on any exposed surface is assumed to be that shown in Equation 2.30,

\[ D \left( \frac{\partial h}{\partial t} \right)_S = f (h_{en} - h_S) \]  

Equation 2.30

where \( f \) is the surface factor, \( h_{en} \) and \( h_S \) is the \( rh \) in the environment and at the concrete surface respectively. The physics of evaporation through a boundary layer is quite involved but for simplicity, Hall (1994) reports that it can be represented as a constant flux boundary condition. The rate of transport of a fluid through a structure is controlled by the rate of its evaporation from a porous surface for different fluids and depends on the vapour concentration at the surface and on the gas diffusivity. Hall (1994) also reviewed the processes that occur as evaporation continues and set out a theoretical framework for the
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description and analysis of transport processes.

In their paper, Akita et al. (1997) developed an analytical procedure for establishing an equation to predict evaporation rates from concrete surfaces. They accepted that the surface factor must be known for the boundary conditions and assumed that the vapour evaporation from the surface depended on the number and size of capillary pores open to the surface. They presented an equation (Equation 2.31) to represent this surface evaporation,

\[ \alpha_M (H_S - H_O) = kD_w \frac{H_S - H_O}{d} \]

Equation 2.31

where \( \alpha_M \) is the moisture flux through the surface, \( H_S \) and \( H_O \) are the humidities at the surface and the ambient air, \( k \) is a factor that adjusts for the difference in water densities in concrete and that in air, \( D_w \) is the diffusion coefficient of vapour in air and \( d \) is the thickness of the boundary layer. This equation is based on the relationship between the near surface w/c ratio (which varies the water density in the concrete) and the surface evaporation rates determined by trial and error to match calculated values of the decrease in mass to the experimental data in the early stages of drying, where, the rate of evaporation is proportional to the difference in vapour densities between the material and the environment (Lockington et al., 2002). Here, the external environment vapour density is assumed constant while the internal vapour density is a function of the moisture content (Selih et al., 1996).

The ‘partly on theory’ data for surface factors are based on the assumption that the surface factor is correlated to the diffusion coefficient of vapour in air, if the boundary layer of evaporation from the surface is of constant thickness and if the \( rh \) varies linearly throughout the layer. They concluded that the influence of the surface factor on the water content or decrease in mass is small, except in the initial stages of drying. Also, the surface factor could be derived from the diffusion coefficient of vapour in air, under suitable conditions. Figure 2.8 shows the evaporation rates from the experimental and calculated results and demonstrates that the evaporation rate decreases with increasing w/c ratio. However, Figure 2.8 also shows that there is a relatively small difference in evaporation rates for the various w/c ratios (30 – 100%). For example, the figure shows that the
evaporation rates for a w/c ratio of 30% is approximately 3.8 cm/day compared with 3.0 cm/day for the 100% w/c ratio. The higher evaporation rate with corresponding lower w/c ratios may be a function of the lower actual water content in the concrete.

2.4 PHYSICAL MECHANISMS OF DRYING IN POROUS MEDIA

This section presents how moisture in concrete can be represented and the various processes that influence it, such as self-desiccation and the pore structure. It also presents typical rh profiles through the depth during drying until it reaches equilibrium with the ambient environment. In concrete, this may take a long time, and varies with thickness and w/c ratio.

2.4.1 Relative humidity in concrete

As already stated concrete dries mainly by a dual process. Initially, moisture is lost from the concrete by evaporation through the surface and creates a rh gradient through the concrete under these conditions. The transport of moisture to the exposed surface(s) through the depth occurs by diffusion. Both of these processes are dependent on
concentration gradients, either in the concrete itself (diffusion) or between the concrete and the ambient air (evaporation). Here, this concentration gradient is the difference in the \( rh \) between the top and bottom of the concrete when drying is one-dimensional. The \( rh \) is mathematically written in Equation 2.32 as the ratio of the actual vapour pressure \( (P) \) to the saturated vapour pressure \( (P_s) \) at the same temperature and is expressed as a percentage.

\[
RH = \frac{P}{P_s} \quad (\%) \tag{Equation 2.32}
\]

It can also be expressed as a percentage of the ratio between the water vapour in the concrete \( (W_v) \) and the saturation of water vapour \( (W_{v_{\text{max}}}) \) of the air (or a certain empty volume), at a particular temperature, as shown in Equation 2.33.

\[
RH = \frac{W_v}{W_{v_{\text{max}}}} \quad (\%) \tag{Equation 2.33}
\]

Figure 2.9 shows schematic diagrams of the state of water in a typical concrete pore system. When the pore is near saturation, there is little air space and so a high pressure is present (Figure 2.9(a)). When the pore empties, there is more space within the pore and the air experiences a reduction in pressure (Figure 2.9(b)). Bazant and Najjar (1971) concluded that the \( rh \) is a more suitable variable to describe moisture movement in concrete as it is directly related to the Gibbs’ free energy per unit mass of evaporable water, \( \mu \), whose gradient is the actual driving force of diffusion. Figure 2.9(c) shows this meniscus that develops between the air and water in a typical pore. The curved interface between the liquid water and the gas is due to the fact that the pressures of the gas and liquid at this interface are not equal, as shown previously in Figure 2.5.

A desorption isotherm defines the relationship between the moisture content \( (W) \) and the \( rh \) of the concrete. This allows it to be used as a valid property to represent the moisture condition/profiles in concrete. A typical isotherm relating the moisture content to the \( rh \) is shown schematically in Figure 2.10. The shape of these isotherms are dependent on the pore structure and the gap between the drying (desorption) and wetting (absorption) curves is caused by the irregular shape of the pores, for example, large pores with narrow
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a) Pore near saturation, therefore, high pore pressure and high rh

b) Pore partially saturated, therefore, more space available and reduced pore pressure

c) Meniscus in a typical pore between air and water (Martys et al., 1997).

Figure 2.9 Schematic view of the state of water in a typical concrete pore system

Figure 2.10 Typical absorption and desorption isotherms (Andrade et al., 1999) openings (Roncero, 2000).
2.4.2 Self-desiccation in concrete

An additional loss of moisture from concrete can be due to self-desiccation brought on by the effects of early age hydration (Persson, 1997). The total variation of the $rh$ may therefore be obtained by considering the dual effects of self-desiccation and normal drying (moisture loss) in the concrete. Figure 2.11 shows a schematic decay of the $rh$ in concrete from both normal drying and self-desiccation effects. At time $t_0$, when drying begins, the internal $rh$ has already decreased partially due to self-desiccation. However, after the concrete is exposed to the ambient air, the internal $rh$ continues to decrease with normal drying and the reduction in the $rh$ is more and more due to normal drying and the effect of self-desiccation is attenuated. As a result, the influence of self-desiccation is minimal and is not always considered (Parrott, 1991; Selih and Bremner, 1996).

2.4.3 Typical relative humidity profiles during drying

As stated earlier, moisture in concrete moves through the pore structure via a diffusion process, set up by the internal $rh$ gradient between the top and bottom of the concrete (for 1-dimensional movement), as shown in Figure 2.12. This $rh$ gradient develops during the initial drying of the concrete, where the $rh$ is assumed to be 100%, or fully saturated through the depth at time $t_0$. Early on, the top area of the concrete begins to lose moisture with little or no drying taking place deep in the slab at $t_1$. Over time, as more moisture is lost from the surface and the $rh$ gradient is created through the depth, the concrete begins to dry through the thickness of the slab and a non-linear $rh$ profile is created ($t_2$ – $t_4$). As drying continues, the moisture at the base of the concrete slowly begins to move vertically under this humidity gradient. However, since more and more water is being lost through the surface by evaporation, the concentration gradient between the top and bottom of the concrete is increasing ($t_2$ to $t_4$) whilst gradually decreasing between the concrete surface and the ambient air, leading to a decreased rate of moisture loss overall.

Eventually, after a significant drying time, the $rh$ in the concrete will reach equilibrium with the surrounding air and the $rh$ profile will approach a constant profile at $t_e$, after which, further drying will not occur and this moisture can only be lost by drying the concrete at $105^\circ$C or above in an oven (Neville, 1995).
2.4.4 Stages of drying in concrete

Water movement in a porous system may be as a liquid, vapour or both with the rate of which is dependent on the gradient. The equilibrated state of vapour and liquid water in a typical concrete pore has been previously shown in Figure 2.5. Vapour flow takes place through a system of pores partly filled with water. This water may act as a barrier to vapour diffusion or as a short circuit in the path, thus apparently accelerating the process.
Philip (1955) assumed that water vapour behaves as an inert gas and Philip and de-Vries (1957) later tried to allow for interactions of the vapour and liquid water in a porous system and suggested that vapour transfer occurs as a series-parallel process through regions of vapour and liquid flow. They showed that, whereas the simple theory treats liquid ‘necks’ between particles as obstacles blocking the passage of water vapour, these are in fact regions of very rapid transport of water.

Under an applied vapour pressure gradient, condensation at the upstream end of the neck and evaporation at the downstream end leads to changes in the curvature of the meniscus at each end (see Figure 2.9), resulting in very low resistance to flow, which acts as a short circuit path for vapour movement (Pihlajavaara, 1963; Pihlajavaara, 1965). Philip and de-Vries (1957) also considered that no interaction will occur under isothermal conditions because the vapour pressure gradient comes solely from a gradient of moisture content, and even very small changes in meniscus curvature produced by evaporation and condensation would suffice to reverse the direction of vapour transfer.

Drying of water from the pores of a solid material to the surrounding air generally includes unsaturated flow of liquid and vapour within the porous solid, the liquid-vapour phase change and convective-diffusive transfer of vapour from the surface of the solid to the surroundings. The first of these sub-processes may be described in terms of the concepts of unsaturated flow theory (Parrott, 1988). The second appears to present no great difficulties because vapour permeability in porous solids is conceptually simple. It is in the third of these sub-processes to which the term evaporation may be applied. This transfer of water vapour to the surroundings is strongly influenced by the airflow across the drying surface and this introduces environmental and aerodynamic considerations (Harriman, 1995). Thus, drying may be expected to depend markedly on external factors as well as on material parameters. Drying under constant external conditions occurs in two distinct stages and is referred to as the constant drying rate period (Stage I) and the falling rate drying period (Stage II). These are discussed below and are well established in the literature on drying and for building materials and can be traced back to Cooling (1930).

(a) Stage I Drying
There is considerable evidence (van Brakel, 1980) that the Stage I drying rate in a wide
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range of porous materials is equal to the evaporation rate of free water at the surface under the same conditions. In comparing the drying of three types of clay brick it appeared that there was little variation in initial drying rate between them and a close similarly exists between the initial drying rate and the evaporation from a free water surface. This is due to an increase in the effective surface area both on and near to the surface layers of the brick accounting for the increased evaporation rate during stage I. As the first stage of drying appears to be essentially unaffected by the material properties, it is generally accepted that free evaporation of liquid is occurring at the solid surface. Thus, the rate of drying is controlled by the saturated vapour pressure, its diffusion coefficient in the air and environment factors. El-Razek and Abo-Enein (1999) stated that stage I drying includes evaporation, which will depend on climatic conditions as water exists at the surface of concrete due to bleed water in the early stages of drying.

(b) **Stage II Drying**

In Stage II, the drying rate eventually ceases to be constant and slowly begins to decrease. At Stage I, the evaporation rate is controlled by vapour phase diffusion at the surface (Shimomura and Maekawa 1997) and it is believed that the rate of unsaturated flow within the porous solid, which is determined by the material properties and the diffusion coefficient, limits the drying rate (Gudmundsson, 2000). These desorption parameters fundamentally determine the Stage II drying rate. Previous work on water absorption made extensive use of the hydraulic sorptivity parameter ($S$) to characterize the capillary adsorption property of materials (Gummerson *et al*., 1980). At the beginning of Stage II drying, the initial water content distribution is far from being uniform and so the drying rates cannot be expected to depend simply on the desorptivity. The rate of drying in this stage is always less than Stage I and moisture migration becomes progressively slower as it reaches the critical-moisture content where equilibrium occurs (Pihlajavaara, 1982).

(c) **Transition from Stage I to Stage II Drying**

Stage I drying is characterized by a constant rate of evaporation under constant drying conditions and as drying proceeds, the surface water content falls with time, eventually approaching a uniform water content (Rose, 1963). A relationship between the vapour diffusion ($K_v$) and liquid water transport ($K_L$) is shown in Equation 2.34, developed by Shimomura and Maekawa (1997). This relationship demonstrates that the transport of
liquid water occurs at a near-saturated state and the dominant mechanism of moisture transfer gradually becomes vapour diffusion, as the water content reduces. Comparing their experimental results with their analytical work, Shimomura and Maekawa (1997) concluded that this relationship between the vapour and liquid transport was acceptable.

\[
K_L = \frac{K_V}{50}
\]

Equation 2.34

The existence of two distinct stages during drying has been discussed above. The rate of drying during Stage I is strongly influenced by both air flow and temperature and an increase of one or both of these will result in more rapid drying during this stage. Increasing the ambient temperature by \(10^0\)C approximately doubles the drying rate, as does reducing the ambient \(rh\), which indicates that during drying, the first stage-drying rate is directly proportional to the humidity (Jensen and Hansen, 1999). A similar increase in drying rate results from quadrupling the air speed. However, practical considerations might suggest that increasing the air speed is likely to be the most cost effective method of increasing the Stage I drying, achieved by introducing fans or even by good natural ventilation within a building. The end of drying is not physically very sharply defined and it may be expected (and is found experimentally) that the process is somewhat protracted. As the water content nears equilibrium in the porous solid, liquid phase capillary continuity is lost and vapour phase diffusion becomes the only transport mechanism within the pores.

El-Razek and Abo-Enein (1999) suggests that as concrete dries, a further stage of moisture movement may be distinguished as shown in Figure 2.13. In this third stage, a desorption-resorption process takes place, that is, moisture that vaporises is re-condensed and the concrete slowly gains equilibrium with its environment (Gummerson et al, 1980). As shown, Stage 1(a) shows moisture movement across the pore as a capillary flow as it is filled with water. In Stage 1(b), as drying continues, the rate of flow is affected as voids are created in the pore and moisture must take a longer flow path. In Stage 2, as the void in the pore increases, moisture movement is via vapour diffusion across the pore from a region of high concentration to a region of low concentration. In Stage 3, moisture is being absorbed by the pore walls and the rate of drying is much reduced.
2.5 **INFLUENCE OF THE PORE STRUCTURE ON MOISTURE MOVEMENT**

The movement of moisture in concrete is largely influenced by the pore structure and its development is dependent on the w/c ratio and how the concrete is compacted and cured. However, even well cured concrete has a high proportion of voids, most of which are invisible to the naked eye.

Pores are developed when water is added to cement whereupon, in the absence of aggregate, hydrated cement is formed which is made up of solid products together with gel and capillary water, which is not consumed in the hydration process. For a w/c ratio of 0.24 in a sealed environment under complete compaction, there is just enough water in the capillary pores to fully hydrate the cement grains. These hydrated products occupy over twice the volume of the unhydrated cement by expanding into (and consuming) the capillary water, as shown in Figure 2.14. Many of the mechanical properties of hardened concrete depends more on the physical structure of the products of hydration rather than the chemical composition of the hydrated cement. During hydration, the hardened paste consists of very poorly crystallized hydrates of the various compounds, such as Calcium
Figure 2.14 Volume changes of Cement Paste (Neville, 1995)

Silicate Hydrate (CSH) gel Ca(OH)$_2$, some un-hydrated cement and a residue of the water-filled voids. These voids are called capillary pores and within the gel itself interstitial voids exist, also known as gel pores. During hydration, a large amount of free water is adsorbed onto the surface of the solid phase. However, if no water movement to or from the cement paste is permitted, the hydration reactions use up this water until an insufficient amount is left to saturate the solid surfaces, and the $rh$ within the paste decreases.

This process reduces the capability of the gel pores to form as they can only develop under saturated conditions, which leads to reduced products of hydration. Since hydration only affects the water held in the capillary pores, the volume of capillary pores increases rapidly if the w/c ratio exceeds 0.44, as shown in Figure 2.15. These capillary pores eventually dry out in a dry external environment, leaving behind a system of pores that influence the porosity of the concrete. When a concrete has fully dried out, the only water remaining is chemically bound to the cement due to the hydration process, as the rest has evaporated. In Figure 2.16 it can be seen that, for 50% hydration, the volume of capillary water is much higher than for 100% hydration.

The permeability of concrete will be influenced by any action that increases the interconnectivity of the pores and the primary concrete property that has this effect is the
Figure 2.15 Composition of hydrated cement paste at the final stage of hydration in a sealed sample (Neville, 1995).

Figure 2.16 Volumetric proportions of cement paste at different stages of hydration (Neville, 1995).

w/c ratio (West, 1997), as seen in Figure 2.17(a) and (b) (Portland Cement Institute, 1994).
As shown in Figure 2.15, any increase in the w/c ratio above 0.44 will significantly increase the number/volume of capillary pores in the paste. Additional influences on the concrete porosity are curing and compaction, especially in the covercrete because the core of a concrete section is naturally self-curing due to the slow rate of drying (West, 1997). If adequate curing is not provided, the surface porosity is increased leading to a more ‘open’ pore structure, as shown in Figures 2.17(a) and (b). Compaction and the addition of pulverised fuel ash or ground granulated blast-furnace slag can leads to lower porosity and a finer pore structure respectively, thus leading to a less permeable paste.

2.5.1 Types of voids in concrete

There are several pore types in concrete ranging over several orders of magnitude from $10^{-2}$ to $10^{8}$ mm. In addition to the capillary and gel pores, air entrapped during mixing or compaction and entrained air pores using air entraining admixtures, are used to make up the total pore volume. Air voids (or macro-pores), which are generally visible to the eye comprise of both entrapped and entrained air and vary in size from 0.02 – 1 mm. Capillary pores can range in size from $10^{-1}$ to $10^{5}$ mm and arise from incomplete hydration and/or a high w/c ratio. The so-called micropores form a very fine pore system with the gel pores and block up the capillaries and range in size from $10^{-4}$ to $10^{-7}$ mm.
In addition to the concrete pore system, naturally occurring pores in the aggregate and cracks that arise in the concrete matrix can also affect the overall porosity of the concrete. Of all the pores mentioned above, the macropores, capillary pores and the surface cracks are most relevant for durability. The capillary pores, at any stage of hydration, represent the majority of the gross volume which has not been filled by the products of hydration and, as these products occupy more than twice the volume of the original solid phase (cement) alone, they are essentially a residue of the original water filled spaces in the fresh concrete. Therefore, the volume of the capillary pore system is reduced with ongoing hydration. The capillary porosity of the paste itself depends on the w/c ratio as well as the degree of hydration. As mentioned previously, with a sufficiently low w/c ratio, the volume of the gel is insufficient to fill all the space available to it so there will be some volume of capillary pores left, even after the process of hydration has been completed.

Gel pores can hold large amounts of non-evaporable water and there are interconnected interstitial spaces between the gel particles. Since the gel pore diameter is less than a molecule of water, the vapour pressure and mobility of the adsorbed water are different from the corresponding properties of free water. As the total volume of gel increases (as hydration continues) the total volume of gel pores also increases. Drying of gel causes shrinkage as the negative capillary pressure creates balancing compressive stress in the network (Scheer et al., 1995). With time, the network becomes more rigid and it shrinks less during drying.

2.5.2 Water held in hydrated cement paste

The actual water content of the paste depends on the ambient humidity, particularly for capillary pores near the surface. These pores can become empty if the humidity falls below 45% (Verbeck, 1955), but water is adsorbed into the gel pores even at very low ambient humidities. The amount of water in hydrated cement is made up from free water, chemically bound water (which forms an integral part of the hydrated compounds) and, between these two categories, gel water, which is held in a variety of ways. Water held in by the surface forces of the gel particles, called absorbed water, is known as interlayer or zeolitic water. Since it is difficult to determine the division, or to know how the water is distributed between the various stages, it is convenient to divide the pore water into two
categories; evaporable and non-evaporable water. The amount of non-evaporable water increases as hydration proceeds but, in a saturated paste, non-evaporable water can never become more that half the total water present. In properly hydrated cement, non-evaporable water is about 18% by mass of the anhydrous material and this rises to approximately 23% in fully hydrated cement (Lea, 1970).

2.6 CONCLUSIONS

This chapter has presented the theoretical background to the movement of moisture in porous materials and concrete. Its intention was to provide an insight into the process of drying and the various factors that influence it. This knowledge was important when the experimental programme was designed so as to take into account the major factors that affect drying overall and to provide the context in which to interpret the results.

The main points discussed were the physical mechanisms involved in moisture movement which included both liquid and vapour flow. Indeed, the main method of moisture movement during drying has been shown to be diffusion, which is due to moisture (or \( \text{rh} \)) gradients (concentrations) being set up. These arise due to the uneven drying through the depth of the slab, initiated by the second method, evaporation.

In terms of monitoring this drying process in concrete, it has been demonstrated that the \( \text{rh} \) can give a good estimation of the actual moisture content and can be related to the actual moisture content via desorption isotherms. Therefore, establishing the \( \text{rh} \) at depth is an accurate method of presenting the moisture content during drying. As a result, this will be the main property that will be measured in the experimental work as a means of assessing the moisture content in the concrete slabs as they dry over time.

Also discussed is the influence of the pore structure in the concrete. It is well known that for any movement of moisture in any material, it must be adequately porous for the moisture to move through it. Within concrete there are a number of pores that exist which may influence how the moisture can migrate over time. However, of all these pores, none has more of an influence on how moisture can move than the capillary pores. These macro-
pores are large enough to both store water and let water move through them under suitable conditions.
3. REVIEW OF PREVIOUS LITERATURE ON CONCRETE DRYING.

3.1 INTRODUCTION

This chapter presents a review of published literature on moisture in concrete during drying. As part of this, a review of experimental methods to measure the moisture condition in concrete during drying both in terms of the water content and the rh is presented. Previously published work on both destructive and non-destructive tests and other well established tests to monitor the movement of moisture are also presented and discussed.

A review of the published literature on establishing diffusion coefficients and evaporation rates for drying concrete, which may be constant or dependant on the internal pore water content or humidity is presented. All of these methods have their individual merits and each one is discussed with a view to determining which best suits the aims and objectives of this work. A discussion of the relatively limited work on numerical methods, including the finite element method, to model and predict the drying of porous materials, including concrete, is presented. Also, how moisture can affect floor coverings and a review of the types of damages which can occur to coverings due to internal moisture is presented.

The main aim of this chapter therefore is to describe what work has been done to date and to highlight the gap in the knowledge that this thesis can fill as outlined in the aims and objectives in Chapter 1. It is important to ascertain what has been published so the experimental programme is appropriate to fill those gaps in the literature and an accurate finite element model can be set up taking into account the relevant points of previous research and to inform the selection of suitable diffusion and evaporation rates for the material model.

3.2 A REVIEW OF EXPERIMENTAL METHODS TO MONITOR THE MOVEMENT OF MOISTURE IN CONCRETE

This section presents a review of the most common experimental methods used to date by
previous researchers to monitor the changing moisture movement during drying and includes those used to measure the physical water content within the concrete and the internal pore \( rh \). For this, numerous tests have been used by researchers to monitor the changing moisture condition within the concrete, including non- and destructive tests.

### 3.2.1 Methods used to determine the water content in concrete

The determination of the moisture content in building materials using gamma-ray attenuation was performed by several authors in order to study a variety of porous materials, including concrete (de Freitas et al, 1996). In this method, the radiation from the gamma rays is absorbed or attenuated by matter, either partially or completely. This absorption depends on the energy of the photons, the chemical composition of the absorber and the distance between the source and the detector. A relationship exists between the emitted and transmitted radiation (depending on the thickness of the specimen) and the water content \( W \) (kg/kg) if the mass attenuation coefficient of the water \( (\mu_w) \) and the density of the wet \( (\rho_w) \) and the dry material \( (\rho_o) \) are known, as shown in Equation 3.1,

\[
W = \frac{\rho_w \theta}{\rho_o} \quad \text{[kg/kg]}
\]

where \( \theta \) is the moisture content (kg/kg). Calibration of this type of test consists of a comparison between the mass variation of the samples obtained by weighing and the mass variation calculated by the integration of the experimental profiles of moisture content, at the same moment. de Freitas et al (1996) states that good agreements between actual moisture contents and this method prove that gamma-ray attenuation methods can be used to obtain a valid determination of the moisture profiles. However, this depends on the thickness of the specimens (which affects the accuracy) and complicated calibration methods. It could also be argued that using gamma-ray methods may not be practical on busy construction sites.

Chen and Chen (1998) conducted a number of desorption experiments to determine the desorption isotherm for gypsum board cylinders. They developed a desorption isotherm by testing a number of specimens (180 x 13mm diameter) by coating the samples and placing
them inside a desiccator jar for 40-days in order to establish an equilibrium moisture content in the specimens. After removal from the jar, the samples were placed in an environment with a steady $rh$ and weighted at regular intervals. Results from these tests gave an indication of the moisture sorption for the material, and is used to determine the moisture content. The results from this work are summarised in Figure 3.1, where the desorption isotherm (discussed previously in Chapter 2) for the gypsum board, that relates the equilibrium moisture content ($W$) to the $rh$ $\varphi$, is presented. This relationship has been studied by Kerestecioglu et al (1989) (see Equation 3.2), where $W$ is the water content and $\varphi$ is the $rh$. From Equation 3.2, for a $rh$ of 100 and 60% the water content is calculated as 0.04 and 0.05% respectively. As shown in Figure 3.1, the water content appears to drop rapidly when the ambient $rh$ drops from 100-80% from 0.04 to 0.01kg/kg respectively. This trend is expected as more rapid drying occurs early on and slows down as the moisture in the concrete reaches equilibrium with the ambient air over time. However, a test like this would again be impractical on busy construction sites.

$$W(\varphi) = \frac{0.024\varphi}{(1+9.075\varphi)(1-0.9354\varphi)}$$  

Equation 3.2

Another method to directly determine the moisture content is the dry-slice method (Parrott, 1990). Specimens or cores are normally cylindrical, with varying boundary conditions to simulate either uni- or multi-directional moisture movement. They are sliced into discs, usually with a diamond saw, lubricated with deionised water, weighed, dried and re-weighed again. The moisture content is determined as the water in the disc evaporates during the drying and the water content can be calculated from the weight loss. The drying procedure is achieved in a number of ways. The quickest way is to place a disc in an oven at 105°C for up to 24-hours. In the place of oven drying, concrete samples may be placed in an environment with a drying agent, most probably silica gel or sulphuric acid. This method is destructive and the slicing will produce heat that may affect the initial moisture condition in the sample when cut. This method is regarded as the most direct and accurate way of obtaining the water content of the material and is often used to calibrate other methods of obtaining the water content. Despite the fact that this method may offer the most direct and reliable procedure for obtaining the water content, it is affected by two shortcomings: (1) only the average water content for each piece is obtained and (2)
different specimens are used each time and a large number of specimens is required. Also, removal of concrete samples for these tests as part of an ongoing monitoring of the moisture content of the concrete is impracticable on site, unless soft spots in the concrete are identified beforehand.

Akita et al (1997), in their investigations into moisture movement in concrete, measured the water content at various positions on a number of 100x100x400mm samples with various w/c ratios. The specimens were split into a number of slices of various thicknesses (Figure 3.2) and the mass of each slice was compared before and after oven drying at $105^\circ$C. Before the splitting of the samples began, they were notched in preparation to induce only one-dimensional moisture transfer through the specimen. Five of the six sides were covered with plastic film and paraffin, allowing moisture to escape through the top face only.

Figure 3.3 shows the results for the experimentally determined isotherms for the various w/c ratios used with fixed ambient temperatures and humidities. Figure 3.3 demonstrates how the moisture content is reducing with time where $H$ is the $rh$ and $R$ is the relative water content defined as $R = \frac{\psi}{\psi_S} \times 100$, where $\psi$ and $\psi_S$ are the actual water content and the water content at saturation ($\%$). As shown, for a given $H$, $R$ depends on the w/c ratio. For example, for a $H$ of 80%, $R$ is approximately 55 and 80% for a w/c ratio of 100 and 30%
Figure 3.2  Dimensions of specimens subjected to one-face drying by Akita et al (1997)

Figure 3.3  Experimentally determined isotherms for various the w/c ratios (Akita et al, (1997)).

respectively. However, for a $H$ of 40%, $R$ is approximately 15 and 55% for a w/c ratio of 100 and 30% respectively, suggesting that as the $rh$ reduces, the relative water content also decreases over a range of w/c ratios.

Electrical methods are also well established for measuring the water content of the concrete and two methods are commonly used; measuring the variation of electrical conductivity and measuring the variation of electrical capacitance. For most materials, the
water content is related to the electrical conductivity which increases with increasing water content. This test is conducted by establishing the electrical resistance between two electrodes, which are in direct contact with the material. The water content is estimated by comparing the recorded resistance with a calibration curve for the material being tested. A hand held meter that works on this principle was used in the experimental programme and will be discussed in detail in Chapter 4. The second method works on the principle that the capacitance increases with the moisture content as a result of the high dielectric constant of water. It is less influenced by temperature and material densities but does requires a more complicated laboratory set-up. The accuracy of the test is approximately ±0.25% of moisture content mass per mass in the range 0 – 6.5%. Although both methods are expensive, the conductance method is particularly expensive to perform.

Another test used to measure the water content is the nuclear magnetic resonance (NMR) method. According to Janz (1997), the accuracy of this method is approximately 0.5- 1.0% and can distinguish between the free, physically and chemically bound water and so is well suited for measuring transient water movements in building materials. In an NMR measurement, the number of hydrogen nuclei are counted, and an exterior permanent magnetic field is applied perpendicular to the constant magnetic field. During this test, some of the energy is absorbed which is proportional to the number of hydrogen nuclei in the measurement volume. The NMR is, in other words, a measure of the water content in the material tested. de Freitas et al (1995) compared the gamma-ray attenuation results (mentioned previously) and the NMR results and concluded that no significant difference in accuracy was evident.

The above methods are not very practical for quick analysis on existing concrete slabs on busy construction sites. Also, some of the tests above are quite expensive and complicated calibration work is also required. The following section presents published experimental work using probes to measure the rh in concrete during drying.

3.2.2 Relative humidity measurements in concrete

The use of rh probes in measuring concrete has been commonplace since the early 1960’s when Monfore (1963) first designed a miniature rh probe for measuring gradients of
moisture in concrete. This work quickly spread to the fields of fire resistance, curing, shrinkage, permeability, concrete composition and climatic differences (Kropp and Hilsdorf, 1995). These probes normally consist of a sensing element where changes in length, resistance or capacitance are detected. These probes are now commercially available and are commonly used for measuring the \( rh \) in concrete.

Figure 3.4 shows results from work carried out by Kropp et al (1995) to measure the \( rh \) profiles in concrete using humidity probes cast into 7mm diameter cavities perpendicular to the axis of drying where the surface of the sample was kept at 60\% \( rh \). The results show \( rh \) profiles through the depth at various times. The profiles demonstrate how the \( rh \) profiles change with time with a very non-linear profile early on (at 18 days), changing to a less non-linear profile after a long drying time (542 days). However, forcing the surface \( rh \) to be kept at 60\% does not give a true representation of the \( rh \) through the depth. For example, at 18 days, the humidity drops from 92\% at 10mm depth to 60\% at the surface, where it is fixed. It is postulated that the surface \( rh \) would be approximately 90\% if one were to follow the profile to 20mm and beyond. Also, other results may be strongly affected by the constant ambient \( rh \) at the surface. At 46 days, it appears that at 30mm, the profile is influenced by the ambient \( rh \) and it again drops significantly after this point. However, at 542 days, it is believed that the surface \( rh \) would not influence the internal \( rh \) as much because the \( rh \) at 90mm is much less than that at 46 days. The use of a removable humidity probe allows the user to perform regular measurements at various depths over time and allows a profile of \( rh \) to be obtained.
Kim and Lee (1999) measured \( rh \) profiles in drying concrete over time using sealed 210x100x100mm specimens. The internal \( rh \) was measured at depths of 30, 70 and 120mm from the surface with five sides coated with paraffin wax to ensure only vertical moisture migration took place during drying and were exposed to a constant ambient temperature and humidity of 20±1\(^\circ\)C and 50±2% respectively. The internal \( rh \) in the concrete was measured using a Vaisala HMP44 probe and a Vaisala HM141 indicator. The set-up for their experiments is shown in Figure 3.5. As shown, the probe is inserted into a plastic sleeve with a rubber plug at the surface to keep the influence of the external humidity to a minimum. Figure 3.6 presents the measured \( rh \) profiles in the concrete during their tests and shows how the \( rh \) varies through the depth, with a greater loss of moisture nearer the surface than deeper in the concrete as expected.

From Figure 3.6(c), the concrete with the w/c ratio of 0.28 appears to dry faster. For example, for the concrete to reach 80% at 30mm, it takes approximately 80 days, compared to 90 and 160 days in Figure 3.6(b) and Figure 3.6(a) with w/c ratios of 0.40 and 0.68 respectively. At 70mm, 80% is achieved at approximately 180 days in Figure 3.6(c) compared to 200-days in Figure 3.6 (b) and not achieved in the time frame shown in Figure 6.6 (a). The samples with the lower w/c ratios are drying faster as a result of the reduced free water in the concrete following hydration, as discussed in Chapter 2. It appears to contradict the results by Akita \textit{et al} in Figure 3.10, who indicated how the diffusion coefficient increases with increasing w/c ratios. Indeed, Akita \textit{et al} (1997) concluded that the rate of diffusion increases from 0.8cm\(^2\)/day to 6cm\(^2\)/day for w/c ratios of 0.28 and 0.68 respectively.

Basheer and Nolan (2001) performed an extended test series that monitored the moisture distribution of different concretes exposed to the environment by periodically assessing the \( rh \) in the concrete using a commercially available chilled mirror dew-point probe. The concretes were manufactured with w/c ratios of 0.45, 0.55 and 0.65. After production of the samples they were removed from the mould and placed in a controlled temperature and \( rh \) environment of 20±2\(^\circ\)C and 50±5% respectively. The test specimens (450 x 200 x 500mm) were allowed to dry with one face fully exposed to the weather and the opposite face partly sheltered by a nearby building, approximately 1.5m away. The \( rh \) measurements were performed at the surface and at a depth of 10mm on a monthly basis.
Figure 3.5  Experimental set-up used for monitoring the changing internal $rh$ in concrete during drying by Kim and Lee (1999).

Figure 3.6  Typical $rh$ distributions in concrete due to moisture diffusion and self-desiccation (Kim and Lee, 1999).

The variation of the measured $rh$ of the 0.45 w/c concrete over the 18-month exposure period is shown in Figure 3.7. It is evident that the $rh$ increased and decreased over the 18 month period due to the increase and decrease in the ambient $rh$ in the winter and summer months respectively. For example, from March to June, there is a decrease in the $rh$, while from September to February, the $rh$ increases on average due to the changing ambient conditions experienced over the 18-month period. For example, from March to June, one
would expect the ambient temperature and humidity to rise and fall respectively. From September to February, one would expect the ambient temperature and humidity to decrease and increase respectively. The results also indicate that the surface is more affected by these ambient changes than that at 10mm. For example, in June, the \( rh \) at the surface is approximately 54%, while, at 10mm, it is approximately 68% for the fully exposed case. Also, as expected, the \( rh \) is lower for the sheltered case than for the exposed case. As can be seen, in June, the \( rh \) at the surface and at 10mm in the sheltered case is approximately 50 and 63% respectively, compared with 55 and 68% for the exposed case.

The apparatus is shown in Figure 3.8.

**Figure 3.7**  Variation in the \( rh \) of the 0.45 w/c concrete (Basheer and Nolan, 2001).

**Figure 3.8**  Apparatus to measure the \( rh \) at the surface and in 10mm-deep holes developed by Basheer and Nolan (2001).
The above has shown that portable humidity probes offer a quick and informative measurement of the $rh$ in drying concrete, particularly if the measurements are taken at various depths. On busy construction sites, it is the most suitable method as it is relatively simple to setup the tests and conduct the measurements.

### 3.3 REVIEW OF DIFFUSION COEFFICIENT AND EVAPORATION EQUATIONS DURING DRYING

As shown in the previous section, moisture movement in concrete takes place as a diffusion driven process in both liquid and vapour flow. The diffusion coefficient and evaporation rate are dependent on the moisture concentration and w/c ratio, which makes the moisture diffusion in concrete highly nonlinear (Bazant and Najjar, 1971). As a first approach to modelling the problem Shimomura and Maekawa (1997) and Chaube et al (1993) used the gradient of evaporable pore water content $w_e$ as the driving force for moisture flow. The approach of using the diffusion coefficient as a function of the pore water is discussed in section 3.3.1. Others have proposed the gradient of the internal pore $rh$ as the driving force of the drying process and this is discussed in section 3.3.2. This approach is supported by the fact that the water content is related to the partial pressure of water vapour in the pores and, therefore, the $rh$ method leads to a more convenient formulation.

### 3.3.1 Formulation of the diffusivity in terms of the pore water content

The diffusion of evaporable water is based on Fick’s first law (Equation 3.3), where $J$ is the total mass flux ($g/m^2/sec$) and $D_w$ is the moisture diffusion coefficient ($m^2/sec$), where $w_e$ is the evaporable water not chemically bound by the hydration process. Again, building on Section 2.2 and using Equation 3.3 with the total water content $w$, the equation of moisture diffusion for drying in terms of the water content in the pores is given in Equation 3.4.

$$J = -D_w \frac{d w_e}{d x}$$

Equation 3.3
Using $w_e$ as the primary unknown has a number of disadvantages. Firstly, the boundary conditions for this type of analysis are not easily expressed in terms of $w_e$. Secondly, using the equation in terms of the water content is not convenient when the effect of the hydration is considered since the volume of pores is decreasing. Pel (1995), in his PhD thesis, formulated the moisture diffusivity as a function of the pore water content using results from NMR measurements on the internal moisture. From this work, Pel concluded that the moisture diffusivity is not dependent on the position in the concrete and that moisture transport during drying for porous materials can be modelled using a diffusion equation. For mortar, Pel give an estimate of the moisture diffusivity during drying of $3 \times 10^{-9} \text{ m}^2/\text{sec}$.

Akita et al (1997) developed a diffusion equation, based on experimental observations for a wide range of concrete mixes, which allowed the analysis of the effect of one- and six-face drying on the water content profiles and mass decreases in prismatic specimens. These equations represent curves that give a best fit to experimental measurements as described in section 3.2.1. In order to calculate the diffusion coefficient from the relative water content, $R$, the authors used a hyperbola (Equation 3.5) to fit the experimental results, where $a$, $b$, $\eta$ and $f$ are experimentally determined constants, given in Table 3.1. Taking $D_1$ to denote the value of $D$ when $R=100\%$, Figure 3.9 shows the calculated ratio $D/D_1$, which is expressed by Equation 3.6, which relates the relative water content to the diffusivity. As shown, there is a significant drop in moisture diffusion with reducing water content. For example, for a reduction in $R$ between 100-80%, there is a rapid decrease in the moisture diffusivity of approximately 90% from the saturated diffusion coefficient.

\[
\frac{\partial w_e}{\partial t} = \frac{\partial}{\partial x} \left( D_w \frac{\partial w_e}{\partial x} \right) \quad \text{Equation 3.4}
\]

\[
\frac{R}{100} = 1 + f - \left( \frac{a}{(\eta + b)^2} \right) \quad \text{Equation 3.5}
\]

\[
D = D_1 \left[ \frac{1}{29 \left( 1 - \frac{R}{100} \right) + 1} \right]^{1.4} \quad \text{Equation 3.6}
\]
Table 3.1  Values of the constants used in Equation 3.5 and 3.6 (Akita et al, 1997)

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>w/c Ratio</th>
<th>$a$</th>
<th>$b$</th>
<th>$f$</th>
<th>$\eta$</th>
<th>$D_1$ (cm$^2$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.059</td>
<td>0.36</td>
<td>0.0044</td>
<td>3.3</td>
<td>4.1</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>0.058</td>
<td>0.34</td>
<td>0.0042</td>
<td>3.4</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>0.107</td>
<td>0.44</td>
<td>0.0041</td>
<td>4.7</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Figure 3.9  Relationship between $R$ and $D/D_1$ developed by Akita et al (1997)

Figure 3.10 shows the influence of the w/c ratio on the diffusion coefficient as determined by Akita et al (1997). The figures shows the influence the w/c has on the moisture diffusivity, where between a w/c ratio of 100 and 40%, there is a gradual decrease in the rate of diffusion from 11cm$^2$/day (or 1.3x10$^{-8}$ m$^2$/sec) to 1cm$^2$/day (or 1.2x10$^{-9}$ m$^2$/sec) approximately. Comparing these with the moisture diffusion suggested by Pel (3x10$^{-9}$ m$^2$/sec) it would appear that the rates of diffusions by Akita et al (1997) and Pel (1995) are of the same order of magnitude. From Figures 3.9 and 3.10, it is clear that the moisture diffusivity is highly dependant on and strongly influenced by both the internal moisture and the w/c ratio. Any subsequent modelling of drying must incorporate a moisture diffusivity that takes both of these factors into account. This appears to agree with the previous chapter where concretes with high w/c ratios have more interconnected capillary pores, which aids the movement of moisture and it is not surprising that with high w/c ratios, higher rates of diffusion are experienced.
3.3.2 Formulation of the diffusivity in terms of the pore relative humidity

Formulation of the diffusivity in terms of the pore $rh$, requires an expression for the diffusivity $D(h)$. This area of research is well published and a number of expressions have been developed were the moisture flux is proportional to the gradient of the pore $rh$ (Equation 3.7), where $k$ is the permeability. By introducing the desorption isotherm that relates the moisture content ($w$) of the concrete to the $rh$, Equation 3.8 can be written using the chain rule, where $\partial w / \partial h$ is the moisture capacity and represents the slope of the desorption isotherm. If this slope is constant over a wide range of humidities, or the moisture content is assumed to be a piecewise linear function of the $rh$ over a small range of humidities, Equations 3.7 and 3.8 can be rearranged to yield Equation 3.9. This represents Fick’s second law of diffusion with the diffusion coefficient as a function of $rh$, as presented earlier in Chapter 2.

\[
J = -k \cdot \text{grad}.rh
\]

Equation 3.7

\[
\frac{\partial w}{\partial t} = \frac{\partial w \partial h}{\partial h \partial t} = \frac{1}{c} \frac{\partial h}{\partial t} = -\text{div}J
\]

Equation 3.8

\[
\frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left[ D(h) \frac{\partial h}{\partial x} \right]
\]

Equation 3.9
It must be pointed out, however, that the diffusion coefficient is still a function of the moisture content, which in turn is a function of the $rh$, through the desorption isotherm and can be expressed in terms of the $rh$. For the sake of simplicity, most authors in this area assume that drying occurs in quasi-isothermal conditions with almost constant temperature. It has been found (Xin et al, 1995) that the effect of temperature on pore $rh$ variations is small and may be totally neglected when the pore $rh$ in concrete is greater than 90%. Various research studies have been developed to determine theoretically or by experimentation, the influence of temperature on the moisture diffusivity coefficient and have shown that the diffusion increases with temperature for a non-consolidated material, like sand. However, for materials like concrete, it has proved difficult to define laws for the influence of variations in the moisture diffusivity and it is commonly accepted not to be temperature dependent and varies only with the pore $rh$.

Bazant and Najjar (1971) developed an expression that relates the diffusion coefficient to the pore $rh$, where they postulated that it varies with the pore humidity. During their work, they developed Equation 3.10, which is based on an S-shaped curve that gives a good fit with experimental results, presented in Figures 3.11 and 3.12. As shown, the humidity decreases more rapidly over the initial three months with a more gradual decrease over the remaining time. In this equation the diffusion coefficient is a function of the pore $rh$ and $D_1$ represents $D(h)$ when $h$ is 100%, $\alpha_0$ represents the ratio $D_0/D_1$ where $D_0$ is the minimum $D(h)$ for $h = 0\%$ and is approximated as 0.05 and $H_C$ is the pore humidity at $D(h) = 0.5D_1$ assumed to be 0.80 and has been used by CEB-FIP (1992) and Kim and Lee (1999). $n$ is an exponent that represents the shape/gradient of the curve in Figures 3.11 and 3.12 and represents the change of diffusion rate between a $rh$ of 80 and 65%.

\[
D(H) = D_1 \left[ \frac{1 - \alpha_0}{1 + \left( \frac{1 - H}{1 - H_C} \right)^n} \right]
\]

Equation 3.10

However, it should be pointed out that this formulation should not be used for modelling or prediction purposes if the change of material properties due to hydration was to be considered or if the temperature was not constant. If this were the case, Bazant and Najjar
Figure 3.11  *rh* distribution over times (Bazant and Najjar (1971) for ambient humidities ($H_{en}$) of 0.35 and 0.5. Dashed line represents the linear theory.

Figure 3.12  Linear (dashed) and non-linear comparisons for mid-cylinder *rh* values for an $H_{en}$ of 0.1 (Bazant and Najjar, 1971).

(1971) stated that the theory behind using the pore humidity as the driving force causing moisture movement would not be valid. They concluded that the diffusivity decreases sharply when the pore humidity passes from 80-70% using the values above with a $D_1$ of $3.25 \times 10^{-10}$ m$^2$/sec. Figure 3.13 shows a plot of the diffusion as a function of the pore humidity using Equation 3.10. As shown, at approximately 80%, the diffusion rate sharply drops from $3.5 \times 10^{-10}$ to $2.5 \times 10^{-11}$ m$^2$/sec at 70% while below 65% it is constant. Further, the non-linear diffusion theory gives a far better prediction of concrete drying than linear theory for normal dense concretes with low w/c ratios (Holmes and West 2003).

Equation 2.34 suggested that rate of vapour diffusion is $1/50^{th}$ that of liquid diffusion (Shimomura and Maekawa, 1997). Using this relationship, with an initial diffusion rate
(D$_1$) of 3.5x10^{-10} m$^2$/sec (Figure 3.13) the rate of diffusion calculated is 7x10^{-12} m$^2$/sec compared with 2.5x10^{-11} m$^2$/sec in Figure 3.13. When using the calibrated diffusion rates for the finite element study in Chapter 6 (see Figure 6.10(a)) with an initial diffusion rate (D$_1$) of 4.0x10^{-9} m$^2$/sec for a w/c ratio of 0.5, (see Figure 6.10) the rate of diffusion using Shimomura and Maekawa (1997) relationship is calculated is 8.0x10^{-11} m$^2$/sec compared with 2.65x10^{-10} m$^2$/sec at a rh of 65%. While the figures are not that close, it does suggest the rate of vapour flow is within approximately 1/20th to 1/50th that of liquid flow, and, considering all the variables involved, the relationship suggested by Shimomura and Maekawa (1997) is reasonable.

Bazant and Najjar (1972) suggest an approximate value for the diffusion coefficient at a rh of 100% should be in the region 1 – 5x10^{-10} m$^2$/sec. Comparing this with previous authors, CEB-FIP (1990) estimated that an empirical formula (Equation 3.11) related the compressive strength of concrete ($f_{ck}$) to the initial diffusion coefficient ($D_1$), where $f_{cko}$ should be taken as 10MPa and $D_{1,o}$ as 1x10^{-9} m$^2$/sec. Therefore, for a 35N concrete, which is commonly used, Equation 3.11 suggests that $D_1$ should be 2.85x10^{-10} m$^2$/sec, which is within the ranges in Figures 3.13 and 6.10.

The values shown here are for a w/c ratio of 0.5. As discussed earlier, it is widely reported that the diffusion coefficient varies with the w/c ratio. In Chapter 6, where the finite

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**Figure 3.13** Variation of the diffusion coefficient with the internal rh, for example, a normal concrete with a w/c ratio of 0.5.
element model is calibrated, the diffusion coefficient in the material model varies with the w/c ratio and yield results that compare well with measured \( rh \). Hedenbland (1997) obtained an empirical expression (Equation 3.12) of the diffusivity of cement paste in the \( rh \) range 60-100\%, which is based on measurements of the capillary porosity through Mercury Intrusion Porosimetry (MIP). \( D_{60\%} \) and \( D_{100\%} \) are the diffusion coefficients for a \( rh \) of 60 and 100\% respectively, which depend on the capillary porosity. Table 3.2 shows moisture diffusivities at various w/c ratios for both low and high \( rh \) (Hedenbland 1997).

Figure 3.14 shows the calculated diffusion coefficients from Equation 3.12 as functions of the \( rh \), using diffusion coefficients of \( 4.10 \times 10^{-7} \) and \( 1.75 \times 10^{-6} \) m\(^2\)/sec for \( D_{60\%} \) and \( D_{100\%} \) respectively. As shown, the diffusion coefficient is a factor of \( 10^3 \) greater than those suggested by both Bazant and Najjar (1971) (Figure 3.13), Akita et al (1997) (Figure 3.10) and Pel (1995) (3.0\( \times 10^{-9} \) m\(^2\)/sec) for a w/c ratio of 0.5.

\[
D(h) = D_{60\%} + (D_{100\%} - D_{60\%}) \left( \frac{H - 0.6}{0.4} \right)^3
\]  

Equation 3.12

<table>
<thead>
<tr>
<th>Cement Paste w/c ratio</th>
<th>Low ( rh )</th>
<th>100% ( rh )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>0.22( \times 10^{-6} )</td>
<td>0.84( \times 10^{-6} )</td>
</tr>
<tr>
<td>0.45</td>
<td>0.41( \times 10^{-6} )</td>
<td>1.75( \times 10^{-6} )</td>
</tr>
<tr>
<td>0.60</td>
<td>0.61( \times 10^{-6} )</td>
<td>2.2( \times 10^{-6} )</td>
</tr>
</tbody>
</table>

Table 3.2  Moisture diffusivities (m\(^2\)/sec) at w/c ratios of 0.35, 0.45 and 0.6 (Hedenbland 1997)

As stated, Figure 3.14 and Equation 3.12 have been derived from NMR test results, which is a measure of the number of hydrogen nuclei where an exterior permanent magnetic field is applied perpendicular to the constant magnetic field and can distinguish between the free, physically and chemically bound water. However, in contrast to previously published diffusion coefficients, it does not compare well and it is postulated that this method may not be best suited for predicting diffusion rates in concrete. Also, it will be shown later in
Chapter 6 that when these values are compared against each other, they yield the poorest comparison with the experimental results here.

Roncero (2000), in her PhD thesis on moisture movement in concrete as a result of plasticizer addition, developed a three-dimensional finite element formulation of the moisture transport properties based on the $rh$ in the pores using the governing nonlinear diffusion equation (Equation 3.9). From this, Equation 3.13 was proposed to calculate the diffusion rate, which was based on $D(h)$ curves,

$$D(h) = D_o + (D_1 - D_o) f(\beta, h)$$

where $D_o$ and $D_1$ are the diffusivity at $rh$ at 0 and 100% respectively, and $\beta$ is a shape parameter that represents the shape of the $rh$ profiles at various times, which is calculated using Equation 3.14. The proposed values to be used in Equation 3.13 are $5.78 \times 10^{-12}$ m$^2$/sec, $3.82 \times 10^{-10}$ m$^2$/sec and 2.55 for $D_o$, $D_1$ and $\beta$ respectively. This expression agrees with previous work in this area by Hedenbland (1997), Akita et al (1997) and Tsubaki et al (1992), who also assume that the diffusivity decreases sharply with decreasing $rh$.

$$f(\beta, h) = \frac{\exp(-\beta)h}{1 + (\exp(-\beta) - 1)h}$$

 Equation 3.14
As shown in Figure 3.15, the previous trend of rapid reduction in the diffusion rate over higher \( rh \) ranges (here from a \( rh \) of 100 to 95\%) is repeated, where it reduces from \( 4 \times 10^{-10} \) to \( 2.5 \times 10^{-10} \) m\(^2\)/sec, which is similar to those suggested by Bazant and Najjar (1971). Also, the diffusion rate at 100% \( rh \) (\( 4 \times 10^{-10} \) m\(^2\)/sec) is similar to that suggested by Bazant and Najjar (1971) (\( 3.5 \times 10^{-10} \) m\(^2\)/sec) and by Akita et al. (1997) (\( 2.5 \times 10^{-10} \) m\(^2\)/sec). Similarly, at lower \( rh \) values, the diffusion rate at 55% \( rh \) (\( 4 \times 10^{-11} \) m\(^2\)/sec) is similar to that suggested by Bazant and Najjar again (\( 2.5 \times 10^{-11} \) m\(^2\)/sec).

It appears from the above review that previous research generally agrees that diffusivity decreases sharply from an initially saturated state (\( rh = 100\% \)) to a uniform or constant diffusivity, at approximately 65% \( rh \). The question is, at what \( rh \) and how sharply does the diffusivity begin to decrease. As shown by Bazant and Najjar (1971), this point is approximately 80% and sharply decreases to approximately 65%, where its remains constant. Akita (1997), Hedenbland (1997) and Roncero (2000) all suggest that it decreases immediately from 100% \( rh \).

It is postulated here that the expression developed by Bazant and Najjar (1971) is more accurate for drying purposes as it combines the various stages of drying described in Chapter 2. Also, they assume that this rate of diffusion is constant down to 80% \( rh \), where it falls sharply and remains constant again at a lower \( rh \). This point is shown in Chapter 5, when comparisons are made between the rate at which the \( rh \) decreases from 100-80% and from 80-60%. This model also provides a better comparison with the experimental results here than those obtained from other authors’ work. For example, during early drying, moisture migration is most rapid (near the surface typically for one face drying) as is suggested by Figure 3.13. As drying continues the rate of drying (at the surface particularly) begins to slow. Similarly, deep in the concrete, moisture migration is faster at high humidities under the \( rh \) gradient between the top and bottom of the concrete, as suggested by Figure 3.13.

This model has been used by other researchers, namely CEB-FIB (1990) and Kim and Lee (1999), as part of a finite element study. The results of their work have shown that Equation 3.10 has produced results that correlate well with measured \( rh \) profiles. This will be shown later as the diffusion coefficient suggested by Bazant and Najjar gives good
Figure 3.15  Relationship between the diffusivity and the $rh$ (Roncero, 2000).

comparisons with the measured $rh$ profiles through the depth of slabs poured as part of this thesis and gives the best comparison with other published values.

3.4  PREVIOUS NUMERICAL MODELLING OF MOISTURE MOVEMENT IN POROUS MEDIA

Most of the numerical work on drying concrete has been in developing empirical equations calibrated against experimental results to predict diffusion coefficients and evaporation rates. However, recent work in developing numerical tools has resulted in a number of models to predict drying regimes of porous media. This section presents a review of such tools that have been developed for porous materials and concrete.

The theoretical study of the heat and mass transfer in unsaturated porous materials has been the target of important research work based on various models. Since the beginning of the 1970s, many numerical programs have been developed to calculate the one-dimensional heat and mass transfer in construction elements (Van Der Kooi, 1971 and Hall, 1989). Glaser (1959) developed a thermal and moisture diffusion model based on Fick’s law, which presents one-dimensional moisture transfer in the vapour stage. However, it assumes steady state movement only and, while it allows the user to predict condensation, de Freitas (1996) reports that comparisons with experimental results show that it was insufficient to predict moisture diffusion. The Krischer-Vos model (de Freitas et
al, 1996) represents a first attempt to describe the moisture transfer in a porous material in both the liquid and vapour stage. This method uses the humidity gradient as the driving force but does not consider the temperature influence on moisture movement. Philip and de Vries (1957) state that any predictive model must assume that the materials are non-deformable, isotropic and macroscopically homogeneous. It was also assumed that there is no hysteresis and no freezing, boiling or melting occurring.

de Freitas et al (1996) used their computer program TRHUMIDADE to simulate the behaviour of moisture and heat transfer in a building wall for a one-dimensional case. It uses the method of finite differences to solve the combined heat and mass transfer equations. In their paper, the authors state that computer programs for determining the evolution of the moisture content profiles and temperature inside walls are an indispensable instrument to simulate the corresponding behaviour in relation to moisture as a function of the interior and exterior climatic conditions. TRHUMIDADE is made up of the main program and eight sub-routines that allows for variations in the ambient conditions, such as the $rh$, temperature, radiation and rain. The simplified mass and energy conservation equations in TRHUMIDADE are based on the assumptions that the effect of gravity is negligible and the transport of heat due to the phenomenon of evaporation/condensation is also negligible when compared to transportation by diffusion. Comparing their simulations with experimental results on drying, they concluded that a satisfactory comparison was made since there are many parameters being used and the physical phenomena being analysed are very complex.

Sadouki and van Mier (1997) presented a simple flow model for simulating mass or heat transfer in heterogeneous materials like concrete. A generated particle structure of concrete is projected on the lattice where different properties are assigned to ‘pipes’ falling in different phases of the composite. During this analysis, the drying of a two-phase composite was analysed and all mass and heat transfer is described by means of a single diffusion equation. Typical results from this analysis are shown in Figure 3.16, which are compared with continuum finite element analysis and show good correlation. The finite element package used was the commercially available DIANA, which can be used for simulations of continua and lattice type analysis. The equation to describe the flow between two neighbouring nodes in DIANA is given in Equation 3.15 (Fick’s second law),
where $\lambda$ is the diffusivity as a function of the humidity ($P$) in the case of moisture flow and the thermal conductivity in the case of temperature flow. The model can be used for computing both humidity distributions from moisture flow and temperature and gas concentrations. They concluded that this type of analysis was suitable for modelling moisture movement in concrete. However, only a constant diffusion coefficient was used and the authors agreed that there is need for experimental validation of the results. Figure 3.16 shows that near the exposed surface (at node No. 189) drying is more rapid than deeper in the concrete (No. 179). This agrees with previous published work in this area and the results from the experimental programme here, shown in Chapter 5. It appears that this model is capable of using Fick’s laws for diffusion and yields reasonably accurate $rh$ profiles in drying concrete. The model here used a constant diffusion rate but DIANA has the capability of using a diffusion coefficient as a function of time, temperature and, which is important in this thesis, as a function of the pore $rh$. More on this model will be discussed in Chapter 6.

Shimomura and Maekawa (1997) developed a micromechanical model for moisture diffusion within concrete to predict the associated shrinkage of concrete. In this model they developed simplified mechanical and thermodynamic assumptions and the drying
shrinkage of finite concrete specimens under various conditions was modelled. Their model is described in Figure 3.17, where the basic concept of the model is to synthesize mathematical expressions of microscopic phenomena within concrete related to drying shrinkage. The material characteristics of the model are the total volume \( V_0 \) of pores per unit concrete volume \( \text{m}^3/\text{m}^3 \), parameters that define the configuration of the pore size distribution, parameters for the vapour \( K_V \), liquid water \( K_L \) transport and \( E_s \), the elastic modulus for capillary stress (Pa). All these values were identified from test data obtained from prismatic specimens. The authors concluded that the model was verified using systematic drying shrinkage experimental tests and that the model was a good first step towards predicting the drying shrinkage behaviour of concrete on the basis of the micro-mechanisms.

**Figure 3.17** Outline of the micromechanical model developed by Shimomura and Maekawa, 1997.
Perre and Turner (1999) used a 3-D model (Transpore) to predict the non-linear moisture profiles in porous media at the macroscopic level using state variables (energy, moisture and gas phase conservation) to describe the drying process. Phenomena such as capillary and convective liquid flow, bound and gaseous diffusion and convection gaseous migration and thermal conductivity are treated in the formulation of the model. For concrete, a case study is presented which deals with the high temperature convective drying of a cube of an isotropic material (lightweight concrete), as shown in Figure 3.18. To model the drying of the concrete by convective air-flow, a very simple configuration is used. Figure 3.19 represents the computed variable iso-surfaces after 2-hours of drying. At this point, only the core of the cube retains a high degree of moisture.

**Figure 3.18** Mesh example of 1/8th of a 4x4x4cm cube used for computing 3-dimensional moisture distribution using the Transpore model (Perre and Turner, 1999).

**Figure 3.19** Numerical simulation of concrete drying for 3-dimensional variable fields after 2-hours of drying (Perre and Turner, 1999).
In their work into determining the diffusivity during the drying process of a porous building material, Krus and Holm (1988) used a commercial heat and moisture simulation program, WUFI, to determine the diffusivity using results from measured and calculated weights. The results from this analysis are compared with the experimental results as shown in Figure 3.20, where the samples have been dried through one exposed face at $20^\circ C$ and 65% $rh$. The authors conclude that a comparison of calculated results using these approximations and exactly determined coefficients shows only moderate but acceptable deviations from reality.

![Figure 3.20](image)

**Figure 3.20** Course of drying of initially saturated samples with one-sided drying at $20^\circ C$ and 65% $rh$ with the measured and calculated results shown as dots and solid lines respectively (Krus and Holm, 1998).

Schlangen *et al* (2002) developed a simulation tool called HEAT to model the effects of drying shrinkage and moisture diffusion in concrete floors in a user-friendly environment. The set-up to predict the moisture content profiles in a concrete slab drying in a building is shown in Figure 3.21, with the corresponding moisture content profiles of a concrete floor slab in Figure 3.22. As shown, the model gives a good indication of the moisture profiles in the concrete. However, no experimental results are presented that could validate the model. Work is currently under way to incorporate reinforcement and interface elements into the model (Schlangen *et al*, 2002). The material parameters for all the models
Figure 3.21  Structure of the floor and its environment (after Schlangen et al, 2002).

Figure 3.22  Results from the floor in Figure 3.31 (Schlangen et al, 2002).

(analysis) presented above are based on theoretical values and calibrated to suit the
experimentally determined moisture condition. This appears to be a common trend, again, a consequence of the large variation of published diffusion and evaporation rates.

3.5 APPLICATION OF IMPERMEABLE COVERINGS

Over the past 30-years, the number of complaints in relation to wet, curled or loose floor coverings or blistered coatings has increased sharply (Grady, 1995). Indeed, Grady (1995) reports that moisture has been causing floor covering installer’s problems since straw was first put down on floors. In the case of timber flooring, severe buckling may also occur between walls as the moisture is absorbed into the timber causing it to swell. Moisture in concrete has always presented a problem for glue-down flooring systems and the delamination of flooring due to moisture and subsequent increase in vapour pressures under the coverings has cost architects, contractors, flooring contractors and building owners dearly. Indeed, the floor can be covered for many months or years without any problems occurring. Some of the problems that occur due to excessive moisture after installation include

- Adhesive deterioration,
- Bumps, ridges or bubbles occurring on the covering,
- Colour changes,
- Mold, mildew or bacteria growth,
- Efflorescence (alkali build-up at tile joints, for example), and
- Tile peaking or curling.

These problems can occur at any time after the floor is installed. Figure 3.23 shows a number of different types of damage that may occur to floor coverings from an excessive moisture condition at the time of application. Many of these problems are a consequence of fast-track construction activities. Suprenant and Malisch (1998) presented an example of this where, according to the construction schedule, the floor covering for the building (a cinema, multiplex, etc) was due to be applied. However, according to the floor installer, there was an excess of moisture present. The owner’s message was adamant - get the floor covered so they can begin to generate revenue instead of waiting for a concrete floor to dry. This is a common dilemma where, in an attempt to stay on schedule, contractors have
applied the floor regardless of the moisture condition. In this case, the floor did indeed experience moisture problems and had to be lifted, the concrete allowed to dry further and re-laid. All this adding time and cost to the project.

There are a number of tests that are recommended to be undertaken before any floor covering is applied. In the UK, the British Standard (BS 8203) recommends that before any resilient floor covering is applied to a concrete surface, the surface $rh$ must reach 75% using a surface hygrometer, at which point the floor is deemed dry enough to apply the covering without any future damage. This 75% $rh$ threshold is based on experimental evidence that when the $rh$ falls below this moisture level, enough water has evaporated and the slab is sufficiently dry to allow the safe installation of a resilient (impervious) floor covering. In fact, the standard states that below 80% $rh$ it is sufficiently dry to apply the covering, but it allows a further 5% for errors in reading the $rh$. The hygrometer referred to
in BS 8203 is used as part of this thesis and will be described in Chapter 4. This method may not be suitable on power floated concrete slabs or proprietary screeds as the low porosity surface commonly experienced in these cases results in extended testing periods due to the low \( rh \) values commonly experienced. It must be highlighted that the hygrometer provides a surface determination of the moisture condition of the concrete. It takes no account of the moisture condition deeper in the concrete, which has been shown to contain a residue of moisture, particularly if the slab has been force dried. Therefore, to assess the extent of this moisture residue deep in the slab, the ASTM are developing a standard test method to determine the \( rh \) in concrete floor slabs using in-situ \( rh \) probes (ASTM F 2170-02, 2002). The test involves the measurement of the \( rh \) in the concrete by inserting probes at a certain depth, depending if drying is taking place through one- or two faces, into a drilled hole (created using a rotary hammer drill) with a hollow sleeve to line the hole. Alternatively, a hole in the fresh concrete may be formed and compacted using a hollow cylindrical tube. The depth of the hole and \( rh \) measurement in the concrete are determined from Table 3.3. As shown, it is recommended that only the \( rh \) at the top 20 and 40% of the slab depth are measured, depending on the number of faces exposed. This proposed test, which has yet to be formally adopted by ASTM, is very clearly aligned with the tests conducted for this thesis and the experimental results presented here give strong support to its approach. For example, the \( rh \) at 60mm (40% for the 150mm thick slabs) at the point of covering has been shown (see Chapter 7) to give a good indication of the long-term equilibrated \( rh \) through the depth. This is important as it allows floor covering contractors to identify what the long-term equilibrated \( rh \) is likely to be and they are in a position to assess if placing the covering at that point would be cause future problems.

### Table 3.3

<table>
<thead>
<tr>
<th>Drying Conditions</th>
<th>Drill-to depth from top of slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab drying from top only</td>
<td>40% 1.5 in. (40mm) deep in a 4 in. (100mm) thick slab</td>
</tr>
<tr>
<td>Slab drying from top and bottom</td>
<td>20% 0.75 in. (20mm) deep in a 4 in. (100mm) thick slab</td>
</tr>
</tbody>
</table>

In the USA, the most common method to establish the point to safely apply a floor covering is the Vapour Emission Test (VET). This test measures the amount of vapour escaping from a square area of the concrete surface over 24-hours. The test involves placing of a dish of calcium chloride in a sealed ‘tent’ which is fixed to the concrete
surface for 3 days. The subsequent increase in mass of the sample is related to the vapour emission rate and is expressed in units of \( \text{lbs/1000ft}^2/24\text{hrs} \) using an equation (see Equation 4.1) to express the increase in weight to the units above. This method follows a series of tests on drying concrete basements by Harold Brewer (Portland Cement Institute, 1994). In his tests, it was found that it took approximately 90-days for a 100mm thick slab with a w/c ratio of 0.5 to reach a vapour emission rate of 3lbs under environmental conditions of 50% rh and 23\(^0\)C. The rate of vapour emission that must be achieved prior to sealing is 3lbs/1000ft\(^2\)/24hrs. However, in a recent survey of flooring manufactures, organisations and experts, it is more common that coverings are applied when it achieves a rate of between 3-5 lbs/1000ft\(^2\)/24hrs (Floortest, 2002). They concluded that flooring manufacturer’s who do not test for moisture prior to installing a floor, run the risk of total liability for a moisture related failure of the floor.

A common problem on construction sites is determining when a floor covering can be safely applied without future damage. The drying period required will vary with environmental conditions, type and thickness of concrete. For example, slabs laid directly on the ground (with a membrane) require longer drying periods than suspended slabs as drying is occurring through two faces in the latter. Usually, several months of drying are required after casting to reach an acceptable moisture level. Many manufacturers recommend that concrete be at least 60 days old before their floor covering is installed. In some regions special measures may be required, such as dehumidifying and heating the air to dry the concrete sufficiently. Chaplin (1987) reports an empirical rule of thumb, that, under ideal conditions, one day of drying be allowed per millimetre of concrete depth for screeds up to 50mm thick, while other empirical rules suggest waiting for at least 6-months (or over 180-days) before apply a covering. Another rule of thumb suggests that 1 month be allowed per inch thickness of concrete before any covering be applied. However, as shown in Chapter 5, these rules do not realistically represent the drying time and they only highlight the need for further research into drying concrete with varying properties.

All this highlights that the current practices to determine the point in time to apply a floor covering are lacking in understanding of the issues and problems like those shown above. However, the question of what causes these problems is still outstanding. Some authors accept that residual moisture causes these flooring failures. This residual moisture has two
effects. Firstly, it can contain agents (salts) that cause chemical reactions with the floor adhesive causing the bond strength to be reduced over time. Secondly, it can generate a vapour pressure under the covering causing the problems mentioned above on these impervious coverings. The following section presents how a vapour pressure can be created under the covering over time.

### 3.5.1 Development of a vapour pressure

Many authors (Grady, 1995 and Floortest, 2002) commonly accept that most of the problems associated with damage to floor coverings are primarily due to vapour pressure build-up under the covering. Vapour pressure can be related to the $rh$, via the gas laws, which, in turn, are related to the moisture content via the desorption isotherm, as shown above. Therefore, for any $rh$, there is an inherent vapour pressure, as the $rh$ is a function of the ratio between the actual vapour pressure and the saturated vapour pressure, at a given temperature. Equation 3.16 presents an equation to calculate the actual vapour pressure, $V$ (Pa) for a given temperature, $T$ ($\degree$C) and $rh$ (Padfield, 1999). For example, for a temperature of 14$\degree$C and $rh$ of 55%, the vapour pressure is approximately 877Pa using Equation 3.16 and Figure 3.24 shows a linear relationship between the $rh$ and the water vapour pressure at a fixed temperature of 20$\degree$C. This expression will be used in Chapter 6 in an attempt to use the VET results to calculate the rate of evaporation from the concrete.

$$V = \left( 610.8 \exp \left[ 17.27 \left( \frac{T}{T-35.86} \right) \right] \right) \times \frac{rh}{100}$$

Equation 3.16

When a concrete slab is covered, there will almost certainly be a residue of moisture in the concrete which will migrate upwards due to the concentration gradient that exists in the slab, provided the base and the sides remain impervious. The application of the covering now seals completely the slab and traps this moisture, now accumulated underneath. Thus can be shown in Figure 3.25 where typical $rh$ profiles are presented for a natural and forced drying environment at the point of sealing (when the surface reaches 75% $rh$) and afterwards, as developed by the author (Holmes and West, 2002).

As shown, when covered, the $rh$ at the surface will increase under the humidity gradient
**Figure 3.24** Relationship between the $rh$ and the vapour pressure at 20$^0C$.

**Figure 3.25** Moisture equilibration over time in concrete slabs under a covering for different initial drying conditions (Holmes and West, 2000).

setup in the concrete. The final long-term $rh$ at the surface and the distribution through the depth upon sealing will depend on the type of drying that was carried out previously. For example, the increase in surface $rh$ after covering is approximately 5% after drying in a natural or open environment. However, following drying in a sealed warm room where the surface region dries faster than that deeper in the concrete, this increase can be up to 10%. In conjunction with this increase in the $rh$ under the covering, the vapour pressure also increases, as described by the gas laws (Equation 3.16) and as shown in Figure 3.24. Over time, the rate of pressure increase will slow as equilibrium is reached inside the concrete.
However, provided the surface remains covered and impervious, this pressure will remain. Water vapour conditions such as these can exist in places where the slab has never been covered or has been covered with a floor covering that allows moisture to pass through it, causing problems such as wet rugs and carpets, damp and musty smells, rotting of wood, wet insulation, rusting of nearby metal and bacterial growth (Penttala and Wirtanen, 2002).

This has been studied by Hedenbland (1997) theoretically, who concluded that, when a floor is covered, the internal moisture will be redistributed and the concrete’s internal $rh$ near the surface will increase as shown in Figure 3.26. Here, profile (A) shows the $rh$ before any drying takes place (at 100%). Profile (B) represents typical profiles following drying at the point of covering (shown as 50% which is not a practicable point to apply a covering). After the floor is covered, he postulated that the residual $rh$ will slowly equilibrate and the final surface $rh$ will be greater than when it was sealed (Profile C). As shown, the long-term final $rh$ is approximately 85% through the depth compared to 50% at the surface when it was covered and this creates the vapour pressures discussed above. Hedenbland also produced expected $rh$ profiles for various boundary conditions, as shown in Figures 3.27 (a) to (d).

Figure 3.27(a) shows a typical $rh$ profile when one face of the slab is allowed to dry only. As expected, the $rh$ at the surface is less than that deeper in the concrete. Figure 3.27(b) shows the expected $rh$ profile when both faces are drying with the $rh$ greater in the centre of the concrete than at the two exposed faces. In fact, if one was to mirror the profile in Figure 3.27(a) along the line of the water barrier, the profile in (b) would occur. Of all the boundary conditions shown, Figure 3.27(b) would lead to the fastest drying as moisture is being lost from two faces. This condition might represent a suspended concrete flat slab prior to sealing. In ASTM F2170-02 (2002), the $rh$ would be measured at 20% of the depth (see Table 3.3).

In Figure 3.27(c), normal drying through one face (top) and only partial drying in the other is shown. The boundary condition at the bottom surface may represent a pervious covering such as a carpet, unbonded screed or surface fixed timber floor without a vapour barrier. The profile would also be similar to one produced if the ambient $rh$ was different along both faces with a different ambient conditions existing at the top and bottom of the slab.
**Figure 3.26** Prediction of moisture distribution after a concrete slab receives an impervious covering (Hedenbland, 1997).

**Figure 3.27** $rh$ profiles with various boundary conditions (Hedenbland, 1997).
Figure 3.27(d) represents an \( rh \) profile without any drying and the impervious covering applied immediately after curing. One may consider that drying only leads to problems over time and it may be best, and simpler, not to allow any drying to occur and cover the concrete immediately after casting. However, as shown by Equation 3.16, the high \( rh \) would still lead to high pressure existing under the covering. Therefore, due to the high pressure and moisture present under the covering that may affect the glue, it is still likely that future damage would still occur and why covers are applied after some drying occurs.

### 3.5.2 Case studies of moisture damage to floor coverings

This section presents three case studies of problems occurring to floor coverings some time after they were initially applied (Floortest, 2002).

**Case 1: Department Store, California, USA.**

This is a three storey 7000m\(^2\) building in which the lower level was covered with three types of resilient floor covering, each made by different manufacturers. After covering, the tiles in the lower level began peaking, or rising up from the floor and, after a number of tests, it was found that a moderate to high moisture condition existed in the concrete. The consultants suggested two methods to eradicate the problem. Firstly, a 10-year warranted vapour emission compliance treatment be carried out and, secondly, the flooring and adhesive be removed and the concrete shot-blasted to create a porous surface structure for the relatively easier ‘flow’ of moisture through open pores exposed to the ambient air.

These steps, along with the application of a penetrant (to control the emission of soluble salts) and a moisture-suppressing coating (to reduce vapour emission), was applied to bring the concrete into compliance prior to the application of the new floor covering. Figure 3.28 shows the moisture levels (%) in a plan of the lower floor using the Tramex CME meter over the floor as measured by the consultant. As shown, the variation in the moisture condition over the floor is quite large, ranging from 2-6%.

**Case 2: Chemist, Northern California, USA.**

A vinyl composition tile floor covering in a popular drug store in a well-maintained shopping centre in Fresno, California began to experience problems shortly after the
original flooring installation. The tiles, installed with a water-based adhesive, began peaking and rising up from the floor. Additionally, glue began leaking through the tile joints. In an attempt to solve the problem, the client tried replacing the tiles, but the symptoms persisted. After a series of moisture and alkalinity tests throughout the interior sales floor, a high moisture and alkaline condition was found to exist. It was found that a lack of adhesion, a high concrete moisture condition coupled with the excessive alkalinity, had prevented the adhesive from curing properly and caused the tile to rise.

**Case 3: Housing Development, California, USA**

During construction of a 300m² housing development, the flooring subcontractor conducted routine moisture vapour emission tests on the concrete slab and deemed it “unsuitable” for flooring treatment. Months later, consultants were called to determine whether the concrete was still unsuitable for flooring installation, and if so, what could be done about it. After a series of moisture and alkalinity tests throughout the building, a relatively high moisture condition still remained in the concrete and it was concluded that the concrete did not have a ‘suitable’ moisture condition to install a covering. To remedy
the problem, two measures were recommended. Firstly, allow the slab dry on its own requiring keeping the affected areas at a stable climate with good air circulation and to continue to check the slab until it becomes sufficiently dry (according to the flooring manufacturer’s specified levels) to install the new floor. The second option was to speed up the process by shot-blasting the concrete (thereby opening up the near-surface pores), repair the joints and cracks and apply a moisture-suppressing membrane to reduce the vapour emissions down to the flooring manufacturer’s specified level. After these steps have been taken, the concrete slab should be ready for its new floor.

3.6 CONCLUSIONS

This chapter presented a review of some of the published experimental and numerical work that has been carried out on moisture movement in concrete. The volume of literature reviewed demonstrates that moisture movement in concrete has become one of the major research areas in concrete technology. However, what appears to be missing is a simple reliable method to measure the moisture content before and after application of impermeable coverings. Also missing is a simple and suitably calibrated numerical model to predict the changing moisture levels during drying and after application of an impermeable covering. This is the main focus of this thesis and, to achieve that, the following Chapter will describe the experimental work performed to measure the changing moisture levels in concrete. From these results, a finite element model will be calibrated to predict the changing moisture levels in drying concrete.

Moisture (liquid or vapour) movement in concrete can be monitored by a number of experimental methods. For liquid water, the use of destructive (dry-slice and direct weighing methods) and non-destructive (NMR) have been presented with their merits and shortcomings. However, the use of non-destructive methods may be more useful in a practical sense as the concrete floor will be in-situ and monitoring will often be required on busy construction sites. Measurement of the $rh$ as an indicator of the moisture migration is a very popular method as it can be related to the liquid (water) content via the desorption curve. As presented here, a number of empirical and analytical equations have been developed to estimate the diffusion coefficient in the concrete both in terms of the water content and the pore $rh$. The general trend is that the diffusion coefficient reduces with
decreasing w/c ratio and internal $rh$. While all the literature here agrees that the diffusion coefficient decreases with the internal $rh$, some authors assume that the diffusion coefficient decreases immediately from 100% $rh$. However, Bazant and Najjar (1971) take the view that it is constant from 100% to approximately 80% where it sharply decreases to 60% and remains constant afterwards. This follows previous research where it was shown that the diffusion rate for saturated concrete is much faster than that for unsaturated concretes, as much as fifty times.

This chapter presents the current knowledge in terms of the theory behind moisture migration in concrete and where a gap in the published research exists. This gap is the absence of a simple, reliable, repeatable and robust numerical method to predict the changing moisture condition in concrete as it dries, at the surface and through the depth. From the above, it is clear that no model is available that is calibrated from real experimental data from measurements from various slab thicknesses, w/c ratios and drying environments. This thesis presents such a model using a commercial finite element package, DIANA, using calibrated material models.

The area of moisture problems relating to impervious coverings is receiving increasing attention in the literature. While it is accepted that residual moisture will equilibrate after a covering is applied, little is available in the literature concerning experimental monitoring of the equilibrating moisture under a covering. Furthermore, no numerical methods have been published to predict the long-term equilibrium $rh$ after sealing the concrete. This thesis presents such a model by using the finite element method to account for the impervious boundary condition and predicts the $rh$ profiles as the internal moisture redistributes over time. The aim, therefore, is to reduce the occurrences of moisture related problems to floor coverings by allowing predictions of when it is safe to apply such a covering.

Moisture related damages to floor coverings, particularly impermeable floor coverings, were also discussed. Some instances of these problems occurring were reviewed and the remedial work required to address the problems was described. The problem stems from insufficient knowledge of why this problem occurs and what can be done to solve it. At present, floors are installed when the surface reaches a surface $rh$ of 75% using a surface
hygrometer, as described by BS 8203. However, a common practice on many construction sites is the use of heaters and dehumidifiers and the like to achieve this 75% threshold prematurely so that the floor can be applied much quicker than if it were naturally dried. The long-term effect of this is that a large residue of moisture will still remain deep in the concrete that will, over time, slowly equilibrate and cause a build-up of moisture under the covering.

This thesis presents methods and recommendations that will allow accelerated drying to continue so that the long-term $rh$ in the concrete falls within safe bounds such that problems to floor coverings can be reduced or eradicated. These recommendations will also show how by using accelerated drying methods can also save significantly on waiting time to apply the floor covering compared to if one was to use naturally drying methods only.

Following the review of the theory behind moisture movement in concrete and the published research that has been carried out on it over the years, the following highlights the gaps in the current knowledge that this thesis will aim to address:

- Calibrated diffusion and evaporation rates from ‘real’ experimental results and trends.
- Provide a simple, reliable, repeatable and robust numerical method to predict $rh$ trends in drying concrete slabs on grade.
- Perform comparisons between the numerical model and measured experimental trends.
- Use the results to influence the setting up of a new experimental technique to measure $rh$ at depth to avoid long-term moisture related problems.
- Monitor of $rh$ trends after the covering application as it redistributes under an impermeable covering over time.
- Measure the associated rise in vapour pressure under impermeable covering over time.
- Use the finite element model to mesh a concrete slab with a suitable density of elements to predict $rh$ trends in concrete slabs with varying thicknesses, w/c ratios and drying environments.
• Propose a new method to allow continued use of accelerated drying so that the redistributed moisture under the covering will be within known ‘safe’ limits.

The following chapter will describe the experimental work carried out to that the new work that this thesis offers is achieved.
4 DETAILS OF EXPERIMENTAL WORK

4.1 INTRODUCTION

This chapter describes the set-up of the experimental programme, which includes the design of the test series, how the size, thickness and constituents of the twenty slabs were chosen and the various tests performed to monitor the surface moisture content and \( rh \) at the surface (using a surface hygrometer, VET tests and using some new apparatus) and through the depth during drying. The aim is to study the influence which various physical parameters, such as the ambient conditions, w/c ratio and slab depth, have on the moisture condition in concrete slabs on grade during drying. From these studies it will be possible to calibrate a finite element model using material properties derived from the results here and previously published literature in Chapter 3. This will enable one to predict the drying of a OPC slab in terms of the \( rh \) profiles in the concrete both before and after an impermeable covering is applied (as discussed in Chapter 7). In addition to monitoring the changing \( rh \) under natural drying conditions (in an open natural environment in a laboratory), a number of slabs will be dried artificially in a control room with elevated ambient temperatures and reduced ambient humidities. The objectives of the work are therefore:

1. To design and set-up an experimental programme to verify some of the conclusions in Chapters 2 and 3.
2. To monitor the changing \( rh \) in concrete slabs, both at the surface using conventional methods and a newly developed apparatus and through the depth using hand-held instruments during drying.
3. To monitor the surface moisture content using hand-held instruments.
4. To assess the effect of w/c ratio, thickness and ambient conditions on the \( rh \) with depth and surface moisture content with drying time.
5. To investigate the results from traditional methods of assessing the moisture condition and discuss their practical use.
6. To compare results with previous authors using similar experimental programmes.

Section 4.2 outlines the design of the experimental programme describing how the various concrete properties analysed were chosen and how the specimens are designated. Section 4.3 describes the manufacture, preparation and the set-up for the two drying environments.
for the concrete slabs. Section 4.4 describes the tests performed to achieve the objectives set out to monitor the changing moisture condition at various depths and at the surface. For this, a number of instruments were used, namely portable hand-held humidity probes housed in plastic tubes at various depths in the slabs. The surface $rh$ was monitored using a plastic tent and surface hygrometer, as described by BS 8203 (1996) as well as some newly developed apparatus. In addition to these tests, a number of vapour emission tests (VET) were performed. This is the standard test in the United States of America (U.S.A.) to estimate the point at which it is deemed safe to apply floor coverings. The second stage of the experimental work undertaken in this research involved applying an impermeable floor covering to the surface of the concrete and monitoring the $rh$ in the concrete until equilibrium was reached. The set-up, testing and experimental results of this second stage are presented later in Chapter 7.

4.2 DESIGN OF EXPERIMENTAL PROGRAMME

Tables 4.1 and 4.2 summarise the tests performed as part of this research. A total of 20 slabs (9 No. 500x500x100mm deep slabs, 3 No. 500x500x200mm deep slabs and 8 No. 700x700x150mm deep slabs) were cast with varying w/c ratios (0.4, 0.5 and 0.6). These slabs will be dried in a natural and artificial environmental in a laboratory and control room respectively. The experimental programme has been designed so that many of the common concrete construction properties such as slab thickness, w/c ratio and drying environments can be analysed. Based on a technical publication by the Cement and Concrete Association (Deacon, 1974) (Table 4.3), the slab thicknesses chosen for the experimental programme represent typical sizes for most applications and typical loading conditions. The 100mm thick slab was chosen as it represents a lower bound thickness. These thicknesses also fall within the sample sizes used by previous researchers, as discussed in Chapter 3. The w/c ratios were selected as again they span typical ranges used in practice and are specified in the above publication as suitable for concrete slabs on grade for most loading conditions and fall within those presented in Chapter 3. As stated in the introduction, one of the main objectives was to investigate the effect of an accelerated drying regime on the internal moisture contents as it was reported in Chapter 2, that by increasing the temperature by $10^\circ C$, one can effectively double the drying rate. The results from these are presented in Chapter 5. Figure 4.1 shows a plan of the set up for all the slabs.
### Table 4.1  
Details of tests used for the 500mm square 100 and 200mm thick slabs

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Size</th>
<th>w/c</th>
<th>Environment</th>
<th>Test Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Surface $rh$ using plastic tent</td>
</tr>
<tr>
<td>1.2</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Surface $rh$ using hygrometer</td>
</tr>
<tr>
<td>1.3</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Vapour emission tests</td>
</tr>
<tr>
<td>1.4</td>
<td>500x500x200mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Surface $rh$ using plastic tent</td>
</tr>
<tr>
<td>1.5</td>
<td>500x500x200mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Surface $rh$ using hygrometer</td>
</tr>
<tr>
<td>1.6</td>
<td>500x500x200mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Vapour emission tests</td>
</tr>
<tr>
<td>1.7</td>
<td>500x500x100mm</td>
<td>0.4</td>
<td>Laboratory</td>
<td>Vapour emission tests</td>
</tr>
<tr>
<td>1.8</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Vapour emission tests</td>
</tr>
<tr>
<td>1.9</td>
<td>500x500x100mm</td>
<td>0.6</td>
<td>Laboratory</td>
<td>Vapour emission tests</td>
</tr>
<tr>
<td>1.10</td>
<td>500x500x100mm</td>
<td>0.4</td>
<td>Room</td>
<td>$rh$ at depth only</td>
</tr>
<tr>
<td>1.11</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Room</td>
<td>$rh$ at depth only</td>
</tr>
<tr>
<td>1.12</td>
<td>500x500x100mm</td>
<td>0.6</td>
<td>Room</td>
<td>$rh$ at depth only</td>
</tr>
</tbody>
</table>

### Table 4.2  
Details of tests used for the 700mm square 150 mm thick slabs

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Size</th>
<th>w/c</th>
<th>Environment</th>
<th>Test Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>700x700x150mm</td>
<td>0.4</td>
<td>Laboratory</td>
<td>Surface $rh$, tent + hygrometer</td>
</tr>
<tr>
<td>2.2</td>
<td>700x700x150mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Surface $rh$: tent + hygrometer</td>
</tr>
<tr>
<td>2.3</td>
<td>700x700x150mm</td>
<td>0.6</td>
<td>Laboratory</td>
<td>Surface $rh$: tent + hygrometer</td>
</tr>
<tr>
<td>2.4</td>
<td>700x700x150mm</td>
<td>0.4</td>
<td>Room</td>
<td>Surface $rh$: tent + hygrometer</td>
</tr>
<tr>
<td>2.5</td>
<td>700x700x150mm</td>
<td>0.5</td>
<td>Room</td>
<td>Surface $rh$: tent + hygrometer</td>
</tr>
<tr>
<td>2.6</td>
<td>700x700x150mm</td>
<td>0.6</td>
<td>Room</td>
<td>Surface $rh$: tent + hygrometer</td>
</tr>
<tr>
<td>2.7</td>
<td>700x700x150mm</td>
<td>0.5</td>
<td>Laboratory</td>
<td>Vapour emission tests</td>
</tr>
<tr>
<td>2.8</td>
<td>700x700x150mm</td>
<td>0.5</td>
<td>Room</td>
<td>Vapour emission tests</td>
</tr>
</tbody>
</table>
Table 4.3  Suggested thickness of slab for typical loading conditions (Deacon, 1974).

<table>
<thead>
<tr>
<th>TYPICAL LOADING</th>
<th>CLASSIFICATION OF SUB-GRADE</th>
<th>RECOMMENDED THICKNESS OF SLAB (MM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices, shops, classrooms, garages, mainly for private cars, light industrial</td>
<td>Weak</td>
<td>175</td>
</tr>
<tr>
<td>premises with unit loading up to 5kN/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garages mainly for commercial vehicles, industrial premises, warehouses with</td>
<td>Weak</td>
<td>200</td>
</tr>
<tr>
<td>unit loadings between 5 and 20kN/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>175</td>
</tr>
</tbody>
</table>

Figure 4.1  Set-up for (a) 100 and 200mm and (b) 150mm thick concrete slabs (NTS)

The results will give an insight into the influence of slab depth (100, 150 and 200mm), w/c ratio and drying environment on the \( rh \) profiles and the drying time. The influence of concrete thickness in terms of drying has not received much, if any, attention in the literature as may be observed in Chapter 3 so this work will add to the knowledge in this regard. The slab plan dimensions where chosen so that a wide range of tests could be performed within a suitable space on the surface of the slab without interfering with measurement of the \( rh \) through the depth. As the direction of drying is vertically upwards, due to the base and all four sides being sealed, the actual plan dimensions have been selected so that sampling the \( rh \) will not interfere with readings in other adjacent holes. As part of another project (Farrell, 2003), a number of shrinkage tests were performed using gauges cast into the concrete and, to accommodate this, the width of the slab was increased.
to 700mm in order to fit all apparatuses on the slab. These shrinkage tests will not be discussed here.

In addition to varying the thickness, three w/c ratios were selected. These w/c ratios give a good range for comparison purposes and fall within typical w/c ratios used for normal grades of structural concrete. Akita et al (1997) and Hedenbland (1997) have both demonstrated that the w/c ratio influences the diffusion coefficient and the rate of moisture migration in the concrete and both concluded that the rate of diffusion increased with increasing w/c ratio. It is important therefore that this point was investigated in this experimental programme in advance of calibrating any finite element model.

Two drying environments were chosen so that the differences between the rh profile in natural and artificial surroundings could be measured. In the control room, the ambient temperature and rh were increased and decreased using a heater and dehumidifier respectively. It is becoming more and more common to force-dry concrete so that the waiting time to apply a floor covering can be reduced. Previous experimental work by Kropp et al (1995) and Kim and Lee (1999) have fixed the ambient conditions. Here, the ambient conditions will be allowed to vary naturally, as is the case with normal drying on construction sites and represents a more typical drying environment. It has been shown in Figure 3.4 that fixing the surface rh can produce misleading results where early near surface rh profiles can be strongly adversely influenced by fixing the ambient rh, particularly fixing it at a much lower ambient rh.

### 4.2.1 Designation of test specimens

Each of the specimens tested was given a unique designation that describes the drying environment, its geometry, w/c ratio, thickness and the test series number that corresponds with Tables 4.1 and 4.2. An example of this designation is given using the labels below:

- a) its location designated as L = Laboratory and R = Room
- b) the length (and width) of the slab in millimetres in brackets
- c) the w/c ratio
- d) the thickness of the slab in millimetres in brackets
- e) test series as described in Tables 4.1 and 4.2 above
### 4.3 MIX PROPORTIONS AND SPECIMEN PRODUCTION

The base concrete \((w/c = 0.5)\) was designed to have a mean characteristic compressive strength \((f_{cu})\) of \(35N/mm^2\) and an average slump of \(75\pm25mm\), which was considered to be an acceptable slump for floor slabs. The mix constituents per \(m^3\) are given in Table 4.4. The cement used for all the concrete slabs was bagged CEM I grade 42.5 ordinary Portland cement (OPC) supplied by Irish Cement. The aggregate was rounded pre-washed limestone aggregate retained on 10 and 20mm sieves. The concrete was designed in accordance with the BRE report on design of normal concrete mixes (BRE, 1988). The quantity of concrete made was to produce the slabs for that pour and 4 No. 100x100x100mm cubes for compressive strength testing and an allowance of 20% for wastage. The 100 and 200mm thick slabs were made at the same time with the same concrete. The 150mm thick slabs were made up later with a different batch of mix constituents, but with the same mix design, cement, aggregate and equipment.

#### Table 4.4: Mix constituents per \(m^3\) for the concrete slabs.

<table>
<thead>
<tr>
<th>Slab No</th>
<th>w/c ratio</th>
<th>Fine aggregate (kg)</th>
<th>10mm aggregate (kg)</th>
<th>20mm aggregate (kg)</th>
<th>Cement (kg)</th>
<th>Water (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7, 1.10 2.1, 2.4</td>
<td>0.4</td>
<td>633</td>
<td>345</td>
<td>689</td>
<td>487.5</td>
<td>195</td>
</tr>
<tr>
<td>1.1-1.3, 1.8, 1.11 1.4, 1.6</td>
<td>0.5</td>
<td>706</td>
<td>353</td>
<td>706</td>
<td>390</td>
<td>195</td>
</tr>
<tr>
<td>1.9, 1.12 2.3, 2.6</td>
<td>0.6</td>
<td>787</td>
<td>348</td>
<td>695</td>
<td>325</td>
<td>195</td>
</tr>
</tbody>
</table>

#### 4.3.1 Concrete mixing

The concrete was made up in the Department using a rotating drum mixer, which had a capacity of 0.1m\(^3\) and is shown in Figure 4.2. Within ten minutes of mixing, a slump test was carried out. As previously stated, the required slump was 75mm ± 25mm. If the
concrete failed this specification, it was discarded and re-made, having had appropriate adjustments and checks. However, only one batch had to be discarded. The average slump value for the six slabs was 90mm. However, the 150mm slabs with the 0.4 w/c ratio (2.1 and 2.4) had to be made with the addition of a commercial plasticizer (WRDA-97), as the workability of these mixes was very dry when initially mixed.

The data sheet for the plasticizer specified that between 120ml and 360ml of plasticizer should be added per 100kg of cement. For the 0.4 w/c ratio slabs, where 35.8kg of cement is used, this correlated to adding between 43ml – 128.9ml. The mix was made up with approximately 90ml added to the mix giving a slump of 70mm and a much-improved workability. The addition of the plasticizer will not affect the moisture content, the w/c ratio, the internal $rh$ or the drying results and was only added to improve the workability.

At this stage, the concrete was placed into the timber formwork (as shown in Figure 4.3), which was made up in the Department, in two layers. The formwork had a layer of mould
oil applied to the base and sides to aid removal of the concrete from the moulds after curing. After the concrete was placed into the formwork, it was compacted using a vibrating table for approximately two minutes per layer, or whenever the air bubbles ceased to appear at the surface. Two steel reinforcement lifting eyes were also set into the concrete to aid lifting and moving afterwards. Four concrete cubes were made up from each slab mix and were compacted in equal layers. After the slabs were fully compacted, they were left to cure under wet hessian for one day where they were carefully cured. The cubes were placed inside a curing tank, at an average temperature of 20°C ± 2°C. After 7 and 28-days, two cubes for each slab were removed from the curing tank for strength testing. The actual compressive strengths can be found in Appendix A14 with an average of 47.5MPa. The results shown are unexpected as the normal relationship between the w/c ratio and the compressive strength is well known and these results do not appear to give a strong correlation between the w/c ratio and the strength at either 7 or 28 days. The batching was carefully checked with the effect of moisture in the sand and the course aggregate was also accounted for (AASHTO T-217, 2002). One plausible explanation is that the course aggregate used was rounded, thereby yielding a variety of compressive strengths. However, the consistency of the trends observed in Chapter 5 during drying for given w/c ratios give confidence that the w/c ratios originally designed were achieved.

Figure 4.3  (a) Formwork for the slabs and cubes and (b) fresh concrete in the formwork with lifting eyes for ease of movement later.
After curing, the slabs were ‘stripped’ from the formwork, taken to the testing laboratory and prepared for the testing regime.

4.3.2 Slab preparation before testing

The experimental set-up is for all drying to occur in one direction only, that is, vertically upwards through the top surface. Therefore, to ensure this, five of the six sides of the slabs were coated with a waterproofing silicone sealant painted onto the surface, leaving only the top surface exposed. This represents typical arrangement of domestic and commercial floor slabs on grade where, by using damp-proof membranes and/or radon barrier systems, laid prior to pouring of the slab, the concrete can only breathe in one direction, namely vertically upwards. A total of five coatings were applied to all 5 sides of every slab over two days, to ensure that no moisture would escape from the sides or the base. As will be observed later, the experimental evidence will confirm that the sealing was effective.

The holes for the plastic tubes were drilled so that the $\text{rh}$ at various depths within the concrete could be measured. The holes were drilled using a Hilti drill to depths of 50, 60, 80 and 95mm for the 100 and 200mm thick slabs and particular care was taken not to puncture the base of the 100mm thick concrete slab while creating the 95mm deep hole. For the 150mm thick slabs, 6 holes were drilled to depths of 15, 40, 65, 90, 115 and 135mm to give a more refined $\text{rh}$ profile through the depth using more data points. The drilling would have generated some heat but it was felt that it would not affect the moisture condition around the holes over time. In order to determine the correct hole diameter, a number of drill bit sizes where chosen to achieve a tight fit between the plastic tubing and the concrete. In the end, the drill bit chosen had a diameter of 22mm for the 100 and 200mm thick slabs and 12mm for the 150mm thick slabs. When the required depth was reached, the dust in the holes was removed using a portable industrial vacuum cleaner and any excess dust on the concrete was removed by careful hand brushing.

4.3.3 Drying conditions

After the slabs were prepared, they were allowed to dry in two different environments, one naturally in the laboratory (Figure 4.4(a), and the other in an accelerated or forced drying
environment in a controlled room (Figure 4.4(b). The slabs drying in the laboratory had ambient temperature and humidity ranges of between 11 to 16°C and 40 to 70% respectively for the 100 and 200mm thick slabs (Figure 5.1) and 11 to 20°C and 40 to 70% for the 150mm thick slabs (Figure 5.2). This ensured that these slabs dried in normal conditions, such as those found on site in an enclosed space without draft or heating.

When the ambient conditions settled down the slabs drying in the controlled room did so with ambient temperature and humidity ranges between 25 to 29°C and 20 to 40% respectively for the 100mm thick slabs (Figure 5.6) and 36 to 41°C and 12 to 19% for the 150mm thick slabs (Figures 5.16). The purpose of an accelerated drying condition was to analyse the effect it has on the moisture profiles, such as that when forced drying is employed by contractors to deliberately attempt to reduce the waiting time to apply a covering. The observed variation in humidity and temperature may have been caused by, for example, the opening and closing of the door into the room when the readings were being taken and the room not being fully insulated and, therefore, being influenced by external factors.

The differences between the ambient conditions for the 100 and 150mm thick slabs also allow the finite element model to be calibrated for different ambient conditions and to check the accuracy of the results against these experimental results and other published results. It will be seen later, in Chapter 5, that overall, surface variations make little
difference to the $rh$ deep in the slabs compared to those with a forced drying condition. The ‘message’ that a harsher drying environment exists does not reach the moisture deep in the slab until much later, although the surface $rh$ will be much less than for those slabs in the laboratory.

The accelerated drying environment was set up in the control room using a dehumidifier (Figure 4.5) and a small heater (Figure 4.6), thus setting up a higher humidity concentration difference between the humidity in the ambient air and that in the concrete. The ambient conditions were recorded using a hand-held meter, as shown in Figure 4.7. The heater and dehumidifier was switched on some 20-days in advance of the slabs actually been placed inside. This was to ensure that the environment had stabilized beforehand and to allow proper comparisons between the two sets of slabs in the two environments at the same drying time.
4.4 EXPERIMENTAL TESTING

4.4.1 Monitoring of the relative humidity

The $rh$ in the slabs was monitored using portable humidity probes shown in Figure 4.8. The probes have an operating range of between 0 to 100% $rh$ and $-4^\circ$ to $85^\circ$C with accuracies up to $\pm1\%$ $rh$ at $25^\circ$C and a long-time stability with a loss of accuracy of less than 1% $rh$ per year. The probe is made from a black polycarbonate plastic and weighs approximately 14g. It is attached to a hand-held meter called the CE-RH (Concrete Encounter – Relative Humidity) meter or more recently known in a newer version as the CRH (Concrete Relative Humidity) (Figure 4.9). The CRH is a hand-held battery operated device that is capable of recording both the near-surface moisture content and the $rh$ at any depth in concrete slabs using the humidity probes. The meter is manufactured by Tramex Ltd (Tramex, 1980) who has been producing moisture meters since 1980 incorporating the latest PIC micro-controller.

When the meter is switched on, the surface moisture condition can be measured on the CRH meter by pressing the instrument down on the surface and reading the result from the LCD display panel (Figure 4.9 (a)). This is achieved using eight conducting electrodes on the back of the meter, shown in Figure 4.9(b). In essence, when the meter is depressed onto the surface of the slab, an electrical impulse is imparted to the surface using four transmitting electrodes and the capacitance offered by the concrete is reflected in the reduced signal measured at four receiving electrodes a short distance away. The device has been calibrated so that the signal reduction is related to the moisture content of the slab ranging from 2 to 6% for concrete. When the humidity probe is attached, the $rh$ is read from the LCD display panel, along with the air temperature. In addition, the instrument has the built-in capacity to store up to 625 readings, with each stored reading including the $rh$, probe temperature, moisture content, ambient temperature, time and date. An RS232 computer interface can be employed to download readings to a PC.

To monitor the $rh$ at the various depths, the probe was inserted into a plastic tube of varying length, which was placed into the drilled holes. Figure 4.10 shows the plastic tube used for the 100 and 200mm deep slabs. The tubes came in lengths of 50, 60, 80 and
Figure 4.8  \( rh \) probes used to measure the \( rh \) at various depths.

Figure 4.9  Hand-held CRH meter
Figure 4.10  50, 60, 80 and 90mm tubes used in the 100 and 200mm slabs

95mm. The plastic tube has an internal diameter of 17.5mm with a sleeve thickness of 2.5mm and is supplied with two rubber membranes, a cap and three slots that allow the ingress of $rh$ from the pores of the concrete. The rubber rings are placed around the outer circumference of the tube just under the top of the tube and just above the slots (see Figure 4.11 and 4.12), thus stopping ambient $rh$ affecting the result. The latter creates a ‘chamber’ of $rh$, which is representative of the $rh$ at 10mm from the base of the tube (Figure 4.12). When the humidity probe is inserted into the plastic tube, the $rh$ taken is approximately 10mm above the bottom of the hole, as demonstrated in Figures 4.10 and 4.11. However, for the 100mm thick slabs, the rubber membrane was located at 5mm above the base in order to measure the $rh$ at an average depth of 90mm. Therefore, for the 100 and 200mm slabs, the $rh$ was assumed to be measured at depths of 40, 50, 70 and 90mm.

A similar set-up has also been used by Kim and Lee (1999) (Figure 3.5) where they also used a rubber membrane to seal the humidity at the top of the plastic sleeve. However, here, the locations of the rubber membranes both seals in the humidity to create a local chamber of humidity and block the ambient humidity entering the tube.

The $rh$ in the 150mm thick slabs was monitored using the probe shown in Figure 4.13. This probe works in exactly the same manner as that used for the 100 and 200mm thick slabs (Figure 4.8). This later version of the probe is made up of a stainless steel tube casing.
Figure 4.11  Plastic tubes used for reading rh at depth (NTS).

Figure 4.12  Detail of rh chamber created by rubber tube (NTS)

Figure 4.13  Humidity probe used to measure the rh in 150mm slabs (NTS).
reduced length of the slots for $rh$ ingress and a reduced diameter (now 10mm). This probe was inserted into plastic tubes that were again placed inside hand-drilled holes in the concrete. These tubes (Figure 4.14) work in an identical manner as those shown above.

These newer plastic tubes were 72mm long with an external diameter of 15mm. A number of holes were drilled in each to depths of 15, 40, 65, 90, 115 and 135mm using a 15mm drill bit. These extra holes gave an improved representation of the $rh$ through the depth that would demonstrate a more refined curve of the humidity through the depth, due to the increased number of points. For depths greater than 72mm, the tubing was attached to one another by gluing. With the arrangement of the rubber bung (Figure 4.14), an average $rh$ reading was recorded approximately 5mm above the base of the hole.

This probe was attached to a new device, a RHR (Relative Humidity Reader), which is an updated version of the CRH that displays the $rh$ at depth using the probe and does not measure the surface moisture content (Figure 4.15). It has a high capacity non-volatile memory chip, which stores and retains the data. Therefore, the $rh$ and temperature can be recalled at any time by scrolling and reading directly from the instrument’s own display or downloaded on to a personal computer for inclusion in a spreadsheet or report and can

![Figure 4.14](image)

**Figure 4.14** Plastic tube used to measure the $rh$ in the 150mm thick slabs (NTS)
also store up to 625 readings. The RHR operates on a 9-volt PP3 lithium battery with a dot matrix LCD and a RS 232 serial interface. The dimensions of the meter are 150mm x 80mm x 35mm deep and it weighs approximately 350g. Figure 4.16 shows the typical experimental set-up for the 100, 150 and 200mm thick slabs with the sides sealed, holes drilled, tubes inserted and probes in place.

4.4.2 Monitoring of the relative humidity at the concrete surface

In addition to measuring the $\text{rh}$ through the depth, the surface humidity was also measured in many cases (see Table 4.1) using a standard surface hygrometer (Figure 4.17) as
Figure 4.17  Surface hygrometer apparatus during testing (plastic sheet not shown)

described in BS 8203 (1996) and two new apparatus, one using a plastic tent (Figure 4.18) and the other using a hard plastic shell (Figure 4.19). All of the above work on the same principle of trapping a pocket of air between the concrete surface and the instrument. It is attached to the concrete using a strong adhesive after the area is prepared by gently scraping the concrete surface using a wire brush and removing the dust.

The \( rh \) in this pocket of air is allowed to equilibrate and is measured using a calibrated gauge like those described above. The time taken for this pocket of air to equilibrate may take up to 48 hours as shown in Figure 4.20, taken from a surface hygrometer test by way of an example but typical for the other tests. Here, an initial increase in the \( rh \) occurs in the first 24 hours as the \( rh \) changes from approximately 55\% to 85\%. Over the following 24 hours, the \( rh \) only increases a further 5\% and there is no difference in the surface \( rh \) as it remains constant at approximately 90\% up to 90-hours. This rapid increase in the \( rh \) over the initial 24-hours followed by a more gradual increase is as a result of the trapped air slowly reaching equilibrium within the tent over time, as is the case with the chamber created by the plastic tubes in the concrete as shown in Figures 4.12. It is usual to continue this test for up to 3 days (72 hours) but it would appear that it would not be necessary to continue for a further 24 hours. As the slabs dry out over time, often many months, when 75\% \( rh \) is achieved in the surface tent, as determined by this instrument, impermeable coverings are deemed safe to apply, as suggested by BS 8203, 1996.
**Figure 4.18** Plastic tent apparatus to read the $rh$ at the surface.

**Figure 4.19** Apparatus used to measure the surface $rh$ for the 150mm slabs (NTS).
As this test was being carried out, there was a concern that the remaining surface area of the concrete, not under the hygrometer or plastic tents, would continue to dry, while under the hygrometer would not. To avoid unequal drying of this kind, the remainder of the concrete surface was covered with a plastic sheet and sealed to the sides. By doing this, the escaping moisture would equilibrate under the plastic, like the hygrometer, and drying would effectively stop. The plastic tent was carefully removed after each test to avoid any condensation falling onto the concrete and affecting the results.

A second method to measure the surface $rh$ was a plastic tent apparatus, as shown in Figure 4.18. The tent is made up of a plastic cover, similar to that used in the VET (Vapour Emission Test, 1994), with a tube at the side to allow a CRH humidity probe to be inserted into the sealed chamber created between the tent and the concrete to read the $rh$ of the trapped air equilibrated within. The test works on the same principle as the surface hygrometer and was attached to the concrete using adhesive pads on the bottom of the tent and was ‘stuck’ to the concrete using hand pressure until the pad adhesion paste began to spread out over the base of the lip of the tent. Some gently scraping of the concrete around the perimeter of the tent is required to ensure a good bond. A rubber stopper is placed at the end of the attached tube to avoid loss of humidity from under the tent. A layer of white strya-foam was attached to the tent around the edges to avoid possible accidental lifting from the surface. This test may take up to 3-4 days to reach equilibrium as is the case with the hygrometer.
A third method to measure the surface $rh$, used for the 150mm thick slabs involved the apparatus shown in Figure 4.19, which is made from a hard plastic base. A sealed plastic tube is provided to insert the humidity probe in order to read the humidity in the area sealed by the tent. The apparatus, when sealed to the concrete, creates a chamber of humidity in the plastic tube, as shown in Figure 4.19 when the rubber cap is in place. The tent is a sturdy apparatus and certainly more so than the plastic tent apparatus. It has proven easier to seal to the surface of the concrete by simply applying some silicone adhesive to the base and pressing firmly onto the concrete surface, which, as before, has to be gently wire brushed beforehand to achieve a good bond. After waiting 72 hours, the probe (Figure 4.13) is inserted into the slot and the $rh$ is read immediately and the rubber cap replaced. Also, it was found that the time taken for equilibrium to occur within the plastic tube and to measure the $rh$ was less than that using the surface hygrometer and the plastic tent. This is due to the smaller space in the plastic tube where the humidity equilibrates faster compared to the other tests. Indeed, it was found that after 24 to 36-hours after placing the tent, the surface $rh$ could be measured, as the difference in the readings between 24 and 36-hours was ±1%.

### 4.4.3 Measurement of the surface moisture content

The near-surface moisture content was monitored using a hand-held device, the CME (Concrete Moisture Encounter), which was developed by Tramex Ltd and is shown in Figure 4.21. As with the CRH, the CME works by depressing the device onto the surface of the concrete and taking an instantaneous reading on the display panel which uses an analogue needle that points to the moisture content (O’Neil et al., 1998). When the meter is switched on, the surface moisture condition can be measured on the CRH meter by pressing the instrument down on the surface and reading the result from the display panel (Figure 4.21(a)). This is achieved using eight conducting electrodes on the back of the meter, shown in Figure 4.21(b). In essence, when the meter is depressed onto the surface of the slab, an electrical impulse is imparted to the surface using four transmitting electrodes and the capacitance offered by the concrete is reflected in the reduced signal measured at four receiving electrodes a short distance away (Figure 4.22).

The CME was used to measure the surface moisture content on the slabs along with the
Figure 4.21  CME hand-held meter used to measure the surface moisture content

Figure 4.22  Schematic diagram describing the principles of the CME meter (NTS)

CRH where 6 readings were taken around the perimeter of the concrete surface and the average result was recorded. The range of moisture contents measured range between 2 to 6% for concrete.

4.4.4 Vapour Emission Tests (VET)

In addition to the hygrometer and various tent tests described above, a number of Vapour Emission Tests (VET) were performed. This test relates the weight gain of an anhydrous calcium chloride sample to the rate of vapour emission from the surface of concrete slabs, in units of lbs/1000ft$^2$/24hrs. This test measures the rate of moisture loss from the concrete slabs and is used in the United States of America (USA) to determine when a concrete slab
can be covered with an impermeable covering (Vapour Emission Test, 1994).

The apparatus consists of a sealed plastic tent, a sample of anhydrous calcium chloride in a plastic dish and sensitive weighing scales. The set-up for the test is shown in Figure 4.23. The test involves weighing a sample of the calcium chloride before placing it underneath the plastic tent which is then firmly fixed to the concrete surface. A wire brush may be required to create a rough finish before the rubber will adhere to the concrete. After between 60 to 72 hours, the sample is removed and re-weighed. The increased weight of the sample is a result of the moisture being absorbed under the tent, following which, the expression in Equation 4.1, is used to ascertain the moisture emissions from the surface. The coverings may be applied when the rate of emissions are less than 3 to 5 lbs/1000ft²/24 hrs.

![Figure 4.23 Typical Vapour Emission Test set-up](image)

**Equation 4.1**

\[
\frac{108.846 \times \text{Weight Gain}}{\text{Total Hours}} = \text{reading \cdot in \cdot lbs / 1000 ft}^2 / \text{24 hrs}
\]

### 4.5 CONCLUSIONS

This chapter has described the design of the experimental programme and the experimental tests used to monitor the moisture movement in the concrete as it dries over time. The experimental programme involved 20 slabs with various thickness (100, 150 and 200mm), w/c ratios (0.4, 0.5 and 0.6) and drying environments in a natural (laboratory) and forced
(controlled room) drying environments. Properties were selected based on a review of typical concrete thicknesses used in practice by reviewing previous work in this area and the need to study the effect of accelerated drying methods on the surface and internal moisture in concrete slabs. The forced drying involved reducing the ambient $rh$ and raises the ambient temperature using a dehumidifier and a small heater respectively. The results generated will demonstrate how the internal moisture varies with these various concrete properties and drying environments and will be discussed in Chapter 5. Also, these results, along with previous literature, will be used to calibrate the physical and material properties for the Finite Element (FE) model in Chapter 6 to allow prediction of $rh$ profiles in similar slabs.

The tests conducted include measuring the $rh$ at depth (and at the surface) using hand-held $rh$ probes that are inserted into plastic tubes at various depths in the concrete. Extra holes in the 150mm thick slabs will allow a more detailed $rh$ profile through the depth. The probes were attached to two hand-held meters (CRH or RHR) that indicate the $rh$ readings as a digital reading on the display panel. These tests have the advantage that they yield almost immediate results. All these meters work on the same technology and only represent development of the instrument.

The $rh$ was also measured at the surface using a surface hygrometer and a number of plastic tents which all operate on the same principle. These apparatus trap the escaping moisture from the concrete and either the calibrated gauge in the surface hygrometer or a $rh$ probe is used to give an indication of the $rh$ of the trapped moisture in the air. These tests give a very clear indication of the moisture condition in the concrete using non-destructive tests within the error range of the instrument, which are suitable to monitor/measure the moisture condition through the depth and at the surface of concrete slabs. In addition, the surface moisture content was measured using two hand-held meters (CRH and CME). These tests give instantaneous results, which is a considerable advantage over the tented methods. Again, these meters work on the same technology and only represent the development of the instrument over the duration of the project.

In addition to measuring the surface $rh$, a number of vapour emission tests were also conducted. These tests measure the increase in weight of a sample of calcium chloride
placed on the surface of the slab and sealed under a plastic tent that traps in the escaping moisture. The test was conducted over 72-hours and the result (in units of lbs/1000ft²/24hrs) indicates the mass flux of vapour escaping from the concrete. This test is used in the USA to determine the point in time at which a covering can be applied. Currently, it is considered safe to apply a covering when the hygrometer reading reaches 75% $rh$ or when the VET result reaches an emission rate of between 3-5 lbs/1000ft²/24hrs.

The following chapter presents a discussion of the results arising from the tests described here.
5. EXPERIMENTAL RESULTS

5.1 INTRODUCTION

The results from the experimental tests described in Chapter 4 are presented here. As a reminder, these tests set out to:

- Monitor the changing surface and internal rh through the depth of the slabs during drying.
- Investigate the influence of the ambient conditions (temperature and humidity), on the drying time and rh trends during drying.
- Assess the effect of the slab thickness.
- Study how varying the w/c ratio affects drying.
- Monitor the changing surface moisture content.
- Discuss the results from traditional tests (such as the surface hygrometer) and compare with results using the two plastic tent apparatus.
- Discuss the results from the vapour emission tests (VET)
- Compare these results with other published results using similar experimental set-ups.

As part of the experimental work described in Chapter 4, twenty concrete slabs were subjected to a variety of tests to measure and observe the changing rh at the surface and through the depth as they dried in natural (laboratory) and accelerated (room) environments. Due to the volume of information generated by the tests, the results, analysis and discussions of the results have been broken down into a number of sub-sections that concentrate on how the variations in slab thickness, w/c ratio and drying environments influence the rh trends and the time taken for the slab to be sufficiently dry (currently deemed to be 75% rh on the surface) to safely apply an impermeable covering. Readings for the 150mm thick slabs were only taken up to approximately 90 days because, at that point in time, the surface had reached 75% rh, whereupon, the impermeable covering was applied (see Chapter 7).

Section 5.2 presents the main findings from a 500x500x100mm thick slab with a w/c of 0.5
to give an overview of how the $rh$ typically varies in the concrete through the depth during drying. The results from this slab will highlight the important points in the drying process, as equilibrium is slowly reached with the ambient air. Results from those slabs drying in the laboratory (5.2.1) and the control room (5.2.2) are discussed to demonstrate the influence of the ambient conditions on the humidity profiles through the depth and the time required for the surface to reach 75% $rh$.

Section 5.3 presents the surface moisture content measurements for the 100mm thick slabs drying in the laboratory and in the control room, as measured using the CME and CRH moisture meters. This aims to give an overview of how the surface moisture content varies as the concrete dries.

Results from the 100mm, 150mm and 200mm thick slabs with a w/c ratio of 0.5 will be presented in Section 5.4 to demonstrate the influence of the slab thickness on the $rh$ profiles. Again, using a single w/c ratio allows one to see the effect of the slab thickness only. The results show, unsurprisingly, the thicker the slab, the slower and more gradual the drying is, for equal w/c ratios.

The effects of the w/c ratio on the $rh$ profiles and the drying time of concrete as presented in Chapter 3 are discussed in Section 5.5 for those slabs with w/c ratios of 0.4, 0.5 and 0.6 for the 100mm thick slabs drying in the two environments. The results will show that the lower the w/c ratio, the lesser the time the concrete takes to dry and the quicker the slab reaches 75% $rh$ on the surface. Again, using 100mm thick slabs as a base for the discussion allows one to see the effect of the w/c ratio only while not couples with the effect of thicker slabs.

In addition to monitoring the internal $rh$ and the surface moisture content variations during drying, a number of additional tests were performed, namely the VET and measuring the surface $rh$ using the two tent apparatus as shown in Figures 4.18 and 4.23 are discussed in Section 5.6. Section 5.7 presents a comparison of these results with published results by Kim and Lee (1999) who used a similar experimental set-up as used here.

Throughout the discussions of the results, trends that both agree or disagree with the
theoretical background (Chapter 2) and previous literature (Chapter 3) will be highlighted where appropriate. Also, findings from the results that will influence the setting up of the finite element model in Chapter 6 will also be discussed.

5.2 RELATIVE HUMIDITY TRENDS DURING DRYING

5.2.1 Laboratory trends

Figures 5.1 and 5.2 shows the ambient temperatures and \( rh \) experienced by the 100, 200 and 150mm thick slabs respectively in the laboratory. The figures show that the ambient temperature and humidity had a range between \( 11-16^\circ C \) and \( 40-70\% \) respectively for the 100 and 200mm thick slabs. The variation in ambient temperature and humidity for the 150mm thick slabs ranged from \( 11-20^\circ C \) and \( 40-70\% \) respectively. From the figures, the calculated average ambient temperature and humidity for the 100mm and 200mm slabs may be taken as \( 13.4^\circ C \) and \( 53\% \), for the 100mm and 200mm thick slabs and \( 16.3^\circ C \) and \( 56\% \), for the 150mm thick slabs respectively. The reason for the minor differences in the ambient conditions is probably due to the fact that the 100 and 200mm thick slabs were first poured and allowed to dry during the winter/spring/summer months while the 150mm thick slabs were first poured and allowed to dry during the spring/summer months.

Although there are considerable fluctuations in the ambient conditions, they will not have a significant influence on the overall drying regime over time. For example, as discussed in Chapter 4, if the ambient temperature were to rise or fall by \( 5^\circ C \) in a day (diurnal changes), this would not affect the \( rh \) deep in the concrete and would only have a minor affect on the surface \( rh \) as only the near surface area is affected in the short-term. Therefore, it is appropriate to only consider the typical ambient conditions when the finite model is being generated. However, in saying this, seasonal variations may have some influence due to the probable rise and fall of average ambient conditions (Holland, 1961). Indeed, Xin (1995) (Section 3.3.2) concluded that above \( 90^\circ rh \), the effect of temperature can be ignored. Also, none of the equations to calculate the diffusion coefficient in Chapter 3 takes any account of the ambient temperature. However, it is widely reported and accepted that the rate of evaporation is temperature dependent and this will be shown in the following discussions.

One noticeable effect from the experimental tests is the small drifts in individual
experimental results that may be explained by random experimental variation. This holds true for most of the small variations in results as no two slabs would have been poured, mixed, compacted etc identically, so it is inevitable that some minor variations will be seen throughout. Also, as the instruments have an accuracy of ±1-2% on average, the instruments may not always give identical results, despite being properly calibrated. For example, by rotating the CME, a slightly different result might be obtained, due to slight differences in the electrical current emitted from the electrodes, which is dependent on the immediate sub-surface compaction and moisture content. This is why the result recorded is the average of 6 measurements taken over the surface of the slab. Further, the results from different devices and probes may differ slightly and each instrument has its own stated accuracy. While these minor variations will be presented and discussed where appropriate,
a statistical analysis of these variations is not appropriate as it is not the main focus of this thesis.

The results presented here provide an overview of typical drying trends using a 100mm thick slab with a w/c ratio of 0.5. Figure 5.3 shows the \( rh \) readings through the depth of slab \( L(500)0.5(100)1.1 \) at 3, 5, 7 and 10-days after the concrete was first exposed to the ambient air. As shown, the initial drying is occurring near the surface (100 to 96\% \( rh \) after 3 days) with a slower rate of drying deeper in the slab at 90mm (100 to 98\% \( rh \)), a difference of 2\% \( rh \) between the top and bottom of the slab after 3 days. However, after 10-days, the surface \( rh \) is approximately 92\% compared to approximately 96\% at 90mm, a difference of 4\% \( rh \). Recalling Figure 2.12, where the \( rh \) profiles during drying were shown at various times, one could postulate that \( t_2, t_3 \) and \( t_4 \) could represent the \( rh \) at 3, 7 and 10-days respectively. For example, at \( t_2 \) (3-days), there is some drying at the surface (100-96\%) with little drying deeper in the concrete (98\%) below 50mm.

The \( rh \) profile after 7 and 10 days in Figure 5.3 is a good opportunity to present and discuss two examples of experimental error that may have occurred. Results with depth do not yield a smooth transition as might be expected at these times. In particular, results at 70 and 90mm are identical (at 96\%) indicating some experimental error has occurred. There are three main reasons why this occurs. Firstly, although there are rubber rings along the depth of the plastic tube to create a chamber of humidity and prevent any leakage (see Figures 4.9 and 4.10), some leakage may have still occurred leading to a smaller and misleading humidity reading, which, on inspection, may have arisen at 10-days as one would expect the \( rh \) to be less than at 7-days. Secondly, the top of the tube was sealed with a rubber cap (Figure 4.8). However, when this was removed, some humidity may have escaped, especially if the probe wasn’t inserted immediately. Thirdly, when the probe was inserted, it takes a few minutes until equilibrium is reached and the reading can be taken. However, if the reading was taken too fast, sufficient time would not have been provided for equilibrium to be reached in the chamber and an incorrect or inaccurate reading can be recorded. Again, it is more likely that this occurred at 10-days, as shown by the \( rh \) profile. Another possibility for this experimental error may be that the calibration of the probe itself was not correct but this is less likely. The accuracy of the probe is quoted as \( \pm 1\% \).
Since a \( rh \) gradient has been set up between the top and the bottom of the slab, the results demonstrate that moisture deeper in the slab is slowly diffusing to the surface under this humidity gradient as the \( rh \) reduces from 100 to 96% over the initial 10-days. This internal humidity gradient was set up when the concrete was first exposed to the ambient air and moisture was only lost through the exposed surface, here the top of the slab. This gives credence to the discussions that took place in Section 2.4.3 and demonstrated in Figure 2.12 where the top of the concrete begins to lose moisture with little or no drying taking place deep in the slab in the very early stage. As more and more moisture is lost from the surface areas, the increasing \( rh \) gradient in the concrete allows moisture to diffuse at a steadier rate over time, under natural drying conditions, towards the surface. Also, early on in the life of any concrete element, the condition of the pore structure is such that moisture can move relatively easily between the pores, as they are open to diffusion and moisture movement. This has been discussed in Section 2.4.4, where the three stages of drying were outlined. As stated, Stage I is essentially saturated flow with evaporation being the main driver. In Stage II, drying slows and drying is occurring as an unsaturated flow with a reduced rate of diffusion decreasing as the pore structure is closing due to ongoing hydration. This has been discussed in Chapter 2 where Figure 2.14 presented the changing capillary pore structure at 0 and 100% hydration (Neville, 1995).
Furthermore, the results confirm that the bottom and sides of the concrete slab are fully sealed as intended and drying is only taking place through the top surface. If moisture were escaping from the top and bottom of the slab, the shape of the $rh$ profile would be convex, as moisture would move in both directions under the dual ambient effects and the $rh$ at 50mm would be greater that at 90mm as demonstrated in Figure 3.27(b).

The results in Figure 5.3 also show that if the same slab were covered after, say, 10 days, a considerable amount of moisture would still exist deep in the concrete. Over time, this moisture would continue to diffuse upwards under the humidity gradient between the top and bottom of the concrete and, long-term, this moisture would build up under the covering and would affect the adhesive. Problems such as blistering etc would occur as this higher amount of moisture will also have a higher vapour pressure. Therefore, this is the reason for specifying that the concrete must dry until 75% $rh$ exists on the surface, as stated by BS 8302 as discussed in section 3.5.1, Figure 3.27(d). However, waiting for 75% $rh$ to be achieved at the surface would yield a long-term $rh$ through the depth of the concrete of between 75-80% following natural drying which is within the range suggested by BS 8302 that should be achieved at the surface before any covering is applied. The standard assumes that if the concrete achieves a $rh$ within this range, it is unlikely that long-term problems will occur.

As drying continues, the moisture deep in the slab will continue to diffuse to the surface under the humidity gradient. The profiles in Figure 5.4 again indicate a steady state flow as the moisture is diffusing naturally through the depth over a relatively long time period. For example, from Figure 5.4 at 30-days, the difference in $rh$ between the surface and 90mm is approximately 7% (83% at the surface and 90% at 90mm) while after 220 days this difference is still 7% (62% at the surface and 69% at 90mm). However, over time, as the surface $rh$ slowly reaches equilibrium with the ambient humidity, the rate of drying near the surface will slow while the moisture deep in the concrete will continue to gradually diffuse upwards to the surface under the internal humidity gradient. Figure 5.4 also demonstrates how the rate of diffusion appears to be more rapid early on and slowing with decreasing $rh$. For example, it takes over 30-days for the surface $rh$ to fall from 100 to 80%. For it to fall a further 20%, it takes over 190-days (220-days). This is also true at 90mm where to reach 80% it takes over 70-days and, it is postulated, a much greater time to reach 60% as this point has not be achieved in the time frame here.
This point has been discussed by Bazant and Najjar (1971) who concluded that the diffusion coefficient remains constant to 80% $rh$ and sharply falls afterwards. The results here appear to agree with that conclusion. For example, for the surface to reach 80%, it takes approximately 40-days (see Figure 5.5). For the surface to reduce a further 20%, to 60% surface $rh$, it takes approximately 180-days. Also, at 90mm depth, again the difference between the initial time to achieve 80% (approximately 70-days), is much less than that for it to fall a further 20%, which, for the time frame shown, has not been achieved. This gives further credence to the discussion and conclusions in the previous chapters that their equation to represent the diffusion coefficient is a suitable method for the finite element material model in Chapter 6.

In terms of evaporation, the initial point to make is that the rate of moisture lost from the surface decreases with time, as shown in Figure 5.5, where a plot of the varying surface $rh$ and the ambient humidity is presented over time. As shown, over time, the ambient $rh$ and the surface $rh$ are slowly converging. At 10 days, the difference between the two is approximately 35% (93 and 58%), and, at 220-days, this difference has reduced to 12% (57 and 45%). Indeed, this difference increased further if one assumes an average ambient $rh$ of 53% (Figure 5.1). The important point here is that these differences over time will result in a decreased rate of evaporation as equilibrium is reached between the two.
Figure 5.5 Gradual equilibrium between the humidities for slab L(500)0.5(100)1.1.

Figure 5.5 also shows that this decreased rate of evaporation can be considered in three stages. Three dashed lines are shown that follow the general trend of the surface relative humidity over time. The first line, from 0 to 60-days presents an initial rapid rate of evaporation with a slope of $\theta_1$, while the following line (20 to 110-days) indicates a more gradual rate of evaporation $\theta_2$ where $\theta_2 < \theta_1$. The third line (50 to 220-days) indicates the most gradual rate of evaporation where its slope $\theta_3$ is less than $\theta_1$ and $\theta_2$ ($\theta_3 < \theta_2 < \theta_1$). Considering where these three lines approximately intersect, it appears that the rate of evaporation from 0 to 30-days is the most rapid followed by a more gradual rate from 30 to 70-days and an almost constant rate thereafter (70-days onwards). This gives further credence to the discussion and conclusions in the previous chapters that the rate of evaporation will decrease over time as equilibrium is slowly reached with the ambient air. These times will be developed further in the following chapter when calibrating the evaporation rates for the material model. While it may not be novel that the rate of evaporation reduces with time, the time at which it appears to change is useful. While the rate of evaporation and its calculation has been reported in the literature (see Chapters 2 and 3), there is little information on how it varies with time, which must be taken account of in the FE model.

5.2.2 Control Room Trends

Section 5.2.1 presented the results for the 100mm thick slabs with a w/c of 0.5 drying
naturally in the laboratory. This section will present the rh profiles for slab R(500)0.5(100)1.11 which was artificially dried in the control room using a heater and dehumidifier, as discussed in Chapter 4. Again, the results presented are to provide an overview of how an accelerated drying environment typically influences the internal and surface rh. Figures 5.6 shows the ambient temperatures and humidities experienced in the control room during the accelerated drying. As shown, the ambient temperature and humidity stabilised after approximately 20-days with an ambient temperature and humidity ranging from approximately 25-29°C and 20-40% respectively. The calculated average ambient temperature and humidity following equilibrium of the environment was 26.7°C and 34.7% respectively. The time taken to reach equilibrium (20-days here) and these variations may have been a result of frequent opening and closing of the door into the room and the room not being fully insulated and therefore being influenced by external factors. However, the time taken for the room to reach equilibrium was as anticipated and the heater and dehumidifier were turned on in advance of the slabs being placed in the room. This allows for a better comparison between the natural and artificial drying results. The results presented hereafter had the same drying time as those in the laboratory but were dried in the accelerated environment.

As discussed earlier in relation to the slabs in the laboratory, this daily variation in ambient conditions would not significantly influence the internal rh over time and only the average will be considered in the finite element analysis.

Figure 5.7 presents the early drying profiles through the depth at 9 days in the control room and 10 days in the laboratory slabs. Drying is faster at 40mm than at 90mm in the slab, as noted previously. For example, over 9 days, the rh in the control room has reduced from 100% to 90% at 40mm where the rate of drying is less, with a rh of approximately 96%. This demonstrates how the rh deep in the concrete is relatively unaffected by the environmental conditions early on and especially not by the minor variations in the day-to-day changes in the ambient conditions. Indeed, the rh in the naturally dried slab is also 96% at 90mm which further highlights that accelerated drying has practically no effect (or benefit) at depth, particularly early on. This suggests that although artificial drying leads to a lower rh at or near the surface, there is still a large residual of moisture deeper in the concrete. This leads to problems long term unless drying is allowed to continue until a
Figure 5.6  (a) Ambient temperature and (b) $\text{rh}$ for the 100mm thick slabs drying in the control room.

Figure 5.7  Comparison between the $\text{rh}$ profiles through the depth for slabs L(500)0.5(100)1.1 and R(500)0.5(100)1.1.

suitable surface $\text{rh}$ is reached in the more severe drying environments so that the long-term equilibrated $\text{rh}$ following covering will not cause delaminations. Note that, henceforth, the data points for each individual profile with depth will be joined by a smoothed line to aid in the comparisons.

Over time, the surface moisture content of the slabs in the room will continue to be lost at a faster rate than that deeper in the concrete until equilibrium is reached with the ambient $\text{rh}$. As may be expected, Figure 5.7 shows the surface $\text{rh}$ in the room continuing to dry at a faster rate than in the laboratory. For example, after 68 days in the room, the $\text{rh}$ at 40mm is
below 70% compared to 76% in the laboratory slab at 70-days. At 70 and 90mm the \( rh \) is approximately 78% whereas in the laboratory, the corresponding \( rh \) are 80% and 82% respectively. Again, there is relatively little difference in drying between the two slabs, particularly below 70mm. As before, residual moisture content exists in the room slabs as drying continues and a clear difference between the two drying environments at 40mm. From this, it is easy to see how accelerated drying can give a false account of the moisture condition where the \( rh \) at the surface will be significantly less than that at depth (69% compared to 78% in Figure 5.7 at 68-days). It is also clear how identifying the \( rh \) profiles through the depth at various times would prove to be a major advantage over just determining the surface \( rh \), which is the current practice. Also, being able to predict when a slab is sufficiently dry to avoid long term problems when an impermeable covering is used, irrespective of drying conditions, would be a valuable asset to flooring contractors and the finite element analysis in Chapter 7 facilitates this. This point is particularly important for the application of floor coverings and it has been suggested theoretically by Hedenbland (1996) that accelerating the drying will ultimately lead to profiles like those shown here. This work adds experimental evidence to this assertion.

In terms of the diffusion rates, what can be seen from Figure 5.7 is that it is not influenced by the ambient conditions. At 10 and 70-days, the \( rh \) at 70mm and below is approximately equal and the difference between the \( rh \) in the two drying environments above 70mm is a consequence of the evaporation from the surface. This was discussed in Section 2.3.3 where, in saturated concrete, diffusion is not the controlling process during drying early on as evaporation creates the initial \( rh \) gradient in the concrete so that diffusion develops in the slab. As drying continues, both evaporation and diffusion become equally involved in the drying process, as the moisture in the concrete develops an internal equilibrium and so drying is slower (Menzel, 1954). The trend observed here support this earlier work. The influence of the accelerated drying environment on the evaporation rates will be discussed in the following section.

### 5.2.3 Conclusions

The above has shown typical \( rh \) profiles through the 100mm thick slabs drying in a natural and artificial environment with a w/c ratio of 0.5. From the discussions, a number of
conclusions can be made. The hourly/daily fluctuations in the ambient temperature and humidity will only have a minor effect on the surface moisture condition and little or no effect on the moisture condition deep in the concrete. Therefore, it is acceptable to consider average temperatures and humidities for the finite element model in Chapter 6. The results show that applying an impermeable paint to five sides of the slab has sealed the concrete against drying through those sides. As expected and discussed in previous chapters, drying is taking place faster at the surface that deeper in the concrete. Over time, after the humidity gradient is set-up through the depth of the concrete, moisture will slowly diffuse upwards.

In terms of diffusion, it has been shown that early on in the humidity range 100-80%, moisture movement is faster than for below 80% \( rh \). This agrees with previous work in this area by Bazant and Najjar (1971) and gives further credence to the conclusions earlier that their expression to calculate the diffusion coefficient may reasonably be used in the finite element material model in Chapter 6. It has also been shown that the rate of evaporation decreases over time as equilibrium is slowly reached with the ambient air and has been shown to vary between approximately 0 to 30-days, 30 to 70-days and appears to be approximately constant thereafter. This is important when the evaporation model is calibrated in the following chapter. It has also been discussed that the rate of diffusion is not influenced by the ambient conditions and the more rapid decrease in the surface and near surface moisture content is as a result of the increased rate of evaporation. Again, this will be important when considering the material models for the accelerated drying environment in Chapter 6.

Results from the accelerated drying regime has shown that despite the rapid drying at the surface compared to the laboratory based slabs, as expected, there is still a residue of moisture deeper in the concrete. When compared with the naturally dried slabs, it was found that both are approximately equal at 70mm and below early on in the drying process. The important point in relation to floor coverings is that this residue of moisture will continue to diffuse through the slab (vertically upwards if drying is one-directional) and build-up over time under any imposed covering (Holmes and West, 2002). This will be examined in Chapter 7 in more detail via an experimental and finite element study.
5.3 SURFACE MOISTURE CONTENT TRENDS DURING DRYING

This section considers the change in surface moisture content as drying continues in the laboratory (section 5.3.1) and in the control room (5.3.2). Results from each environment will be discussed separately and then compared to demonstrate the influence of the forced drying environment on the surface moisture content.

Again, in order to gain an appreciation of the typical trends of the surface moisture during drying, the results from slabs L(500)0.5(100)1.1 and R(500)0.5(100)1.11 only are presented. The influence of the slab thickness and w/c ratio on the surface moisture content will be discussed in sections 5.4 and 5.5 respectively. In order to relate the moisture content to the \( rh \) profiles discussed in 5.2, a desorption isotherm will be produced for each environment which relates the surface moisture content and \( rh \), recorded at the same time. These isotherms will show how a surface \( rh \) of 75%, the point deemed safe to apply floor covering according to BS 8302 (1996), relates to the surface moisture content.

5.3.1 Laboratory trends

As discussed in Chapter 4, the changing surface moisture content was measured using the CME meter for all the slabs during testing. Figure 5.8 shows the surface moisture content over a 220-day period for slab L(500)0.5(100)1.1. The results show an initial rapid decrease in the surface moisture content from 5.0% at 10-days to 4.0% at 60-days. This initial rate of fast drying slows and between 60 to 130 days, the surface moisture content plateaus at approximately 4.0% as it appears to reach equilibrium with the environment and remains relatively constant, apart from some minor fluctuations. At 130 days, the moisture content falls sharply to approximately 3.7% at 140-days and between 140-days and the end of the testing period, the moisture content continues to fall slowly where finally at 220-days, it is approximately 3.3%. This ongoing moisture loss may be due to a change in the ambient conditions as it occurred during the summer months (see Figure 5.1(a)). Also, as drying continues, salts diffuse to the surface and may affect the surface moisture content long-term. If a contractor waiting to apply a floor covering were taking these readings, it would be assumed that equilibrium had been reached after 60 or 70-days and the covering could be applied, especially as it remained at 4% for the following 70-
Figure 5.8 Surface moisture content as measured by the CME for slab L(500)0.5(100)1.1.

days. It is unlikely that a contractor would continue to take readings for longer than 10-
days especially if the readings remained at 4.0%. However, in saying this, surface moisture
content only decreased by 0.75% over the next 60-days. The natural random variations in
individual readings also suggest that a number of readings over time and location should be
taken.

Using a similar dashed line as in Figure 5.5 to follow the general trend of the surface \( rh \)
over time, one can see how the rate of evaporation reduces and can again be considered in
three stages. The first stage is from 0 to 30-days, where the slope of the line \( (\theta_1) \) represents
the fastest drying of the three. The second line, from 30 to 70-days presents a more gradual
rate of evaporation \( \theta_2 \) and \( \theta_2 < \theta_1 \). The third line from 70-day onwards, indicates a constant
rate of evaporation with \( \theta_3 \) less than \( \theta_1 \) and \( \theta_2 \) \( (\theta_3 < \theta_2 < \theta_1) \). Where these lines intersect agree
with those in Figure 5.5 above and supports the suggested approximate times at which the
rate of evaporation will change.

Figure 5.9 shows the relationship between the surface \( rh \) and moisture content taken at the
same drying time, known as a desorption isotherm as discussed in Section 2.4.1. There is
an approximately linear relationship, with a correlation coefficient of \( R^2 = 0.96 \). It is
interesting to note that 75% \( rh \) (the point to safely apply floor coverings according to BS
Figure 5.9  Relationship between the surface moisture content and surface \( rh \) for slab L(500)0.5(100)1.1.

8203, 1996) corresponds to a moisture content of approximately 4.3%. In terms of applying a floor covering, if it were applied at 4%, this would equate to a \( rh \) of less than 75%. However, this 4% surface moisture content gives no indication of the moisture condition through the slab’s depth and future damage to floor coverings may still occur. However, because of potential variations in the moisture content, as demonstrated here, the actual surface moisture content is not used in any code to estimate the point at which coverings can be safely applied. These variations in measured moisture contents may be caused by more than just moisture as some chemical constituents, particularly salts, can also affect the impedance characteristics of the concrete.

5.3.2 Control room trends

Figure 5.10 shows the surface moisture content measurements for slab R(500)0.5(100)1.11 using the CME meter in the control room. The results show that the surface moisture over the initial 50-days falls from 5.0% at 5-days to approximately 4.0%. By 50-days, the rate of drying appears to have slowed with a reduction in the moisture content of approximately 0.25% over the following 40-days. As discussed above for Figure 5.6, it appears from the dashed lines in Figure 5.10, which follow the general trend of the surface moisture content, the rate of evaporation from 0 to 50-days \((\theta_1)\) is faster than from 50-days onwards where
Comparing this with the laboratory results in Figure 5.8, the influence of the accelerated drying regime is clear, where, for example, a surface moisture content of 3.25% was achieved in the room at 50-days compared to 210-days in the laboratory. These results confirm previous work by Menzel (1954) and Holmes and West (2002) that the evaporation rate is strongly dependant on the ambient environment which the concrete is drying. These findings are also important for calibrating the evaporation material model in Chapter 6.

Figure 5.10 shows the desorption isotherm for slab R(500)0.5(100)1.11 with a reasonable correlation relationship ($R^2 = 0.92$) between the surface $rh$ at 40mm and the surface moisture content. As may be observed, a $rh$ of 75% corresponds to a surface moisture content of approximately 3.5% which is less than the corresponding moisture content of 4.3% moisture content in the laboratory for a surface $rh$ of 75%. This is obviously a function of the warmer concrete and the moisture contained within it to dry faster than for a concrete with a more normal temperature. Indeed, the time taken to reach 4% surface moisture content in the control room was approximately 32-days (Figure 5.10) compared to 60-days in the laboratory (Figure 5.8). In neither case was equilibrium reached at this stage as the surface moisture content continues to decrease. What is shown is how flooring installers can be led into a false sense of security where, despite the fact that the surface may be relatively dry, there may be still a large residue of moisture deep in the concrete,
Figure 5.11 Relationship between the surface moisture content and surface $rh$ for slab R(500)0.5(100)1.11.

particularly if it was force dried. It is also apparent that a simple isolated test, such as the CME, which is entirely non-destructive, can be misleading in suggesting that equilibrium has been reached and the concrete as a whole, not just the surface, is still not ‘dry’ enough for sealing.

5.3.3 Conclusions

The results here show that the slabs in the control room are surface drying more rapidly than those in the laboratory as expected. For example, to achieve a moisture content of 4%, it took approximately 60 and 32-days in the laboratory and control room respectively. This may lead contractors to believe that the surface was dry enough to apply a covering where, under the accelerated drying regime, the contractor would be satisfied that it is achieved some 28-days earlier than the naturally dried slabs. At 75% $rh$, the isotherms shown here correspond to a surface moisture content of 4% and 3.5% for the laboratory and control room dried slabs respectively. Furthermore, if 75% $rh$ (or 4% surface moisture content) is used to define when the slab is sufficiently dry to apply a covering safely, there can be largely varying amounts of residual moisture trapped in the slab, depending on the previous drying environment.
The surface moisture content results demonstrate how the rate of evaporation varies over time. For the results here, the general trends indicate that it varies from approximately 0 to 30-days, 30 to 70-days and 70-days onwards in the laboratory. In the control room, it appears to vary from 0 to 50-days and 50-days onwards. This is an important point when developing the evaporation material model in Chapter 6.

It is clear from the foregoing that the state of being ‘dry’ depends on a number of factors including the environment, with equilibrium being reached at largely varying times and, as will be shown in the following sections, a further dependency on both the slab thickness and w/c ratio.

5.4 INFLUENCE OF THE SLAB THICKNESS

This section presents the results for the three thicknesses of slabs cast as part of the experimental programme with a w/c ratio of 0.5, namely L(500)0.5(100)1.1, L(700)0.5(150)2.2 and L(500)0.5(200)1.4. The results include the $rh$ profiles and the surface moisture content in the laboratory (in section 5.4.1) and in the control room (in section 5.4.2).

The readings for the 150mm thick slabs are only shown up to 90 days, where, at this point, the slab was covered with an impermeable covering as part of the second series of experimental tests (see Chapter 7). The readings for the 200mm thick slabs are only taken to 90mm deep, as a longer tube had not been developed at the time of these tests. The longer tubes were available for the 150mm thick slab tests that followed the initial experimental programme, as discussed in Chapter 4.

5.4.1 Laboratory trends

The ambient conditions for the 100 and 200mm thick slabs have been shown in Figure 5.1 and in Figure 5.2 for the 150mm thick slabs in the laboratory. As shown, the calculated average temperature and humidity was 13.4°C and 53% respectively for the 100mm and 200mm thick slabs and 16.3°C and 56% respectively for the 150mm thick slabs.
Figure 5.12 shows the surface $rh$ until 75% is achieved for the 100, 150 and 200mm thick slabs. As shown, the time taken to reach 75% on the surface was 70, 90 and 140-days for the three slabs respectively. If one considers the slopes of the three profiles $\theta_1$, $\theta_2$ and $\theta_3$, which represent the rates of drying at 85% $rh$ for the 100, 150 and 200mm thick slabs respectively, it can be seen that it is decreasing as the slab thickness increases ($\theta_1 > \theta_2 > \theta_3$). Also, to reach 85%, it takes 27, 35 and 60-days for the 100, 150 and 200mm thick slabs respectively. It is interesting to note that it takes approximately twice the time for the 200mm thick slab to reach 75% $rh$ than the 100mm thick slab. It should also be noted that the approximate faster rate of drying in the 150mm slab in comparison to what might be anticipated or expected from the other two thicknesses, may be due to the slightly higher average temperatures.

For a given diffusion coefficient, it will take significantly longer for equilibrium to be reached for a 200mm thick slab than a 100mm thick slab due to a longer flow path. If one considers a molecule of moisture at 50% of the depth of a concrete slab with an identical w/c ratio and diffusion rate, it will take longer for the molecule to diffuse to the top of a thicker slab, with an identical pore structure. Hence the expected longer drying times shown in Figure 5.12. As drying continues, the slopes of the profiles at 75% $rh$ ($\theta_4$, $\theta_5$ and $\theta_6$) for the three slabs are less than those at 85% $rh$ as the rate of drying decreases over time ($\theta_4 < \theta_1$, $\theta_5 < \theta_2$, and $\theta_6 < \theta_3$). However, the rate of drying is still most rapid for the 100mm thick slab which is not unexpected considering the above.

Figure 5.13 shows the $rh$ profiles through the depth for the three thicknesses at 5 and 10-days and indicates again that the 100mm thick slab is drying faster overall. As shown, after 5-days, the surface $rh$ for the 100mm thick slabs is 94% compared to 95% and 97% for the 150 and 200mm thick slabs respectively. This trend is also repeated at depth where it can be seen that at 90mm in the 100 and 200mm slabs and 85mm in the 150mm thick slabs at 5-days, the $rh$ is 96.5, 97.5 and 98.7% in ascending order of thickness at 5-days. Also, the $rh$ of the 200mm slab below 40mm appears to remain constant at 98.7%, while below 40mm it varies from 95.5 to 96.5% in the 100mm thick slab. The profiles show that this slow rate of drying deep in the thicker slabs is due to the increased flow path the moisture must take to reach the surface. Also, the humidity gradient set up through the concrete during the initial drying (at $t_1$ or $t_2$ in Figure 2.12) continues to have a minor effect on the
Experimental Results

Figure 5.12  Surface $rh$ for slabs $L(500)0.5(100)1.1$, $L(700)0.5(150)2.2$ and $L(500)0.5(200)1.4$ up to 75% drying in the laboratory.

Figure 5.13  $rh$ profiles for slabs $L(500)0.5(100)1.1$, $L(700)0.5(150)2.2$ and $L(500)0.5(200)1.4$ at 5 and 10-days.

moisture deep in the concrete with the increasing slab depth. As shown, the $rh$ at 70 to 90mm in the 100mm thick slab, at 135mm in the 150mm thick slab and 40 to 90mm in the 200mm thick slab is constant at 96.5, 98 and 98.7% respectively.

At 10-days, these trends continue where the surface $rh$ is 92, 93 and 94.5% for the 100, 150 and 200mm thick slabs respectively. Deep in the concrete, the drying is still slower in
the thicker slabs as the rh at 90mm in the 100 and 200mm thick slabs are 93.5% and 95.2% respectively and 95.8% in the 150mm thick slab at 85mm. This, and previous trends, where the rh is almost constant with depth continues at 10-days for the 200mm thick slabs, where it is approximately 95.8% at 70 to 90mm. This is not quite the case for the 100 and 150mm slabs while the rh varies from 93.4 to 93.8% from 40 to 90mm in the 100mm thick slab and from 94 to 96% from 40 to 135mm in the 150mm thick slabs. However, in both these cases, there is still a relatively minor difference in the rh below 50% of the depth early on. For instance, it varies from 93.5 to 93.8% from 50 to 90mm in the 100mm thick slabs, 95.0 to 96.0% from 75 to 135mm in the 150mm thick slabs and it is assumed constant at 95.8% below 100mm in the 200mm thick slabs.

Figure 5.14 shows the rh profiles over time at 90mm for the 100 and 200mm thick slabs and 85mm for the 150mm thick slabs. The figure demonstrates the point, again, that with thicker concretes higher residual moisture will exist at any point in time. For instance, at 90-days the rh was 79, 83 and 87% in the 100, 150 and 200mm thick slabs respectively. Also, the slope of the rh profile in the case of the 200mm slab indicates a more gradual rate of drying than the other slabs.

The 150mm thick slab was covered when the surface reached a rh of 75%, so no readings are available past that point. At 200-days, the rh is 71 and 83% for the 100 and 200mm thick slabs at 90mm respectively. From the figure, it appears that the 100 and 200mm rh profiles are diverging over time and this will create a greater residue of moisture in the thicker slab, as shown in Figure 5.13. This follows the general trends in Section 5.2 where the rh deep in the concrete will dry at a slower rate than at the surface. However, drying deep in the concrete will continue for longer because, due to the humidity gradient in the slab, moisture will still diffuse to the surface despite the surface rh reaching equilibrium with the environment, and, as shown here, will continue for longer in the thicker slab, as can be see by the diverging profiles between the 100 and 200mm thick slabs in Figure 5.14. This is an important point for floor covering contractors where, due to the higher rh residue in thicker slabs, a larger long-term final rh will exist after sealing. This will also cause an increase in the vapour pressure under the covering with the associated enhanced risk of defects and it will take longer for equilibrium to occur.
EXPERIMENTAL RESULTS

Figure 5.14  \( rh \) profiles at 90mm for slabs \( L(500)0.5(100)1.1 \) and \( L(500)0.5(200)1.4 \) and 85mm for slab \( L(700)0.5(150)2.2 \) drying in the laboratory.

5.4.2 Surface moisture content in the laboratory

Figure 5.15 shows the surface moisture content readings (from the CME) for the 100, 150 and 200mm thick slabs. Again, comparing the slopes of the profiles, \( \theta_1, \theta_2 \) and \( \theta_3 \), for the three thicknesses at 4.5\%, the results show that the surface moisture content for the 100mm thick slab is drying at a faster rate than the 150mm and 200mm thick slab. For example, at 40-days, the surface moisture content is 4.8, 5.0 and 5.5\% for the 100, 150 and 200mm thick slabs respectively. At 50-days, the rate of drying in the 150mm thick slab appears to slow, where over the next 40-days, it dries from 4.75\% to 4.5\% at which point it was covered. The rate of change of moisture content in the 100mm thick slab does appear to vary gradually over time (as discussed previously) while for the 200mm thick slab, the profile appears to remain more constant as may be observed from the slope profile over the 220-day period. At 220-days, the moisture contents are 3.2 and 3.7\% for the 100 and 200mm thick slabs respectively. Following on from the discussion on Figure 5.12 and 5.14, where the \( rh \) variations at the surface and at depth were presented, it appears that that the thicker slab will lead to a slower reduction in the surface moisture content.

The following section presents the results from the 100 and 150mm thick slabs drying in
Figure 5.15  Surface moisture content profiles over time for slabs L(500)0.5(100)1.1, L(700)0.5(150)2.2 and L(500)0.5(200)1.4.

The ambient conditions for the 100mm thick slabs drying in the control room have been shown in Figure 5.6 with an average calculated ambient temperature and humidity of 26.7°C and 34.7% respectively. As the results from the 100mm slabs in the room gave consistent trends, as discussed in Section 5.2.2, a more severe drying environment for the 150mm slabs was used. Therefore, the ambient temperature and humidity was increased and decreased respectively until it reached an average of 39.7°C and 13.4% as shown in Figure 5.16. As before, the heater and dehumidifier was switched on 20-days before the slabs were placed in the room to allow the ambient conditions to equilibrate with drying taking place in a normalised environment when the slabs were first placed in the room. The more severe drying for these slabs was created by increasing the output from the heater and dehumidifier in Figure 4.5 and 4.6. By changing the drying conditions for the 150mm thick slabs, it will allow an opportunity to observe the influence of two varying forced drying environments on the experimental rh trends and to allow further calibration of the finite element model for comparison with the experimental results.
Figure 5.16  Ambient temperature (a) and rh (b) for the 150mm thick slabs drying in the control room.

Figure 5.17 shows the rh profiles through the depth for the 100 and 150mm thick slabs at 20 and 44-days in the control room. The rh near the surface is reducing much more rapidly than that deeper in the concrete, where, at 20-days, the rh at the surface and at 135mm in the 150mm thick slab are 81% and 92% respectively. This point has been discussed already, but, unlike the previous case, the 150mm thick slabs are drying more rapidly than the 100mm thick slabs. For example, at 40mm, the rh is 90% and 88% at 20 days and 82% and 78% at 44 days in the 100 and 150mm thick slabs respectively. Similarly, deeper in the concrete, the more severe drying condition for the 150mm thick slabs has caused the rh at depth to be less than the 100mm thick slabs. For instance, at 90mm, the rh is 96% and 92% at 20-days and 87% and 84% at 44-days for the 100 and 150mm slabs respectively. Also, at 20-days, the profiles of the two thicknesses are approximately constant at depths greater than 70mm at 96% and 92% and 87% and 86% at 44-days for the 100 and 150mm thick slabs respectively. This follows similar trends discussed in section 5.2 where, despite rapid drying at or near the surface, there was relatively little evidence of a forced drying environment deep in the concrete. The trends in Figure 5.17, where the 150mm thick slabs are drying faster than the 100mm thick slab are is due to the more severe drying environment that is forcing the moisture out of the surface more rapidly and even influences the rh at depth so that overall drying is more rapid for the 100mm slabs. However, in saying this, at 20-days for the 150mm slab, the rh below 60mm is approximately equal at 92% and at 44-days it is constant below 110mm at 85%. Despite this, there is only a 2 to 3% rh difference between the results for the 100 and 150mm thick
Figure 5.17  \( rh \) profiles of the 100 and 150mm thick slabs at 20 and 44-days.

slabs even though they are drying under different ambient conditions. For example, at 20-
days, the \( rh \) at 40 and 35mm is 90 and 88\% for the 100 and 150mm thick slabs respectively. Also, at 90 and 85mm, the \( rh \) is 85 and 87\% for the 100 and 150mm thick slabs respectively. Indeed, if one were to extent the trends of the 100mm thick slabs to the surface, as shown using the dashed lines, it is postulated that the surface \( rh \) for both slabs would be approximately equal.

As discussed previously, as moisture continues to escape from the surface, moisture movement deeper in the concrete slowly ‘catches up’, where, as shown, the \( rh \) is constant at 110mm onwards at 44-days, while at 20-days, the \( rh \) was constant at 60mm and below. This suggests that drying is taking place at depth and the ambient conditions are having a greater influence over time. Also, comparing the time for the 100mm deep slab to reach 75\% \( rh \) at the surface in the room, here 44-days compared to 70-days in the laboratory, it is clear that the drying rate is much more sensitive to the drying environment than it is to the depth of concrete. Also, if the slab were covered after 44-days, with the profile shown in Figure 5.17, significant quantities of moisture would build-up underneath it and may lead to long-term problems. These profiles clearly demonstrate the misconception that faster drying is an acceptable practice and how only measuring the surface \( rh \) gives a misleading representation of the moisture condition through the entire slab. Therefore, measuring the \( rh \) through the depth can only be beneficial. Indeed, using the new ASTM recommendation
of measuring the $rh$ at 40% of the depth (for 1-face drying as is the case here), at 60mm, the long-term equilibrated $rh$ could be up to 82% under an accelerated drying regime. This will be shown to be a useful method to indicate what the long-term $rh$ through the concrete will be after sealing and the recommendation was influenced strongly by the results here.

Figure 5.18 shows the $rh$ profiles with time at 40 and 90mm in the 100mm slabs and at 35 and 85mm in the 150mm slabs over time. As shown, the $rh$ profile at 35mm for the 150mm thick slabs indicates that drying is taking place at a steady rate but due to the more severe drying environment, it has initially dried more at 9-days (89% compared with 91% for the 100mm slabs at 40mm) and continues to do so over time. At 44-days, the $rh$ at 40 and 35mm are 82 and 77% in the 100mm and 150mm slabs respectively. Deeper in the concrete, the $rh$ profile at 90mm in the 100mm thick slab shows a constant $rh$ of about 95% from 9 to 20-days, where it begins to reduce after 20-days. A similar trend is shown for the 150mm thick slabs as the $rh$ at 85mm is approximately constant between 9 to 20-days at 92%. However, at 27-days, both the 100mm and 150mm thick slabs $rh$ profiles at 90 and 85mm respectively appear to fall at a constant rate-drying has now started. It appears that the surface moisture in the 150mm thick slabs is being driven out of the concrete at a faster rate than the 100mm thick slabs due to the more severe drying environment and is resulting in the moisture deeper in the concrete migrating upwards faster as the concentration gradient in the concrete is greater than in the 100mm thick slabs.

![Figure 5.18](image-url)

**Figure 5.18** $rh$ profiles at 40 and 90mm from the 100mm slabs and at 35 and 85mm from the 150mm thick slabs in the control room.
5.4.4 Surface Moisture Content in the Control Room

Figure 5.19 shows the surface moisture content readings for the 100 and 150mm thick slabs drying in the control room. As shown, the surface moisture content in the two slabs are similar at 5-days but due to the more severe drying environment surrounding the 150mm thick slabs drying is much more rapid than the 100mm thick slabs, as shown by the slopes \((\theta_1\text{ and }\theta_2)\), where \((\theta_2>\theta_1)\). At 20-days, for instance, the surface moisture contents are 4.25% and 2.75% in the 100 and 150mm thick slabs respectively. Similarly, at 40-days, the surface moisture contents for the 100 and 150mm thick slabs are 3.5% and 2.0% respectively. This is again due to the more severe drying condition employed for the 150mm thick slabs in the control room, as discussed previously, which causes the near-surface moisture to be forced out of the concrete faster. However, the difference in the surface moisture content at 20 and 40-days is approximately 1.5% at the most, which would suggest that the slab depth, which has been shown to make drying slower, is not as dominant here as the severe drying environment and appears to cancel out its influence.

In terms of evaporation, it is clear from the 150mm thick slab surface moisture content profiles and the dashed trend lines shown, over 5 to 20-days drying is very rapid and is slowly reducing from 20 to 44-days, when the concrete was covered. For the 100mm thick slabs, Figure 5.19 indicates that the rate of evaporation varies from 0 to 45-days and levels off from 45-days onwards. These two profiles demonstrate that the evaporation model to be setup in the next chapter and calibrated from these results, will have to correspond with faster rates of evaporation over the range 20 to 45-days and slower afterwards.

5.4.5 Conclusions

This section observed the influence of the slab thickness on the surface and internal \(rh\) profiles and the surface moisture content for those slabs dried in the laboratory and in the control room. The results show that in the laboratory based slabs, the thicker the slab, the slower the drying will be for a given w/c ratio with longer flow paths for the moisture deeper in the concrete. In the control room, the ambient conditions for the 150mm slabs had a more severe temperature and humidity regime compared to the 100mm slabs Due to this more severe environment, drying of the 150mm slabs was much more rapid than the
100mm slabs, despite the larger thickness. However, comparing the results from the 100 and 150mm thick slabs, there is only a 2 to 3% difference at most between them in $rh$ terms and approximately 1.5% in surface moisture condition terms. The results show the more severe drying environment experienced by the 150mm thick slabs reduced the influence of the thicker slab was to such an extent that drying was more sensitive to environment than thickness.

Also, it has also been shown by the surface moisture content results that the rate of evaporation varies from 0 to approximately 20-days and 20-days onwards. In terms of the evaporation model to be setup for the finite element analysis in the following chapter, it should have a more rapid rate of evaporation in the range 0 to 20-days with reducing or constant rate afterwards.

### 5.5 INFLUENCE OF THE W/C RATIO

This section will present the $rh$ profiles and surface moisture content results for those slabs with w/c ratios of 0.4, 0.5 and 0.6 using a slab thickness of 100mm as a benchmark in the laboratory (5.5.1) and the control room (5.5.2). From the results, the influence of the w/c ratio on the drying time will be presented and discussed. Section 5.5.3 presents the surface
moisture content results that indicate similar trends to the \( rh \) results.

### 5.5.1 Relative humidity trends in the laboratory

Figure 5.20 presents the \( rh \) profiles over time at the various depths for the slab with a w/c ratio of 0.4. As shown, there is a considerable amount of variation in the results, which are probably due to one or a combination of the errors associated with the method of testing, possible instrument error and/or the natural variations in the constitution of the concrete slabs that have been discussed previously. In order to produce a graph with clearer trends, the method of 5-day averages is used. Here, the first 5 results are averaged and that result is plotted. The next data point plotted is the average of the second to sixth results and so on. For example, Figure 5.21 shows the same results as in Figure 5.20 using this method over time at 40, 50, 70 and 90mm for a concrete slab with a w/c ratio of 0.4 (L(500)0.4(100)1.7). As may be observed, the trends and profiles are now easier to identify, such as the variations in the rates of drying with depth.

![Figure 5.20](image-url) Raw \( rh \) profiles over time for slab L(500)0.4(100)1.7 (Jackson, 2003).

Figure 5.22 shows the \( rh \) over time at a depth of 40mm for slabs L(500)0.4(100)1.7, L(500)0.5(100)1.8 and L(500)0.6(100)1.9. As shown, although the initial \( rh \) is similar for all the slabs, i.e. 93 to 95\% at 5-days and the environments that they are drying in are identical, the 0.4 slab continues to have a lower \( rh \) than the 0.5 and 0.6 slabs over the drying time because it has a reduced free evaporable water content. To reach a \( rh \)
Figure 5.21 Example of method of 5-day averages $rh$ profiles over time for slab L(500)0.4(100)1.7.

Figure 5.22 5-day average $rh$ profiles over time for slabs L(500)0.4(100)1.7, L(500)0.5(100)1.8. and L(500)0.6(100)1.9 at 40mm.

of say 85% at 40mm depth, it takes approximately 57 and 73-days for the w/c of 0.4 and 0.5 respectively but not shown in the time frame here in the 0.6 w/c slab. Also, the 0.4 slab appears to dry at a faster rate than the other slabs for the initial 20-days while after this point it dries at a more steady rate and similar to the other slabs as shown from 40 to 70-days. The important point to be made from these results is that, in general, the lower the
w/c ratio, the faster the drying process appears to be and is a function of the volume of free water available as hydration continues in the slabs, with obviously less in the w/c=0.4 slabs than in the w/c=0.5 and 0.6 slabs. As discussed earlier (Section 2.5), the theoretical w/c ratio for full hydration is 0.23 in a sealed environment under complete compaction of cement paste, where there is just enough water in the capillary pores to fully hydrate the cement grains. However, for a w/c ratio of 0.23, there would be a substantial amount of unhydrated cement even if fully cured. A more practical value of using a concrete with a minimum w/c ratio of 0.44 increases the likelihood that all the cement will be fully hydrated, but this will lead to additional free water available for drying and evaporation. A further consequence of this is the increase in the volume of capillary pores when the w/c ratio exceeds 0.44 (Figure 2.15). As the w/c here is only 0.4, there is less free water as the majority of it has been used to hydrate the cement. This is causing the 0.4 slab to be drier earlier than the others, as seen previously. This appears to disagree with findings by Akita (1997) and Roncero (2000) who concluded that the lower the w/c ratio is, the lower the rate of diffusion is. Also, Hedenbland (1997) used lower diffusion rates at low w/c ratios in his expression to calculate the diffusion (Equation 3.12). Furthermore, despite the reduced volume of pores (particularly capillary pores) in the slab due to the w/c ratio less that 0.44, and nearly all the water hydrating the cement grains (see Figures 2.15 and 2.16), the evidence is that drying is still largely controlled by the amount of water in the mix. Also, at a w/c ratio of 0.4, the changes from saturated (liquid) flow to unsaturated (vapour) flow will occur sooner than for a concrete with a higher w/c ratio and would be expected to lead to slower diffusion. However, as the concrete with a higher w/c ratio has higher water contents, it will take longer to dry that one with a low w/c ratio, as discussed previously.

Also, the clarity of the results with respect to the w/c ratio trends divies confidence to the mix constituents were the compressive strength results may have raised doubts as to proper mix quantities.

5.5.2 Relative humidity trends in the control room

Figure 5.23 shows the rh profiles for slab R(500)0.4(100)1.10, R(500)0.4(100)1.11 and R(500)0.4(100)1.12 at 40mm using the 5-day averages method. Again, the results yield similar trends as those presented earlier with the slab with the lower w/c ratio drying
Figure 5.23 5-day average $rh$ profiles over time for slab R(500)0.4(100)1.10 using the 5 day averages method.

fastest. For example, comparing the time taken for the concrete to reach, say, 85% at 40mm depth in the room with that in the laboratory for the three w/c ratios, it is clear that the forced drying conditions influence the drying significantly. For instance, in Figure 5.23, the time it takes to reach 85% is 19, 24 and 50-days approximately. In Figure 5.22, the corresponding time taken to reach 85% were approximately 57 and 73-days for the slabs with w/c ratios of 0.4 and 0.5 respectively but was not achieved in the 0.6 w/c slab.

Figure 5.24 shows a plot comparing the $rh$ through the depth for the 0.4 and 0.5 w/c slabs. As shown, the $rh$ at 40mm is less for the slab with a w/c ratio of 0.4 at both 10 days (85% compared with 88.3% for the w/c=0.5 slab) and at 50-days (73% compared with 77% for the w/c=0.5 slab). However, below 50mm, the $rh$ is more similar with only a minor difference, approximately <1% between them. Also, from 70 to 90mm, there is little (at 10-days) or no change in the $rh$ for either slab. For instance, at 50-days, the $rh$ at both 70 and 90mm is approximately 85.5% and 86.5% for the w/c=0.5 slab. This has been seen and discussed previously for slabs drying in the artificial environment. The conclusions drawn are that drying environment is more influential than w/c ratio and that, irrespective of w/c ratio, the surface dries very quickly, leaving behind a high moisture residual at depth in a strong drying environment.
Figure 5.24  *rh* profiles through the depth at 10 and 50-days over time for slabs R(500)0.4(100)1.10 and L(500)0.5(100)1.8 using the 5-days averages method.

5.5.3 Surface moisture content

Figures 5.25 and 5.26 show the raw surface moisture content readings for the three w/c ratios in the laboratory and control room respectively. As indicated, the lower the w/c ratio, the quicker the slabs appear to dry, again, due to the reduced moisture content in the mix, confirming the earlier trends. In Figure 5.25, the effect of the w/c ratio is clear, where for a surface moisture content of 4.5% to be achieved, it took 50, 72 and 77-days for the w/c ratios of 0.4, 0.5 and 0.6 respectively in the laboratory. The results show that the time taken for the slabs, with w/c ratios of 0.5 and 0.6 to reach 4.5% are quite similar, but, for the lower w/c ratio concrete of 0.4, this point was achieved much faster. As discussed previously, this is due to the majority of the water being used up during hydration, while for higher w/c concretes there is a much larger quantity of ‘free’ capillary water in the concrete.

By comparison, in Figure 5.26 the time taken to reach a moisture content of 4.5% takes 21, 39 and 42-days for the slabs with w/c ratios of 0.4, 0.5 and 0.6 respectively. Again, the times are similar for the 0.5 and 0.6 slabs (within 3-days) but much faster for the 0.4 slab. Comparing these with the laboratory trends in Figure 5.25, it can be seen again that drying is much faster in the control room where the 4.5% moisture content target was achieved.
Figure 5.25  Surface moisture contents for L(500)0.4(100)1.7, L(500)0.5(100)1.8 and L(500)0.6(100)1.9, using the CME.

Figure 5.26  Surface moisture contents for slabs R(500)0.4(100)1.10, R(500)0.5(100)1.11 and R(500)0.6(100)1.12, using the CME.

approximately 30-days earlier (on average) than the laboratory based slabs. Also, the w/c=0.4 slab moisture profile over the initial 30-d ays shows a more rapid moisture loss where, while both have a moisture content of 5% at 10-days, the moisture content at 30-days is 4.8% and 4% in the laboratory and control room respectively. This has been discussed previously for the rh trends in Figure 5.22 where there is a slightly faster decrease in the humidity over the initial 20-days, after which it slowed to a steady rate of drying. The results in Figure 5.26 suggest that despite the w/c ratio, the drying
environment has a more significant effect on the drying rate. In terms of evaporation, it could be concluded that with faster drying at lower w/c ratios, the rate of evaporation will also be faster at lower w/c ratios.

5.5.4 Conclusions

The main conclusions from this section is that for a given concrete depth, the lower the w/c ratio is, the faster drying appears to be. This is a result of less moisture initially in the mix for lower w/c ratios and less free water being available for evaporation as hydration continues, as the majority of the total water is used to hydrate the cement grains. This appears to disagree with the theory that with reduced water content, there will be fewer interconnected capillary pores that will lead to slower moisture movement by diffusion, up to 1/50th the rate between a saturated (liquid) and unsaturated (vapour) concrete.

The results also show that the rate of evaporation is in two or three stages, depending on the drying environment. For the laboratory based slabs, the evaporation rate varies from 0 to approximately 30-days, 30 to 70-days and would appear to be constant thereafter. In the control room, the rate of evaporation varies in the range 0 to 20 to 45-days and approximately constant thereafter. The results suggest that at lower w/c ratios, the faster the rate of evaporation should be. These findings will be important when the finite element material model is being calibrated.

The profiles from both the surface moisture content results and the $rh$ at 40mm show that initially, there appears to be a rapid loss in moisture leading to reduced moisture contents at the surface for a lower w/c ratio. This leads to a higher residue of moisture deeper in the concrete where the distribution is much more uniform with little or no difference below 50% of the depth. The problem for floor installers is that if only surface readings are taken to assess the moisture condition prior to applying floor covering, a misleading image will be portrayed of the state of dryness and long-term problems are more likely to occur. Again, a profile of the $rh$ through the depth or the surface moisture content over time are the only reliable ways to assess when the slab is ready for a covering as both of these methods give an indication of when equilibrium is reached, thereby avoiding long-term moisture damage.
The important point that will be made from these results is that the lower the w/c ratio, the faster the drying process appears to be despite the lower diffusion coefficient as discussed in Chapters 2 and 3.

The following section presents the results from the Vapour Emission Tests (VET).

**5.6 RESULTS FROM VAPOUR EMISSION TESTS**

In the USA, the standard test to assess the moisture condition before applying any floor covering is the Vapour Emission Test (VET) and it is assumed safe to apply a covering when the rate of vapour emission falls within 3-5 lbs/1000ft\(^2\)/24-hrs. It was decided, therefore, to conduct a number of these tests on the concrete slabs as they dried in the laboratory for the 100, 150 and 200mm thick slabs with a w/c ratio of 0.5. Figures 5.27 to 5.29 show the results of these VET tests for slabs L(500)0.5(100)1.3, L(700)0.5(150)2.7 and L(500)0.5(200)1.4. Again, as the results in Figure 5.28 are from the 150mm thick slabs, the results are only available up to 90-days as the slab was covered with the impermeable covering (see Chapter 7) at that point.

Figures 5.27 to 5.29 show that the 3lbs threshold had been achieved after approximately 70-days for the 100mm thick slab, 90-days for the 150mm thick slab and 153-days for the 200m thick slabs. Comparing these times with that taken to achieve 75% \(rh\) for these slab thicknesses, i.e. 70, 90 and 140-days (see Figure 5.12), it is interesting to note that the times are similar, with the same drying environment for all slabs. As shown, there appears to be a rapid rate of moisture emissions initially which then slows quickly to the point at which it reaches the 3lbs threshold where, after this point, it remains almost constant. For example, in Figure 5.27, the rate of emission falls from 12lbs at 10-days to 2lbs at 70-days. From 70-days onwards, the rate remains constant with some minor changes over time. In Figure 5.28 and 5.29, the change in the rate of emissions is more gradual up to the point were it reaches 3lbs. This is due to the increased thickness of the concrete which, as seen earlier in Figure 5.12 for instance, leads to a more gradual loss in moisture than the thinner slabs. The test clearly has the ability to indicate when equilibrium has been reached, but testing must be on-going despite the fact that it is slow and cumbersome. However, these results do not give any indication of the moisture condition deep in the concrete and
**Figure 5.27**  Vapour emission results for slab L(500)0.5(100)1.3.

**Figure 5.28**  Vapour emission results for slab L(700)0.5(150)2.7.

**Figure 5.29**  Vapour emission results for slab L(500)0.5(200)1.4.
whether or not the slab has been artificially dried.

The VET test has a flaw that has been demonstrated in the results here. In Figure 5.27 there are a number of relatively ‘high’ VET results between 70 to 110-days for the 100mm thick slab after 3lbs was reached. Initially the author believed that this was due to an increase in ambient conditions but, on reflection, due to the set-up of the test, the ambient conditions would not have had that much of an influence over such a long time. Therefore, another possible reason for this poor result is that the plastic tent may not have been completely sealed and the sample was absorbing some external moisture as well as that escaping from the slab. To confirm this, it may be noted that the second set of VET tests were performed under closer control and the results in Figures 5.28 and 5.29 reflect a smoother curve over the test duration. With the \( rh \) probe method, at least when the results are drawn up instantaneously, a poor reading is observed immediately and retaken if necessary. The VET takes at least 3 days and to keep repeating tests would not be as convenient or practical.

As a consequence of these results presented here and practical experience, the ASTM in the USA are moving away from the VET as the standard test, to be replaced by an \( rh \) reading at a certain depth at a proportion of the total depth of the slab depending on the drying regime employed, namely, 20 and 40\% of the slab depth for one or two face drying respectively. This is believed to give a more representative view of the average moisture profile through the depth, and this view is supported and promoted by the research presented here.

### 5.7 COMPARISON WITH PREVIOUS EXPERIMENTAL WORK

This section will present some comparisons between the results here with those from Kim and Lee (1999) as the experimental set-up there is similar to that used here and this is suitable for comparison. As discussed previously, they measured the \( rh \) at depths of 30, 70 and 120mm in a 210mm thick slab with \( w/c \) ratios of 0.28, 0.4 and 0.68 and with fixed temperature and humidity of \( 20\pm1^\circ C \) and \( 50\pm2\% \) respectively. They also sealed all five sides with only the surface exposed. The nearest slab for comparison as part of the tests here is a 200mm thick slabs in the laboratory with a \( w/c \) ratio of 0.5 (L(500)0.5(200)1.5).
Figure 5.30 shows a plot of the results from the two slabs with results at 40 and 80-days at 30mm (Kim and Lee, 1999) and at 40mm here. As shown, the \( rh \) in the 200mm thick slab here appears to show that it is drying slightly faster than the 210mm thick slabs despite the higher w/c ratio for the 200mm thick slabs and the fact that the \( rh \) was measured closer to the surface by Kim and Lee (1999). However, a number of different properties are influencing the results that may not allow a true comparison. For instance, the thicknesses of the slabs are slightly different and Section 5.4 has shown that thicker slabs, on average, take longer to dry. However, Section 5.5 has shown that concretes with a lower w/c ratio will dry faster than those with higher ratios. Here, the concrete with the higher w/c ratio is drying faster, but only slightly. In fact, if one compares the two sets of results over the 200-days testing period, the results are within 5% of each other. The set-up of the plastic tubes and rubber rings used by Kim and Less (1999) is much different to that used here. For instance, the plastic tube extends out of the concrete and the rings are placed at the plastic tube. By doing this, it is likely that some ambient humidity would have found its way into the tube and may have affected the results leading to an increased \( rh \) reading. As shown, all results in Figure 5.30 are higher than the 200mm thick slabs here. Also, different humidity probes are used. Despite this, the general trends in Figure 5.30 show that the \( rh \) at 30mm is less than the \( rh \) at 70mm, as is the case for the \( rh \) at 40 and 70mm. It may be concluded that while the results differ slightly, the trends and orders of magnitude are satisfactorily similar.

**Figure 5.30** Comparison between \( rh \) profiles from Kim and Lee (1999) for 210mm thick slab and the results here for the 200mm thick slab.
5.8 CONCLUSIONS

This chapter presented the results from the tests performed on twenty slabs with thickness of 100, 150 and 200mm and with w/c ratios of 0.4, 0.5 and 0.6. The slabs were also allowed to dry in two different environments, a laboratory (with normal ambient temperatures and \( rh \) regimes) and a control room (that artificially dried the concrete by accelerating the drying using heaters and dehumidifiers). This generated a significant volume of results that were presented in five sections. Chapters 2 and 3 identified a number of gaps in the knowledge on slab drying. These included, in particular, a strong need for a numerical/finite element model that can predict humidity profiles through the depth of concrete slabs due to fast track construction activities for any thickness, w/c ratios and natural and forced drying environments. These results and conclusions will allow calibration of the physical and material models in Chapter 6 to verify the trends seen for OPC concretes.

Variations in the results may be as a consequence of natural variations and experimental errors. Natural variations are a result of the reality that as no two slabs would have been poured or mixed, compacted etc in the same way, so it is inevitable that some minor variations will be seen throughout. Experimental error is where improper measurement may have been taken which leads to an inaccurate result. For instance, removing the cap from the plastic sleeve for too long or not putting the humidity probe in quickly to take the reading leading to some moisture leaking from the chamber, leading to an incorrect reading. Further, each test device has its own degree of accuracy in its readings. Due to the subsequent variations in some of the raw data, the method of 5-day averages was used to produce clearer trends, particularly in Section 5.5.

The results from Section 5.2 showed that when the surface reaches 75\% \( rh \), there can be a large variation in the residual moisture in the slab through the depth, depending on environmental conditions. This residual moisture will continue to diffuse through the slab and build-up under any imposed covering. What was also seen is that it may be possible to continue to use accelerated drying methods to a point where, after the slab is covered, the long-term equilibrated \( rh \) will not cause lifting problems. This will be achieved by altering the required surface \( rh \) threshold to below 75\% before covering, such that the long term
uniform \( rh \) is not detrimental to the covering. This can be achieved in a lesser time than for natural drying to 75\% \( rh \), as will be ascertained during the finite element study.

Section 5.3 presented the surface moisture content readings taken using the CME and in some cases, the CE-RH with a thickness of 100mm and a w/c ratio of 0.5 as a benchmark for the discussions to show typical trends. The surface moisture results showed very similar trends as the humidity plots where the surface moisture content gradually reaches equilibrium with the ambient air. When a comparison was made between the laboratory and control room results, the influence of the accelerated drying environment was again evident with the moisture content reducing sharply until equilibrium was reached with the ambient air. Using a number of desorption isotherms, it was shown that a surface \( rh \) of 75\% approximated to a surface moisture content of 4\%. However, it is clear that this gives no indication of the residual moisture condition deeper in the concrete and one cannot depend on just the surface moisture content as an indication of the true moisture condition. This indicates strongly a disadvantage of relying solely on the CME readings. Also discussed was the fact that the rate of evaporation, from surface moisture content readings appears to vary between 0 to 30-days, 30 to 70-days and an almost constant rate thereafter (70-days onwards) in the laboratory. In the control room the trends show that it varies from 0 to 30 and 30-days onwards, as drying is much faster, as expected.

Section 5.4 discussed the influences of the slab thickness only, using a w/c ratio base of 0.5 for the discussions on the \( rh \) profile and surface moisture content through the depth and over time. Although the ambient conditions for all three slabs were very similar, the only difference here (assuming all things are equal in relation to slab mixing, w/c ratio etc) was the thickness. In particular, the influence of the depth on the point in time at which the surface reaches 75\% \( rh \) was quantified. From studying the various profiles, it was shown that, not surprisingly, the thicker the slab, the more gradual the drying is and it takes longer to reach 75\% in particular. In the laboratory, the 100mm slab took 70-days, the 150mm slab took 90-days and the 200mm thick slab took 135-days to reach 75\% on the surface. This was also evident for the artificially dried slabs where similar trends existed, albeit at faster rates. However, there was only a small difference between the results of the 100 and 150mm deep slabs drying in the control room with different ambient conditions and the results suggested that the more severe drying environment effectively cancelled out the
slower drying that a thicker slab would result in. The surface moisture content readings from the control room demonstrated that the rate of evaporation appears to vary between 0 to 45-days and remains approximately constant thereafter.

Section 5.5 presented a study into the influence of the w/c ratio using the 100mm thick slabs as a benchmark for the discussions on both the profile through the depth and the time for the surface to reach certain $rh$ values. It was found that, repeatedly, the lower the w/c ratio, the faster the drying process appears to be and is a function of the free water available for drying in the concrete as hydration continues for lower w/c mixes as the majority of the water is used to hydrate the cement grains. This appears to disagree with the theory where due to the reduced water content, there will be fewer capillary pores and poor pore interconnectivity which would hinder diffusion. Research from others also confirm that the lower the w/c ratio, the slower the rate of diffusion is, which is true, but here it is shown that the $rh$ arising from the remaining free water is just as important if not more so, in determining the time to reach 75% $rh$ on the surface.

Section 5.6 presented the results from a number of vapour emission rates (VET), which showed how the rapid rate of emissions early on changed to give a more constant rate over time. This method is used in the USA to determine the point at which to safely apply a floor coverings etc, namely, when a vapour emission rate between 3 to 5 lbs/1000ft$^2$/24-hrs is achieves. However, using the results presented here, work by the relevant ASTM Committee has resulted in the development of a new test, where the $rh$ is being measured at a percentage of the total depth depending on one or two face drying, which may result in this test becoming obsolete. The results shown here demonstrate the risk associated with relying on the 3lbs rule, where it gives no indication of the actual residual moisture condition through the concrete.

Section 5.7 presented a comparison between the results here and those by Kim and Lee (1999) using a 200mm thick slab with a w/c ratio of 0.5 5 (L(500)0.5(200)1.5) with their 210mm thick slab with a w/c ratio of 0.68. The results showed that although the slabs are somewhat different (with different w/c ratios), the general trends did correlate well and it was concluded that both sets of results did compare well despite the differences, which gives credence to the results here.
The following chapter presents the finite element model (DIANA) that was developed by the author to predict the $rh$ in any OPC-based drying concrete slab. As stated, the material properties will be developed from the results presented in this chapter to calibrate and, later, predict trends in behaviour taking account of the w/c ratio and the drying environment via calibrated diffusion coefficients and evaporation rates. A further model will be set up to compare these predictions with the experimental results with previously published results to demonstrate its robustness and usefulness in practical situations.
6. FINITE ELEMENT ANALYSIS

6.1 INTRODUCTION

The experimental work has shown that the \( rh \) profiles, trends and concrete drying times vary with w/c ratio, drying environment and slab thickness with a more accelerated or forced drying regime creating a larger residue of moisture deep in the slab for a given surface \( rh \). The experimental results have also shown that a significant amount of time and effort is required to assess the moisture condition in the slab, both through the depth and at the surface. Because of these factors, and the apparent unavailability of a suitable predictive method, as discussed in Chapter 3, it was decided to undertake a numerical study using the finite element method. This study aims to set up and calibrate a model to predict the experimental trends and drying time for a range of factors including slab depth, w/c ratio and drying environment. Also, the results from this model will be compared with previously published literature using similar experimental set ups as here which will demonstrate robustness and applicability.

The material model was calibrated using the experimental results and it is postulated that it could be used to reasonably predict the \( rh \) profiles and drying times for a range of concrete slabs with typical w/c ratios using Ordinary Portland Cement in similar drying environments as described in Chapter 4. In addition, a number of sensitivity studies into various physical and geometrical properties were performed to determine the optimum model for the slabs used in the experimental tests.

6.2 DIANA FINITE ELEMENT MODEL

The finite element package used was DIANA, which is a large-scale general finite element system based on advanced database methods. Civil, mechanical and other engineering problems ranging from simple to very complex can be solved using advanced CAD/CAM systems. DIANA was initiated and continues to be developed at TNO Building and Construction Research by top scientists, Dutch Technical Institutes and Universities. The DIANA package used here was version 7.2 developed in 1999. The theory behind this version of DIANA is described in its online manual (DIANA User's Manual, Release 7.2, 1999) and the various input modules etc are described in Appendix B. This finite element
package was chosen as it has capabilities to model the combined diffusion and evaporation processes. Although there may be other software packages available that also carry out this type of analysis, and there is nothing particularly unique about DIANA above other models, it was chosen because the input and command files were easy to understand and set up while allowing for 2-D, non-linear analysis of moisture movement in concrete.

DIANA was used by Sadouki and van Mier (1997) to model mass and heat transfer in concrete using a lattice structure to model the concrete. A constant diffusion rate was used for the analysis. Comparisons between measured and predictive results showed there was a good comparison between both. They concluded that this type of analysis using DIANA was suitable for modelling moisture movement in concrete and a non-linear diffusion rate that varied with the internal humidity would give improved predictions.

The general flow elements in DIANA may be applied for all diffusion-type problems (including heat transfer analysis). DIANA offers general flow elements for two-dimensional, axi-symmetric and three-dimensional models. Flow elements for two-dimensional models must be positioned in the XY plane, where the Z coordinates of the nodes are zero. DIANA comprises three categories of elements for general two-dimensional flow analysis, namely triangular, quadrilateral and line-shaped boundary elements and quadratic elements particularly suited to general flow analysis. The material input for diffusion problems is specified via the DIFFUS command. The diffusion coefficient can be specified as constant, varying with the concentration (using POTENT representing humidity in this case), time (TIME), or a combination of these. The evaporation rate is given as a boundary condition, with the convection coefficient, K (CONVEC), given as a constant, a function of the concentration, time or a combination of both. The initial conditions or ‘loads’ for diffusion type problems consist of the initial rh, assumed to be 100% (or taken as the specified rh profile through the depth in Chapter 7), and the boundary conditions. The boundary condition is the ambient rh for drying or an impermeable boundary for a covered slab. The ambient temperature can be given in a table (TEMPER) that can be specified as a constant or varying with time. It has been concluded previously that the variation in the ambient conditions would not affect the rh deep in the concrete and only has minor effects on the surface rh. It is therefore appropriate to consider only the average ambient conditions (Figures 5.1, 5.2, 5.7 and 5.19).
DIANA uses Equations 6.1 and 6.2 to model diffusion, which are Fick’s first and second laws of diffusion respectively (see Chapter 2), where $J$ is the mass flux through the material, $D$ is the diffusion coefficient and $P$ is the potential (here the internal $rh$). $D$ can be expressed as a function of time, concentration ($rh$) or a combination of both. The boundary conditions in DIANA can be a prescribed boundary condition $\phi_B$ (the ambient $rh$ here) in Equation 6.3, or a natural boundary condition with a prescribed boundary flux ($q_B$ in Equation 6.4).

$$J = -D \frac{dP}{dx} \quad \text{Equation 6.1}$$

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial x} D(P) \frac{\partial P}{\partial x} \quad \text{Equation 6.2}$$

$$\phi = \phi_B \quad \text{Equation 6.3}$$

$$q.n = -q_B \quad \text{Equation 6.4}$$

The mixed boundary condition (Neumann / Robin) (Equation 6.5) is a boundary flux that depends on a free boundary potential $\phi_B$ (surface $rh$) and a prescribed environment potential $\phi_E$ (ambient $rh$). If no boundary condition is specified then the natural condition of full insulation is valid (Equation 6.6), which applies to the painted sides of the slabs here. The finite element calculation used in DIANA is based on the Galerkin procedure (DIANA User’s Manual, Release 7.2, 1999).

$$q.n = K (\phi_B - \phi_E) \quad \text{Equation 6.5}$$

$$q.n = 0 \quad \text{Equation 6.6}$$

6.3 MODEL GENERATION

This section presents a summary of the sensitivity studies used to set up the model for the various physical and material properties, aimed at creating a sufficiently accurate model of
the drying process over time. These preliminary analyses were all performed on models of concrete slabs with dimensions of 500x500x100mm thick, as shown in Figure 6.1.

As shown, the upper 40mm of the slab, or 40% of the depth for one-face drying for the 100mm thick slab, has a finer mesh than deeper in the slab. This follows the recent ASTM publication (ASTM F2170-02, 2002) which proposes that the \( rh \) should be measured at 40% of the depth for one-face drying or 20% of the depth for two-face drying. This finer mesh is also appropriate as the rate of change in moisture in this region has shown to be greater than deeper in the slab, as drying is more rapid at or near the surface, as shown in the experimental results (Chapter 5) and the initial analyses. For example, in Figure 5.3, the near surface \( rh \) is decreasing at a faster rate than deeper down, particularly above 40mm. At 3-days, the \( rh \) between 40 and 90mm is 98%, while, at 5-days, the \( rh \) is 96% and 97% respectively for the slab with a w/c of 0.5. As drying continues, Figure 5.4 demonstrates that this trend continues over time, where, at 70-days, the \( rh \) at 40mm and 90mm are 76% and 80% respectively. In addition, as will be shown in the next chapter, the \( rh \) at 40% of the depth when an impervious covering is applied gives a good indication of the final long-term equilibrated \( rh \) throughout the depth. Therefore, it appears that the most severe \( rh \) changes take place over the initial 40mm (or 40% of the depth) and this appears to be a suitable cut-off point for the finer mesh.

A 2-D model was chosen as the drying is one-dimensional due to the experimental set-up and the evidence from the results in the previous chapter is that the impervious coating applied at the base and sides during the experimental set up did properly seal the slabs as the profiles indicated that no moisture escaped from the four sides or the base.

### 6.3.1 Mesh considerations

The CQ8HT element (Figure 6.2 (a)), an eight-noded quadrilateral isoparametric element, was chosen for the analysis as it is suitable for general flow and diffusion type analysis in DIANA. The B2HT element (Figure 6.2 (b)) is a two-noded isoparametric boundary element used in DIANA for evaporation from the surface. These elements are typical for general flow analysis in DIANA.
A sensitivity analysis was carried out using the CQ8HT element using mesh densities of 10x10, 20x15 and 25x18 elements with 20, 40 and 50 B2HT boundary elements respectively for a 100mm thick slab drying naturally with an average ambient \( rh \) of 55% and a 10-day time step. The material properties for these tests were a constant diffusion coefficient of \( 3.23 \times 10^{-9} \text{ m}^2/\text{sec} \) and \( 1.5 \times 10^{-8} \text{ m/sec} \) for evaporation, as suggested by Bazant and Najjar (1971) as typical. The intention is to merely develop a sense of what effect varying the model’s physical properties has on the results. The results in Figure 6.3 show that the greater the density the better the comparison is between the experimental and finite element results, unsurprisingly, between both the profiles through the depth and at the surface. As may be observed, the mesh density of 12x10 elements produces the poorest comparison with the experimental results. Indeed, by increasing the mesh by 50%, the results/comparison is much improved with only an average difference of 3% with the experimental results. However, by almost doubling the mesh density in the vertical plane from 10 to 18 elements, the comparison is similarly improved. Indeed, as drying is 1-dimensional, the number of horizontal elements is of relatively little importance. However, the entire slab will be physically modelled here. The profiles through the depth and over time are two important conditions that the finite element model must be capable of predicting to give users an accurate indication of the true moisture condition through the depth of the slab at any point in time.
Following this study, it was decided to use a mesh density of 25 x 18 CQ8HT elements with 50 B2HT evaporation elements for the 100mm (Figure 6.1) and 200mm (Figure 6.4) thick slabs with 35 x 37 CQ8HT elements with 70 B2HT elements for the 150mm thick slabs (Figure 6.5). The mesh(s) were generated using the FEMGV pre-processor program and the *.dat file was completed by hand with the material, boundary and initial conditions for the model. Using FEMGV to generate the mesh also allows the user to view the mesh on the display screen (ISO, 1085) and check that it has been generated correctly.

### 6.3.2 Time-stepping considerations

As part of the initial model set-up, two sets of analyses were performed over a time period of 220-days using the mesh shown in Figure 6.1, with the same material properties (a diffusion coefficient of $3.23 \times 10^{-9} \text{ m}^2/\text{sec}$ and an evaporation rate of $1.5 \times 10^{-8} \text{ m/sec}$), using a time-step, firstly, of 1-day (86400 sec) and, secondly, 10-days (864000 sec) to determine what influence the time step would have on the accuracy of the results. Figure 6.6 shows the results where, as expected, the time steps make little difference when compared with the experimental results with a difference of 1.3% on average over 220-days between the results. However, the processing time taken for the 1-day step analysis (over the 220-days) was much greater than for the 10-day step steps. Therefore, it was decided that 10-day steps would be used as an initial base and adjusted accordingly for comparisons with the experimental results, as will be seen in Section 6.4.
6.3.3 Boundary conditions

The boundary conditions for this model were relatively straightforward with the top face exposed to the surrounding air and the remaining sides fully insulated to mimic the
experimental set up described earlier in Chapter 4. In DIANA, the model assumes that if no condition is specified for a boundary, it is fully insulated (DIANA, 1999) (Section 6.2). Therefore, only the boundary conditions for the top surface are required as it is free to evaporate. The evaporation rate is input via table ‘MATERIALS’ (see Appendix B).

The ambient humidity is input via table ‘BOUNDARY’ in which the EXTPOT data represents the external humidity. The temperature is specified in table ‘TEMPERATURE’ with the ambient temperature varying with time (TIME). These tables are described in Appendix B with the appropriate syntax for DIANA input. As stated earlier, it was decided to only include the average ambient conditions as the daily fluctuations are not expected to have a significant effect on the overall drying regime over time with only minor effects on the surface $rh$ and no effect on the $rh$ deep in the concrete. Also, using a constant ambient $rh$ may prove more practical for prediction analysis, where, an average value for the ambient humidity would only be assumed or known in a practical application future variations would certainly not be known beforehand.

### 6.3.4 Time-stepping methods for initial-value problems

In all time-stepping analyses, the time axis is divided into a succession of time steps ($\Delta t_i, i = 1,2, \text{etc}$) beginning at time $t_0$, as shown in Figure 6.7. Some methods permit the steps to be of varying lengths while others require uniform steps. Then, instead of seeking a solution for $\{a(t)\}$ over the continuous time domain, an approximate solution consisting of discrete values is sought for $\{a(t)\}$ at the end of each step, that is, $\{a\}_1$ at time $t_1$, $\{a\}_2$ at time $t_2$ etc., starting from the known initial value $\{a\}_0$ at time $t_0$. The $i^{th}$ component of $\{a(t)\}$ (indicated by Figure 6.8), is sought.

The purpose of this type of analysis is to carry the solution forward from, for example, time $t_{n-1}$ to time $t_n$ as illustrated symbolically in Figure 6.8 for a typical time degree of freedom (DOF) $a_i(t)$. The solution has been stepped forward through the first $n-1$ time steps, thereby determining the solution at time $t_{n-1}$ but not at $t_n$. The discrete values $\{a\}_n, n = 1,2,$ are computed from a recurrence relation, which is an algebraic equation that relates the values $\{a\}_n$ at two or more successive times. The recurrence relation is an approximation to the differential equation. There are a wide variety of recurrence relations.
for any given differential equation, and any recurrence relation can be derived using several different methods (Zienkiewicz et al., 2000). In practice though, only a dozen or so different recurrence relations and time-stepping methods have actually been used in commercial finite element programs, and almost all can be classified as linear multi-step (LMS) methods (Burnett, 1987). The adjective ‘linear’ refers to the nature of the recurrence relation, not to the differential equation, which is non-linear. Therefore, LMS methods can be applied to both linear and non-linear differential equations (Zienkiewicz et al., 2005).
6.3.5 Material Properties

This section is concerned with determining the material properties namely the diffusion and evaporation rates for the various w/c ratios and environmental drying conditions to be used here. The material models have been calibrated against the experimental results in Chapter 5 after a series of analyses. As discussed previously, the thicker slabs take longer to dry but this is a result of the increased total volume of water in the mix and the longer-flow-path. The rate of diffusion in the concrete and evaporation from the surface will not be influenced by the specific geometry for the case considered. Therefore, calibrating the material properties against the experimental results for the 100mm thick slabs is appropriate as the properties will not vary with slab thickness (West and Holmes, 2003). However, there will be an influence for the w/c ratio and the model will be calibrated accordingly for the three w/c ratios used and will be compared with the experimental results presented in Chapter 5 and with other published results (Kim and Lee, 1999).

The literature review in Chapter 3 has shown that a number of expressions and values are available for the diffusion and evaporation rates and non-linear diffusion and evaporation models give a superior prediction of the actual drying regimes as compared with linear theory (Bazant and Najjar, 1971; Akita et al, 1997, Sadouki and van Mier, 1997, Holmes and West, 2001, West and Holmes, 2003 and West and Holmes, 2005). This section will present results from a series of analyses using these values to give a ‘best-fit’ with the experimental results for the 100mm thick slab with a w/c ratio of 0.5 in the laboratory.

As stated earlier (Section 3.3), the range of diffusion coefficients in the previous literature varies from \(1 \times 10^{-9}\) to \(1 \times 10^{-11}\) m\(^2\)/sec for normal dense concretes. The selection of the diffusivity and the evaporation rates are based on previous research by Bazant and Najjar (1971) and Akita et al (1997) for the diffusivity and Shimomura and Maekawa (1997) and Akita et al (1997) for the evaporation rates and are subsequently calibrated to suit the results here. As stated earlier in Section 3.3, following a review of the theoretical background and the experimental results, Equation 6.7 will be used to calculate the diffusion rate for the numerical study here as a function of the internal pore \(r_h\), which is based on the work by Bazant and Najjar (1971).
Here, as recommended, \( D_1 \), which is the initial diffusion rate at 100% \( rh \), is assumed to be approximately \( 3.23 \times 10^{-9} \) m\(^2\)/sec at the beginning of the drying period (at \( t=0 \)). To calculate the non-linear diffusivity, Equation 6.7 uses values of 0.05, 0.85 and 15 for \( \alpha \), \( h_c \) and \( n \) respectively, as suggested by Bazant and Najjar (1971), CEB-FIP (1990) and CEB-FIP (1992). These values have been shown by them to give a good approximation of the non-linear moisture diffusion coefficients for the humidity distributions during drying, as compared with experimental measurements. The effect of w/c ratio in Equation 6.7 is accounted for by varying the initial diffusion rate \( (D_1) \) when \( h = 100\% \). Figure 6.9 shows the results from an analysis carried out using other published diffusion coefficients as shown in Table 6.1, for a w/c ratio of 0.5 using the mesh shown in Figure 6.1. A constant evaporation rate of \( 1.5 \times 10^{-8} \) m/sec was also used in the analysis. As shown, the best comparison with the experimental results arises from the diffusion rate from Bazant et al (1971), as predicted. The others gave reasonable comparisons, especially those by Akita et al (1997) and Hall (1994) but they both use higher initial coefficients when \( h = 100\% \). The results using the values derived by Hedenbland (1997) and McParland (1997) particularly do not compare well, probably because Hedenbland assumed a higher initial rate of diffusion with no initial period when their diffusion coefficient is constant for a time. McParland assumes that the diffusion coefficient varies with time and not the internal \( rh \) as assumed here.

\[
D(h) = D_1 \left[ \alpha + \frac{1-\alpha}{1+(1-h)(1-h_c)^n} \right]
\]

Equation 6.7

Figure 6.9  Comparison of published diffusion coefficients with experimental results at 80-days through the depth for a 100mm deep slab with a w/c ratio of 0.5.


Table 6.1  Previous diffusion coefficients and the mesh used in preliminary analysis
Figure 6.10 (a) shows the diffusion coefficients for the three w/c ratios to be used in the finite element analysis here, following a series of analyses where the predictions of $rh$ with depth compared well with the experimental results in Chapter 5. For example, for a w/c ratio of 0.5, the diffusion co-efficient at $rh=100\%$ is $4 \times 10^{-9} \text{ m}^2/\text{sec}$ compared to $3.23 \times 10^{-9} \text{ m}^2/\text{sec}$ used by Bazant and Najjar (1971) for a w/c ratio of 0.5 (see Table 6.1 above). This value of diffusion when the $rh$ is 100\% is also close to that suggested by Roncero (2000), Hedenbland (1995) and Hall (1992). Also, as stated in Chapter 3, Shimomura and Maekawa (1997) suggested that the ratio of unsaturated flow rate to saturated flow rate would be approximately 1/50$^{th}$. This would be particularly true for the higher w/c concrete, here 0.6. From Figure 6.10(a), the rate of diffusion flow in the saturated state is $5.0 \times 10^{-9} \text{ m}^2/\text{sec}$ for a $rh$ of 100\%. At a $rh$ of 65\%, where the diffusion is almost certainly through an unsaturated concrete, this reduces to $2.51 \times 10^{-10} \text{ m}^2/\text{sec}$ which corresponds to 1/50$^{th}$ of the saturated flow rate. This gives credence to the values chosen and confidence that they are within the range suggested by published research.

![Figure 6.10](image)

**Figure 6.10** Diffusion and evaporation rates used in the finite element model.

Figure 6.10(b) shows the non-linear evaporation rates used to model the evaporation of moisture during drying over time, which fit well with other published work in this area (Bazant and Najjar (1971), CEB-FIP (1992) and Kim and Lee (1999)). The non-linear evaporation rates are chosen to give a ‘best-fit’ to the experimental results as shown in Chapter 5 for w/c ratios of 0.4, 0.5 and 0.6.

It may be possible to calculate appropriate evaporation values using the VET results if one considers them to be a measure of vapour emission from the surface. The common
equation for evaporation takes the form

\[ J_S = K(C_S - C_A) \]  \hspace{1cm} \text{Equation 6.8}

where \( J_S \) is the mass flux of moisture from the surface (g/m\(^2\)/sec), \( K \) is the rate of evaporation from the surface (m/sec) and \( C_S \) and \( C_A \) are the concentrations just inside the concrete surface and the ambient air respectively (g/m\(^3\)). If one considers the units of the VET which are lbs/1000ft\(^2\)/day, it is possible to convert these units to suit the units in Equation 6.8 above and also to convert the \( rh \) from percentage to a concentration (g/m\(^3\)) so that both \( C_A \) and \( C_S \) can be calculated. By doing this, a basic value for the rate of evaporation, \( K \), may be calculated. As shown in Figure 6.11, it appears that the rate of evaporation varies from 10 to 30-days, 30 to 70-days and is approximately constant thereafter. Using the VET results at these times (approximately 12, 5.5 and 3 lbs/1000ft\(^2\)/24hrs at 10, 30 and 70-days respectively) and converting these into metric units yields \( 6.78 \times 10^{-4}, 3.11 \times 10^{-4} \) and \( 1.70 \times 10^{-4} \) g/m\(^2\)/sec respectively using a factor of \( 5.65 \times 10^{-5} \) (453.592 / 92.903 / 86400) used to convert lbs into grams, 1000ft\(^2\) into 1m\(^2\) and 1-day into seconds. Converting the \( rh \) in the ambient air and at the surface into units of g/m\(^3\) can be achieved using Padfield’s (1999) equation that converts the \( rh \) at a given temperature into a pressure (in Pa) and then into a concentration, for a given temperature (Equation 6.9),

\[ C_A = 610.78 \exp \left[ 17.269 \left( \frac{T}{T + 238} \right) \right] \left( \frac{rh}{100} \right) \left( \frac{461 x(T + 273)}{x1000} \right) \]  \hspace{1cm} \text{Equation 6.9}

where \( T \) is the temperature (\(^o\)C). Table 6.2 summarizes the calculations.

![Figure 6.11 Change of Vapour Emission Test profile over the test period in the laboratory for slab L(500)0.5(100)1.3.](image)
Table 6.2  
Calculation of evaporation rates from the VET results

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>VET (lbs/1000ft²/24hrs)</th>
<th>Jₜ (g/m²/sec)</th>
<th>Surface rh (%)</th>
<th>Air rh (%)</th>
<th>Temp (°C)</th>
<th>Surface Conc. (g/m³)</th>
<th>Air Conc. (g/m³)</th>
<th>Evaporation Rate- K</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12</td>
<td>6.78x10⁻⁴</td>
<td>93</td>
<td>47</td>
<td>13</td>
<td>10.54</td>
<td>5.33</td>
<td>1.30x10⁻⁴</td>
</tr>
<tr>
<td>30</td>
<td>5.5</td>
<td>3.11x10⁻⁴</td>
<td>87</td>
<td>50</td>
<td>14</td>
<td>10.48</td>
<td>6.02</td>
<td>6.97x10⁻⁵</td>
</tr>
<tr>
<td>70</td>
<td>3</td>
<td>1.70x10⁻⁴</td>
<td>78</td>
<td>55</td>
<td>14</td>
<td>9.40</td>
<td>6.63</td>
<td>6.12x10⁻⁵</td>
</tr>
</tbody>
</table>

The evaporation rates were calculated as 1.30x10⁻⁴, 6.97x10⁻⁵ and 6.12x10⁻⁵ at 10, 30 and 70-days respectively. Following a series of finite element analyses using these values and the diffusion coefficient rates in Figure 6.10(a), it was concluded that these evaporation rates were too high and give unrealistic results when compared with the experimental results. These high evaporation rates assume that moisture is driven out of the concrete at a much higher rate (approximately 10⁴ times the calibrated rate and previously published rates) of the slabs in the natural and accelerated drying environments.

The profiles of the evaporation rates in Figure 6.10(b) were derived from a series of analyses and the points in time where the evaporation rate appears to change significantly as discussed previously in Chapter 5. It may be recalled that the evaporation rate appears to vary between 0 to 30-days, 30 to 70-days and is constant thereafter in the laboratory. This is also shown in the VET results in Figure 6.11. As discussed in Chapter 5, the lower the w/c ratio, the faster the rate of moisture loss from the surface is and the evaporation rates here represents that also for the three w/c ratios here.

Following a series of analyses of the slabs in the control room, it was found that the rh results using the evaporation rates in Figure 6.10 did not correlate very well with those measured. As discussed in the previous Chapter, the rate of evaporation in the control room will be much higher because the moisture is being driven out of the concrete at a faster rate due to the ambient temperature and humidity. Therefore, only the evaporation rates should be calibrated in the model for this drying environment, because, for a given OPC concrete and w/c ratio, the rate of diffusion is independent of the slab thickness and ambient conditions.
As shown previously, using the surface moisture content profiles, the rate of evaporation was shown to vary between 0, 20 and 45-days, and is approximately constant afterwards. Therefore, following a second study (involving a series of analyse) to derive evaporation rates for those slabs drying in the control room with diffusion characteristics as shown in Figure 6.10(a), the now calibrated evaporation rates that gave good comparisons with the experimental results are presented in Figure 6.12(b). As shown, for a w/c ratio of 0.5, the initial evaporation rate at t=0 is approximately $5.5 \times 10^{-8}$ m/sec for the control room compared with $1.5 \times 10^{-8}$ m/sec in the laboratory for a slab also with a w/c of 0.5. As may be seen, the evaporation model has been plotted to vary between 0 to 30-days and 30 to 50-days, where it remains constant afterwards. Also, the rate of evaporation for the slab with a w/c ratio of 0.4 is again higher than the others which were shown to be the case previously in Chapter 5. In the control room condition, the rates of evaporation for all three slabs remain approximately constant over the 70-days. For example, for the 0.5 slab, the rate of evaporation is $5.0 \times 10^{-8}$ m/sec at 70-days compared with $5.6 \times 10^{-8}$ m/sec initially, which is due the more constant nature of the ambient conditions in the control room.

![Graph](image)

(a) D(h) values used for the 100 and 150mm thick slabs in the controlled room. (b) K(t) values used for the 100 and 150mm thick slabs in the controlled room.

**Figure 6.12** Diffusion coefficients and evaporation rates used in this study for the 100 and 150mm thick slabs in the controlled room for the three w/c ratios.

### 6.4 FINITE ELEMENT ANALYSIS RESULTS

This section will present the comparisons between the experimental results and the finite element analyses using the appropriate mesh for the various slabs (Figures 6.1, 6.4 and 6.5)
and the appropriate diffusion and evaporation rates in the laboratory (Figure 6.10) and control room (Figure 6.12). The finite element analyses were carried out using a 1-day time step so comparisons can be made with the experimental results for any time which has been shown above to be most accurate. A full set of results is given in Appendix D.

### 6.4.1 100mm thick slabs in the laboratory

Results from the finite element analyses for the 100mm thick slabs in the laboratory are shown in Figures 6.13, 6.14 and 6.15 for w/c ratios of 0.4, 0.5 and 0.6 respectively. The finite element results exhibit consistency and uniformity with no imperfections, as might be expected, but are they accurate? As may be observed, there is reasonably good agreement between the predicted and measured $rh$ profiles through the depth of the slab over time. This is not surprising since the material model (Figure 6.10) has been calibrated against these particular results but it does provide validity to the diffusion and evaporation models. In some of the cases, there may be some small variations between the finite element analysis and the experimental results and this can be explained in most cases by isolated measurements, sampling or mixing errors, as discussed previously. The finite element analysis results tend to be smoothed and show no such instrument/reading errors. For instance, in Figures 6.13(a) and Figure 6.15(a) at 42 days, some intertwining of the experimental results around the predicted $rh$ profiles through the depth is shown.

One of the aims of the numerical model was to predict the trends both through the depth and at the surface, which are both important in the application of floor coverings. As shown, both the profiles through the depth and the trends over time at the various depths are in good agreement throughout. It is anticipated that the results for any other depths of slab will also give good agreement as only the slab depth is changed and it has been concluded earlier that neither the diffusion coefficient nor the evaporation rate are functions of the slab depth. Therefore, irrespective of the w/c ratio, it is now possible to predict actual $rh$ profiles at any time and at any depth after pouring, with some confidence, for OPC mixes. Other cement types will have different pore structures and are outside the scope of this thesis.
Finite Element Analysis

(a) Profile through depth at various times
(b) \( rh \) at various times

Figure 6.13 Comparisons between finite element analysis and experimental measurements of the internal \( rh \) for slab L(500)0.4(100)1.1.

(a) Profile through depth at various times
(b) \( rh \) at various times

Figure 6.14 Comparisons between finite element analysis and experimental measurements of the internal \( rh \) for slab L(500)0.5(100)1.2.

(a) Profile through depth at various times
(b) \( rh \) at various times

Figure 6.15 Comparisons between finite element analysis and experimental measurements of the internal \( rh \) for slab L(500)0.5(100)1.2.
6.4.2 100mm thick slabs in the control room

The results for the control room are presented and again it is anticipated that these results will also compare well as the evaporation rate has been calibrated against the experimental results. The diffusion coefficient is identical for both as it is not a function of the ambient conditions. Figures 6.16 to 6.18 show similar comparisons between the predicted and measured $\text{rh}$ profiles for the slabs in the control room. The analysis was carried out using the identical physical model as for the previous section but with the material models in Figure 6.12(b) as the evaporation rate now is the dominant driving force in relation to moisture loss in the control room.

As may be observed, particularly in Figure 6.16, a non-linear profile exists early on, with rapid drying near the surface due to the ambient conditions and drying environment but there is relatively little influence of this initially deep in the concrete. This has been discussed at length previously but it is reassuring that the numerical analysis shows similar trends to the measured results. It is clear, therefore, that the model can reasonably predict the effects of a forced drying environment on the $\text{rh}$ in concrete slabs with varying w/c ratios. As discussed in Chapter 5, the finite element trends clearly demonstrate the disadvantages of force-drying slabs, where, although the surface appears dry (approaching 75% $\text{rh}$ on the surface), there is still a large residue of moisture deep in the concrete.

The reasonably good comparisons between the finite element and the experimental trends in Figure 6.16, for example, give confidence to the evaporation model utilised for drying in the control room. As shown, there is close agreement at both 47 and 72-days and the experimental profiles show rapid drying near the surface with little drying below 70mm, as was shown in the control room results in Chapter 5. For example, at 47-days, the measured surface $\text{rh}$ is 74%, while at 70 and 90mm, they are at approximately 85 and 86% respectively. Indeed, the finite element results indicate the $\text{rh}$ is at 88 and 89% at 70 and 90mm respectively.

However, at 20-days, there is a less satisfactory comparison as the finite element profile is approximately 5% higher (at most) than the experimental result at the same time. However, at 40mm, the difference between the two sets of results is only 2% (at 85 and 87% for the
(a) Profile through depth at various times  
(b) $rh$ at various times

Figure 6.16 Comparisons between finite element analysis and experimental measurements of the internal $rh$ for slab R(500)0.4(100)1.10.

(a) Profile through depth at various times  
(b) $rh$ at various times

Figure 6.17 Comparisons between finite element analysis and experimental measurements of the internal $rh$ for slab R(500)0.5(100)1.11.

(a) Profile through depth at various times  
(b) $rh$ at various times

Figure 6.18 Comparisons between finite element analysis and experimental measurements of the internal $rh$ for slab R(500)0.6(100)1.12.
experimental and predicted results respectively). However, there is more confidence that the evaporation rate is accurate, when one considers the results at 47 and 72-days, where both sets of results are equal.

After 62-days, at 90mm in Figure 6.17(a), there is a discrepancy between the results. From the profiles through the depth, it appears that the recorded \( \text{rh} \) at 90mm is a result of experimental error where one would expect the \( \text{rh} \) to be approximately 82% as opposed to the 85% shown. One reason for this is that the cap may have been removed and too long a time was taken for the probe to be inserted into the tube when the reading was taken. By not inserting the probe as quickly as possible allows ambient humidity to enter the tube and the recorded result is higher as it contains both concrete and ambient humidity.

In Figure 6.18(a), there is a noticeable difference between the measured and predicted results at 52 days at 50 and 70mm. As may be observed, the predicted and measured results are approximately 87 and 90% at 50mm and 92 and 94% at 70mm. In the measured profile, the \( \text{rh} \) at 70 and 90mm appears to remain the same at 94% whereas the predicted profile does not reflect this and shows a more gradual \( \text{rh} \) profile through the depth. However, at the surface, there appears to be good correlations between both. As drying continues, there is a better comparison between the two at 79-days. Despite this, there is a small difference over the depth of the concrete which would not be significant long term. The apparent error in the experimental result at 52-days can be put down to instrument error.

However, the important point here is that the reasonably good agreements with the experimental results continue for all three w/c ratios. This is important to floor installers who will wait until 75% \( \text{rh} \) is achieved at the surface and the results give credence to previous discussions that the surface \( \text{rh} \) is reducing much faster than that deeper down. However, one may also conclude that, due to experimental variations, it is not advisable to rely on a single isolated surface reading, or on set of at depth readings, when deciding if it is safe to cover the slab. Properly calibrated finite element predictions have so such drawbacks.

Little movement occurs at depth initially as a result of forced drying (as discussed in Chapter 5) and is not reflected in the moisture deep down. It is only due to the growing
concentration gradient between top and bottom that the moisture deep in the concrete does move upwards.

6.4.3 150mm thick slabs in the laboratory

In the case of the 150mm thick slabs, Figures 6.19, 6.20 and 6.21 show \( rh \) profiles and trends that are similar to those in the previous section, were the finite element model again shows reasonably good agreement with the experimental measurements. In the figures, there is little difference between the measured and predicted results through the depth. Considering that the finite element model was calibrated, initially, against the 100mm thick slabs, this good comparison here suggests that, one calibrated for one depth of an OPC concrete, a finite element model can predict drying for a range of slab depths, \( w/c \) ratios and drying environments. Also, the predicted \( rh \) at the surface is also satisfactory, with only at most 2 to 3% difference over the drying period. To a floor contractor, this 2 to 3% may not make a significant difference to applying the covering, as it is likely that they would simply just allow the floor to dry a further couple of days before application. Indeed, BS 8203 (1996) suggests that a covering can be applied when the surface \( rh \) falls between 75 to 80% but specifies 75% as a conservative safer point.

A further example of experimental error is shown in Figure 6.21(a) at 15mm after 58-days. Again, the \( rh \) is higher than expected which is probably due to some ambient humidity entering the tube resulting in a higher measured \( rh \). A further example is seen in Figure 6.19(b) at 50-days where the surface \( rh \) is again higher than expected.

![Diagram](image.png)

(a) Profile through depth at various times  (b) \( rh \) at various times

**Figure 6.19** Comparisons between finite element analysis and experimental measurements of the internal \( rh \) for slab L(700)0.4(150)2.1.
Figure 6.20 Comparisons between finite element analysis and experimental measurements of the internal $rh$ for slab L(700)0.5(150)2.2.

Figure 6.21 Comparisons between finite element analysis and experimental measurements of the internal $rh$ for slab L(700)0.6(150)2.3.

6.4.4 150mm thick slabs in the control room

Figures 6.22, 6.23 and 6.24 show the $rh$ predictions for the 150mm thick slabs drying in the controlled room using the diffusion and evaporation rates in Figure 6.12 and the mesh shown in Figure 6.5, compared to the experimental results. As seen previously in Figures 6.19 to 6.21, while there are some differences between the $rh$ values, the predictions are still acceptable. For instance, in Figure 6.22, the difference between the results at the surface at 9 days is approximately 7%. However, at 20 and 40-days, the difference is 1 and 4% respectively.
Figure 6.22 Comparisons between finite element analysis and experimental measurements of the internal $\text{rh}$ for slab R(700)0.4(150)2.4.

Figure 6.23 Comparisons between finite element analysis and experimental measurements of the internal $\text{rh}$ for slab R(700)0.5(150)2.5.

Figure 6.24 Comparisons between finite element analysis and experimental measurements of the internal $\text{rh}$ for slab R(700)0.6(150)2.6.
The profiles through the depth are not quite as good as with previous predictions for the 100mm thick slabs in the control room. For example, at 40-days with a w/c ratio of 0.4, there is a difference of approximately 3% at worst at 40mm, while, at 130mm, the predicted values all give good comparisons and this holds true for all the profiles with the exception of the \( rh \) predictions at 130mm in Figure 6.23 at 9-days. As shown, the measured \( rh \) remains almost constant at 95% from 60mm to 130mm. However, over time, this difference between the two reduces and the correlations at both 20 and 44-days are much improved. Again, as anticipated, the finite element model produces smoother and more consistent results while the experimental results are subject to operator, instrument and sampling errors.

This trend, where the \( rh \) below 50% of the depth remains almost constant, has been commented previously in Chapter 5 (Section 5.5.2).

### 6.4.5 200mm thick slabs in the laboratory

As discussed in Chapters 4 and 5, the 200mm thick slabs were produced with a w/c ratio of 0.5 only. Figure 6.25 shows the results from the analysis of the 200mm thick slabs for a w/c ratio of 0.5. As the thickness does not affect the diffusion or evaporation rate, the same material model (Figure 6.10) has been used for the 100, 150 and 200mm thick slabs. Again, the finite element predictions give good correlations with the experimental predictions, but more so at the surface than deeper down in the slab. In Figures 6.25(a) and (b), there appears to be a large difference between the results from 140 to 220-days, as much as 5% \( rh \). For example, in Figure 6.25(a) at 140-days, there appears to be a large difference between the measured and predicted \( rh \) between 40mm and 90mm, where at 90mm, the difference is as much as 6%. This is almost certainly due to experimental error. However, it is unlikely that the error of not placing the probe into the tube quickly enough has occurred here as it is repeated over such a long time and it should have been highlighted sooner. Therefore, it is more likely that the rubber membrane that surrounds the outside of the tubes moved and ambient humidity found its way into the tube and the results were compromised. This can be seen in Figure 5.14, where, between 130 to 140-days, the \( rh \) appears to increase. From 140-days onwards, the \( rh \) decreases. Despite this, the results at 220-days have improved somewhat but the predicted \( rh \) is still less than
finite element analysis

(a) Profile through depth at various times (b) $rh$ at various times

Figure 6.25 Comparisons between finite element analysis and experimental measurements of the internal $rh$ for slab L(500)0.5(200)1.10.

that measured. It would appear therefore that despite the ambient humidity leaking into the tube, the concrete is still drying as the $rh$ over time is still reducing. The predicted $rh$ profiles give ‘smoother’ profiles and the experimental error is more pronounced in these slabs over time.

6.5 COMPARISON WITH PREVIOUSLY PUBLISHED RESULTS

The analysis in Sections 6.2 to 6.4 have shown that the finite element model, when suitably calibrated against real experimental results allow good correlations in the trends for all the slabs in the two drying environments here using the mesh shown in Figures 6.1, 6.4 and 6.5 for the various slab depths with the three w/c ratios used. However, in order to assess its robustness and whether or not it can be used in a wider context, comparisons should be made with previous published measurements of the $rh$ at depth using a similar experimental set-up as here. In Chapter 3, $rh$ profiles published by Kim and Lee (1999) have been presented in Figure 3.6 and compared well with the experimental results in Chapter 5. In their work, they used a Vaisala humidity probe to measure the $rh$ at depths of 30, 70 and 120mm in slab thicknesses of 210mm (x 100mm wide) with drying through one face only using w/c ratios of 0.28, 0.4 and 0.68. Therefore, it is appropriate to compare their results with results here following a series of finite element analyses using suitable diffusion and evaporation rates and accurate physical models.
Figure 6.26 shows the mesh used for the analysis for the 100mm wide x 210mm thick slab. As shown, the top 40% (amounting to 84mm) of the model has a finer mesh as discussed previously and matches the physical model in the analyses. Figure 6.27 shows the diffusion and evaporation rates proposed in this analysis which are calculated pro rata from those shown previously for the slabs drying in the laboratory (Figure 6.10). For instance, for the w/c ratio of 0.68 used by Kim and Lee (1999), the rate of diffusion at $rh = 100\%$ is calculated as $(0.68/0.6)\times5.0\times10^{-8}\text{m}^2/\text{sec}$ where $5.0\times10^{-8}\text{m}^2/\text{sec}$ is the diffusion coefficient at $rh = 100\%$ for a w/c ratio of 0.6 in Figure 6.10(a). This is repeated for the other w/c ratios used by Kim and Lee (1999) (that is, for 0.28 and 0.4) for both the diffusion coefficients and evaporation rates.

Figures 6.28, 6.29 and 6.30 show the comparisons between the experimental results by Kim and Lee (1999) and those predicted using the finite element model here for a 210mm thick slab with w/c ratios of 0.28, 0.4 and 0.68 respectively. As shown, the comparisons between the two sets of results are reasonably good with an average difference of only 3 to 4\% $rh$ at most between them with many predictions within 2\% of those measured. It is noted that the finite element model always over predicts the results, indicating some minor adjustment to the calibration may be required. The results with a w/c ratio of 0.68 are particularly good and this is reassuring in a practical sense as this would be a more common w/c ratio for concretes than a w/c ratio of 0.28 due to hydration, workability, and placing problems.

**Figure 6.26**  Mesh used to compare results between the finite element analysis here and experimental measurements by Kim and Lee (1999).
Figure 6.27  Diffusion and evaporation rates used to compare results between the finite element model here and experimental measurements by Kim and Lee (1999).

Figure 6.28  Comparisons between finite element analysis and experimental measurements by Kim and Lee (1999) with a w/c ratio of 0.28 at 40, 120 and 200-days.

Figure 6.29  Comparisons between finite element analysis and experimental measurements by Kim and Lee (1999) with a w/c ratio of 0.4 at 40, 120 and 200-days.
Figure 6.30 Comparisons between finite element analysis and experimental measurements by Kim and Lee (1999) with a w/c ratio of 0.68 at 40, 120 and 200-days.

It is perhaps not surprising that the two sets of results are reasonably close as the experimental set-ups were very similar with both using OPC and drying taking place through one face only as the other five sides are fully impervious. Also, the conditions for the use of humidity probes at various depths (with plastic sleeve and rubber plugs to ensure no ambient humidity leaked into the sleeve) were similar in both cases. Overall, the results in Figures 6.28 to 6.30 gives support and added confidence that the physical models for the slabs and the material models calibrated using the experimental results here demonstrate reasonable robustness and applicability in practice.

6.6 CONCLUSIONS

In this chapter, simulations using finite element analyses on different slab thicknesses (100, 150 and 200mm), w/c ratios (0.4, 0.5 and 0.6) and two drying environments (natural and accelerated) were performed to compare with measured $\text{rh}$ profiles with an to aim to accurately predict $\text{rh}$ profiles in concrete slabs for any slab thickness and w/c ratio during drying. The results fell within 5% of measured $\text{rh}$ values and regularly predicted within 2%. The finite element model, DIANA (version 7.2), was used to predict the $\text{rh}$ profiles which accounted for each of the relevant variables using a 2-dimensional model. This package was chosen as it is easy to understand, set up and run.
The concrete slabs were modelled using a mesh with 8-noded general flow elements suitable for diffusion type analysis. The top 40% of the slab was modelled with a finer mesh than the remaining slab, as concurring with the ASTM on measurement depth. This also responds to trends observed in the experimental results. Also, the sides and base of the model assumed they were impervious as no boundary conditions were specified. The evaporation was modelled using a 2-noded boundary element suitable for boundary flow analysis. These elements are common for general flow analysis. The findings from the sensitivity study found mesh densities adjusted for the three slab thickness gave a good comparison with measured results. Varying the time steps showed no significant difference in results between a time step of 1 or 10-days. Indeed, so comparisons could be made with the experimental results at any age, the time step chosen was 1-day.

The model was quick to converge and was used to examine a number of parameters to determine the optimum geometry and model to achieve the best results including:

- Varying mesh densities,
- Varying time stepping lengths,
- Fully insulated sides and base, and
- Comparison with previous literature.
- Suitable material models

The model was calibrated to best suit the experimental results as determined here for the three w/c ratios and type of drying environment employed for the 100mm thick slabs in the laboratory and control room. The same material model was then used for the 150mm and 200mm thick slabs in the laboratory and the results compared well with the actual experimental data for OPC concretes. In the control room, the diffusion coefficient was identical to that used for analysis the laboratory-based slabs as it is assumed that diffusion characteristics are not affected by the ambient conditions. However, the evaporation rates were separately calibrated to account for the more severe drying conditions in the control room. The results from the modelling of these slabs drying in the laboratory and control room compared well with the experimental data. The increase in evaporation rate in the control room is a practical way to account for the accelerated drying conditions and it is concluded that the model gave accurate predictions of the $rh$ both through the depth and at
the surface with time.

Comparing research from previous authors using their proposed diffusion rates showed that the proposed non-linear diffusivity by Bazant et al, 1971, which varied with the internal humidity, gave the best results compared to experimental measurements. Other authors proposed diffusion models which did not compare so well, mostly due to higher initial diffusion rates as they assumed an immediate reduction in the diffusion rate rather than a constant rate of diffusion up to 85% $rh$, which has been shown to be the case in the experimental results. The accuracy of the finite element predictions strongly supports the Bazant and Najjar (1971) model. A method to use the VET results to determine an evaporation rate did not give suitable comparisons with the experimental measurements here nor with previously published values and so it is discounted. Comparing the finite element results here with published $rh$ measurements from a similar experimental set-up gave good comparisons using a range of w/c ratios and a slab depth of 210mm. The slab depth and w/c ratios used in these previous analyses were incorporated into a physical model with a finer mesh over the top 40% of the depth using diffusion and evaporation rates calculated pro rata from those calibrated here. Following good agreements between the results, it can be concluded that the model here, with the calibrated material models, demonstrated reasonable robustness and can be widely applicable, particularly for OPC concretes. Further studies into appropriate diffusion/evaporation rates are required for other binders.

Comparing the finite element analysis results with the measured $rh$ profiles gave overall good agreement that should not be surprising since the material model was calibrated against the 100m slab experiment results. However, the analysis does give credence to the set-up of the physical and material models especially for a range of w/c ratios, of different depth slabs in different environments. The predicted results fall within 5% for most of those measured where the difference is mostly due to the experimental and instrumental errors discussed previously. The two important requirements of the predicted results, namely a good correlation with the $rh$ throughout the depth, and good comparisons of the time taken to reach 75% $rh$, were satisfactory.

Even considering the differences in the results, a model like this would still be highly
advantageous to a floor covering contractor that can now avoid the need to rely on surface readings alone and time consuming and costly experimental tests.
7. EFFECT OF IMPERMEABLE COVERINGS ON CONCRETE FLOORS

7.1 INTRODUCTION

The preceding chapters have shown that when the concrete surface achieves a $rh$ of 75%, a residue of moisture will exist at depth in the slab. BS 8203 (1996) assumes that 75% $rh$ is a safe point to apply floor coverings. However, this does not consider the effect of residual moisture through the slab at the point of covering and the long term problems that can occur. The effect of applying the covering with this internal $rh$ is discussed here with the aid of experimental tests and finite element analysis.

This residue of moisture is principally a function of the slab depth, w/c ratio and the drying environment. The previous chapter has demonstrated that the finite element method is capable of predicting the $rh$ profiles in concrete during drying. The method provides a valuable insight into drying for concrete manufacturers and floor-covering contractors alike who can be better informed of how the $rh$ varies as drying continues and the various factors that influence it.

Moisture migration in concrete floors is of some practical importance as it, for instance, is playing an increasingly important role in modern industry, as a ‘working platform’ for most domestic and industrial activities. Floor covering can also be found in specialist applications such as warehousing, sports halls and other leisure facilities. In the UK, concrete floors have an annual value in excess of UK£100 million with more than 6 million square metres of floor being constructed each year (Hulett, 2002). Figure 7.1, reproduced from the TR34 technical report (Hulett, 2002) on concrete industrial floors, presents a flow chart from the clients requirements, through design and finally onto construction.

To investigate the effect of residual moisture on concrete floor coverings, experimental results will be presented that demonstrate how the internal $rh$ will slowly equilibrate after the application of an impermeable vinyl covering. This work, in terms of measuring the actual change in the internal $rh$ after the application of an impermeable covering and the associated vapour pressure build-up has not received any attention before in peer
reviewed publications. It offers a real insight into the effect of impervious coverings on concrete floors and how moisture builds up and ultimately leads to long-term problems of delamination, buckling, blistering, swelling etc. The results show that moisture equilibrium is gradually achieved in the concrete as the residual moisture slowly and steadily continues to diffuse upwards, due to the humidity gradient between the top and bottom of the slab at the time of covering (West and Holmes, 2003).

It will also be shown that the final equilibrium $rh$ can be considerably greater than the 75% surface $rh$ that is normally achieved before any covering is applied (BS 8203, 1996), particularly so if the slab has been forced dried as generally, more residual moisture remains deep in the concrete in this case, as has been shown already. The vapour pressure that accompanies the increase in $rh$ under the covering has also been measured using pore pressure gauges in some slabs dried in both the laboratory and the control room. The
results show that, as equilibrium is reached in the concrete, an increase in the vapour pressure under the covering is observed. To assess the measured pressures under the covering, a series of tests to measure the pull-off force and tensile stress required to lift the vinyl off 12 concrete cubes (150x150x150mm), were carried out.

In addition to the experimental measurements, the existing finite element model has been further developed and employed to predict this redistribution of moisture through the slab and to identify the point at which equilibrium occurs. To do this, the surface boundary condition is now set-up to provide an impervious boundary through which no moisture can be lost. Also, the initial moisture condition will be the actual \( rh \) profile through the depth when the surface was at 75% \( rh \). Previously the \( rh \) was taken as 100% prior to drying taking place. The only material property specified for the finite element study is now the diffusion coefficient as diffusion will continue in the concrete due to the humidity gradient between the top and bottom of the slab during drying (West and Holmes, 2005). As seen in Chapter 5, the use of accelerated drying methods resulted in the surface reaching a \( rh \) of 75% faster than if it was allowed to dry naturally. However, this results in a large residue of moisture in the concrete and may cause long-term problems as it continues to slowly migrate upwards and ultimately builds up under the covering over time. The diffusion rate used in the model will be identical to that calibrated in Chapter 6.

Notwithstanding the above, a method that allows the continued use of accelerated drying methods while not resulting in these types of problems long-term would be an advantage. Section 7.7 considers how this can be achieved by allowing drying to continue using accelerated drying until the surface \( rh \) reaches a significantly lower \( rh \) than 75% so that the long-term \( rh \) through the concrete falls within ‘safe’ limits. This would be particularly advantageous to contractors that are under pressure to apply the covering sooner.

### 7.2 EXPERIMENTAL WORK

When the 150mm thick slabs in the laboratory and the control room reached 75% \( rh \) on the surface they were covered with an impermeable covering. The covering, a standard floor vinyl with a sponge back, was applied using evo-stick super acrylic adhesive glue suitable for sticking vinyl type floorings to concrete surfaces. Before application, the concrete
surface must be fully cured, sound and free from contaminants. Therefore, before application, the surface was gently ‘smoothed’ using a wire brush to remove all bumps with the resulting dust removed using a hand-brush and a heavy-duty industrial hoover. In addition, the heater and dehumidifier in the control room were turned off for 48 hours before the covering was applied and the door of the control room was left open to allow the heat to escape, as the manufacturer required that the vinyl was applied in normal conditions. The vinyl was cut into square pieces (710x710mm) and left for 24-hours to become acclimatised to the environment in which they would be kept.

The glue was applied with a V-notched trowel with serrated edges at 1.5cm intervals at an angle of 60° (Figure 7.2). This was in accordance with the instructions provided by the glue manufacturer. When the glue became ‘tacky’ to touch, the covering was applied by laying it over the central area of the slab, removing it for a few moments and then re-laying it using direct pressure ensuring the covering was adhered evenly to the concrete surface. The holes for the humidity tubes, pressure gauge and lifting eyes were carefully cut out using a Stanley knife. Any cuttings made on the covering were sealed using silicone to ensure that the concrete surface was totally impervious to moisture loss and vapour pressure build up. The extra 10mm on all four sides was removed using a Stanley knife. Figure 7.2 shows a typical covered slab and the trowel used to apply the glue.

![Figure 7.2](image)

**Figure 7.2** Covered slabs with the serrated edged trowel used to apply the glue.

### 7.2.1 Measurement of the $rh$ and vapour pressure underneath the covering

After the slabs were covered, the $rh$ at the various depths in the slabs (10, 35, 60, 85,
110 and 130mm, as before) were regularly monitored to determine the redistribution of the moisture in the concrete, along with the vapour pressure just under the covering at the centre of the slab, as shown in Figure 7.3. The vapour pressure was measured using PDCR 81 pore pressure gauges (Figure 7.4) which are regularly used in soil mechanics. These probes are capable of measuring small changes in pressure and consist of a ceramic filter suitable for rugged construction. The standard specification for the gauge ranges from 1-35 bar (100-3500 kPa) and must be used in an airtight environment. To achieve this, a rubber bung, like that used to cap the plastic tubes (Figure 4.14), as it also fitted the diameter of the pressure gauge (6.8mm). The pressure gauge was inserted into the rubber bung and placed into a pre-drilled hole in the centre of the slab to a depth of 15mm. Figure 7.5 shows a schematic of the set-up. The pressure is measured as a function of the difference in voltage between the input (10V) and output voltages (mV). As only four probes were available, only four slabs could be monitored for vapour pressure, namely, the slabs with w/c ratios of 0.5 and 0.6 slabs dried in the laboratory and the controlled room. These w/c ratios were chosen as they represent the more typical range used in modern construction due to their improved workability of fresh concrete on site (see Chapter 4).

The probe was attached to a voltmeter via four thin wires (red, blue, yellow and green) where two were used for input (red and blue) and two used for the output (yellow and green) (see Figure 7.4). The resistance had been calibrated using a water pressure...
Figure 7.4  PDCR 81 Pore pressure probe used to measure the vapour pressure under the impermeable covering.

Figure 7.5  Set-up used to measure the increase in pressure under the covering (NTS)

instrument, where, using an input of 10V and by increasing the water pressure, the output (in mV) was noted. The results yielded a number of calibration graphs, shown in Figures 7.6(a)-(d). The pressure was increased in steps of 0.5 Bar to a maximum of 3 Bar, and then decreased in steps of 0.5 Bar to ensure the same output voltages were measured.

Only one measurement of the pressure was available per slab, and, ideally, it would be better that at least four probes per slab were used. This would provide a better representation of the pressure build-up, where, if one probe was operating poorly, or if a local variation in pressure existed it would be obvious and by using more probes an average of the vapour pressure could be calculated. Despite this, as four slabs were monitored, one can still observe the increase in pressure particularly so in those slabs that
Figure 7.6  Calibration graphs for the four pressure probes for the slabs with the w/c ratios of 0.5 and 0.6 in the laboratory (a and b) and the controlled room (c and d) respectively. (e) Pressure gauge used to calibrate the pore gauges.

have been artificially dried where the greater residual moisture exists deep in the slab. However, shortly after the experiment began, the probe measuring the pressure in the w/c=0.5 slab in the laboratory, stopped working.
7.2.2 DataScan set-up

As part of the vapour pressure measurement a DataScan 700 apparatus was used to record the voltage output. The DataScan apparatus is a series of intelligent measurement and data collection units developed for the industrial and scientific sectors (DataScan, 1995). Data measurement is made through measurement processor modules that contain an A/D converter, microprocessor with a battery backup and power supply, along with a RS232 link capability to a host computer. The measurement processor used here is version 7221 that provides 8 analogue inputs including channel excitation, as shown in Figure 7.7, with all the component parts labelled. A typical DataScan installation is shown in Figure 7.8 with the complete set-up in Figure 7.9.

![Figure 7.7 7221 Measurement Processor](image)

![Figure 7.8 Typical DataScan installation (DataScan, 1995).](image)


Figure 7.9 Set-up used to monitor the increase in vapour pressure under the covering.

7.3 EXPERIMENTAL RESULTS

The following sections will present the experimental readings taken of the $rh$ at the various depths and the vapour pressure increase after the impervious covering was applied, for those slabs dried in the laboratory and in the controlled room at various times during equilibration of the moisture for the 150mm thick slabs. The complete set of results can be found in Appendix E. The main observations of the results to be discussed here, for both the laboratory and control room slabs, are

- effects of the covering on the internal $rh$,
- effects of the w/c ratio on moisture equilibrium within the slabs,
- long-term moisture equilibrium values,
- time for equilibrium to occur,
- vapour pressure increase under the covering, and
- pull-off tests from concrete cubes

7.3.1 Laboratory results

Figures 7.10, 7.11 and 7.12 show the results from the experimental programme described
Figure 7.10  Experimental results for slab L(700)0.4(150)2.1 showing the $rh$ profiles (a) through the depth and (b) over time.

Figure 7.11  Experimental results for slab L(700)0.5(150)2.2 showing the $rh$ profiles (a) through the depth and (b) over time.

Figure 7.12  Experimental results for slab L(700)0.6(150)2.3 showing the $rh$ profiles (a) through the depth and (b) over time.
above with the \( rh \) as a function of (a) the depth through the concrete and (b) over time for the laboratory dried slabs with w/c ratios of 0.4, 0.5 and 0.6 respectively. As shown, the \( rh \) in the slabs is slowly reaching equilibrium within the concrete as the moisture diffuses upwards to the surface due to the humidity gradient existing between the top and bottom of the concrete. The profiles indicate clearly the rate at which the near surface \( rh \) is increasing and the \( rh \) near the base (at 130mm) is decreasing. In Figure 7.12(a), at 30-days at 60mm, there is a further example of experimental error in which a reading of 78.5% was taken where it would be expected to be over 79%, considering the profile through the depth.

In the figures, the \( rh \) appears to slightly decrease even close to the surface after 20-days following sealing. For example, in Figure 7.12(b), at 35mm, the \( rh \) decreases from 78.5% to approximately 78% from 0 to 20-days where one would expect it to increase as the internal moisture equilibrates. This is probably a result of the way the slab was prepared to receive the covering as the surface was prepared by gently smoothing with a wire brush so the adhesive would better adhere to the concrete when the covering was applied. By doing this, the near surface pores could have been opened and exposed allowing moisture to be lost to the environment. As well as this, the adhesive may have absorbed some of the near surface moisture as the pores would have been exposed by wire brushing, causing the moisture in those areas to decrease. Further, the drying process at the surface prior to covering does take some time to reverse locally. Taking all of these into account, it is reasonable to assume that they would combine to cause the near surface \( rh \) to decrease temporarily as shown.

From the graphs, one could deduce that equilibrium appears to have been reached after approximately 120, 60 and 90-days in Figures 7.10 to 7.12 for the w/c ratios of 0.4, 0.5 and 0.6 respectively. At first glance, this appears to be inconsistent however, if one considers the initial condition of the three slabs at the time of covering and their representative diffusion coefficients, the reason becomes clearer. For example, in Figure 7.10, the initial \( rh \) at 10 and 130mm are approximately 76.8% and 79.9% respectively. In Figure 7.11, the initial \( rh \) at the time of covering are 76.1% and 78.2% at 10 and 130mm respectively. Therefore, due to the larger differential in the initial \( rh \) at the time of covering between 7.10 and 7.11, it is reasonable to assume that Figure 7.11 would reach equilibrium sooner than Figure 7.10. This also holds true when one compares the initial condition for Figures
7.10, 7.11 and 7.12 as the initial \( rh \) at 10 and 130mm are approximately 76.9 and 81.5\% respectively.

When comparing Figures 7.10 and 7.12, the slightly more onerous initial conditions in Figure 7.12 might suggest it should take longer for equilibrium to occur for the 0.4 w/c ratio slab, while, in fact, it took 90-days compared to 120-days respectively. This anomaly can be explained when one considers that moisture will diffuse at a faster rate in a higher w/c ratio concrete. Therefore, even with the more onerous initial surface condition in Figure 7.10, there is a more open physical pore structure in Figure 7.12 which may lead to faster moisture diffusion through the concrete with equilibrium occurring more rapidly.

At 60mm, or 40\% of the slab depth, the measured \( rh \) appears to give a good representation of the long term equilibrium \( rh \). For example, in Figure 7.10, the measured \( rh \) throughout the 120-days is approximately 78\%. In Figure 7.11 at 145-days, the measured \( rh \) is approximately 77.4\% very close to its initial value of 77.5\% \( rh \) at \( t=0 \). In fact, it would appear that to identify the most appropriate depth at which to measure the \( rh \) in order to obtain an estimate of the long-term \( rh \) is to identify the point where the \( rh \) does not change with time in the two profiles. In Figures 7.10 and 7.11, this balance point appears to be at approximately 60mm, or 40\% of the slab depth for the 150mm thick slabs. In Figure 7.12, while less obvious due to experimental error, this balance point appears to be between 60 and 85mm, that is 40 to 55\% of the depth for the 150mm thick slabs. Therefore, Figures 7.10 and 7.11 provides strong evidence to support the proposal that ASTM have suggested to measure the \( rh \) at 40\% of the depth as this gives a good estimation of the long-term \( rh \).

7.3.2 Control room results

Figures 7.13, 7.14 and 7.15 provide the \( rh \) profiles in the three slabs previously dried in the controlled room after the impermeable covering was applied. The trends in Figures 7.13 to 7.15 are similar to those already discussed for the laboratory-dried slabs. However, the initial \( rh \) profiles with depth are much more pronounced here, which is, of course, due to the more onerous drying regime in which they were dried. For example, in Figure 7.13, the initial \( rh \) range is between 75 to 86\% as compared to 75 to 79.5\% in Figure 7.10.
**Figure 7.13** Experimental results for slab $R(700)0.4(150)2.4$ showing the $rh$ profiles (a) through the depth and (b) over time.

**Figure 7.14** Experimental results for slab $R(700)0.5(150)2.5$ showing the $rh$ profiles (a) through the depth and (b) over time.

**Figure 7.15** Experimental results for slab $R(700)0.6(150)2.6$ showing the $rh$ profiles through the depth (a) and over time (b).
What this does mean is that (a) it will take longer for equilibrium to occur especially when compared with the laboratory-based slabs and (b), the surface \( rh \) increase (to reach equilibrium) will be higher. For example, the time for effective equilibrium to occur in this slab (at least over the time period shown) is approximately 250-days, compared to approximately 160-days in the same slab in the laboratory with a w/c ratio of 0.4 (see Figure 7.10). Also, the surface \( rh \) at these times are approximately 84% in Figure 7.13 compared to 78% in Figure 7.10.

For the w/c = 0.5 slabs, the times taken for equilibrium to occur are approximately 251 and 145-days in the control room and laboratory, with a final \( rh \) through the depth of 81.5 and 77.5% respectively. Finally, in the w/c = 0.6 slabs, the times taken for equilibrium to occur are approximately 240 and 175-days in the control room and laboratory with a final \( rh \) through the depth of 82.4 and 79.5% respectively. This slight anomaly in final \( rh \) values can again be explained when one considers the initial conditions. The times to equilibrium, while being admittedly subjectively estimated, are in practice indicated for each w/c ratio due to both the initial conditions and the various diffusion rates.

In Figure 7.13(b), a ‘flatter’ \( rh \) profile exists at 130mm than in Figures 7.14(b) and 7.15(b). This is due to the initial profile through the depth in Figure 7.13(a) when the surface is at 75% \( rh \) where it appears the \( rh \) sharply ‘drops’ to 40mm depth, below which there is only a small decrease in the \( rh \). As shown in Figures 7.14(a) and 7.15(a), the profiles there appear to be more constant or gradual through the depth. The consequence of this is that very little change takes place at 130mm until about 200-days in Figures 7.13(a) and (b), while the opposite is true in the other two Figures. This is due to the different \( rh \) profiles with depth and the relevant diffusion coefficient rates with w/c ratio.

Due to the longer time for equilibrium to occur in the control room slabs, it is clear why the problems with floor coverings often occur some-time after they were first applied and not immediately after. However, as was also observed for the laboratory slabs, the moisture also builds up under the covering in those slabs in a normal drying environment; so the question arises as to why the problems of delamination etc occur much more to slabs that are force dried? The answer lies in the fact that the level of moisture that builds up under the covering is much greater for force dried slabs than that in the laboratory dried slabs, as
much as 4-5% higher on average in the cases observed here. This is clearly due to the much larger residual moisture deep in the slab when a covering is applied to the slab, which has been forced dried, irrespective of the w/c ratio.

Another interesting observation showing a difference between the w/c results can be made by comparing the progress of moisture movement in Figures 7.13(a) and 7.14(a). For the 0.4 w/c ratio, with a more severe profile with depth, progress at 130mm is more gradual with time. In Figure 7.14(a), there is a rapid change in $rh$ at 130mm depth in the first 80-days, with a more uniform distribution of $rh$ at that stage, unlike the previous case. This may possibly be due to the faster rate of diffusion, a suggestion given some support by reference to Figure 7.15(a) in which, while the trends are not so pronounced, significant redistribution of $rh$ also occurs in the first 80-days.

As may be observed, the measured $rh$ at 60mm, or 40% of the slab depth again gives a good estimate of the long-term equilibrated $rh$. For example, in Figure 7.15(a), the measured $rh$ at 60mm is approximately 82% as it is at 240-days. In Figure 7.14, the measured $rh$ initially at 60mm is 81% and at 251-days, the point of equilibrium, is 81.5%. However, in Figure 7.13, the ‘balance point’ is not as obvious as before where the $rh$ at 60mm initially and at 269-days is 85.5% and 84.5% respectively. Despite this, these results give further credence to the ASTM proposals to measure the $rh$ at 40% of the depth for one face drying. It also justifies the selection of the finer mesh over the top 40% of the finite element models used here (see Figures 6.1, 6.4 and 6.5).

7.3.3 Vapour pressure results

Figures 7.16(a) and (b) show the increase in vapour pressure underneath the covering for the 150mm slabs with w/c ratios of 0.5 and 0.6 in (a) the laboratory and (b) the controlled room. As stated earlier, one pressure gauge broke after approximately 20-days and so full comparisons are only available between the vapour pressures for the w/c = 0.6 slabs in the laboratory and control room which is still useful as a concrete with a w/c ratio of 0.6 is common in practice.

It is clear in Figure 7.16 that the w/c = 0.6 slabs have a greater vapour pressure than the
Figure 7.16  Experimental measurement of the vapour pressure increase (a) in slabs L(700)0.5(150)2.2 and L(700)0.6(150)2.6 and (b) in slabs R(700)0.5(150)2.5 and R(700)0.6(150)2.6.

w/c = 0.5 slabs on average, approximately 250Pa over the 210-days. This is hardly surprising since both w/c=0.6 slabs have a greater residue of moisture remaining in the slab (on average) at the time of covering than the w/c=0.5 slabs, as may be deducted in Figures 7.12 and 7.15.

A comparison between the pressures under the covering in the w/c=0.6 slab dried in the laboratory and the control room are shown in Figure 7.17. As shown, there is a significantly greater vapour pressure in the control room slab. For instance, after 180-days, there is a difference between the two of approximately 4000Pa. This difference is due to the larger residue of moisture at the time of covering in the control room slabs compared to the laboratory based slabs, as shown in Sections 7.3.1 and 7.3.2.

The importance of these tests is that along with an increasing build-up of moisture under the covering (see Figures 7.12 to 7.15), there is a corresponding increase in vapour pressure and the combination of the two is partially responsible for the floor covering damage and problems mentioned above. This is particularly true for those slabs dried in the control room where the vapour pressure is much higher than that in the laboratory. However, it is unlikely that, alone, the pressures here are likely to cause the lifting of tile etc reported earlier. The fact is that the maximum pressure recorded is approximately 10,500Pa, or 0.01MPa, which appears to be a small pressure in practical terms. It would be more likely in this instance that if damage did occur, it would be the combination of poor
workmanship, poor glue strength or air bubbles being present at the time of covering and the effect of moisture build-up that would be the likely cause of any damage. Also, the presence of salts in the migrating moisture reacting with the glue may also contribute to possible damage. Despite this, this pressure corresponds to a vertical force applied under the covering, for the 700x700mm surface area, of 5.145kN, which, in itself, is quite high. However, this force was not enough, in this instance to lift the vinyl as no damages was observed in the control room specimens. Therefore, in order to assess what force is required to physically lift the covering, a number of pull-off tests were undertaken. This involved casting 12No. 150x150x150mm concrete cubes with w/c ratios of 0.5 and 0.6 (to match those above) and measuring the force required to pull off a 100x100mm piece of vinyl directly (see Figure 7.18) using a Denison tensile testing machine, as shown in Figure 7.19. The covering was applied in the same manner as it was to the concrete slabs. The concrete cubes were made up using the material proportions as shown in Table 4.4. The mixes were designed with the same slump and compressive strength as before and were made in an identical manner as the slabs used for the drying experiments (as described in Chapter 4). After mixing, they were compacted in the moulds in two layers and cured for 3-days in a water-bath with an average water temperature of 20°±2°. After curing, the cubes were air dried for the requisite number of days and then covered with the vinyl on one face as directed by the supplier.

The pull-off tests were conducted at 3, 28 and 56-days with the covering being applied 1-day prior to each test to investigate the effect the drying had on the pull-off loads required.
The results from the tests are shown in Table 7.1. As shown, the cubes with a w/c ratio of 0.5 have a greater pull-off force required as there is less water than...
Table 7.1  Experimental results for the pull-off tests

<table>
<thead>
<tr>
<th>TIME</th>
<th>CUBE NO.</th>
<th>W/C RATIO</th>
<th>PULL-OFF FORCE (KN)</th>
<th>TENSILE STRESS (MPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-days</td>
<td>1</td>
<td>0.5</td>
<td>5.26</td>
<td>0.234</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.5</td>
<td>5.34</td>
<td>0.237</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.6</td>
<td>5.20</td>
<td>0.231</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.6</td>
<td>5.24</td>
<td>0.233</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.5</td>
<td>6.00</td>
<td>0.267</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.5</td>
<td>6.19</td>
<td>0.275</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.6</td>
<td>5.40</td>
<td>0.240</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.6</td>
<td>5.58</td>
<td>0.248</td>
</tr>
<tr>
<td>28-days</td>
<td>9</td>
<td>0.5</td>
<td>6.35</td>
<td>0.282</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.5</td>
<td>6.30</td>
<td>0.280</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.6</td>
<td>5.90</td>
<td>0.262</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.6</td>
<td>5.92</td>
<td>0.263</td>
</tr>
</tbody>
</table>

those cubes with a w/c ratio of 0.6. Also, over time, the pull-off force increases for both w/c ratios as the cubes dry more and more and the glue adheres better to the drier concrete. The average tensile stress exerted to remove the vinyl in Table 7.1 is 0.234MPa, 0.244MPa and 0.252MPa for the tests at 3, 28 and 56-days respectively. Comparing this to the measured vapour pressures in Figure 7.17 above (0.01MPa), it is clear that they were not high enough to cause the vinyl to blister or rise from the concrete.

This may be due to a number of reasons. Firstly, there may have been some leakage of pressure around the pressure probe as it may not have been adequately sealed. Secondly,
the probes themselves may have been faulty although the water calibration suggests this is not the case. This area clearly requires further work.

What the above does demonstrate is that the vapour pressure alone is unlikely to cause delamination. However, in conjunction with the moisture resulting in solubility of the glues, increased effects of efflorescing salts in addition to poor workmanship and poor placing of the materials in the first place all contribute to the possibility of long-term problems to the covering.

7.4 **FINITE ELEMENT ANALYSIS**

From the experimental results in Figures 7.10 to 7.15, it is clear that, after an impermeable covering is applied, moisture will continue to migrate upwards until equilibrium occurs. Also, the final $rh$ distribution through the slab, on average, will be higher than 75%, especially if the concrete was forced dried.

If floor installers knew this final equilibrium $rh$ value, they would have more of an insight into the effects of applying the floor covering when moisture remains deep in the concrete, particularly if the slab has been forced dried even if the surface is at a satisfactory $rh$. This presents an opportunity to increase the current knowledge in this area by performing a numerical study into the magnitude of the final moisture equilibrium after an impermeable covering is applied, and the expected time for this final equilibrium to occur under a range of conditions. Therefore, the finite element model, as described previously, was further developed to account for the changes which arise when applying an impermeable covering, namely

- a new impervious surface boundary condition,
- the removal of the evaporation boundary, and
- a new initial conditions that reflect the $rh$ through the thickness of the concrete slab when the surface reaches 75% $rh$.

The mesh used for this analysis is identical to that in previously to model the drying through the 150mm thick slabs, shown again in Figure 7.20.
Figure 7.20  Finite element mesh set-up for the analysis into the moisture equilibrium in the sealed 150mm thick slabs in the laboratory and the control room.

7.4.1 Boundary and initial conditions

As stated above, the changes to the existing model to allow prediction of the effects of applying a covering on the internal $rh$ are to alter the top boundary condition and input the initial conditions. The surface condition must represent the impervious floor covering where the surface elements are specified to have ‘no flow’ through them over the entire analysis which is specified in DIANA in tables ‘BOUNDARY’ and ‘TIMEBO’. In DIANA, if a boundary does not have a condition applied, it is assumed to be perfectly insulated, as discussed in Chapter 6. Therefore, the previous evaporation condition is simply omitted from the input file along with the B2HT elements used to model it.

The initial condition for these models is the $rh$ profile through the depth of the concrete when the surface (at 75% $rh$) is sealed. For example, Figure 7.21 shows the experimental initial $rh$ profiles for the w/c = 0.5 slabs in the laboratory and the room. These profiles must be specified in the input file with the syntax for the initial conditions (in table ‘INIVAR’). In this table, an initial condition must be specified for every node in the mesh as DIANA will not interpret the initial conditions between nodes. Indeed, if a node has not been allocated an initial condition, DIANA will specify a default value, which, for diffusion type analysis, is zero.

However, as drying is 1-dimensional here, the $rh$ at a certain depth is the same through the slab. This is confirmed in Figure 7.22, which shows the bands of $rh$ in the concrete using the post-processor in DIANA at 20-days.
7.4.2 Material properties

The only material property that needs to be specified now is the diffusion coefficient. As stated earlier, a humidity gradient still exists in the concrete due to the residual moisture in the concrete upon covering and moisture will continue to diffuse inside the concrete. The diffusion coefficient model used is identical to that used for the drying analysis, as shown in Figure 6.10(a) for the three w/c ratios (0.4, 0.5 and 0.6). The input for the diffusion coefficients is the same as before, with the model incorporating the appropriate diffusion rate for the various \( rh \) values.
7.4.3 Preliminary analysis

This section will present a number of preliminary analyses carried out using the new surface impervious boundary and initial conditions through the depth with the diffusion coefficients in Figure 6.10(a) after the covering was applied as equilibrium is reached for the 150mm thick slabs in the laboratory and the controlled room. The preliminary analysis carried out involved:

- Very early (≤12-hours), using 1-hour time steps, and early (≤10-days) predictions of the \( \text{rh} \) after the covering is applied and
- Long-term prediction of the \( \text{rh} \) changes after application of the covering.

**Early \( \text{rh} \) predictions**

Figures 7.23 and 7.24 show the very early (≤12 hours) and early (≤10 days) finite element predictions of the \( \text{rh} \) profiles after the impermeable covering was applied to the surface for a 150mm thick slab with a w/c ratio of 0.5, using the mesh shown in Figure 7.20 with an impervious boundary, the diffusion coefficient shown in Figure 6.10 and the initial condition in Figure 7.21. From Figure 7.23, there is little movement deep in the concrete but some \( \text{rh} \) increase at the surface. For example, in Figure 7.23(a), the surface \( \text{rh} \) increases from 75 to 75.75% over the initial 12-hours. However, there is no noticeable difference in the \( \text{rh} \) at 130mm over the same period.

In Figure 7.23(b), the surface \( \text{rh} \) increases from 75 to 75.9% over the initial 12-hours. However, unlike the laboratory based slab, the \( \text{rh} \) decreases from 85.5% to 84.5% at 130mm over the same period, due to the increased \( \text{rh} \) difference in the control room slab compared with the laboratory based slab. Also, between 4 and 12-hours there is little difference between the \( \text{rh} \) at 130 and 85mm because as no concentration gradient exists no diffusion can occur at depth. However, since the \( \text{rh} \) at 65mm is approximately 81.5%, one would expect the \( \text{rh} \) at 85mm and below to decrease over the coming days due to this humidity gradient.

In Figure 7.24(a), the surface \( \text{rh} \) increases from 75% to approximately 76.5% over the initial 10-days. At 130mm, there is a small decrease of approximately 0.25% over the same
Figure 7.23 Very early (≤ 12 hours) finite element predictions of the changing \( rh \) after (a) application of the impermeable covering in the laboratory and (b) in the controlled room using the initial conditions from the experimental results (w/c = 0.5).

Figure 7.24 Early (≤ 10 days) finite element predictions of the changing \( rh \) after application of the impermeable covering (a) in the laboratory and (b) the controlled room using the initial conditions from the experimental results (w/c = 0.5).

period. However, in Figure 7.24(b), the \( rh \) at the surface increases from 75% to 77.5% over 10-days, where, like the laboratory based slabs, there is only a minor (approximately 0.5%) increase at 130mm.

**Long-term \( rh \) predictions**

Figure 7.25 shows the time taken for equilibrium to be reached theoretically for the w/c = 0.5 slabs (a) for the laboratory specimens (at 450-days) and (b) the control room specimens (at 1200-days) both in the same environment as simulated by the new finite element model described above. This difference is due again to the initial concentration gradients in both slabs as a result of their drying environments where the residual moisture on sealing is
Figure 7.25  Long-term finite element predictions for the slabs (w/c = 0.5) based in (a) the laboratory and (b) the control room when the surface reached 75% rh. 

much higher in the control room slabs. For instance, while both profiles have a rh of 75% at the surface initially, the rh at 130mm is approximately 78.25% and 85% in the laboratory and control room respectively. However, it would be impractical to wait for these times to occur in any experimentation programme to confirm this so it would be reasonable to assume that when the rh difference between the top and bottom of the slab fall within, say, 0.5 to 1.0%, equilibrium has effectively been reached. In practical terms, the rh profile may never achieve a vertical profile like that shown at 450 and 1200-days in Figure 7.25. This is due to the fact that the gel pores will continue to have some moisture and the true theoretical equilibrium may never occur. Also, as the moisture continues to redistribute, there may not be a sufficient humidity gradient for the moisture to diffuse between the pores. This has been seen in Figure 7.23(b) between 85 and 130mm. The ‘balance point’, as discussed earlier in Section 7.2.3, is 60mm and the fact that the rh at this depth (at 81.5%) does not change through rh redistribution is clearly evident from the stationary point in both Figures 7.25(a) and (b).

This gives further credence to the ASTM recommendations that the rh be measured at 40% of the depth for 1-face drying. However, it was shown in Figure 7.23(b) and 7.24(b) that initially the moisture was migrating upwards in the control room slab faster than in the laboratory as the surface rh was increasing at a faster rate due to the higher vapour concentration gradient. However, Figure 7.25(b) shows that it takes much longer for equilibrium to occur in the control room slabs which is due to the greater residual rh present in the slab.
In Figure 7.25(a), the final \( rh \) is approximately 77.3\%, some 2.3\% greater at the surface than when it was covered and approximately 1\% less than the initial \( rh \) at 130mm in the slab (i.e., 78.5\%). Equally importantly, the depth of slab at which the \( rh \) on sealing is the same as the long-term value is approximately 60mm, that is, 40\% of the slab depth. For the slab dried in the controlled room, however, the equilibrium point is 81.7\%, corresponding to an increase and decrease of moisture at the top and bottom of the slab of approximately 6.7 and 4.3\% respectively since covering.

Figure 7.26 shows how the \( rh \) through the depth slowly converges with time so that an equal \( rh \) exists throughout. After 240-days the \( rh \) is approximately 81\%. Also, as discussed in Section 7.2.3, the \( rh \) at 60mm appears to be constant at approximately 81\% over the 240-days. It may be concluded from the results presented, the \( rh \) at 40\% the depth of the slab on sealing appears to be a good representation of the final long-term equilibrium \( rh \) irrespective of the drying conditions.

![Figure 7.26](image_url)

**Figure 7.26** Converging surface and bottom \( rh \) for slab R(700)0.5(150)2.5 over time.

### 7.5 FINITE ELEMENT RESULTS

Having confirmed the proper behaviour of the finite element model in the last section, this section presents the results from the finite element analysis and compares them with the experimental results in Section 7.3.
7.5.1 Laboratory predictions

Figures 7.27, 7.28 and 7.29 show the $rh$ profiles in the three 150mm thick slabs (w/c = 0.4, 0.5 and 0.6) which have been previously dried in the laboratory and covered when reading 75% $rh$ on the surface. The figures show variations (a) through the depth at various times and (b) at 10 and 130mm from the surface. The finite element results compare very well with the experimental results and, in terms of the long-term predictions, the figures show that the ultimate $rh$ values are within 0.5% of each other. This is a good reflection on how the finite element model can be used to predict the $rh$ following sealing, given that calibration of the finite element model can be undertaken using real data from site prior to placing the impermeable covering for OPC mixes for which data already exists, such as that from this work.

Further, the initial conditions for the finite element model are the humidity profiles through the depth when the surface reached 75%. Therefore, for any future predictions of how the residual moisture will behave after the covering is applied, this initial profile is required either through measurement or through finite element prediction. In Chapter 6, the finite element analysis has been shown to give good predictions when compared with the actual experimental results. Therefore, the finite element model is deemed suitable to a method to predict the $rh$ profile through the depth with time after a covering is applied.

At 60mm, the $rh$ at the time of sealing and at equilibrium are approximately equal for both the experimental results and, reassuringly, for the finite element results. For example, at 60mm in the figures, the $rh$ is approximately 78, 77.4 and 79% when sealed and at equilibrium. Further, the model demonstrates that it can accurately predict the long-term behaviour of the residual moisture after sealing with reasonable accuracy for OPC concretes mixes.

7.5.2 Control room predictions

Similar comparisons between the predicted and experimentally measured $rh$ profiles for the slabs originally dried in the controlled room are shown in Figures 7.30, 7.31 and 7.32 using the same diffusion coefficients as before (Figure 6.10) for the three w/c ratios. The
Figure 7.27  Finite element predictions compared with the experimental measurements for slab L(700)0.4(150)2.1 (a) over time (in days) with depth and (b) over time for 10 and 130mm depths only.

Figure 7.28  Finite element predictions compared with the experimental measurements for slab L(700)0.5(150)2.2 over time (in days) with depth and (b) over time for 10 and 130mm depths only.

Figure 7.29  Finite element predictions compared with the experimental measurements for slab L(700)0.6(150)2.3 over time (in days) with depth and (b) over time for 10 and 130mm depths only.
results again compare well throughout the tests. However, in Figure 7.30(b) the surface rh does not appear to be reducing in the early stages of the test (0 to 30-days) and compare poorly with the finite element results. This is probably a result of some leakage of the moisture from the slab in the early stages where the silicone was applied after the holes around the tubes were cut away. At 20-days, the original silicone was removed and replaced. As may be observed, after this point the results improved and continued to do so up to 290-days. However, as the moisture was lost over the initial 20-days, the rh does not ‘catch-up’ and continues to be lower than the finite element predictions. It is unsurprising that the comparisons with the finite element predictions are poor during the early stages as it has a perfectly impervious boundary at the surface, unlike the experimental set-up.

In Figure 7.30(b), the curve at 130mm appears to be much flatter than the same curves in Figures 7.31 and Figure 7.32 at 130mm as was observed previously in Figure 7.13(a). The initial rh is at 86% at 130mm and it appears to equilibrate at approximately 84% after 270-days. This flatter curve at 130mm is a result of the shape of the initial rh profile through the depth in Figure 7.30(a) where there is a greater difference between the surface rh and at 130mm (75% and 86% respectively) than in Figures 7.31 and 7.32 and significant uniformity below 80mm. Also, as the rh below 60mm is approximately 86% throughout, all the curves below 60mm would be much flatter than those in Figures 7.31 and 7.32. Since the long-term equilibrium will be approximately 84%, the rh at 130mm will decrease to only 84% over 270-days, hence the flatter curve. This is also shown in the experimental results where the curve at 130mm is also flatter.

Again, at 60mm, the initial rh at sealing gives a good indication of the long-term equilibrium. In Figures 7.30, 7.31 and 7.32, the rh at 60mm on sealing is approximately 81, 86 and 83.5% respectively and at equilibrium is approximately 81, 84.5 and 82% respectively. Despite the minor difference between the rh at sealing and at equilibrium in these cases (within 1.5%), 40% of the depth still appears to be a suitable point to predict the long-term rh through the depth following equilibrium.

These results demonstrate again that the accuracy of the physical and material models in the previous chapter highlight the real possibility of predicting moisture behaviour for any practical w/c ratio, slab thickness and in any drying environment both during drying and
Figure 7.30  Finite element predictions compared with the experimental measurements for slab R(700)0.4(150)2.4.

Figure 7.31  Finite element predictions compared with the experimental measurements for slab R(700)0.5(150)2.5.

Figure 7.32  Finite element predictions compared with the experimental measurements for slab R(700)0.6(150)2.6.
after application of an impermeable covering. Once the model is calibrated using real data (as has been done here for OPC concretes), the most useful predictions, namely when 75% $rh$ will be reached at the surface, at 40% of the depth and what the long-term equilibrium $rh$ will be when a covering is applied, can also be made using a non-linear calibrated finite element model for OPC concrete slabs. Also, as the finite element model gives good correlations with the measured profiles through the depth when the surface reaches 75% $rh$, so it is deemed suitable to be used to predict $rh$ profiles through the depth when the surface covering is applied, using the initial conditions as determined by the finite element when 75% $rh$ is reached at the surface.

This reflects a major contribution to the area of moisture behaviour and it offers a real possibility of predicting $rh$ trends both during drying (as shown in Chapter 6) and after application of impermeable coverings in concrete slabs. This will aid floor-covering personnel to have an accurate estimate of the point to apply a floor covering (when the surface will reach 75% $rh$) and an indication of the $rh$ distribution through the depth. It is anticipated, therefore, that by using the finite element model developed here and measuring the $rh$ at 40% of the depth at the point of sealing will give an indication of the long-term equilibrated $rh$. This will both ultimately lead to a reduction in the cases of floor failures, as current practices to assess the moisture condition of concrete prior to the application of coverings produces uninformative and incomplete results. This can be achieved without the need for expensive monitoring practices.

However, if a flooring contractor is not aware of the drying regime employed prior to application of the covering, or the moisture distribution through the depth, then problems are likely to continue to occur. It is important, therefore, that this work empowers the contractor to decide what a safe threshold on sealing is. By using the simple model here and the initial profiles through the depth when the slab has a surface $rh$ of 75%, the contractor can predict what the long-term equilibrium $rh$ will be over time. If, for example, the predicted long-term $rh$ is greater than 75 to 80%, then it may be prudent to hold off on sealing the concrete until such time as it does falls within these limits. The higher the residual $rh$ is the greater the risk of failure becomes because, as shown here, a higher long-term $rh$ will ultimately exist (albeit much later after application) if accelerated drying has been undertaken or if working in a naturally more severe drying environment. Also, as
shown here, the w/c ratio also affects the time for equilibrium to occur. For instance, a higher w/c ratio will have a greater water content so diffusion will be faster on average, but starts with a much higher evaporable water content.

It is outside the scope of this thesis to be definitive about what percentage residual \( rh \) would be damaging to a floor as it depends on many factors, such as glue type and application, chemical reactions with salts/water from concrete, vapour pressure and presence under membrane etc. However, practice has shown that long-term \( rh \) below the surface of less than 77 to 78% do not generally cause problems. The following section presents some preventive measures that should be considered to reduce the likelihood of problems like those above, occurring.

### 7.6 PREVENTATIVE MEASURES

Much has been reported on the damage to concrete floor coverings as a result of excessive moisture conditions at the time of application. A finite element model, along with numerous experimental measurements, have shown that this residual moisture will continue to diffuse upwards and slowly cause the surface \( rh \) to increase under the covering along with a corresponding increase in vapour pressure. This section discusses possible preventative measures to ensure that this problem is reduced or possibly eradicated in the future, thus saving flooring installers, contractors and the client time and money. The following will present a number of possible measures that may reduce these problems, including proper slab construction, waterproofing and increased moisture testing through the depth of the slab before any covering is applied to the floor.

#### 7.6.1 Moisture testing before application

Of the preventative measures that will be discussed here, increased and targeted moisture testing prior to application of the covering is probably the most informative. Only through proper and thorough moisture monitoring will the flooring installer be in a position to make an informed decision as to whether or not to apply the covering. This decision will be based on an awareness of the actual moisture condition in the concrete through its depth and will inform whether or not future problems are likely to occur. Up until now, mostly
surface or near-surface moisture tests have been performed in accordance with current standards (using the hygrometer in the UK and VET in the USA) and have been shown to be insufficient to determine the actual residual moisture condition through the depth of the slab. The need for future testing is, now, somewhat reduced by the calibration of a simple finite element model in this thesis that allows predictions of the $rh$ profile at any point in time during drying.

The safe threshold of 75% surface $rh$ (BS 8203, 1996) is based on experimental work for typical drying conditions found in the UK and Ireland. This has been deemed a suitable point because, following sealing, the resulting pressure development and sub-surface increase in the residual $rh$ is unlikely to cause long-term problems, all other things being equal.

However, it has been clearly demonstrated here that force drying leads to significantly larger residues of moisture deep in the concrete while the surface of the slab appears quite ‘dry’ on sealing. Only by measuring the $rh$ at various depths in the concrete (or at least at 40% of the depth as suggested by the data presented here and as recently adopted by ASTM) at suitable intervals will one observe the true moisture profile in the concrete. The finite element model has also been shown to be a reasonably accurate method for determining the $rh$ profile and for establishing predicted drying times for the 75% surface $rh$ to be achieved in concrete slabs, using a suitably calibrated material model. This information will assist contractors and engineers alike to predict the $rh$ profile through the depth, at any point in time and the long-term equilibrium $rh$ and the time taken for this equilibrium to occur.

### 7.6.2 Application of the covering

This chapter has demonstrated the effect of on-going moisture migration following sealing in concrete and the long-term moisture and vapour pressure build-up. However, the potential exists for problems to occur as a result of poor laying practices, including the presence of dust on the floor surface when applying the adhesive, along with trapped air bubbles between the floor and the covering during laying and must be considered. Indeed, even if the dust and air bubbles are removed, problems such as inadequate glues, poor glue
application and coverage and general poor workmanship can also lead to long-term issues.

As discussed earlier, when the covering was applied to the slabs for the tests here, it was firmly pressed down onto the concrete to ensure that no air pockets could develop between the covering and the concrete. If air bubbles are created at the time of covering, they may lead to future problems, as a single bubble can spread by walking on the covering and a larger area can be affected (Latta, 2002). This causes the air bubble to spread and enlarge as it attaches to other nearby bubbles since air is assumed incompressible in this situation. The existence of such bubbles can have further implications other than simply spreading over the surface. Since a void now exists between the concrete and the surface, evaporation from the surface will continue and moisture will accumulate and develop over time, particularly if a large residue of moisture exists deep in the concrete at the time of covering. In addition, the vapour pressure generated will also cause this moisture to be held in the air void under a high pressure. It has been shown that conditions like these can cause the trapped moisture to squirt several feet into the air when burst (Floortest, 2002). Indeed, some floor manufacturers require that a 68kg roller be passed over the covering a number of times to reduce this risk of multiple trapped air bubbles.

Also, moisture under the covering induces solubility of some glue’s and increases the effects of the efflorescing salts, in addition to the increase in vapour pressure, poor workmanship and poor placing of the materials in the first place. All of these add to the possibility of long-term problems to the covering. As shown in section 7.3.3, the moisture and associated increase in vapour pressure is not the only factor that causes delamination of vinyl as the relatively small vapour pressure measured still caused a high force to be applied underneath the covering.

7.6.3 Conclusions

This section presented a summary of construction activities, such as moisture testing through the depth as well as the removal of dust, avoiding air bubbles and proper workmanship that should be executed in order to minimize the risk of future damage to impervious coverings, which has been on the increase over the past 30-years. During the drying phase an assessment of the moisture condition through measurement must be
carried prior to application of the covering or by using predictive finite element models that have been suitably set up and calibrated against real data. It is suggested here that monitoring the moisture condition at the surface only is inadequate as damages to floor coverings are due to moisture and vapour pressure build-up as a result of residual moisture deep in the concrete at the time of covering. Surface moisture measurement offers little insight into the moisture condition deep in the slab. Also, while the internal moisture and vapour pressures under the covering contribute to the problems, other factors such as poor workmanship, dissolving salts and soluble glues can all affect the floor covering integrity.

Accelerated drying may achieve a requirement for surface $\text{rh}$ before covering but ignores the residual $\text{rh}$ which, as has been shown, can cause long-term problems and so might suggest that such problems are inadvisable. However, the following section presents a method that allows accelerated drying methods to continue while reducing long-term moisture problems.

### 7.7 CONTINUED USE OF ACCELERATED DRYING METHODS

The experimental results and the finite element analyses both show quite clearly that, after covering, the residual moisture in the concrete will slowly equilibrate over time. This ultimately leads to a higher $\text{rh}$ at the surface than at the time of covering. It has also been shown in the experimental work and finite element analyses that accelerated drying methods result in greater residual moisture deep in the concrete and, therefore, a considerably higher long-term equilibrated $\text{rh}$, which is responsible for the majority of problems discussed above.

As shown in the previous sections, the long-term equilibrium residual surface $\text{rh}$ of the concrete (after covering) that was dried naturally prior to covering is within a range of 77 to 80%. On the other hand, when accelerated drying methods are employed prior to covering, the residual moisture deep within the slab on covering can be such as to cause long-term equilibrium $\text{rh}$ of 80 to 86%, depending on the original drying conditions. If this lower range of residual $\text{rh}$ is known not to cause moisture related problems to coverings, all other things being equal (proper workmanship etc), it may be possible to use accelerated drying methods so that the residual long-term $\text{rh}$ in the concrete also falls.
within this range. For example, if an accelerated drying regime was employed to dry the concrete to, say, 67% \( rh \) at the surface prior to covering, the long-term residual \( rh \) could fall within 77 to 80% \( rh \) where it is known it will be safe to apply the covering. Furthermore, if there is a significant difference in time between achieving 67% on the surface of the artificially dried slabs and 75% on the surface of the naturally dried slab, it may be worth continuing to use accelerated drying methods. Indeed, targeting a long-term residual of 75% \( rh \) through the depth would seem to be particularly advantageous given that existing practice suggests a low probability of failure for this case. However, what is known now is that if accelerated methods are used to achieve 75% \( rh \) in the surface, the residual will equilibrate to give a long-term \( rh \) considerably higher than 80% and damage is much more likely to occur.

Therefore, an investigation is warranted into the possibility of continuing to use accelerated drying methods so a surface \( rh \) of somewhat less than 75% is achieved before a covering is applied, such that the long-term \( rh \) throughout the slab lies within this acceptable ‘safe’ range of 77 to 80%. Figure 7.33 shows the results from this investigation for two of the 150mm thick slabs with a w/c ratio of 0.5. The graph shows two sets of lines one each for natural (laboratory) and forced (control room) drying. If one selects a surface \( rh \) threshold of 75% on sealing this will ultimately lead to a long-term residual \( rh \) of approximately 77 and 82% in the natural and forced drying environment respectively. If a conservative long-term \( rh \) of 75% is required, the graph shows that the concrete would have to be dried to a surface \( rh \) of approximately 72 and 68% in the natural and forced drying environments respectively.

The drying time for the slab to reach these two points (72 and 68%) as predicted by the finite element model, is approximately 110 days in the laboratory and 65 days in the control room for the 150mm thick slabs, as shown in Figure 7.34, for slabs R(700)0.5(150)2.5 and L(700)0.5(150)2.2. this suggests that although a lower target \( rh \) is required (68% rather than the normal 75%), it is still achieved in a much shorter time than if naturally dried.
Figure 7.33  Surface and long-term residual rh predictions for slabs R(700)0.5(150)2.5 and L(700)0.5(150)2.2.

Figure 7.34  Finite element predictions for L(700)0.5(150)2.2 and R(700)0.5(150)2.5.

Figure 7.35 shows a suggested range of drying times (namely 50 to 65-days) that are required to achieve a long-term safe equilibrium rh of between 80 to 75% after sealing using accelerated drying methods based on the results here for a 150mm thick slab with a w/c ratio of 0.5. Comparing this to the 90-days, it takes to achieve 75% rh using natural
drying methods, in the 150mm thick slabs, this represents a significant saving in time (between 40 and 25-days), while safe in the knowledge that the risk of long term problems are considerably reduced for OPC concretes if this drying regime is adopted.

Figures 7.36 (a) and (b) show the corresponding graphs for the 150mm thick slabs with w/c ratios of 0.4 and 0.6 in the control room respectively. The graphs show that to achieve a long-term residual \( rh \) of between 75 to 80\% in an artificial drying environment, the surface would also have to reach a surface \( rh \) of between approximately 67 to 73\% before covering. As shown, the drying time required (using the environmental conditions here) should be in the range 50 to 60 days and 55 to 75 days for the slabs with w/c ratios of 0.4 and 0.6 respectively. The above clearly demonstrates the saving in time that the continued use of accelerated drying methods can provide, safe in the knowledge that long-term problems can be reduced. For 75\% surface \( rh \) to be achieved in a natural environment it took 82 and 96-days for the 0.4 and 0.6 slabs to dry sufficiently, respectively (see Appendix A). If, alternatively, one were to accelerate drying so that a long-term \( rh \) of 75\% was achieved, only 60 and 75-days respectively are required prior to covering and this would still result in a time saving of 22 and 21-days respectively.

By way of example, if a surface \( rh \) of 75\% was achieved using natural drying methods (here, taking 90-days for the 150mm thick slabs with a w/c of 0.5 in the laboratory) before
the slab is covered, the equilibrium long-term *rh* is approximately 78% and is believed not to give rise to long-term problems based on existing practice (BS 8203, 1996). However, if the slab was forced dried (using the drying methods described in Chapter 4), to 75% surface *rh*, (shown to take 45-days), the long-term *rh* would be approximately 82% with the lifting problems for the floor covering much more likely to occur. However, if the slab was allowed to be dried using forced drying methods to, say, 71% *rh* (after approximately 55-days), the long term residual *rh* would also be approximately 78%. With the added piece of mind that long-term problems to the covering would be considerably reduced, the covering can now be applied some 35-days sooner. This clearly shows how forced drying can be beneficial in terms of safer and quicker application of the covering that has been portrayed up to now to cause long-term problems.

**Figure 7.36** Surface and long-term residual *rh* predictions for slabs R(700)0.4(150)2.4 and R(700)0.6(150)2.6.
8 CONCLUSIONS

8.1 CONCLUSIONS

The aims of the current research were four fold. Firstly, to gain an understanding of the movement of moisture in concrete floors slabs during drying and after the application of an impermeable floor covering. Secondly, to experimentally monitor the change in $\text{rh}$ through the depth of a variety of concrete slabs in a natural and accelerated drying environment both during drying and after application of an impermeable floor covering. Thirdly, to model and predict the changing $\text{rh}$ profiles in concrete during drying and after the application of an impermeable covering using calibrated diffusion and evaporation rates from the experimental results and findings. Finally, to use the finite element model to develop recommendations so that accelerated drying can continue to be used in such a way that problems with lifting of floor coverings caused by residual moisture on sealing can be reduced or eliminated.

During drying, moisture migrates in concrete via a diffusion process that is set-up by the creation of a concentration gradient through the depth soon after casting from a region of high concentration to a region of low concentration. At the exposed surface (or surfaces), the moisture is lost to the environment by evaporation due to a concentration gradient between the moisture at the surface and that in the ambient air. The slab will continue to dry until moisture equilibrium is reached with the surrounding air.

It has been shown that the moisture profiles in drying concrete are highly non-linear during the early stages of drying, where the near surface regions tend to dry much faster than those deeper in the slab as the moisture evaporates rapidly from the surface. This is particularly so if the slab has been subjected to accelerated drying methods (using heaters and dehumidifiers) as is common practice nowadays due to fast-track construction.

The presence of moisture is beneficial to the workability and easy placing of the concrete. However, excessive moisture is detrimental to strength development and surplus moisture present in the slab at the time of application of an impervious floor covering can cause numerous problems, ultimately resulting in expensive repairs. This is a particular problem
when large residual moisture exists deep in the slab at the time of covering, which will continue to diffuse through the concrete to the (now sealed) surface even after the covering is applied. This moisture will build-up under the covering, which, in turn, will generate vapour pressures. At present, a floor covering is applied when the $rh$ at the surface of the concrete reaches 75%, as ascertained using a surface hygrometer, as outlined by the current British Standard (BS 8203, 1996). This research is intended to uniquely investigate the two areas of moisture migration, namely initially during drying and the subsequent diffusion of this residual moisture in the slab after the covering is applied. To achieve this, a series of experimental tests were performed leading to a finite element study to predict the moisture profiles before and after a covering was applied with the material models calibrated against the experimental results.

A testing programme was undertaken in which all tested specimens were rectangular slabs with varying w/c ratios (0.4, 0.5 and 0.6) and thicknesses of 100, 150 and 200mm. The slabs were coated with an impervious paint on five sides that only allowed drying through one face, the top surface, resulting in 1-dimensional drying as is the case in most slabs on grade. They were allowed to dry in two distinctive drying environments; in a laboratory with natural drying conditions and in a control room that enhanced the ambient temperature and depressed the ambient $rh$ using a heater and dehumidifier. The ambient conditions in the room were set up to monitor the effect that elevated temperatures and reduced ambient humidities, such as those when accelerated drying is used on-site, had on the moisture condition and drying in the slabs. The moisture in the concrete was measured as a function of the $rh$ which has been shown previously to be a suitable property to represent the moisture in drying concrete. Measurement of the $rh$ was performed at the surface using a surface hygrometer and a number of newly developed apparatuses and at various depths using portable humidity probes that were attached to hand-held meters, namely a CRH and RHR as developed by Tramex. The probes were inserted into plastic tubes at various depths that were drilled into the concrete after curing. These tubes created a ‘chamber’ of humidity between the bottom of the tube and a pre-fixed rubber gasket, thus measuring the humidity at an average depth of 10mm above the base of the tube for the 100 and 200mm thick slabs and 5mm above the base for the 150mm thick slabs using different tubes but employing the same principles. In addition to this, the surface moisture content was also measured using other hand-held meters, namely a CME and CRH. Also, a
number of supplementary tests were performed to investigate other properties, such as measuring the rate of vapour emissions from the surface of the slabs (using a VET test).

The results from the experimental work provided a valuable insight into the drying phenomena through the depth of the slabs and over time. The initial results showed that, at very early drying, the humidity profiles were non-linear with the surface ‘drying’ much quicker than that deeper in the concrete. Comparing the results from the slabs in the laboratory and control room showed that the environmental conditions had a significant effect on the humidity profiles. The results showed that accelerating the drying only affects the near surface concrete at an early stage where rapid moisture loss is evident. However, there is little difference in the humidity deep in the concrete, when compared with the naturally drying slabs in the laboratory. In addition, the influence of the w/c ratio and the slab thickness on both the drying time, particularly the time to reach 75% rh on the surface and the humidity profiles through the depth show, in essence, that the lower the w/c ratio, the quicker the slab appeared to dry. This is contrary to the fact that lower w/c ratios have slower diffusion rates as shown in the published material. Despite this, the lower water content associated with a low w/c ratio appears to dominate the behaviour.

The rate of evaporation has been shown, from the trends here, to be a function of time. These rates have been shown to vary between drying environments and it is demonstrated that this is the main driving force when the concrete is forced dried. However, the rate of diffusion is dependant on the w/c ratio but is not affected significantly by the ambient conditions as the moisture deep in the slab is not initially sensitive to these outside conditions, nor is it strongly dependent on the slab thickness.

A commercial finite element model (DIANA) was used to predict the rh in the slabs during drying. The physical models for the three thicknesses here were set up with a finer mesh over the top 40% of the concrete. This follows both the general near-surface trends in the results here and recommendations from a new ASTM standard where it proposes that the rh at 40% of the slab thickness be measured as part of any monitoring work undertaken on drying concrete, following findings from this work.

The material models for diffusion and evaporation were based on previous literature and
CONCLUSIONS

calibrated against the results here using a series of analyses to best suit the trends in the results. The rates used all fall within previously published values and are deemed appropriate. Comparisons between the experimental and finite element results have shown good agreement unsurprisingly. However, they have also shown good correlations with published results, within 3 to 5% at most, which demonstrates the robustness of the model.

As discussed, after an impermeable covering is placed on a concrete slab, it is not uncommon for moisture related problems to occur afterwards, such as delamination of vinyl or rising tiles. This is partly due to residual moisture in the concrete at the time of sealing. With this in mind, a second set of experimental tests were undertaken that involved the application of an impermeable covering to the surface of the slabs when the surface reached 75% \( rh \), as established using a surface \( rh \) apparatus on the 150mm thick slabs. The covering, a vinyl, was applied as specified by the manufacturer. The through depth \( rh \) was continually monitored after the covering was applied along with the associated vapour pressure generated under the covering, as established using pore pressure probes placed just under the covering. The results show that the residual moisture does equilibrate gradually and there is a steady increase in the pressure under the covering to reflect this. The results show that the slabs previously dried in the control room took longer to equilibrate and had a significantly higher final \( rh \) through the depth. This is due to the greater difference between the \( rh \) at the surface and deep in the slabs than in the laboratory based slabs. While the trends are similar for the two sets of the slabs, their magnitudes are different. The measured vapour pressures suggested that, in the control room, they were quite small, approximately 0.01MPa. Following a number of pull-off tests using 150x150x150mm concrete cubes with a 100x100mm vinyl laid on top, it was found that the tensile pressures required to lift the vinyl off the concrete were between 0.23 to 0.28MPa approximately, which suggests that the pressure measured were very small compared to the actual pressure required to lift the vinyl off the concrete in its own right. This area requires more investigation.

Current practice suggests when the surface reaches 75% \( rh \), a covering can be safely applied. However, this research has shown that this is not always the case as the slab may not be sufficiently ‘dry’ when this \( rh \) is reached and depends on the ambient conditions and the drying method. Nonetheless, it was observed in the experiments for a variety of slabs
that the long-term $rh$ under a covering is approximately the same as the $rh$ at *circa* 40% of the slab depth at the time of covering, irrespective of the drying regime. This is an important finding because it suggests that when deciding when to cover a slab safely, the $rh$ at 40% of the slab depth should be measured and not the surface $rh$ alone, as is current practice. If floor covering suppliers are satisfied with a long-term $rh$ of, say, 75 to 80%, at which long-term problems are unlikely to occur, then that should be the target value at 40% of the depth. This again is a new finding and certainly adds to the current knowledge. Indeed, the ASTM have developed a new standard in which for drying through one face, it recommends that the $rh$ should be measured, using probes like those here, at 40% of the slab depth. This recommendation was informed by the results presented here.

The results from the experimental work were compared with the predictions of a finite element study. The model used previously to predict the $rh$ during drying in the slabs was adjusted to account for the new impervious boundary condition as the evaporation boundary elements were now redundant. The initial condition was also changed to represent the $rh$ through the depth of the slab when the surface reached 75% $rh$ and the covering was applied, which had previously been set at 100% $rh$ throughout before any drying took place. The diffusion coefficient that was used for drying is used again as it is not influenced by the boundary conditions. Again, the results from the model gave good comparisons with those measured.

Finally, from the experimental and subsequent finite element analyses of a slab after application of an impervious covering, it appears that it may be possible to continue to use accelerated drying methods until such time that a long-term safe equilibrium moisture condition is reached over time. For example, in the case considered, if the accelerated drying methods were employed and the concrete allowed to dry until a $rh$ of approximately 67% was obtained at the surface, the long-term equilibrium $rh$ through the depth of the slab following sealing would be between 75 to 80%, which has been shown by the British Standard (BS 8203, 1996) to be a satisfactory ‘safe’ range of residual long-term $rh$. This range of long-term equilibrium $rh$ has been shown to exist in slabs that have been dried naturally where damage is rare. Continued use of artificial drying using elevated temperatures and reduced ambient humidities, like here, also has the advantage of allowing the floor covering to be installed much sooner than if the slab was naturally dried despite
the lower target \( rh \) on covering. For instance, comparing the times for the naturally dried slabs to achieve 75\% \( rh \) and the time for the accelerated drying to achieve 67\%, the saving in time can be up to 35-days, while safe in the knowledge that damage to the covering would be minimised. It must be pointed out, though, that these times and humidities only apply to OPC concretes and further work is required if blended cements are to be used. The suggested lower targets for surface \( rh \) in accelerated drying environments, with significant time savings, represents new findings and adds to the current knowledge in this area.

Therefore, in summary, the main conclusions arising from this thesis are:

- The drying environment has a more significant effect on the moisture profiles in concrete slabs than the w/c ratio or the depth of the slab.

- The lower the w/c ratio is the faster the threshold of 75\% \( rh \) on the surface appears to be reached even though concretes with reduced w/c ratios have slower diffusion rates. Reaching this threshold during drying is therefore more dependent on the physical water content than the w/c ratio and this is contrary to what might have been expected from other publications in this area.

- The rate of evaporation is dependent on the ambient conditions where the diffusion coefficient is dependent on the internal \( rh \) and the w/c ratio.

- The finite element method has been shown to be a suitable tool to predict the changing \( rh \) profiles over time and through the depth in drying concrete slabs with varying w/c ratios and slab thicknesses using calibrated diffusion and evaporation rates. The comparisons with the experimental results are within 5\% at worst, but are usually satisfactorily similar.

- The new recommendations by the ASTM to measure the \( rh \) at 40\% of the depth (for one-face drying) appears to be suitable as it represents the stationary point where the \( rh \) over time after covering remains relatively unchanged. It is concluded, therefore, that placing probes at 40\% of the slab depth to measure the \( rh \) will give a good approximation of the long-term \( rh \) in the concrete following covering. This
will aid flooring contractors in deciding at what point in time it is safe to apply a floor covering. The development of the recommended ASTM measurement depth has been informed by the data presented.

- Accelerated drying methods lead to significantly earlier times for 75% \( rh \) to be reached on the surface. However, they also lead to much higher long-term \( rh \) under the floor covering due to the significant quantity of residual moisture deep within the slab on covering. This, inevitably, increases the likelihood of future problems occurring with the floor covering.

- If, however, accelerated drying methods are used and maintained until the surface \( rh \) falls well below 75% (for example, down to approximately 67% as shown here), the long-term moisture diffusion through the concrete should yield a \( rh \) of between 75 to 80%, which is known not to normally cause long-term problems after laying. Also, using accelerated drying until a lower than normal surface \( rh \) is achieved allows the covering to be applied much sooner than if natural drying methods only were employed (for example, by as much as 35-days in the case cited here).

- The measured vapour pressures under the covering are much lower than the tensile pressures required to physically lift the vinyl off a series of concrete cubes. It is clear, therefore, that vapour pressure itself is not enough to cause delamination of vinyl’s or lift tiles etc. Other factors such as glue solubility, poor workmanship and the effect of salts in the migrating moisture may all contribute to these problems. More work is clearly required in this area.

8.2 RECOMMENDATIONS FOR FURTHER WORK

Recommendations for further work in this area include:

- Extend the work to include moisture movements in suspended in-situ slabs, precast (both hollowcore and wideslab) with structural screeds and metal deck slabs with concrete toppings. These forms of construction are very common on construction projects and would yield very practical findings.
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- Extend the work to include moisture movements in external concrete walls and its effect on plaster where moisture presence can cause long-term problems.

- Further development of the finite element model could be undertaken to predict the increase in the vapour pressure under the covering when applied, due to the existence of moisture residue at the time of covering. The model could be calibrated against experimental measurements and it could be determined at what point would delamination occur, thus allowing floor manufacturers to determine the typical pressure at which a covering could fail.

- One could develop design tables for predicted drying times depending on w/c ratio, depth, cement types, background ambient temperature and humidity and recommended ambient temperature and humidity. This would remove the need for individual finite element studies in practice.

- Further the finite element model here could be extended to predict the \( rh \) trends when drying is taking place through two or more surfaces with varying ambient conditions such as a wall between a bedroom and bathroom for example.

- There should be a study conducted into the other causes of blistering and delamination, not just the build-up of the vapour pressures, although this is a significant factor. Factors such as the effect of moisture on glues, the effect of poor gluing and the migration of salts to the surface to react with the glue are some areas which would merit investigation in this regard.
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APPENDIX A: EXPERIMENTAL RESULTS - DRYING

A1 INTRODUCTION

The results from the experimental tests of the $rh$ at various depths on the various slabs, in both the room and laboratory are presented here in steps of 10-days. Tables A1 and A2 show the names given to the various slabs (given previously in Chapter 3).

Table A.1 Test Series 1

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<th>Environment</th>
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<td>Laboratory</td>
<td>Surface RH using plastic tent</td>
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<td>Laboratory</td>
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</tr>
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<td>Laboratory</td>
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<tr>
<td>1.6*</td>
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Table A.2 Test Series 2

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<td>Laboratory</td>
<td>Vapour emission tests + pH</td>
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<td>Room</td>
<td>Vapour emission tests + pH</td>
</tr>
</tbody>
</table>
A2  Relative humidity profiles in the 100mm thick slabs in the laboratory (w/c = 0.5)

**Figure A1**  $rh$ profiles for slab L(500)0.5(100)1.1

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Expt</td>
<td>20 Expt</td>
</tr>
<tr>
<td>41 Expt</td>
<td>59 Expt</td>
</tr>
<tr>
<td>70 Expt</td>
<td>100 Expt</td>
</tr>
<tr>
<td>120 Expt</td>
<td>140 Expt</td>
</tr>
<tr>
<td>177 Expt</td>
<td>200 Expt</td>
</tr>
<tr>
<td>220 Expt</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elapsed Time (Days)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>55 Expt</td>
</tr>
<tr>
<td>20</td>
<td>65 Expt</td>
</tr>
<tr>
<td>40</td>
<td>75 Expt</td>
</tr>
<tr>
<td>60</td>
<td>85 Expt</td>
</tr>
<tr>
<td>80</td>
<td>95 Expt</td>
</tr>
<tr>
<td>100</td>
<td>100 Expt</td>
</tr>
</tbody>
</table>

**Figure A2**  $rh$ profiles for slab L(500)0.5(100)1.2

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Expt</td>
<td>20 Expt</td>
</tr>
<tr>
<td>41 Expt</td>
<td>59 Expt</td>
</tr>
<tr>
<td>70 Expt</td>
<td>100 Expt</td>
</tr>
<tr>
<td>120 Expt</td>
<td>140 Expt</td>
</tr>
<tr>
<td>177 Expt</td>
<td>200 Expt</td>
</tr>
<tr>
<td>220 Expt</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elapsed Time (Days)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60 Expt</td>
</tr>
<tr>
<td>20</td>
<td>70 Expt</td>
</tr>
<tr>
<td>40</td>
<td>80 Expt</td>
</tr>
<tr>
<td>60</td>
<td>90 Expt</td>
</tr>
<tr>
<td>80</td>
<td>100 Expt</td>
</tr>
</tbody>
</table>

**Figure A3**  $rh$ profiles for slab L(500)0.5(100)1.3
A3 Relative humidity profiles in the 200mm thick slabs in the laboratory (w/c = 0.5)

**Figure A4** $rh$ profiles for slab L(500)0.5(200)1.4

**Figure A5** $rh$ profiles for slab L(500)0.5(200)1.5

**Figure A6** $rh$ profiles for slab L(500)0.5(200)1.6
APPENDIX A

A4 Relative humidity profiles in the 100mm thick slabs in the laboratory (w/c = 0.4, 0.5 and 0.6)

Figure A7  
$rh$ profiles for slab L(500)0.4(100)1.7

Figure A8  
$rh$ profiles for slab L(500)0.5(100)1.8

Figure A9  
$rh$ profiles for slab L(500)0.6(100)1.9
A5 Relative humidity profiles in the 100mm thick slabs in the control room (w/c = 0.4, 0.5 and 0.6)

Figure A10  $rh$ profiles for slab R(500)0.4(100)1.10

Figure A11  $rh$ profiles for slab R(500)0.5(100)1.11

Figure A12  $rh$ profiles for slab R(500)0.6(100)1.12
A6 Relative humidity profiles in the 150mm thick slabs in the laboratory (w/c = 0.4, 0.5 and 0.6).

Figure A13  \(rh\) profiles for slab L(700)0.4(150)2.1

Figure A14  \(rh\) profiles for slab L(700)0.5(150)2.2

Figure A15  \(rh\) profiles for slab L(700)0.6(150)2.3
A7 Relative humidity profiles in the 150mm thick slabs in the control room (w/c = 0.4, 0.5 and 0.6).

**Figure A16**  \(rh\) profiles for slab R(700)0.4(150)2.4

**Figure A17**  \(rh\) profiles for slab R(700)0.5(150)2.5

**Figure A18**  \(rh\) profiles for slab R(700)0.6(150)2.6
A8 Surface moisture contents for the 100mm thick slabs in the laboratory (w/c = 0.5)

Figure A19 Surface moisture contents slab L(500)0.5(100)1.1

Figure A20 Surface moisture contents slab L(500)0.5(100)1.2

Figure A21 Surface moisture contents slab L(500)0.5(100)1.3
A9 Surface moisture contents for the 200mm thick slabs in the laboratory (w/c = 0.5)

Figure A22 Surface moisture contents slab L(500)0.5(200)1.4

Figure A23 Surface moisture contents slab L(500)0.5(200)1.5

Figure A24 Surface moisture contents slab L(500)0.5(200)1.6
A10 Surface moisture contents for the 100mm thick slabs in the laboratory (w/c = 0.4, 0.5 and 0.6)

Figure A25 Surface moisture contents slab L(500)0.4(100)1.7

Figure A26 Surface moisture contents slab L(500)0.5(100)1.8

Figure A27 Surface moisture contents slab L(500)0.6(100)1.9
A11 Surface moisture contents for the 100mm thick slabs in the control room (w/c = 0.4, 0.5 and 0.6)

Figure A28 Surface moisture contents slab R(500)0.4(100)1.10

Figure A29 Surface moisture contents slab R(500)0.5(100)1.11

Figure A30 Surface moisture contents slab R(500)0.6(100)1.12
A12  Surface moisture contents for the 150mm thick slabs in the laboratory (w/c = 0.4, 0.5 and 0.6)

Figure A31  Surface moisture contents slab L(700)0.4(150)2.1

Figure A32  Surface moisture contents slab L(700)0.5(150)2.2

Figure A33  Surface moisture contents slab L(700)0.6(150)2.3
A13 Surface moisture contents for the 150mm thick slabs in the control room (w/c = 0.4, 0.5 and 0.6)

Figure A34 Surface moisture contents slab R(700)0.4(150)2.4

Figure A35 Surface moisture contents slab R(700)0.5(150)2.5

Figure A36 Surface moisture contents slab R(700)0.6(150)2.6
### A14 Compression test results

<table>
<thead>
<tr>
<th>Slab number</th>
<th>7-day strength (N/mm²)</th>
<th>28-day strength (N/mm²)</th>
<th>w/c ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>45</td>
<td>49</td>
<td>0.5</td>
</tr>
<tr>
<td>1.2</td>
<td>38</td>
<td>45</td>
<td>0.5</td>
</tr>
<tr>
<td>1.3</td>
<td>40</td>
<td>51</td>
<td>0.5</td>
</tr>
<tr>
<td>1.4</td>
<td>34</td>
<td>52</td>
<td>0.5</td>
</tr>
<tr>
<td>1.5</td>
<td>40</td>
<td>45</td>
<td>0.5</td>
</tr>
<tr>
<td>1.6</td>
<td>45</td>
<td>48</td>
<td>0.5</td>
</tr>
<tr>
<td>1.7</td>
<td>43</td>
<td>47</td>
<td>0.4</td>
</tr>
<tr>
<td>1.8</td>
<td>40</td>
<td>43</td>
<td>0.5</td>
</tr>
<tr>
<td>1.9</td>
<td>44</td>
<td>49</td>
<td>0.6</td>
</tr>
<tr>
<td>1.10</td>
<td>45</td>
<td>48</td>
<td>0.4</td>
</tr>
<tr>
<td>1.11</td>
<td>39</td>
<td>43</td>
<td>0.5</td>
</tr>
<tr>
<td>1.12</td>
<td>44</td>
<td>47</td>
<td>0.6</td>
</tr>
<tr>
<td>2.1</td>
<td>41</td>
<td>47</td>
<td>0.4</td>
</tr>
<tr>
<td>2.2</td>
<td>43</td>
<td>48</td>
<td>0.5</td>
</tr>
<tr>
<td>2.3</td>
<td>43</td>
<td>47</td>
<td>0.6</td>
</tr>
<tr>
<td>2.4</td>
<td>46</td>
<td>49</td>
<td>0.4</td>
</tr>
<tr>
<td>2.5</td>
<td>47</td>
<td>49</td>
<td>0.5</td>
</tr>
<tr>
<td>2.6</td>
<td>43</td>
<td>46</td>
<td>0.6</td>
</tr>
<tr>
<td>2.7</td>
<td>44</td>
<td>48</td>
<td>0.5</td>
</tr>
<tr>
<td>2.8</td>
<td>46</td>
<td>49</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>42.5</strong></td>
<td><strong>47.5</strong></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B: DESCRIPTION OF DIANA INPUT AND COMMAND TABLES

B1  INTRODUCTION

Here the table headings for the input and command files within DIANA are described in full. The input and command table headings are described as they are presented in a typical analysis, based on the DIANA 7.2 fourth Edition Users Manual for flow analysis, 1999

B2  INPUT TABLES

This section presents the tables in DIANA allows the user to represent the physical and material properties to accurately model the system.

B.2.1 Nodal Coordinates ‘COORDINATES’

Nodal coordinates are input via table ‘COORDINATES’. The coordinates are expressed in global Cartesian XYZ axes according to the following syntax.

<table>
<thead>
<tr>
<th>'COORDINATES' [DI=dimens]</th>
</tr>
</thead>
<tbody>
<tr>
<td>node</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

‘COORDINATES’ is the table heading for nodal coordinates input. The optional parameter DI=dimens indicates the dimensionality of the nodal coordinate system, for 2-D analysis DI=2. node is the node number which may be input in an arbitrary order and numbers may be skipped. Values x, y and z are the model XYZ coordinates. Omit z for 2-D analysis.

B.2.2 Material Properties ‘MATERIAL’

Material properties are input via table ‘MATERIAL’. Typical examples of data in this table are the diffusion coefficient, D and the evaporation rate, K.
‘MATERIAL

<table>
<thead>
<tr>
<th>matnr</th>
<th>matnam</th>
<th>matdat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

matnr is the material number for reference from sub-table MATERIAL of table ‘ELEMEN’. Keyword matnam indicates the material property name and is followed by matdat, one or more material property values.

B.2.3 Element Geometry Data ‘GEOMETRY’

Geometrical data is input via table ‘GEOMETRY’. Typical examples of data in this table are the thickness of planer elements and user-specified element axes. Actual input of geometry properties depends on the element type.

‘GEOMETRY

<table>
<thead>
<tr>
<th>geonr</th>
<th>geonam</th>
<th>geodat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

geonr is the geometry number for reference from sub-table GEOMETRY of table ‘ELEMEN’. Keyword geonam indicates the geometry property name and is followed by geodat, one or more geometry property values.

B.2.4 Special Element Data ‘DATA’

Special element data, not belonging to material or geometrical data is input via this table. Typical input data in this table is an alternative integration scheme. Actual input of special properties depends on the element type.
## ‘DATA’

<table>
<thead>
<tr>
<th>datnr</th>
<th>datnam</th>
<th>datdat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

`datnr` is the data number for reference from sub-table `DATA` of table ‘ELEMEN’. Keyword `datnam` indicates the data property name and is followed by `datdat`, one or more data property values.

### B.2.5 Elements ‘ELEMENT’

The elements of the FE model are input via table ‘ELEMENT’. This table comprises four sub-tables.

<table>
<thead>
<tr>
<th>‘ELEMENTS’</th>
<th>CONNECTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>Element Number</code></th>
<th><code>Element Name</code></th>
<th><code>Nodes connected to individual element</code></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>Material numbers</code></th>
<th><code>Material type</code></th>
<th><code>Material properties/values</code></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>Geometry numbers</code></th>
<th><code>Geometry property</code></th>
<th><code>Geometry properties/values</code></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

`Element special data numbers`
‘ELEMEN’ is the table heading for element input. The subtables are CONNECTIVITY for element types and nodes, MATERIAL for element material numbers, GEOMETRY for element geometry numbers and DATA for element special data numbers.

B.2.6 Types and Nodes ‘CONNECTIVITY’

CONNECTIVITY is the heading for the subtable with the connectivity, ie. the node numbers for each element.

<table>
<thead>
<tr>
<th>'ELEMENT'</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONNECTIVITY</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

elem | elmtyp | nodes

elem is the element number, elmtyp the element type name and nodes are the node numbers.

B.2.7 Material Numbers ‘MATERIAL’

MATERIAL is the heading for the sub-table with material numbers for all elements.

<table>
<thead>
<tr>
<th>'ELEMENT'</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATERIAL</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

elem | matnr

/ elems /

matnr

elem is a single element number, elems is a series of elements and must be specified between slashes (/) and may comprise numbers or groups or both. The material number
matnr refers to the corresponding material number in table ‘MATERIAL’. This table must be present in the same input file or must have been previously.

B.2.8 Geometry Numbers ‘GEOMETRY’

GEOMETRY is the heading for the sub-table with geometry numbers for all elements.

<table>
<thead>
<tr>
<th>‘ELEMENT’</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOMETRY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>6</td>
<td>80</td>
</tr>
</tbody>
</table>

`elem` `geonr`

| 1 | 5 | 6 | 80 |

`/ elems /

`geonr`

`elem` is a single element number, `elems` is a series of elements and must be specified between slashes (/) and may comprise numbers or groups or both. The geometry number `geonr` refers to the corresponding geometry number in table ‘GEOMETRY’. This table must be present in the same input file or must have been previously.

B.2.9 Numbers for Special Data ‘DATA’

DATA is the heading for the sub-table with data numbers for all elements.

<table>
<thead>
<tr>
<th>‘ELEMENT’</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>6</td>
<td>80</td>
</tr>
</tbody>
</table>

`elem` `datnr`

| 1 | 5 | 6 | 80 |

`/ elems /

`datnr`
elem is a single element number, elems is a series of elements and must be specified between slashes (/) and may comprise numbers or groups or both. The data number datnr refers to the corresponding data number in table ‘DATA. This table must be present in the same input file or must have been previously.

B.2.10 Boundary Conditions ‘BOUNDARY’

There are two classes of boundary conditions, each of which is specified in a separate sub-table of table ‘BOUNDARY’

Nodal    prescribed values on nodes or boundary elements
Discharges  prescribed discharge Q (source) on nodes or ordinary elements

Each case may be specified. Each case may have nodal or element boundary conditions or both. If a condition is not specified for a certain boundary, then DIANA assumes that this boundary is completely insulated, i.e., the flux through it is equal to zero.

‘BOUNDARY’
CASE □ case

NODAL

<table>
<thead>
<tr>
<th>1</th>
<th>5</th>
<th>6</th>
<th>80</th>
</tr>
</thead>
</table>

Nodal boundary conditions

ELEMEN

<table>
<thead>
<tr>
<th>1</th>
<th>5</th>
<th>6</th>
<th>80</th>
</tr>
</thead>
</table>

Element boundary conditions

‘BOUNDARY’ is the table heading for boundary conditions input
CASE case is the number of a new boundary case. A case number specification line must follow immediately after the table heading. The case number may be re-specified at the start of a new sub-table

NODAL is the sub-table for nodal boundary conditions

ELEMEN is the sub-table for element boundary conditions

B.2.11 Nodal Boundary Conditions ‘NODAL’

Nodal boundary conditions are input in subtable NODAL. There are three forms of input syntax: (1) one nodal condition per line, (2) nodes in a series of numbers or groups or both, with one condition value valid for all the nodes in the series, (3) nodes in a series of numbers and/or groups, with a series of condition values: one value for each node.

‘BOUNDARY

NODAL

<table>
<thead>
<tr>
<th>node</th>
<th>type</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

/ nodes /

<table>
<thead>
<tr>
<th>type</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>80</td>
</tr>
</tbody>
</table>

/ node /

<table>
<thead>
<tr>
<th>type</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>80</td>
</tr>
</tbody>
</table>

NODAL is the sub-table heading for nodal boundary conditions

node is a single node number, nodes is a series of nodes, it must be specified between slashes and may comprise numbers or groups or both. type is a type of boundary condition: Q for prescribed discharge (point source) or P for a prescribed potential. value is the value
of the boundary condition; values is a series of condition values, one for each node in nodes.

**B.2.12 Element Boundary Conditions ‘ELEMEN’**

Element boundary conditions are input in subtable ELEMEN. There are two forms of input syntax: (1) one element condition per line and (2) elements in a series of numbers or groups or both, with one boundary condition specification valid for all the elements in the series.

### ‘BOUNDARY

**ELEMEN**

<table>
<thead>
<tr>
<th>elem</th>
<th>bndnam</th>
<th>bnddat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

/ elems /

<table>
<thead>
<tr>
<th>bndnam</th>
<th>bnddat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ELEMEN is the sub-table heading for nodal boundary conditions

*elem* is a single node number, *nodes* is a series of nodes, it must be specified between slashes and may comprise numbers or groups or both.* bndnam is the boundary condition data name and *bnddat* is (are) the boundary conditions data value(s).

**B.2.13 Initial Conditions ‘INIVAR’**

Transient analysis or nonlinear steady state analysis may start with an initial potential field. There are two ways to specify such an initial potential field: (1) directly via input table ‘INIVAR’ or (2) as a potential field found from a previous analysis and indicated by a START command.

There are three forms of input syntax for table ‘INIVAR’: (1) one nodal potential per line, (2)
nodes in a series of numbers or groups or both, with one potential valid for all the nodes in the series, (3) nodes in a series of numbers and/or groups, with a series of potentials: one value for each node.

<table>
<thead>
<tr>
<th>Node Number</th>
<th>Initial value</th>
</tr>
</thead>
<tbody>
<tr>
<td>'INIVAR'</td>
<td>POTENT field</td>
</tr>
<tr>
<td>1</td>
<td>80</td>
</tr>
</tbody>
</table>

'INIVAR' is the table heading for initial nodal potentials.

POTENT field is the field number, used for reference from the analysis commands.

node is a single node number, nodes is a series of nodes and must be specified between slashes and may comprise numbers or groups or both. phi is the value of the initial condition, phis is a series of initial conditions, one for each node in nodes.

B.2.14 Transient Analysis ‘TIMEBO’

For transient analysis, the boundary conditions specified in table 'BOUNDA' must be related to the time. For each case from table 'BOUNDA', linear diagrams can be specified for the multiplication factor of the boundary conditions of that case in a time interval: \( t_1 \leq t \leq t_2 \).

The total boundary conditions on a certain time are a superposition of all the multiplications of the interpolated factors with the boundary conditions belonging to the specified cases. The diagram(s) must be specified in input table 'TIMEBO'.

<table>
<thead>
<tr>
<th>'TIMEBO'</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
</tr>
</tbody>
</table>

\( t_1 \ \Box \ t_2 \ \Box \ case \ \Box \ f_1 \ \Box \ f_2 \)

'TIMEBO' is the table heading for time dependent boundary conditions.

t_1 and t_2 respectively are the start time and the end time of the interval, where t_1 is included
in the interval but $t_2$ is not included. case is the number of the boundary case, active in the interval. This number refers to a case number specified in table 'BOUNDA' and $f_1$ and $f_2$ respectively are the multiplication factors $f_1$ and $f_2$ at times $t_1$ and $t_2$.

**B3 COMMAND FILE**

The command file essentially tells the computer what to do with the input file.

**B.3.1 * FILOS**

The central database for each analysis project with DIANA is handled by the FILOS file (FILe Organisation System). The user must maintain a FILOS file during the entire lifetime of the analysis project for a particular finite element model.

**B.3.2 INITIA**

This serves to initialise the FILOS file. All files must be initialised to become a FILOS file. This command must only appear at the beginning of a command file.

**B.3.3 * INPUT**

This module is primarily used to read the input file.

**B.3.4 * ELPOTI**

This module evaluates the element model using the following steps:

1. Checks and completes the element geometrical properties
2. Creates degrees of freedom and processes fixed nodal potentials
3. Set-up the linear element conductivity matrices
4. Set-up the linear element capacity matrices

Steps 1-3 are necessary for potential flow analysis. Step 4 is only necessary for transient analysis and must be specified explicitly.
B.3.5 *FLUX

This module evaluates the boundary conditions for the Finite Element model, resulting in the composition of the right-hand-side nodal flux vectors for the specified boundary cases.

B.3.6 *TRANSI

Module TRANSI is used to perform a transient analysis as a follow-up of the preliminary analysis. In order to perform a transient analysis, the time-dependent boundary conditions in table ‘TIMEBO’ must be specified.

A transient analysis usually involves two steps: (1) initialisation of initial potential values and boundary conditions due to the INITIA command block and (2), solution of the equations for the specified time steps due to the EXECUT command block. These steps may be performed in one DIANA job or in various subsequent jobs. In addition, command may be given for specified output types.

B.3.7 OUTPUT

Here the type of output required is specified. In this case, the output is specified as tabular with the solution given (POTENT) and the co-ordinates of the node (COOR) specified in SELECT). The additional term ‘FI’ allows the user to name the solution. Using the SELECT command allows the user to specify the nodes at which he/she wants the solution. The list must be finished with a forward slash ‘/’.

B.3.8 INITIA

Each non-linear transient analysis with Module TRANSI must be initialised to indicate the initial conditions. Within this area, the type of analysis that is to be carried out is specified either as linear or non-linear. ALFA invokes time integration according to the one-step generalization trapezoidal rule. Parameter AL is the time integration parameter \( \alpha \). Usual methods are the Euler forward method (\( \alpha = 0 \)), Crank-Nicolson (\( \alpha = 1/2 \)), Galerkin (\( \alpha = 2/3 \)) and Euler backward (\( \alpha = 1 \)) which is the default. Also, if a transient analysis is to be
performed, POTENT.I tells the model to start with initial potentials that were specified as field number field of table ‘INIVAR’ in the input file.

B.3.9 EXECUTE

In non-linear transient analysis, DIANA will execute time steps due to the commands in the EXECUT block. It controls such things as the size of the time steps, the type of iteration used, the convergence criterion and the method to be used to solve the set of system equations.

B4 FEMGV ANALYSIS COMMANDS

FEMGV is an interactive graphical pre- and postprocessor for use in combination with the finite element analysis code DIANA, the logical integration of mesh generation and results assessment for analyses with DIANA-7.2. It can provide common pre- and postprocessing facilities over the range of any finite element analysis requirements. Any finite element analysis comprises essentially of three stages:

Preparation of the model data, known as preprocessing
Analysis of the model.
Assessment of the results, usually called postprocessing

While the development of better algorithms and advances in computing technology have enabled the DIANA code to be applied to increasingly more complex problems, the tasks of data preparation and of result assessment in the DIANA batch mode can be discouragingly time consuming and prone to error. FEMGV addresses itself to the twofold task of generating the finite element model, and of enabling one to present the results of an analysis in an informative and illuminating way.

A variety of techniques for the generation of a model and the display of results are provided in order to meet the individual needs of different models. Moreover FEMGV uses color to add information and to allow a rapid assessment of your model. With a database specifically designed to meet the tasks of mesh generation and results assessment and to
A good interactive response, FEMGV can provide the finite element user with an extremely flexible and powerful graphics pre- and postprocessor.

B.4.1 Preprocessing

The definition of the model geometry is performed by the FEMGV preprocessor Module FEMGEN. The top-down approach used in this module means that the geometry of the model is defined first and then FEMGV generates the mesh. Next the material and physical properties are defined and finally the constraints and the loading. As an alternative to user-defined input, FEMGV also offers interfaces to certain Computer Aided Design systems. These enable specific geometric definition data to be taken from the CAD system and used within the Preprocessing working environment.

B.4.2 Definition of model geometry

The building-blocks in the geometrical model are points, lines, surfaces, and bodies. These form a complete solid model where lines are defined from points, surfaces from lines, and bodies from surfaces. The top-down approach means that one only has to enter coordinates for certain key points. It is therefore very easy to modify a geometry, for example by moving a few points. Then FEMGV can generate a new mesh which conforms to the new geometry.

B.4.3 Mesh generation

FEMGV has fast and efficient mesh generation algorithms which use information about point coordinates, line types etc., specified in the definition of the geometry, and also information about how the geometric objects are connected. During the mesh generation process, elements are described in terms of nodes, but also the connection between the geometry and mesh is established.

B.4.4 Material and physical properties

Material and physical properties may be assigned to the various geometric parts of the
model. FEMGV will transfer these properties to the elements when mesh data is translated to the DIANA batch analysis input format.

**B.4.5 Constraints**

FEMGV provides various facilities for defining constraints such as a point, line, or surface on its own, or may be defined general constraints between different parts of the model. This enables ‘multi-point-constraint’ equations to be generated. All constraints may be defined in local coordinate systems.

**B.4.6 Loads**

Loads are applied to geometric parts, i.e., points, lines, surfaces and bodies. They may be defined in a number of ways:
- Concentrated loads applied to nodes.
- Distributed loads applied to elements.
- Prescribed displacements applied to nodes.
- A gravity load, centrifugal load or heat source.
- Temperatures to nodes.
- Convection boundary conditions.

The variation of the load over the part may be controlled with space curves and the application of the load may be restricted with the use of load masks. In addition a wide range of time dependent load variation may be specified.

**B.4.7 Limitations on model size**

In the Preprocessing environment, FEMGV allocates memory for geometric objects as they are created. Therefore, the limits on the number of points lines, surfaces, bodies etc. that can be created are imposed by the amount of RAM available plus the size of the virtual memory swap file. However, there are few inherent limitations: the maximum number of nodes on a line is 100 and the maximum number of nodes on a body or surface is 18000.
B.4.8 Postprocessing

The presentation of analysis results is performed by the FEMGV postprocessor. Module FEMVIEW allows the selection a load case, attribute and component of analysis results for assessment. Static, dynamic and nonlinear analyses are catered for and results may be submitted as values at the nodes for averaged nodal results, or element wise at the nodes of each element if discontinuities at the element boundaries are to be examined, or as values at Gauß points within the elements or as a single value per element. Where appropriate, FEMGV allows these analysis results to be presented in the following ways:

- Numerical values superimposed on the model.
- Numerical values tabulated to the screen.
- Numerical values tabulated to a file for printing.
- Contour plots, using line contours or color fill
- Graph plots showing variation at a node over load cases.
- Graph plots showing variation along a line.
- Bending moment and shear force diagrams.
- Highlighted extreme values.

B.4.9 Model visualization

To obtain the desired viewpoint, one may rotate or shift the model, or zoom in or out to inspect a particular area of interest. The visualization modes include an outline representation of the element mesh for extra fast drawing and the checking of mesh connectivity and the display of hidden line views.

A drawing of the full mesh or the mesh with shrunken elements is also available, and a cross-section through a three-dimensional model may be obtained. Shell models can be developed about the \( X \), \( Y \), or \( Z \) axis, or about an axis interactively defined with the graphics cursor.

B.4.10 Output devices

FEMGV supports both color and greyscale devices. Where possible the body of the
FEMGV code is device independent, and the device dependent code is restricted to device specific routines which adapt the final output to the particular device being used. To obtain a hardcopy, FEMGV can write plotting instructions to a file in the required format. This file can be sent to a plotter/printer at a convenient time or get a plot immediately if the automatic plotting feature has been set up.

B.4.11 The database

FEMGV works with a structured database. For each model, the geometric data for preprocessing is stored in one database file and the analysis results (including viewdata) are stored in a separate database file and a load case index file. File names are installation dependent, generally the geometry data file will have a `.G61' extension and the results data files will have a `.V61' and a `.M61' extension. For example, a model with the name `FRED' will have a file for geometric data called `FRED.G61' and results files called `FRED.V61' and `FRED.M61'.

The viewdata in the results file consists of basic element and nodal point coordinate information and also special data sets constructed to support the interactive viewing facilities of FEMGV in the Postprocessing environment. These special viewdata data sets may be created using element and coordinate data previously generated by FEMGV in the Preprocessing environment, or they may be created from element and coordinate data obtained externally from FEMGV.

B.4.12 Model Index Environment

Once you have started FEMGV the working window appears on the screen and brings up the Model Index environment. FEMGV offers a choice of commands from the index menu as well as the ability to directly access models by selecting one of the buttons adjacent to a model name. To enter the Model Index environment from either the Preprocessing environment, or the Postprocessing environment.

**FEMGEN** enters the Preprocessing environment.

**FEMVIEW** enters the Postprocessing environment.
ASSEMBLE builds an assembly of existing models.
INDEX produces a display of the Model Index.
ANALYSE initiates the analysis of the finite element model.
DRAWING controls the destination of graphics output.
UTILITY sets up FEMGV and output device characteristics and control other features.
STOP stops the FEMGV session.

B.4.13 FEMVIEW - Postprocessing Environment

In order to assess a finite element model and its analysis results you must issue the FEMVIEW command, which enters the Postprocessing environment.

FEMVIEW [model]
model is the name of the model. Default is the current model. Selecting an existing model via the VIEW button adjacent to the model name in the model index display. If the named model has no post analysis viewdata in existence, then where mesh data generated by FEMGV does exist, this will be accessed and the viewdata automatically created.

FEMGEN enters the Preprocessing environment of FEMGV.
FEMVIEW switches to another model in the Postprocessing environment.
INDEX enters the Model Index environment and display the model index.
RESULTS selects analysis results.
PRESENT presents analysis results.
CONSTRUCT constructs sets.
VIEW controls the visualization of the model.
LABEL controls display of model attribute labels.
EYE specifies an eye position and viewing transformations.
DRAWING controls the contents of the drawing of the model.
UTILITY controls FEMGV features, output devices and other options.
STOP stops the FEMGV session.
Figure B1  FEMGV Analysis Window
APPENDIX C TYPICAL DIANA INPUT, COMMAND FILES, OUTPUT AND FEMGV FILES

C1 INTRODUCTION

This appendix describes typical input and command files for analysis in DIANA for slab L(500)0.5(100)1.2. The output files (*.out and *.tb) from the analysis are also given and described for this analysis, along with the results from this analysis in a MS Excel graph. Section C6 presents a sample of the input and command file for the covering analysis.

In addition to this, the user input to analyse this slab using the FEMGV pre-processor is also given, with a typical coloured simulation also.

C2 DIANA INPUT FILE FOR SLAB L(700)0.5(150)2.1

'CORDINATES' DI=2 ! Nodal coordinates
1 7.000000E-01 1.500000E-01
2 6.883333E-01 1.500000E-01
   lines skipped
1440 6.766667E-01 1.450000E-01
1441 7.000000E-01 1.450000E-01

'ELEMENTS' ! Element connectivity
CONNECTION
1  B2HT  1 2
2  B2HT  2 3
   lines skipped
59  B2HT  59 60
60  B2HT  60 61
61  CQ8HT  62 527  63 558  94 588  93 557
62  CQ8HT  63 528  64 559  95 589  94 558
   lines skipped
509  CQ8HT  524 1409 525 1440 3 4 5 1439
510  CQ8HT  525 1410 526 1441 1 2 3 1440
MATERIALS

! Defines which elements are assigned to the various material properties.
/ 61-510 / 1
/ 1-60 / 2

DATA

! Defines numbers for special data
/ 61-510 / 1
/ 1-60 / 2

GEOMETRY

! Defines geometry numbers for all elements
/ 1-510 / 1

'DATA'

! Special data input (Gauss points etc)
1 NGAUS 2 2
2 NGAUS 2

'MATERIALS'

! Material properties for elements
1 CONDUC 3.23E-9
DIFFUS 3.23E-9 3.23E-9 3.23E-9 3.19E-9
1.70E-9 2.66E-10 1.68E-10 1.62E-10
POTENT 100 95 90 85
80 75 70 65

: SURFACE EVAPORATION
2 CONVEC 1.80E-8

: TIME(DAYS)
0 50 90
CONVTT 1.80E-8 1.50E-8 1.45E-8
TIME 0 4320000 7776000

'GEOMETRY'

! Thickness of elements
1 THICK 0.700

'BOUNDARY'

! Defines the boundary conditions
CASE 1
ELEMEN
/ 1-60 /
EXTPOT 55

'TIMEBO'

! Time related boundary conditions
0.0 19872000 1 1 1
'INIVAR' ! Specifies the initial conditions for nodes
POTENT 1
/ 1-1441 / / 100 /

'END' ! End of input file

C3 COMMAND FILE FOR DIANA ANALYSIS OF SLAB L(700)0.5(150)2.1

*FILOS ! Initializes and maintains the DIANA database
INITIA

*INPUT ! Reads the input file, and checks the syntax
*ELPOTI ! Evaluates the element model
CAPACITY.C

*FLUX ! Evaluates the boundary conditions

*TRANSI ! Sets up the transient analysis
SELECT

NODES 31 511 1243 356 938 201 108 /

! Nodes that output is required from
END SELECT

OUTPUT TABULA FI=150_LAB_0.5 POTENT COOR

! Select type of analysis output and name
! Potential (\(\varphi\)) and node coordinates
END OUTPUT

INITIA ! Initializes the initial conditions and solution routine

ANALYS/NONLIN ALFA AL=1
OPTION CAPACITY.C
START POTENT.I (1) 1.

END INITIA

EXECUTE STEPS ! Executes time steps and how to solve the equations

SIZE 2592000(4) /
PERFOR NEWTON REGULA MI=3
NORM POTENT CO=0.001
SOLVE DIRECT

END EXECUTE

*END ! End of command file
C4  TYPICAL OUTPUT (*.OUT) FILE

1:*FILOS
2:INITIA
FILOS FILE INITIALIZED
DI= 300   BF= 1024  2048  8192  16384  32768
3:*INPUT
/DIANA/DC/ST33  13:46:56  0.05-CPU  0.00-IO  13.-FA BEGIN

*************************************************************************
*** LONG-TERM DRYING ***
*************************************************************************

*** DIANA RELEASE 7.2 LATEST UPDATE: Thu Jul 19 13:21:40 MET DST 2001
*************************************************************************

1
/DIANA/AP/IN40  13:46:59  2.53-CPU  0.00-IO  195.-FA BEGIN
/DIANA/EP/ID30  13:46:59  3.19-CPU  0.00-IO  236.-FA BEGIN

ELEMENT-TYPE DATA READY: HE=         300 NE=         300 MD=  8
ELEMENT DATA EVALUATED : HE=         300 ND=         821 MC=  8

Lines skipped

0SUM OF EXTERNAL FLUXES:
======================
CASE 1  0.0000D+00
/DIANA/PF/IN30  13:47:07  10.55-CPU  0.00-IO  609.-FA BEGIN
ALFA METHOD.......... ALFA= 0.10000D+01
/DIANA/PF/IT30  13:47:07  11.20-CPU  0.00-IO  679.-FA BEGIN
INITIAL TEMPERATURES.... MF=  1 SF.THETIN
### Lines skipped

/\DIANA/\PF/IM30 13:48:37 101.23-CPU 0.00-IO 7054.-FA BEGIN
DECOMPOSITION EXECUTED : SD= 0.29783D-09 HD= 0.12847D-08
SOLUTION NORM = 0.100318D+04 TOLERANCE = 0.100D-02
DECOMPOSITION EXECUTED : SD= 0.29783D-09 HD= 0.12847D-08
RELATIVE SOLUTION VARIATION = 0.301D-13 CHECK = TRUE

/\DIANA/\DC/END 13:48:59 122.76-CPU 0.00-IO 8581.-FA STOP.

### C4.1 Description of terms

Table C1 describes the terms in the output file above

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOPS=</td>
<td>Number of floating point operations</td>
</tr>
<tr>
<td>HD=</td>
<td>Greatest diagonal term</td>
</tr>
<tr>
<td>HE=</td>
<td>Highest element number</td>
</tr>
<tr>
<td>MB=</td>
<td>Maximum band width</td>
</tr>
<tr>
<td>MC=</td>
<td>Highest no of columns per element. transformation matrix</td>
</tr>
<tr>
<td>MD=</td>
<td>Highest number of DOF per element</td>
</tr>
<tr>
<td>ML=</td>
<td>Number of loadings (combinations)</td>
</tr>
<tr>
<td>MT=</td>
<td>Number of different basis types</td>
</tr>
<tr>
<td>MV=</td>
<td>Highest number of ≠ terms elements per transformation matrix</td>
</tr>
<tr>
<td>NB=</td>
<td>Number of basis</td>
</tr>
<tr>
<td>ND=</td>
<td>Number of DOF</td>
</tr>
<tr>
<td>NE=</td>
<td>Number of elements</td>
</tr>
<tr>
<td>NG=</td>
<td>Number of substructures</td>
</tr>
<tr>
<td>NL=</td>
<td>Number of elements</td>
</tr>
<tr>
<td>NL=</td>
<td>Number of nodal loads</td>
</tr>
</tbody>
</table>
### Appendix C

<table>
<thead>
<tr>
<th>NL=</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN=</td>
<td>Number of nodes</td>
</tr>
<tr>
<td>NQ=</td>
<td>Number of equations</td>
</tr>
<tr>
<td>NS=</td>
<td>Number of supports</td>
</tr>
<tr>
<td>NT=</td>
<td>Number of tyings</td>
</tr>
<tr>
<td>NT=</td>
<td>Number of different element types</td>
</tr>
<tr>
<td>NV=</td>
<td>Number of (load, displacement) vectors</td>
</tr>
<tr>
<td>PROFIL=</td>
<td>Size of L-factor matrix</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SD=</td>
<td>Smallest diagonal term.</td>
</tr>
</tbody>
</table>

---

**Figure C1** Results from analysis performed using input and command files above

#### C5 INPUT DATA FOR FEMGV MODULE

**FEMGV SET-UP INSTRUCTIONS**

- SET WORKING ENVIRONMENT
- FEMGEN
- PROPERTY FE-PROG
- YES
  
**USER INPUTS**

- DRYING
- DIANA FLOW_2D

| GEOMETRY POINT COORD | 0 | 0 |
0.5 0.1
0 0.1
GEOMETRY SURFACE 4POINTS  P1 P2 P3 P4
EYE ZOOM IN

SETTING-UP MESH
MESHING TYPES  S1 QU8 CQ8HT
MESHING TYPES  L3 BE2 B2HT
MESHING DIVISION  S1 36 30
MESHING DIVISION  L3 36
MESHING GENERATE
VIEW MESH

DEFINING SETS
CONSTRUCT SET  SLAB APPEND S1
CONSTRUCT SET  SURFACE APPEND L3

MATERIAL PROPERTIES
PROPERTY MATERIAL CONVECTI  DIFFUS 3.63E-9
PROPERTY MATERIAL BOUNDARY  CONVEC 1E-8
PROPERTY PHYSICAL THICK  THK 0.5
PROPERTY ATTACH  S1 MAT DIFFUS
PROPERTY ATTACH  L3 MAT CONVEC
PROPERTY ATTACH  ALL PHY THK

APPLYING LOADS
PROPERTY LOADS EXTPOT  L3 55
PROPERTY INITIAL IPOTENTI  S1 100
LABEL MESH LOADS INITIAL

GENERATING BATCH INPUT
UTILITY WRITE  DIANA DRYING.DAT
YES
INDEX YES - DRYING CONCRETE
ANALYSIS DRYING

POST-PROCESSING COMMANDS
FEMVIEW
DRYING
RESULTS
NODAL
C5.1 Command File for FEMGV Model

*FILOS
INITIA
*INPUT
*INPUT
READ FILE="DRYING.DAT"
*ELPOTI
CAPACI.C
*FLUX
*TRANSI
OUTPUT FEMVIEW BINARY
POTENT
END OUTPUT
INITIA
ANALYS/NONLIN ALFA AL=1
OPTION CAPACI.C
START POTENT.I (1) 1.
END INITIA
EXECUTE STEPS
SIZE 864000(23) /
PERFOR NEWTON REGULA MI=3
NORM POTENT CO=0.001
SOLVE DIRECT
END EXECUTE
*END

Figure C2 Results from FEMGV analysis above at 20 days
C6  TYPICAL INPUT AND COMMAND FILES FOR COVERING ANALYSIS.

0.5 EQUILIBRATION ANALYSIS LAB

'COORDINATES'  DI=2
1  0.000000E+00  0.000000E+00
2  3.500000E-02  0.000000E+00
   lines skipped
970  6.475000E-01  1.500000E-01
971  6.825000E-01  1.500000E-01

'ELEMENTS'
CONNECTIVITY
1  CQ8HT  1  337  2  358  23  378  22  357
2  CQ8HT  2  338  3  359  24  379  23  358
   lines skipped
299  CQ8HT  313  929  314  950  335  970  334  949
300  CQ8HT  314  930  315  951  336  971  335  950

MATERIAL
/ 1-300 / 1

GEOMETRY
/ 1-300 / 1

DATA
/ 1-300 / 1

'DATA'
1  NGAUS  2  2

'MATERIAL'    ! Only the diffusion coefficient used
1  CONDUC
   DIFFUS  2.01E-11
   POTENT 65    70    75    80    85    90    95    100

'GEOMETRY'
1  THICK  0.7
'BOUNDARY'  ! Specifies surface boundary condition is impervious

CASE 1
NODAL
/ 952-971 / Q / 0 /
   lines skipped
/ 377-951(41) / Q / 0 /

'TIMEBOUNDARY'
0.0 19872000 1 1. 1.

'INIVAR'  ! Initial condition is humidity profile when surface at 75%

POTENT 1
/ 1-21 337-356 / 78.2 / :150
/ 357-367 / 78.2 / :147.5
   lines skipped
/ 931-951 / 75.7 / :5
/ 316-336 952-971 / 75 / :0

'END'

*FILOS
INITIA
*INPUT
*ELPOTI
CAPACITY.C
*FLUX
*TRANSI
SELECT
   NODES 31 511 1243 356 938 201 108 /
END SELECT
OUTPUT TABULA FI=150_LAB_0.5
   POTENT COOR
END OUTPUT

INITIA
   ANALYS/NONLIN ALFA AL=1
   OPTION CAPACI.C
   START POTENT.I (1) 1.
END INITIA
EXECUTE STEPS

SIZE 2592000(4) /
PERFOR NEWTON REGULA MI=3
NORM POTENT CO=0.001
SOLVE DIRECT

END EXECUTE

*END
APPENDIX D  
FINITE ELEMENT ANALYSIS-DRYING

This appendix presents the results of the changing \( rh \) in the concrete from the finite element analyses performed on the concrete slabs tested as part of this thesis. The results are presented in three main sections, one each for the 100, 150 and 200mm thick slabs. Table D1 presents a description of the slabs again for clarity, previously shown in Chapter 4. It must be pointed out, however, that only one set of results will be presented for slabs 1.1-1.3 since these slabs have a w/c ratio of 0.5 and are drying in the laboratory with identical drying environments. This also applied for slabs 1.4 - 1.6 and 2.7 - 2.8. Most of the results are given at 10-day intervals, except Figures D3 and D19, where the \( rh \) was monitored for over 220-days in both cases and are presented in 20-days steps.

Table D.1  Test Series 1

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Specimen Type</th>
<th>w/c Ratio</th>
<th>Drying Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.2</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.3</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.4</td>
<td>500x500x200mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.5</td>
<td>500x500x200mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.6</td>
<td>500x500x200mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.7</td>
<td>500x500x100mm</td>
<td>0.4</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.8</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.9</td>
<td>500x500x100mm</td>
<td>0.6</td>
<td>Laboratory</td>
</tr>
<tr>
<td>1.10</td>
<td>500x500x100mm</td>
<td>0.4</td>
<td>Room</td>
</tr>
<tr>
<td>1.11</td>
<td>500x500x100mm</td>
<td>0.5</td>
<td>Room</td>
</tr>
<tr>
<td>1.12</td>
<td>500x500x100mm</td>
<td>0.6</td>
<td>Room</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Specimen Type</th>
<th>w/c Ratio</th>
<th>Drying Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>700x700x150mm</td>
<td>0.4</td>
<td>Laboratory</td>
</tr>
<tr>
<td>2.2</td>
<td>700x700x150mm</td>
<td>0.5</td>
<td>Laboratory</td>
</tr>
<tr>
<td>2.3</td>
<td>700x700x150mm</td>
<td>0.6</td>
<td>Laboratory</td>
</tr>
<tr>
<td>2.4</td>
<td>700x700x150mm</td>
<td>0.4</td>
<td>Room</td>
</tr>
<tr>
<td>2.5</td>
<td>700x700x150mm</td>
<td>0.5</td>
<td>Room</td>
</tr>
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</table>
### APPENDIX D

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#### D1 100mm thick slabs in the laboratory

**Figure D1**  Relative humidity profiles for slab L(500)0.4(100)1.7.

**Figure D2**  $rh$ profiles for slabs L(500)0.5(100)1.8

**Figure D3**  $rh$ profiles for slab L(500)0.5(100)1.1, 1.2 and 1.3
Figure D4  rh profiles for slab L(500)0.6(100)1.9.

D2  100mm thick slabs in the control room

Figure D5  rh profiles for slab R(500)0.4(100)1.10.

Figure D6  rh profiles for slab R(500)0.5(100)1.11.
Figure D7  rh profiles for slab R(500)0.6(100)1.12.

D3  150mm thick slabs in the laboratory

Figure D8  rh profiles for slab L(700)0.4(150)2.1.

Figure D9  rh profiles for slab L(700)0.5(150)2.2 and 2.7
Figure D10  \( rh \) profiles for slab L(700)0.6(150)2.3

D4  150mm thick slabs in the control room

Figure D11  \( rh \) profiles for slab R(700)0.4(150)2.4.

Figure D12  \( rh \) profiles for slab R(700)0.5(150)2.5 and 2.8
**Figure D13** \( rh \) profiles for slab R(700)0.6(150)2.6.

**D5** 200mm thick slabs in the laboratory

**Figure D14** \( rh \) profiles for slab L(500)0.5(200)1.4, 1.5 and 1.6.
Figure E1  \( rh \) profiles after covering applied in slab L(700)0.4(150)2.1 over time.

Figure E2  \( rh \) profiles after covering applied in slab L(700)0.4(150)2.1 through the depth at 41, 80, 120 and 160-days.
Figure E3  
*rh* profiles after covering applied in slab L(700)0.5(150)2.2 over time.

Figure E4  
*rh* profiles after covering applied in slab L(700)0.5(150)2.2 through the depth at 30, 59, 90, 120 and 145-days.
Figure E5  \( rh \) profiles after covering applied in slab L(700)0.6(150)2.3 over time.

Figure E6  \( rh \) profiles after covering applied in slab L(700)0.6(150)2.3 through the depth at 30, 59, 90, 120, 150 and 175-days.
Figure E7  \( rh \) profiles after covering applied in slab R(700)0.4(150)2.4 over time.

Figure E8  \( rh \) profiles after covering applied in slab R(700)0.4(150)2.4 through the depth at 41, 80, 120, 160, 199 and 269-days.
Figure E9  $rh$ profiles after covering applied in slab R(700)0.5(150)2.5 over time.

Figure E10  $rh$ profiles after covering applied in slab R(700)0.5(150)2.5 through the depth at 80, 120, 160, 200 and 251-days.
Figure E11  $rh$ profiles after covering applied in slab R(700)0.6(150)2.6 over time.

Figure E12  $rh$ profiles after covering applied in slab R(700)0.6(150)2.6 through the depth at 80, 120, 160, 200 and 240-days.
APPENDIX F  

FINITE ELEMENT ANALYSIS RESULTS-COVERING

This appendix presents the results of the changing \( rh \) in the concrete from the finite element analysis performed on the concrete slabs after the impermeable covering has been applied. Table F1 presents a description of the slabs again for clarity, previously shown in chapter 4. The predicted \( rh \) profiles are presented through the depth and over time at the surface and at 130mm (in 20-day intervals), until equilibrium is reached, i.e., until the \( rh \) at the top and bottom of the slab are equal.

Table F.1  
Test Series 2

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<th>Test No.</th>
<th>Specimen Type</th>
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<th>Drying Environment</th>
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<td>700x700x150mm</td>
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<td>2.5</td>
<td>700x700x150mm</td>
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<td>2.6</td>
<td>700x700x150mm</td>
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</tr>
</tbody>
</table>

F1  LABORATORY BASED SLABS

Figure F1  \( rh \) profiles for slab L(700)0.4(150)2.1.
APPENDIX F

Figure F2  $rh$ profiles for slab L(700)0.5(150)2.2.

Figure F3  $rh$ profiles for slab L(700)0.6(150)2.3.

F2 CONTROL ROOM BASED SLABS

Figure F4  $rh$ profiles for slab R(700)0.4(150)2.4.
Figure F5  rh profiles for slab R(700)0.5(150)2.5.

Figure F6  rh profiles for slab R(700)0.6(150)2.6.