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2002-09-04

Moisture Migration in Concrete Slabs during Drying

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Recommended Citation

Holmes, N., West, R.: Moisture Migration in Concrete Slabs during Drying. Proceedings of the International Congress-Challenges of Concrete Construction, University of Dundee, pp. 173-180, September, 2002.

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ABSTRACT This paper presents the profiles of relative humidity (RH) readings taken at various depths in concrete slabs during a time period of over 230 days using probes attached to a humidity-reading device. It also examines the effect ambient conditions have on the drying process. For the experimental work, two sets of slabs were tested, one in a controlled environment with an elevated temperature and the other in a laboratory at room temperatures. It was found, not surprisingly that the slabs in the controlled room appeared to dry out at a much faster rate than those held at room temperature. However, a residual of moisture remained within the slab and the average residual RH over the depth of the latter was as much as 85%, as compared with 80% for the former. This suggests that the industry's standard, specified in BS 8203: 1996, concerning the application of floor coverings when the surface reaches a RH of 75% needs to be treated with caution especially when drying is artificially accelerated. Due to this moisture residue remaining in the slab, any impermeable covering applied to the surface may result in a number of defects occurring, leading to expensive repair work later on. A scheme for modelling the process numerically is presented, employing the finite element method that will eventually account for changing ambient RH, non-linear diffusion coefficients and sealing of the surface at some point in time.

Keywords: Diffusion, finite element method, floor slabs, moisture movement relative humidity.

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INTRODUCTION

Establishing the point in time at which a floor covering can be safely applied to a concrete slab is a major concern in the floor construction industry. If a floor covering is applied too early, numerous defects can occur, such as blistering of paint or vinyl, buckling of floorboards or possible rising of tiles [1], [2]. Yet there is a strong economic incentive for a contractor to lay the floor covering as early as possible. The current standard for applying a covering to concrete floors [3] states that it may be applied when the surface reaches a relative humidity (RH) of 75%, usually established using a standard hygrometer test [3].

This so-called safe threshold, however, does not account directly for the moisture condition below the surface and, as shown from the humidity profile in Figure 1, there can still be a considerable residue of moisture in the slab. If a covering is applied at 75% RH, the defects mentioned above may occur due to a vapour pressure forming underneath the covering arising from the trapped residual moisture. If a significant vapour pressure develops under the covering, arising from ongoing gradual non-linear diffusion of the residual moisture to the surface [4], this can lead to expensive repair work later on. This paper reports on the quantification of this effect from experimental work carried out at Trinity College Dublin (TCD), and urges caution when deciding whether the industry standard of 75% surface RH is an acceptable value at which to safely apply such coverings.

The ability to predict the point at which the application of a covering could be safely applied would be a major achievement, reducing the chance of the defects mentioned above from occurring. At present, work is under way at TCD to model the movement of moisture over time using numerical methods and, specifically, to predict the long-term residual vapour pressure that develops under the vapour barrier. The finite element method (FEM) is being employed to represent the mathematical equations that are programmed into a FORTRAN program to model the process. It is anticipated that this model will predict the changes to the humidity profile with depth over time and assist in determining when a covering may be safely applied.

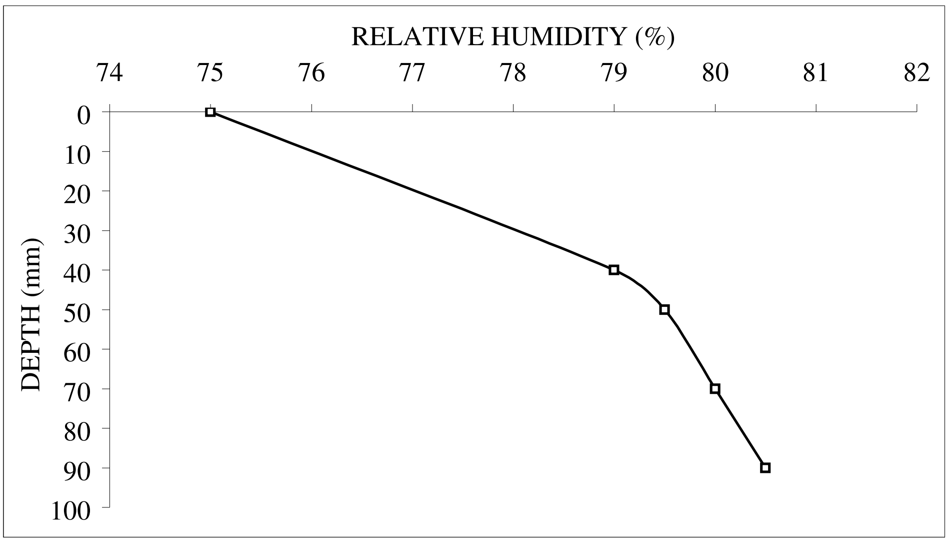

Figure 1 RH profile showing residual moisture in 100mm thick slab when surface is at 75% RH.

EXPERIMENTAL SET-UP

A number of concrete slabs were made up each 500x500x100mm with a w/c ratio of 0.5. The slabs were cured for 7 days under wet hessian before the measurements began. Following this, all the slabs were coated with a sealant on five sides, leaving the top surface exposed. This ensured that drying took place in one direction only, namely upwards and this represented actual drying conditions of a slab on grade on site. At this point, four separate holes were drilled into the concrete to depths of 50, 60, 80 and 100mm. The drilling of the holes did generate some heat but it is expected that this did not affect the moisture condition in the slab too adversely. The holes were 20mm diameter into which plastic tubes, which had slots 10mm above the base were inserted, as shown in Figure 2. Therefore, the average heights of the RH readings were, 40, 50,70 and 90mm. A layer of silicone was applied to the sleeve of the tube to ensure a strong bond developed between the tube and the exposed concrete. In addition, a rubber membrane isolated the slots from the upper part of the hole and developed a 'chamber' of uniform RH between the rubber seal and the bottom of the tube.

In order to read the RH at depth, humidity probes were inserted into the tubes and attached to a CE-RH meter that give an instantaneous reading on a display panel [5]. The surface moisture condition is simultaneously revealed by pressing the device onto the concrete [1] where 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 CE-RH has been developed by a Dublin based company, Tramex Ltd, which design and manufacture moisture meters for concrete and timber materials. The variation in RH was measured over a time period of 230 days. In addition, a number of surface Vapour Emission Tests (VET) and Surface Hygrometer (SH) tests were carried in accordance with the recommended VET [6] and the British Standard [3] procedures to monitor the decrease in the moisture emitted from the surface and to assess the accuracy of the CE-RH meter.

The slabs were placed inside two separate rooms, one at room temperature in a laboratory and the other in a warmer room with a dehumidifier present. The average temperatures and humidities were 14^0C and 55% and 26^0C and 35% in the laboratory and control room respectively. The purpose of this was to monitor the effect the 'forced' drying condition had on the drying process throughout the thickness of the slab compared with that in the laboratory.

The complete experimental set-up is shown in Figure 3. Surface RH readings were also taken using the CE-RH with an insulated tent mounted onto the surface of the slab [3]. The probe was inserted into a plastic pipe on the tent and the RH was recorded after approximately 2 minutes to allow for any fluctuations in RH to settle. This set-up is shown in Figure 4.

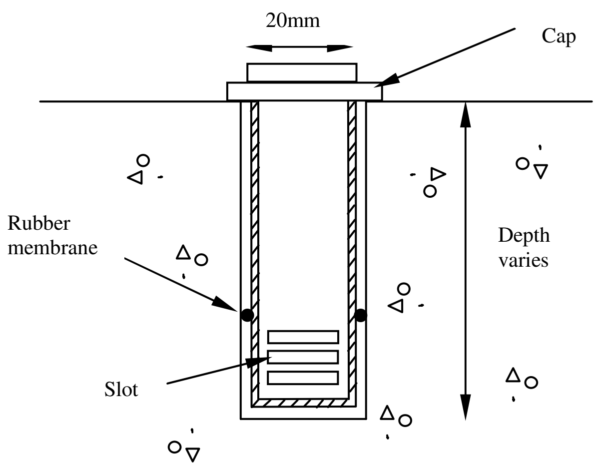

Figure 2 Drilled hole with slotted tube in place for CE-RH readings.

Figure 3 The complete experimental set-up.

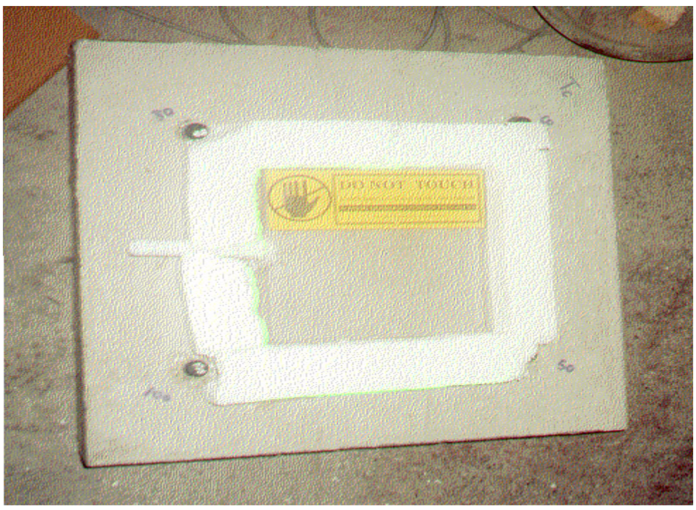

Figure 4 Surface RH apparatus, showing the access tube for the RH probe leading into a sealed plastic tent.

DISCUSSION OF TEST RESULTS

The slabs ‘dry out’ from the surface with time, depending on the ambient conditions, and the concrete’s diffusion characteristics. When a slab is ‘dry’ depends very much on the environment, where an equilibrium is reached between the RH of the air and the residual moisture in the slab. In a previous paper [4], the authors discussed how the trend from numerous VET and SH tests showed the reduction in moisture content over time until they reached their threshold value of 3 lbs/1000ft^2/24hrs and 75% surface RH respectively. However, of course, surface RH reduction tests are usually discontinued at this point in time as the ambient RH has reached the 75% threshold. But, these surface tests say nothing about the moisture condition in the slab deeper down and so continued monitoring of a slab reveals further reduction of the surface RH, assuming suitable ambient conditions.

Figure 5 shows RH profiles at various depths in the concrete as measured using the CE-RH. It is clearly shown from the experimental results that there is still a considerable residue of moisture remaining deep within the slab. For example, at approximately 70 days the surface reaches the BS standard of 75% surface RH to apply coverings. However, it is not until 140 days that the slab had dried sufficiently such that 75% is the maximum RH throughout the thickness of the slab.

Figure 6 shows two RH profiles of identical concrete slabs drying in the two different environments; one in a controlled room at an elevated temperature with a dehumidifier present and the other in the laboratory with normal ambient conditions. From Figure 6 it is obvious (and expected) that the slab in the controlled room is drying at a much faster rate than that in the laboratory, and will reach the 75% surface RH in a much shorter time, approximately 40 days. This accelerated rate of drying results in considerable residual moisture remaining in the slab as the surface dries at a faster rate than lower down.

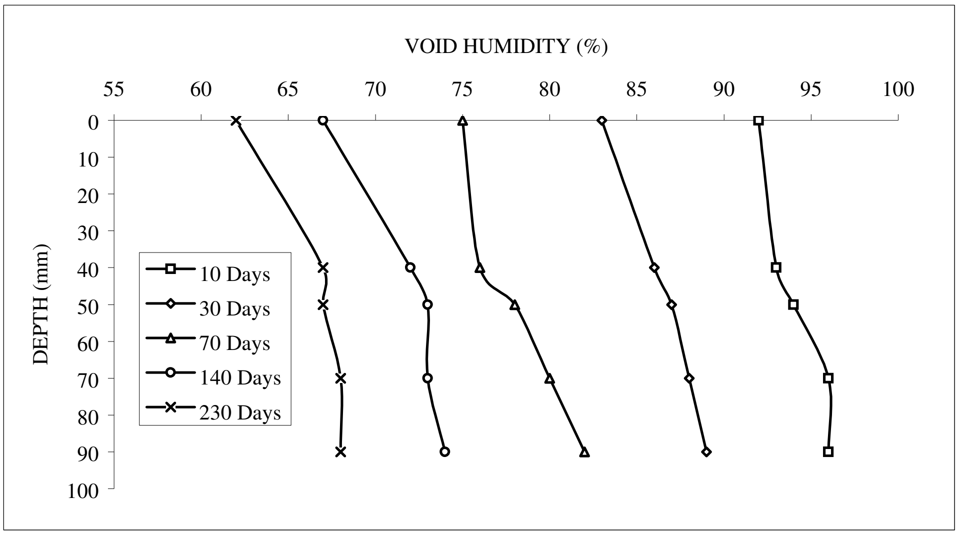

Figure 5 Void RH at various depths over time in the laboratory

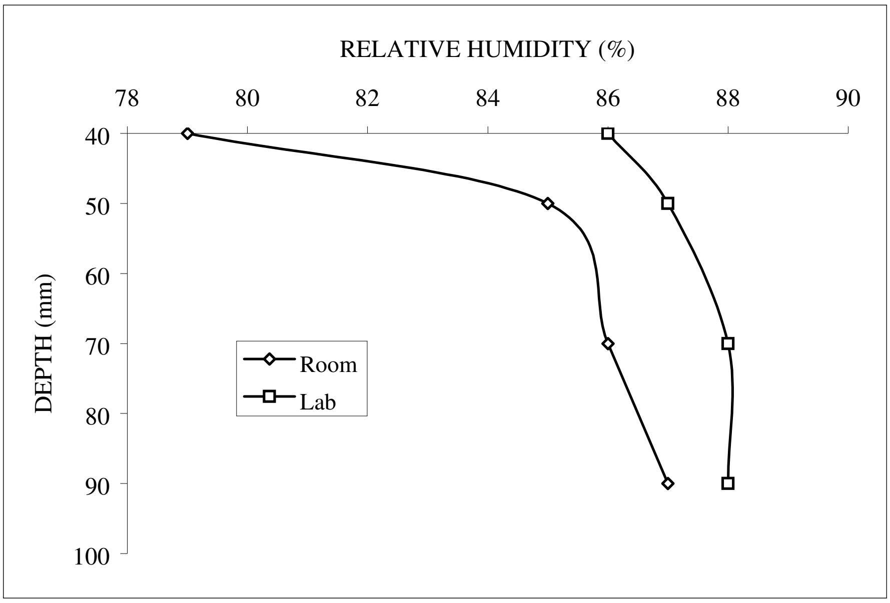

Figure 6 RH profiles for identical slabs at 28 days of drying. One is drying in a heated control room and the other is at ambient laboratory temperature

Following the application of a covering, a vapour pressure will develop underneath the vapour barrier as moisture continues to migrate by diffusion to the surface, under the pressure of a concentration gradient with depth (as seen in Figure 6). An equilibrium RH will be reached some considerable time later between the residual moisture in the slab. This concept is demonstrated in Figure 7. The concrete, drying in the laboratory, will have residual moisture leading to a long-term average RH below the impermeable covering of, for example, 80%. The moisture condition in the slab drying at an elevated temperature, however, causes a greater average long-term vapour pressure to develop (for example 85% in Figure 7) because the drying conditions have accelerated the moisture loss near the surface, leading to premature achievement of 75% RH at which time the surface may be sealed. This may lead to extensive damage to the covering if this vapour pressure is greater than the adhesion force of the covering to the surface.

It is, therefore, vital that concrete slabs are allowed ample time to dry out sufficiently and naturally before the application of coverings is allowed. At present, the current tests for establishing the 'dryness' of slabs and the construction standards do not take full account of this residual moisture. Indeed, in order for a true reflection of the moisture condition, the RH must be assessed through the full slab depth. However, it should be noted that previous experience indicates that if slabs are allowed to dry naturally, then residual moisture on the slabs is not usually enough to develop sufficiently high vapour pressure to cause defects. Traditional tests such as the VET and SH take 1-3 days to complete and even then tell one little about the moisture condition within the slab. The CE-RH is a much faster test and does allow an assessment of the moisture condition through the depth of the slab.

It has become apparent that being able to predict the residual moisture in a concrete slab would be a major advantage for the flooring industry. It would mean that coverings could be applied as early as possible with little risk and the defects mentioned above could be reduced or eliminated with substantial savings made in relation to the repair work needed.

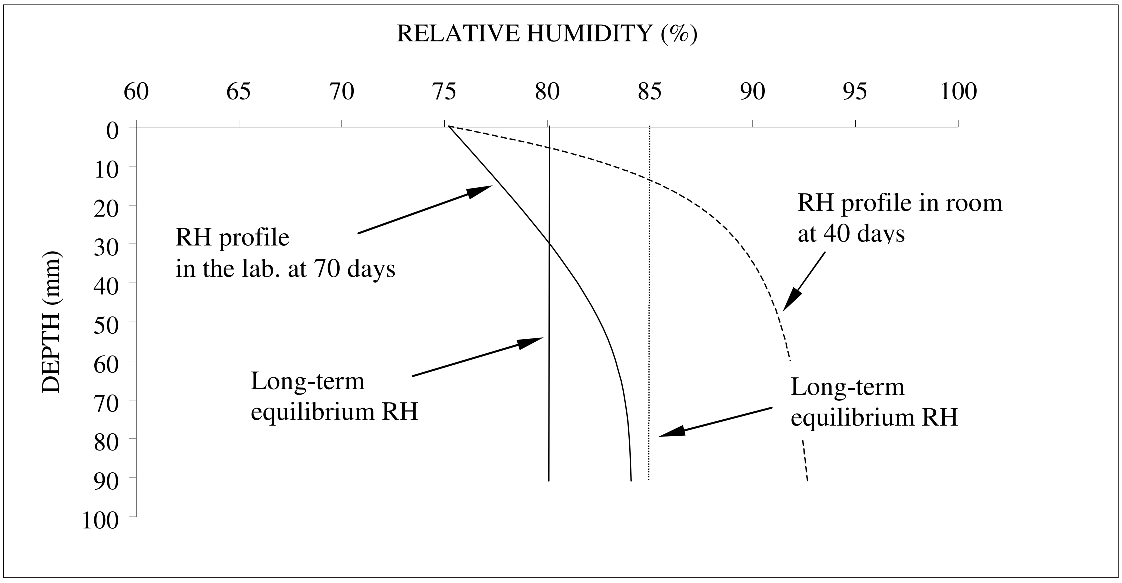

Figure 7 Long-term effect of applying a floor covering in different environments when surface is sealed under RH of 75%

MATHEMATICAL FORMULATION

At present, work is being carried out to mathematically model the transient movement of moisture through the concrete slab taking account of the changing ambient conditions and the non-linear diffusion coefficient [4]. It is anticipated that this model will predict the effect of applying a covering to the surface and the subsequent development of a vapour pressure some time later. Previously [4, 7], prediction methods were used in conjunction with experimental data and by developing empirical equations using various methods. Here, the finite element method (FEM) is being employed, using mathematical principles, to solve the well-known Fick's second law of diffusion [8], given by:

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}(D\frac{\partial}{\partial x}) \tag{1}$$

where H is the relative humidity (%), t is time (days) and D is the diffusion co-efficient (typical units m^2/sec). Following the FE discretisation process, Equation 1 is transformed into a system of ordinary differential equations [9], given as:

$$[C]^{(e)}\left\{\frac{dH(t)}{dt}\right\} + [D]^{(e)}\{H(t)\} = 0 \tag{2}$$

where [C] is the capacity matrix, [D] is the diffusion matrix and H(t) is the humidity as a function of time.

These equations are solved using a time stepping processes [10] with a constant D and boundary conditions. They have been programmed by the authors into a FORTRAN matrices FEMMTC (Finite Element Modelling of Moisture Through Concrete) where the [C] and [D] matrices are assembled. Equation 2 is then solved by FEMMTC using the time-stepping process below:

$$\lfloor K_{eff} \rfloor \{a\}_n = \{R_{eff}\}\{a\}_{n-1} \tag{3}$$

where:

$$\left[K_{eff}\right] = \left[\frac{[C]}{\Delta t_n} + \theta [D]\right] \tag{4}$$

$$\left\{R_{eff}\right\} = \left[\frac{[C]}{\Delta t_n} - (1-\theta)[D]\right] \tag{5}$$

and Δt is the time-step, θ is a dimensionless parameter ranging from $0 \leq 1$, $\{a\}_n$ is the current unknown to be solved and $\{a\}_{n-1}$ is the previous solution, where {a} is the pore humidity.

Results from the program are shown in Figure 8, and are compared with the experimental results. In this example, the diffusion coefficient used was constant throughout (1.0×10^{-12} m^2/sec [11]). As shown, there are slight differences in the early stages, signifying that the diffusion coefficient is indeed non-linear early on. However, over time, the accuracy of the model is reduced as D is varying with time (t), depth(x), concentration (H) and temperature (T), or in mathematical terms [12]:

$$D = f(t, x, H, T) \tag{6}$$

The major difficulty in the modelling analysis will be taking account of the non-linear behaviour and work is underway to use non-linear methods to account for the changing diffusion co-efficient. It is anticipated that the model will be able to predict when a slab will be dry enough to apply coverings by taking into account the mix constituents and the ambient conditions. With calibration of the model, the distribution of the residual moisture trapped under the covering will be predicted over time.

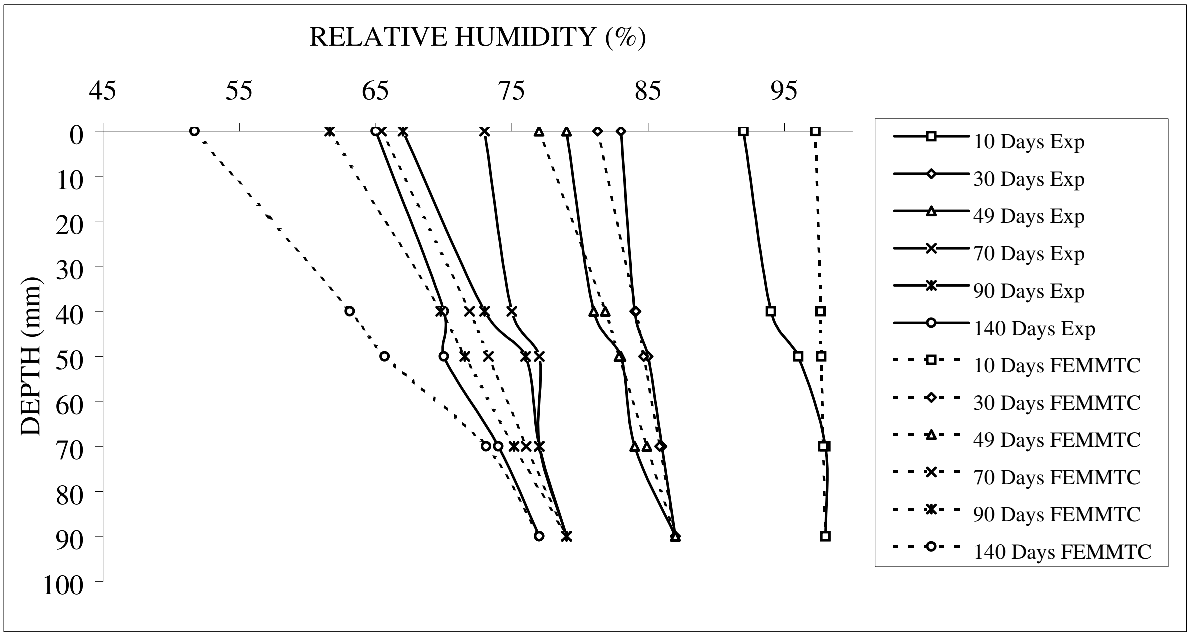

Figure 8 Experimental Results compared to FEMMTC results

CONCLUSIONS

In this paper, the authors present results from experimental work carried out on two sets of identical concrete slabs, one in a laboratory at room temperatures and the other in a control room with an elevated temperature, and the effect the ambient conditions have on the RH profiles within the slab.

The results show, not surprisingly, that the slab in the controlled room dries at a much faster rate than that in the laboratory, particularly at the surface. However, this leads to a significant residue of moisture remaining within the slab, which has been quantified. If a covering were applied at this stage to the slab in the accelerated drying environment, defects may occur leading to expensive repair work. Results from tests carried out over 230 days demonstrate that the normally dried slab had dried sufficiently after 70 days to satisfy the British Standards recommendation that a covering may be applied when the surface reaches a RH of 75%. However, it was shown that the slab needed to dry for a further 70 days to reach a maximum of 75% RH throughout the thickness the slab. Further, it is predicted that the average residual moisture remaining in the slab, if a coating were applied, in the controlled room would have reached 85%, while the slab in the laboratory would have reached an average RH of 80%. This former residue of moisture may have developed a significant vapour pressure under a covering, leading to numerous defects later.

Work is currently underway by the authors to develop a numerical model in FORTRAN, employing the finite element method to model the process using equations developed based on a modification of Fick's second law of diffusion. It is anticipated that this model will be able to predict the residual RH profiles through the thickness of the slab for non-linear diffusion coefficients and varying ambient conditions and to estimate the long-term vapour pressure that develops under a floor covering. By doing this, the risk of damage may be reduced and substantial savings may be made in the costly repair work needed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the technical assistance and advice provided by Mr. Alan Rynhart of Tramex Ltd.

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