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R. P. West
Trinity College Dublin

Niall Holmes
Technological University Dublin, niall.holmes@tudublin.ie

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Experimental Investigation of Moisture Migration in Concrete

R.P. West and N. Holmes
Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin 2, Ireland.

ABSTRACT: The ability to be able to predict the state of dryness of a concrete floor slab is a practical need in the construction industry. Current popular methods, including the surface hygrometer and vapour emission tests, only indicate surface dryness, with consequent uncertainties in the quantity of residual moisture deep within the slab. This paper describes the variation in moisture condition with depth for a number of slabs under different drying conditions, as established using a new probe which can reliably determine the relative humidity at any depth. From this it is concluded that results from the conventional tests need to be treated with caution due to wide variations in the residual moisture, which could give rise to defects in impermeable floor coverings due to trapped moisture leading to excessive vapour pressures.

KEYWORDS: Diffusion, drying, floor slabs, moisture content, moisture movement, relative humidity.

1 INTRODUCTION:

One of the most commonly encountered problems in the concrete flooring industry is the establishment of a point in time at which a concrete slab is dry enough so that a floor covering can be applied safely. If floor coverings are applied too early, residual vapour pressure from the slab may cause a number of detrimental effects to occur such as blistering of vinyl and rising of tiles (O'Neill et al., 1998). In the case of timber floors, buckling of the floorboards may occur due to swelling which results in unsatisfactory repair work or alternatively, shrinkage gaps may open up over time.

The current standard for applying floor coverings (BS 8203) states that when the surface of a slab reaches 75% relative humidity (RH), it is dry enough to apply such coverings. This may seem a suitable value on the surface, but the standard does not mention the residual moisture remaining deeper in the slab, as shown in Figure 1. If a covering of some sort were applied at 75% surface RH, defects, such as those mentioned above, may occur due to vapour pressure developing underneath the covering, as moisture slowly diffuses to the surface. This paper sets out to show, from experimental tests carried out at Trinity College Dublin, that considerable residual moisture still remains deep within the slab (depending to a large extent on the drying conditions), which may cause the problems outlined above.

The main method of movement of moisture through a slab is by diffusion, where a concentration gradient is set up between the top and bottom surfaces within the concrete (if the bottom is sealed, such as with slabs on grade). Moisture deep within the concrete is at a higher concentration than that at the surface. Therefore, the moisture moves from the region of high concentration to low concentration, in a diffusion process. The moisture, in the form of water vapour, very slowly diffuses to the surface through non-interconnected and interconnected pores within the concrete matrix. The initial RH is assumed to be 100%, or fully saturated. During the early stages of the drying process, this movement is non-linear, changing to an almost linear one some time later (West et al., 1999).

Experimental work, which is reported on here, was carried out using a number of freshly poured slabs. Several holes were drilled into the slabs and the pore humidity was measured at various depths over time. To achieve this, portable humidity probes are attached to a hand-held RH meter. This meter gives instantaneous reading of the humidity on a display panel. The meter, a CE-RH (Concrete Encounter-Relative Humidity), has been developed by a Dublin-based company, Tramex Ltd, in association with TCD; they design and manufacture moisture meters for concrete and timber materials. The CE-RH is shown in Figure 2. In addition to the RH being measured at depth, the surface RH was also measured using the CE-RH with an insulated tent attached to the surface of the slab.

A number of other more common tests were also performed on the slabs as part of the test program, namely the Surface Hygrometer (SH) test used in the UK and the Vapour Emission Test (VET) used in the USA.

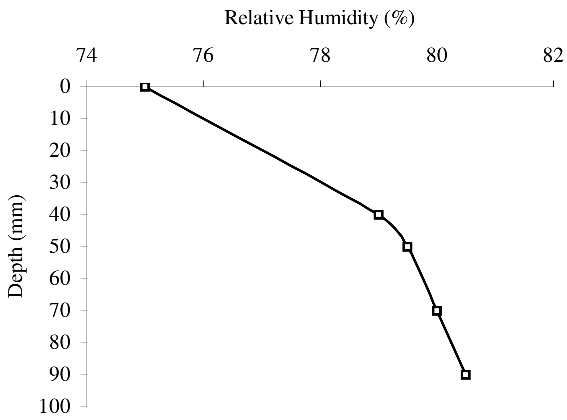

Figure 1: Typical residual moisture in a slab when the surface is at 75% RH.

Figure 2: The hand-held humidity meter, CE-RH.

2 EXPERIMENTAL SET-UP

Six freshly poured slabs, each 500x500x100mm, were made for the experimental work. The slabs all had a w/c ratio of 0.5 and the mix constituents for the slabs are given in Appendix A. The slabs were allowed to cure for seven days under wet hessian before preparation began for the experimental work. Following the curing regime, five sides of the slabs were coated with several layers of a sealant. This was to ensure that drying took place in one direction only, namely vertically upwards. At this point separate holes were drilled into each slab to depths of 50, 60, 80 and 100mm. The drilling of the holes generated some heat but it is expected that it did not affect the moisture condition too adversely. The holes were 20mm external diameter into which plastic tubes were inserted. The tubes were slotted at 10mm above the base (Figure 3) and an external rubber membrane isolated the slots from the upper part of the hole. A layer of silicone was applied along the top of the tubes to ensure that a strong bond developed with the concrete to prevent any movement during the testing regime.

Humidity probes were placed into these holes at various intervals over a 230 day period and connected to the CE-RH meter which measured the variation in RH. However, each reading was taken after approximately 2 minutes to allow for any fluctuations in the equilibrium reading.

The near-surface moisture condition was monitored using another hand-held device, a CME, again developed by Tramex (O'Neill et al., 1998). The CME works by pressing the device onto the surface of the concrete and taking an instantaneous reading on a display panel. In essence, 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. In addition, the ambient temperature and humidity were recorded.

The slabs were allowed to dry in two separate rooms, one at room temperature in a laboratory and the other in a warmer room with a dehumidifier present. The purpose of the latter venue was to monitor the effect the 'forced' drying condition had on the moisture condition throughout the slab and to compare this with the moisture condition of the natural drying regime. The average temperature and humidity was 14^0C and 55% and 26^0C and 35% in the laboratory and control room respectively. The complete experimental set-up is shown in Figure 4. The testing program lasted for over 230 days, with CME and CE-RH readings being taken roughly every two days.

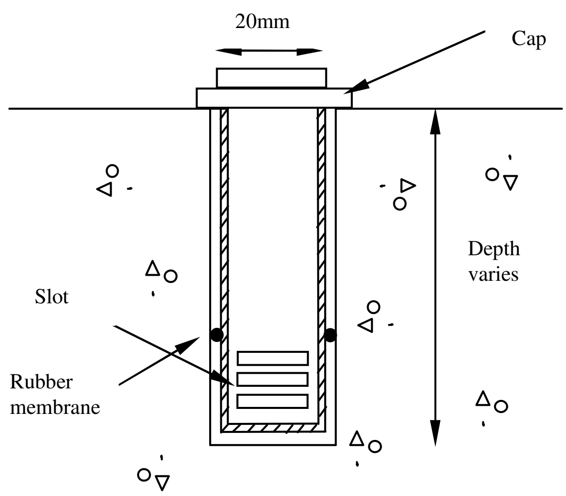

Figure 3: Drilled hole with slotted tube in place for CE-RH readings.

Figure 4: The complete experimental set-up showing the humidity probes, CE-RH and the CME.

Measurement of the surface RH was taken using an insulated tent mounted onto the surface of the slab. The probe was inserted into a plastic pipe fixed onto the tent and the surface RH was recorded on the CE-RH. The set-up is shown in Figure 5.

A number of standard tests such as the surface hygrometer (SH) and a vapour emission test (VET) were performed on the surface to assess the accuracy of the probes and the CE-RH meter (O'Neill et al., 1998). The set-up for these tests is shown in Figures 6 and 7. These tests were performed in accordance with the British Standard (BS 8203) and the recommended VET procedure (Vapour Emission Test, 1994). These tests have the disadvantage that it takes some time to reach equilibrium within the sealed areas, up to three days in some cases.

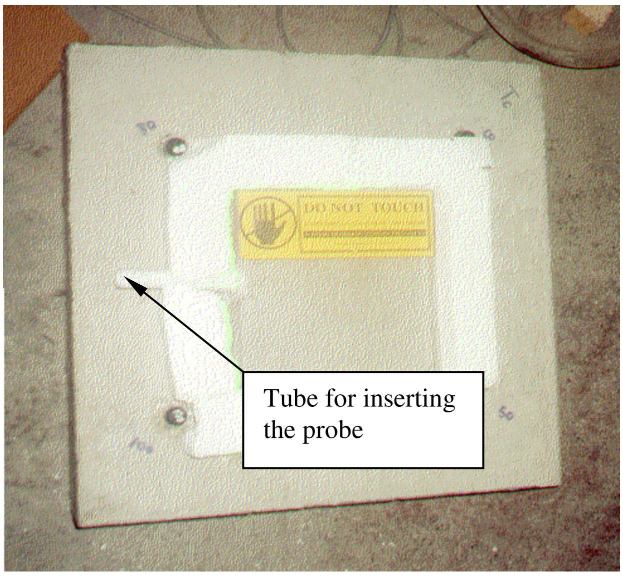

Figure 5: Surface RH apparatus with sealed tent: The humidity probes inserts into the tube on the left.

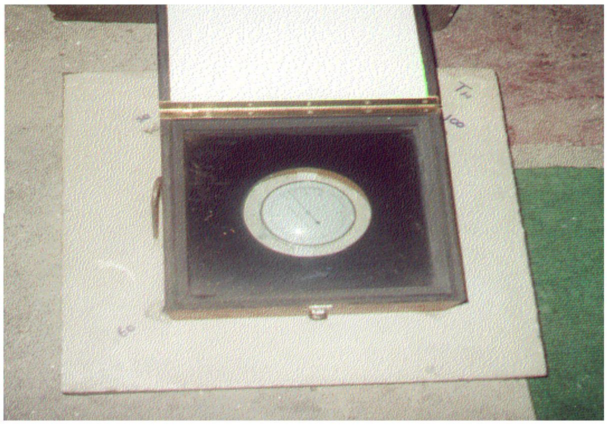

Figure 6: Surface Hygrometer test set-up.

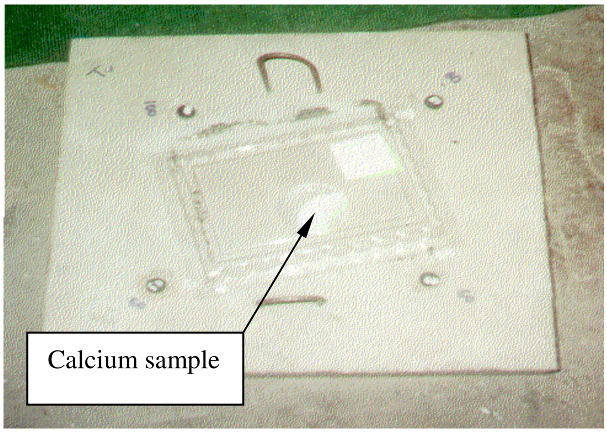

Figure 7: VET set-up showing the calcium chloride sample in the sealed tent.

3 RESULTS AND DISCUSSION

The drop in the VET and SH readings with time in the laboratory are presented in Figures 8 and 9. These would be the conventional way of determining whether the slab had dried, although it would be unusual to have quite so many readings. In the VET, the traditional threshold of 3lbs/1000ft^2/24hrs for establishing when the slab is 'dry' is actually a test of whether the slab has reached equilibrium with the environment in terms of RH. Therefore, this is not a unique state of moisture condition in the slab – in a high RH ambient environment, equilibrium occurs earlier and at a higher slab moisture condition than in a low RH environment. Temperature also has a strong influence. What is important to assess is not the absolute reading of the test, but when is this equilibrium achieved, as determined from the bottoming out of the VET results against time curve (at about 60 days in Figure 8).

Similarly, in Figure 9, when the slab is dry according to the hygrometer test is thought to be at 75% RH (at about 40 days according to the figure), but clearly the slab is not dry at this stage, and yet a floor covering may be allowed to be placed at this RH value on site. This curve appears to bottom out at approximately 85 days.

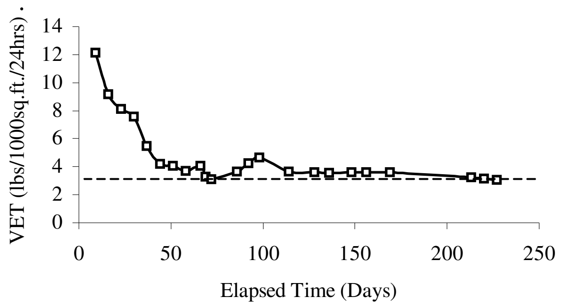

Figure 8: VET variation with time in the laboratory sample.

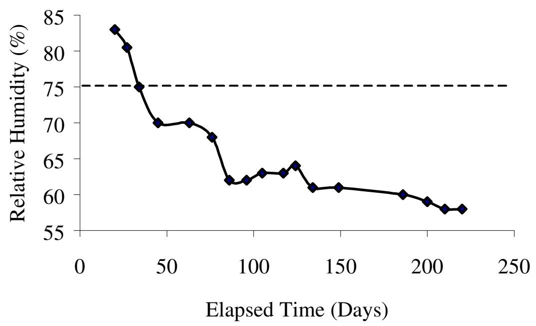

Figure 9: Surface hygrometer variation with time for the laboratory sample.

On the other hand, the CME, which gives an instantaneous reading, can easily produce the trend in the moisture condition of the near-surface concrete, allowing the point at which the equilibrium is reached to be identified (Figure 10). This appears to be at about 75 days, but the RH continues to drop gradually with time as the moisture continues to be lost from the slab.

In every case, for a particular surface reading, the RH within the slab was higher (Figure 11). The CE-RH probe slots, set at 40mm, shows that it takes as long as 200 days to reach equilibrium, although clearly, the concentration gradient of moisture has dropped sufficiently after 120 days to give a very slow diffusion rate.

Temperature and RH of the environment has a strong influence on the drying with depth, as well as the expected differences on the surface (Figure 12). For example, at 28 days of drying, the RH at 40mm below the surface is 78% and 86% for the control and laboratory room respectively. Even at this early age, there is a large discrepancy in the profiles of RH with depth in the different environments.

Results of the pore humidity against depth with age are shown in Figure 13. The moisture distribution begins at 100% RH throughout the depth, but quickly becomes a non-linear one as moisture evaporates from the surface. This changes to an almost steady state after about 200 days. At this point the concentration gradient through the depth of the concrete results in an even rate of diffusion through the slab. At this stage, the surface moisture

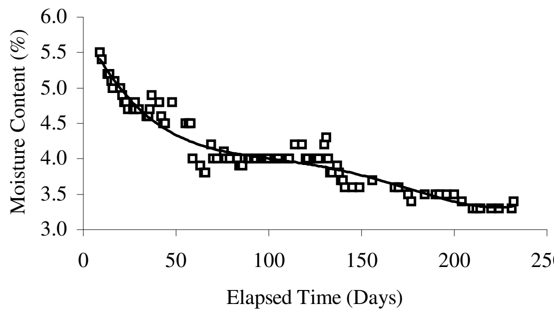

Figure 10: CME variation with time for the laboratory sample.

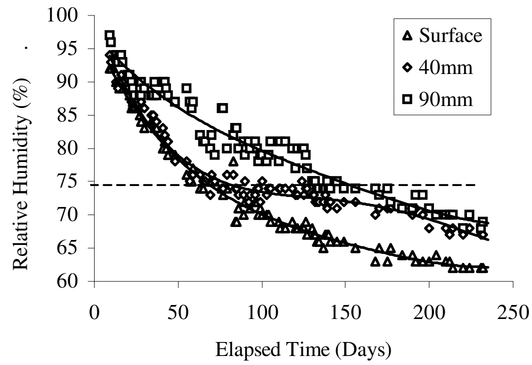

Figure 11: Variation of relative humidity with time for different depths in the laboratory sample.

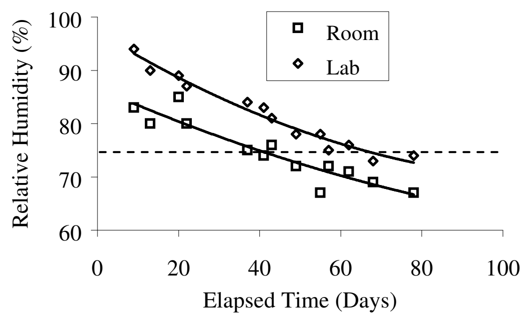

Figure 12: Variation in surface RH reading with time for slabs under different drying conditions (CE-RH).

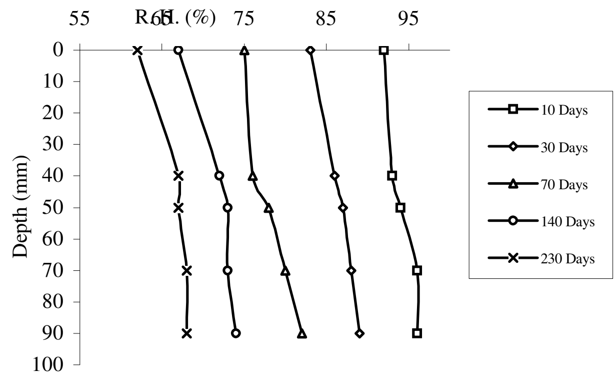

Figure 13: Pore humidity at various depths over time in the laboratory.

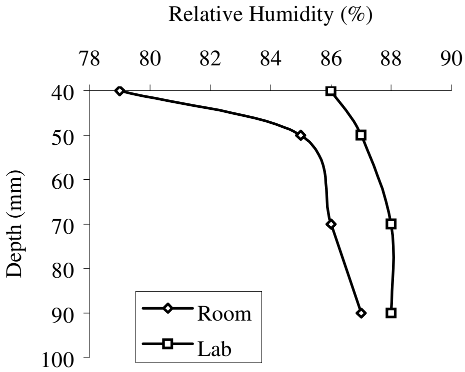

Figure 14: Moisture condition due to different drying condition at 28 days.

condition will vary little with time and the moisture deeper down in the slab will still try to escape through the surface at an even slow rate. The importance of this observation is that the moisture condition is now well below the BS assumption of 75%, the point at which a slab is considered dry enough to receive a covering of some sort.

As stated, the main emphasis of this paper is to highlight the effect of a forced drying regime on the moisture condition deeper down in the concrete. From the tests carried out it is clear that this is the case. Fig. 14 shows two sets of results from identical slabs except for their environment.

If the trend in the results for the control room was extended to the surface, it would be approximately at 75% RH. This is the point at which it is assumed that a slab is dry enough to apply a coating of some sort. However, it is clear that a large amount of residual moisture still remains deep within the slab, almost as much as in the normal drying case (which has not yet reached 75% RH). The 75% threshold on the surface is reached much later in the natural drying environment (at about 60 days), at which point the residual moisture in the slab is much reduced. Figure 15 demonstrates this idea clearly. If a coating was applied at 75% surface RH (regardless of drying conditions), a considerable vapour pressure could develop underneath the covering where the pressure that develops underneath the covering is dependent on the residual vapour remaining in the slab when sealed.

The long term average RH that would exist, trapped, under the floor covering is also shown in Figure 15 for the two cases of exposure, given that they are sealed as soon as the surface reading is 75%. These values have been estimated as 79% and 86% and these would give rise to a significant difference in vapour underneath an impermeable membrane.

4 CONCLUSIONS

In this paper, an experimental method was described that measured the moisture migration through a concrete slab over time. This was carried out using humidity probes

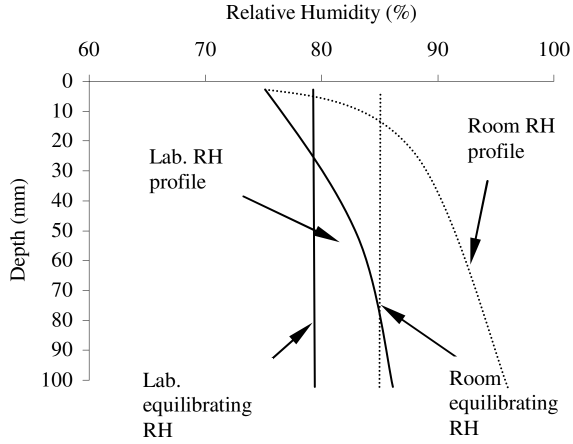

Figure 15: Effect of applying floor covering too early, with forced drying.

attached to a hand-held device that give an instantaneous reading of the relative humidity at various depths. Two identical slabs were placed in different environments, one at room temperature with natural drying conditions and the second in a room at an elevated temperature with a dehumidifier to speed up the drying process.

The results show primarily that the drying regime during the early stages is non-linear, changing to a linear steady-state some time later. Indeed, during the middle stages of the tests, it is obvious that when the surface reached equilibrium with the environment, the moisture deeper in the slab migrates faster. If this where allowed to continue, a constant moisture profile would develop that indicates that the slab has 'dried out' fully. However, this may take some months or even years to complete.

Another issue raised from the tests is the point in time at which a floor covering of some sort can be applied safely to the concrete. The industry's assumption of a threshold of 75% surface RH needs to be treated cautiously because, as shown from the moisture profiles, there is still a residue of moisture deep within the slab which varies considerably, depending on the drying regime. It is clear, then, that if an impermeable floor covering, or, indeed, a timber floor, is to be placed on top of a concrete slab, it is preferable to allow the concrete to dry under natural ventilation only. If a dehumidifier and heater are used to artificially accelerate the drying process due to time constraints, this may lead to unacceptably high levels of trapped moisture deep within the slab, when the supposedly safe threshold of 75% RH has been complied with. This, in turn, may lead to blistering of an impermeable floor covering, lifting of tiles or buckling of a timber floor due to swelling. Clearly this applies equally to industrial and domestic applications.

The next stage of work, currently being carried out by the authors, is to mathematically model the movement of moisture through concrete over time. The finite element method (FEM) is being used to develop a numerical model of the process. It is hoped that the model can successfully predict the moisture distributions over time allowing for changing ambient conditions and, further, it will allow the residual moisture profiles to be anticipated sufficiently accurately to estimate the long-term vapour pressure which will develop underneath an impermeable floor covering. In this way, the risk of blistering and buckling defects may be assessed before any covering is laid.

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APPENDIX A: MIX CONSTITUENTS

The mix constituents for the concrete slabs are given below. The mix achieved an average slump of 90mm and a mean compressive strength of 47.5N/mm^2.

Qty	**Cement (kg)**	**Water (l)**	**Medium sand (kg)**	**10mm agg (kg)**	**20mm agg (kg)**
Per m^3	390.0	195.0	706	353.0	706.0

ACKNOWLEDGEMENTS

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