Articles

School of Civil and Structural Engineering

Enhanced Accelerated Drying of Concrete Floor Slabs

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Enhanced accelerated drying of concrete floor slabs

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Concrete floor slabs dry out through a process of evaporation and diffusion provided the ambient environment promotes such drying. Impermeable floor coverings laid on concrete slabs can be subject to damage caused by high levels of residual moisture trapped by premature sealing of the surface. This damage can include timber floor boards buckling, vinyls blistering or tiles lifting. Whether or not it is safe to apply such a covering depends on whether the slab is sufficiently dry. Furthermore, if accelerated drying techniques are employed to reduce the waiting time before covering, the surface relative humidity reduces more rapidly, but there is an increase in the risk of damage to the covering because of higher levels of residual moisture deep within the slab. By using actual data from a variety of specimens to calibrate a non-linear finite-element model of the moisture migration, this paper shows how numerical predictions can be undertaken to determine a safer long-term relative humidity under an impermeable floor covering.

Introduction

When an impermeable floor covering is laid on concrete slabs, if the concrete is not sufficiently dry, then the risk of damage to that covering, such as arising from blistering of a vinyl carpet or lifting of floor tiles, increases substantially (Grady, 1995). Given that concrete drying is a slow and non-linear process (de J. Cano-Barrita *et al.*, 2004; de Freitas *et al.*, 1996; Shimomura and Maekawa, 1997), it is not straightforward to determine how long one should reasonably wait before covering the floor, recognising the pressures on building contractors to complete the works as soon as possible.

A freshly poured concrete floor is exposed to the ambient environment as soon as curing ceases and quickly loses its surface evaporable water, including bleed water, on the surface to the surrounding air. The evaporation of water from the surface takes place because there is a difference in the relative humidity (RH) of the air and within the pores in the near surface of the slab.

There are considerable reserves of evaporable water deep within the concrete depending on the water content and water-to-cement (w/c) ratio of the concrete mix. The water must migrate, by diffusion, through the pore structure before evaporating from the surface. Drying continues through the slab depth until such time as there is equilibrium between the environment and the entire slab can now be said to be completely 'dry'. The state of dryness of a slab therefore depends on the ambient environment in which it is found, noting that the RH of the air varies considerably from location to location as well as diurnally and seasonally in any one place. For example, if the air is very humid, then an exposed slab will 'dry' relatively quickly, while in an arid climate it may take years to fully dry, practically (de J. Cano-Barrita *et al.*, 2004).

Within the slab, the moisture transport mechanisms which facilitate this drying comprise two essential phases: moisture migration within the pores inside the concrete and evaporation from the surface. When water evaporates from the surface, the pores at and immediately below experience a difference in moisture concentration and diffusion commences, initially at the surface, but relatively quickly in the nearby pores. Gradually, a varying RH gradient is set up through the slab depth and moisture migrates slowly from deep within the concrete, at a rate depending on the openness of the pore structure.

The rate of evaporation from the surface depends on a number of physical characteristics (de Freitas *et al.*, 1996; Shimomura and Maekawa, 1997), such as the drying regime (including the ambient RH, temperature and wind (Jacobsen and Aarseth, 1999) and the surface properties (including the type of surface finish, degree of hydration determined by curing, presence of moisture suppressants, etc.). Mix water is consumed over time through cement hydration, leading to self-desiccation, but significant residual water exists in the capillary pores, which contributes to long-term drying through moisture migration.

Moisture diffusion through concrete (Akita *et al.*, 1997) largely depends on several factors. These include the concrete mix constituents, namely the w/c ratio (primarily as this determines the quantity and connectedness of the capillary pores and the chemically uncombined water), the cement type (for example, some supplementary cementitious materials tend to give denser

packing and lower permeability) and the RH concentration gradient between adjacent pores.

In addition to these two mechanisms affecting drying, the moisture path also has a role (Parrott, 1991), that is, whether or not drying is from one or two faces of the slab and the depth of the slab itself. Furthermore, the water content of the mix has an influence, irrespective of the w/c ratio, because the greater the quantity of water in the slab, the longer it will take to dry out (Martys, 1972). For this reason, water-reducers are usually used to reduce the water content for a given w/c ratio when drying time is to be minimised. Drying can also induce drying shrinkage stress gradients, which can lead to early-age cracking in restrained slabs (Grasley et al., 2006).

As it can take many months or even years for a slab to be effectively 'dry', engineers and those responsible for laying floor coverings must make a pragmatic judgement as to how dry is dry enough in order to safely apply a floor covering (BS 8203, BSI, 2001). If the covering is water vapour permeable, such as timber flooring, the timing still needs careful consideration as the residual moisture in the concrete on laying such a floor will migrate upwards with swelling and possible buckling occurring, often within a matter of days. For impermeable coverings, the problems are less immediate but equally pronounced as the residual moisture stays trapped under the floor covering and damage can take a long time to materialise owing to the slow nature of diffusion within concrete. In either case, with fast-track construction, every viable means is being employed to reach a safe covering threshold as soon as possible.

When an impermeable covering is applied, moisture continues to migrate upwards because a concentration gradient will exist, as the pores near the surface will inevitably have a lower RH on sealing. Over time, as moisture continues to diffuse under this gradient, the RH immediately under the surface covering will increase, leading to a vapour pressure being generated (Hedenbland, 1996). Furthermore, dissolved salts from the cement paste and pores can also accumulate and the combination of both can cause some adhesives to weaken; this process, possibly exacerbated by poor workmanship upon application of the adhesive, can cause a vinyl to blister or tiles to rise (Suprenant and Malisch, 1998).

To avoid the problem of trapped moisture, it is recommended (BS 8203, BSI, 2001) that the concrete surface RH should be no more than 75% before an impermeable covering is applied. In practice, indeed, many flooring contractors insist on a surface RH of 75% being present before they will guarantee their floor covering against blistering and so on, and this appears to be based on the knowledge that once this 75% requirement has been met, there are seldom such problems as described above in practice when natural drying has been used.

One traditional method to establish the surface RH has been a surface hygrometer test (BS 8203, BSI, 1996) which is relatively slow, as it takes 72 h to complete. Alternatively, a surface vapour emission test (VET, 1994) can be used to measure surface emissions of moisture into a plastic tent stuck to the surface; here the defined level of acceptable dryness is when the result of this test is less than the threshold of $3-5$ lb/1000 ft^2 per 24 h (approximately $1 \cdot 5-2 \cdot 5$ kg/100 m^2 per 24 h) (VET, 1994).

Many floor covering problems of the types described above arise because the floors have been covered too early, but some also arise because, in response to needing to meet a specified surface RH requirement, the contractor has deliberately accelerated the drying process through the application of, for example, external forced heating and dehumidification. Alternatively, the concrete may be in a climate which naturally dries under more severe drying conditions. In either case, surprisingly, while faster evaporation and an enhanced state of dryness exist at any point in time, the potential long-term equilibrium RH when the surface covering is applied is much higher for the accelerated drying case. This is because the surface requirement is met much earlier in the drying process with a much higher residual moisture state deep in the slab. This leads to a false belief that the concrete is dry enough to cover and a higher risk of covering failure. Therefore, having knowledge of the status of the RH through the full floor depth at the time of covering is vital to be reasonably sure of avoiding problems, if anything other than natural drying is employed.

This paper will give guidance on how to determine when 'dry' is more likely to be dry enough. It will also show how more rapid drying techniques can be employed without increasing the risk of experiencing damage to the floor covering, while still making worthwhile time savings over natural drying times.

There is lack of practical research evidence to support a decision as to when it is safe to apply an impermeable floor covering to a drying concrete floor slab. The risk of a future covering experiencing problems is reasonably high when trying to meet the continuing need for faster completions of industrial and domestic floor construction projects. By using calibrated finite-element analyses for predicting the residual moisture in slabs during forced drying, it will be demonstrated that the long-term equilibrium RH under the covering can be manipulated to safer levels.

Experimental investigation

An experimental programme was undertaken (Holmes, 2009) to investigate the drying behaviour of 20 concrete slabs made with ordinary Portland (CEM I 42·5N) cement with various w/c ratios (0·4, 0·5 and 0·6), slab depths (100, 150 and 200 mm) and two drying environments. In the laboratory, where some of the tests were conducted, normal fluctuating ambient temperature and RH conditions pertained, with averages of 14°C and 55% RH respectively. Alternatively, in an insulated and sealed control room, the conditions were allowed to fluctuate naturally under permanent

forced heating and using a dehumidifier with an average of 27°C and 35% RH for the 100 and 200 mm thick slabs and 40°C and 13% RH for the 150 mm thick slabs. All slab specimens were sealed on five sides to allow unidirectional (vertically upwards) drying only. There was only normal bleeding and no plastic shrinkage cracking on the concrete slabs after casting and before curing began. Any incidence of laitance was removed before any measurement of the surface RH was taken, where the surface was lightly scrubbed with a wire brush and vacuumed after curing.

The RH was measured at various depths from the slab top surface using a calibrated portable humidity probe. This probe was inserted into individual plastic tubes (with end slots) which had been inserted into drilled holes of the requisite depth. Figure 1 illustrates how a rubber ring on the outside of the bottom of the tube seals in a chamber of air within 10 mm of the base of the hole and the slotted holes at the base of the tube allow permeation of local pore RH into the tube, which has an RH equivalent to the enclosed chamber. When the RH probe is inserted into the plastic tube to take RH readings in the bottom chamber at any stage during drying (these tubes remain in place and RH readings can be taken indefinitely), sensitivity tests have shown that it takes just a few minutes for the RH to equilibrate again in the tubing before a reading is recorded on a hand-held meter connected to the probe. For example, readings were taken in separate holes at 10, 35, 60, 85, 110 and 130 mm for the 150 mm slabs.
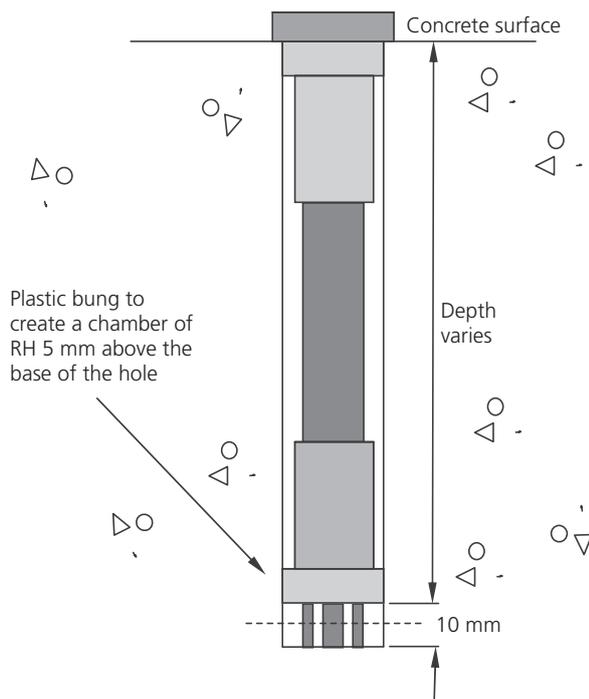
Surface readings were taken in a manner similar to the traditional hygrometer or VET tests, in which a heavy-duty plastic tent is stuck to the surface and, after 72 h has elapsed to allow local vapour emissions to equilibrate in the enclosed space, the humidity probe is inserted into the enclosed space in the tent to register a reading.

When the surface reached 75% RH, the slabs were covered with an impervious vinyl covering using a standard adhesive, which sealed it to the slab. In the specimens used for this research, experienced local flooring contractors were engaged to lay the vinyl sheets on the slabs according to established methods.

Holes for each of the plastic tubes were carefully cut away from the vinyl and silicone was used to seal around the edges to ensure no moisture/vapour escaped from underneath. By doing this, the below-surface RH readings could continue to be taken reliably as the residual RH slowly re-distributed through the slab over the succeeding months.

Experimental results

Drying phase

Figure 2 illustrates two typical profiles of measured relative humidity with depth when the surface RH reaches 75% (Holmes and West, 2002). All surface measurements were taken using the sealed tent (BS 8203, BSI, 1996). In the more benign environment of the laboratory, the profile (after 90 d of drying) is more linear where the RH gradient is more gradual through the depth. As shown, the RH at 135 mm is approximately 78% and the overall residual moisture is relatively close to the RH at the surface (75% RH). The fact there is not a constant RH with depth and that the ambient RH is in the region of 55%, on average, indicates strongly that although this slab has reached 75% RH on
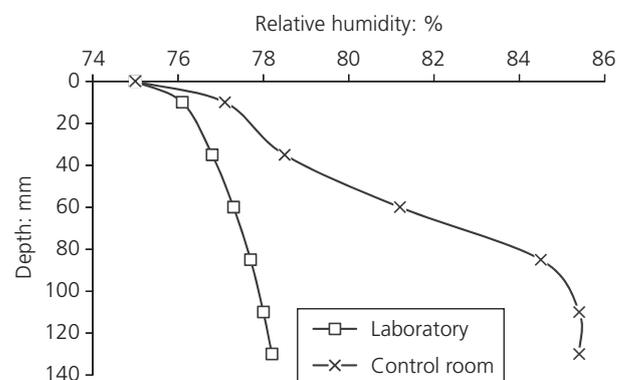

Figure 1. Humidity chamber below the concrete surface in a plastic tube

Figure 2. Relative humidity variation with depth for 150 mm concrete slab with w/c = 0·5 when surface reaches 75% RH under natural (laboratory) and forced (control room) drying conditions

the surface, it is not yet fully 'dry'. These trends and drying rates have been seen previously (Kim and Lee, 1999). Also, it has been found that self-desiccation has an effect in lower w/c concretes.

Previous work (West and Holmes, 2005) has found that for early drying, the comparisons between the experimental results and finite-element analysis are greatest, particularly for the 0·4 w/c mixes in the control room. The assumption in the modelling that the RH is 100% at $t = 0$ may not be valid owing to self-desiccation, chemical binding and ongoing early hydration for these slabs; this has been confirmed by the poor correlation between measured and predicted values. Furthermore, finite-element analysis may confirm what is a suitable initial condition for these low w/c concretes.

In contrast, the slab in the control room with accelerated drying has reached 75% on the surface after just 44 d (Figure 2), an apparent saving in time of some 46 d compared to normal drying. The profile with depth, however, is more non-linear and, indeed, there is evidence that between 90 and 135 mm, there is little difference in RH and drying in that region would be slow owing to a low moisture gradient. Closer to the top, owing to rapid evaporation at the surface, there is a high concentration gradient close to the surface and the diffusion rate is artificially high here and deliberately so.

Although both slabs have the same w/c, curing regime and surface finish, the drying behaviour is clearly quite different. The consequence of the more severe drying regime is that while the surface 75% RH requirement for covering may now be met in both cases, the residual RH deep in the artificially dried slab is about 85% at 135 mm. Therefore, the total residual moisture in this slab is considerably higher than the latter case. It should be recognised that all of these below-surface readings are not exact – both specimens and test methods are prone to local variability (West and Holmes, 2005). Nonetheless, the trends are helpful in understanding the drying behaviour.

Table 1 illustrates typical values for natural and forced drying for w/c ratios of 0·4, 0·5 and 0·6 in the two drying environments.

Although the slabs with higher w/c ratios have more capillary pores and so are expected to dry faster, the 75% surface requirement is met sooner in the lower w/c ratio concrete as these slabs have less free water after hydration.

Analytical investigation

Finite-element model calibration using real data
The finite-element software package Diana (Diana, 1999), can be used to simulate this drying problem (Holmes, 2009; West and Holmes, 2005). Using two element types, a linear two-noded isoparametric element for evaporation for exposed surfaces and a non-linear eight-noded quadrilateral isoparametric element to model diffusion together with zero flux boundary conditions on impervious surfaces, the drying process can be modelled reasonably accurately (Figure 3). The initial RH conditions for all elements are set at 100 (%) to simulate a fully saturated concrete after casting. The external conditions are set at an appropriate ambient RH value.

The diffusion coefficient does depend on the RH condition in a local pore (Bazant and Najjar, 1972; Kim and Lee, 1999), as shown in Equation 1

$$D(h) = D_1 \left[\alpha + \frac{1 - \alpha}{1 + \left(\frac{1 - h}{1 - h_\mathrm{c}} \right)^n} \right]$$
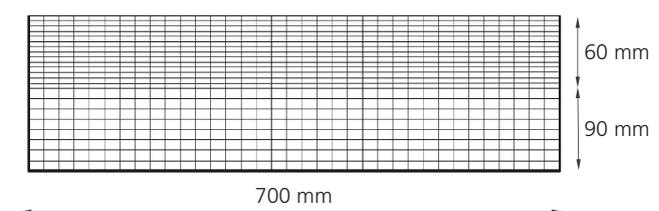
1.

Figure 3. Finite-element model for 150 mm deep concrete slabs

	w/c = 0·4	w/c = 0·5	w/c = 0·6
Natural drying			
RH at 130 mm: %	79	78	81
Time to reach 75% on surface: d	82	90	96
Forced drying			
RH at 130 mm: %	87	85	86
Time to reach 75% on surface: d	40	44	49

Table 1. Sample RH at 130 mm depth in 150 mm deep slabs when surface reaches 75% RH, and time to reach this threshold for natural and forced drying regimes for slabs of different w/c ratios

where D_1 is the initial diffusion rate at 100% RH (which has been calibrated at $4·0 \times 10^{-9}$ m²/s for a w/c = 0·5 based on these results for a CEM I cement). Typical values for the constants α and n (for D when RH = 0%) are 0·05 and 15 respectively (CEB, 1989). h and h_c are respectively the RH in the pores when D is $0·5D_1$, which is taken as 0·85 (Bazant and Najjar, 1971, 1972; Holmes, 2009; Kim and Lee, 1999). In accordance with Equation 1, the change in D with respect to RH, as shown in Figure 4, is critical to simulating the non-linear drying behaviour accurately. As shown, D decreases with RH (Bazant and Najjar, 1971, 1972) and the diffusion model is unaffected by the drying regime employed, as may be expected (Kim and Lee, 1999). This equation was developed following analysis of experimental data on drying concrete and cement paste. It has been found to give a satisfactory fit between the measured and predicted RH profiles with the diffusion coefficient considered to be a function of the pore RH, which makes the diffusion problem of drying non-linear. The diffusion coefficient decreases sharply as the RH falls from approximately 90 to 60% RH, below which it remains constant as it has been found to provide a realistic prediction of drying (Bazant and Najjar, 1971, 1972; Kim and Lee, 1999).

The evaporation model, which was also non-linear, but less so that the diffusion model, is dependent on both the w/c and the drying regime. The two calibrated evaporation models for the laboratory and control room environments are given in Figure 5 (Bazant and Najjar, 1971, 1972) and adapted (Holmes, 2009).

Finite-element simulations of drying
Having calibrated the finite-element model, it is possible to reproduce an idealised history of drying up to the point when the surface reaches 75% RH for both drying regimes, as shown in Figures 6 and 7. It may be seen that while the overall drying rate is slowing down with time, equilibrium is not yet reached in either case. For instance, at 90 and 45 d in Figures 6 and 7 respectively, the RH is not constant through the depth, which it would be if full equilibrium was achieved. Further, the close grouping of the depth lines in Figure 6(b) is in contrast to Figure 7(b) where the accelerated drying is reflected in the clustering of
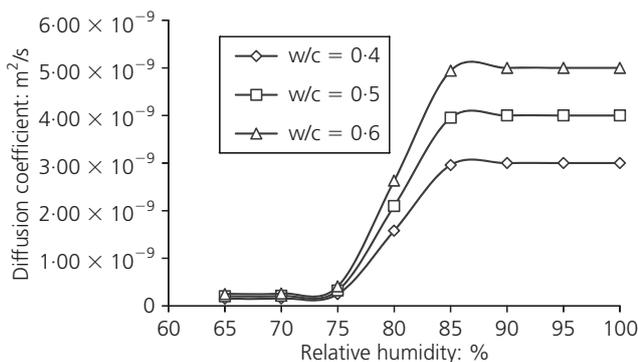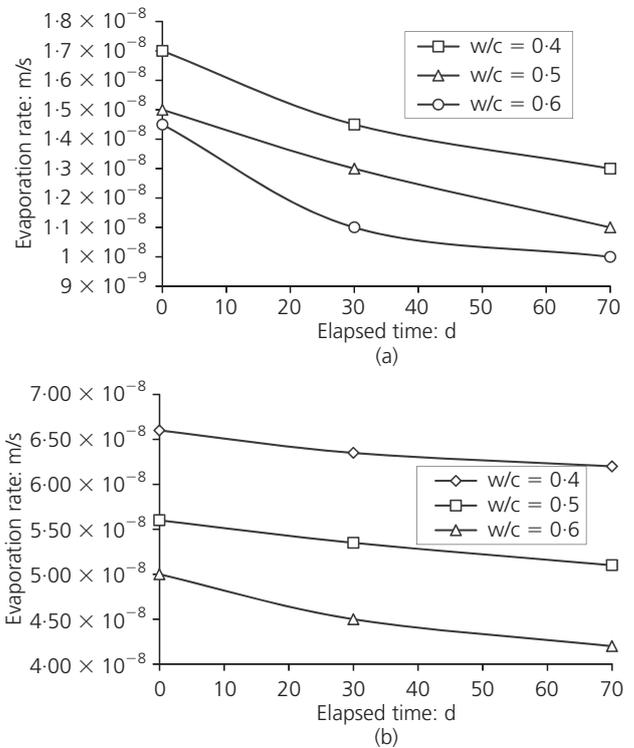
Figure 5. Calibrated evaporation models for (a) natural and (b) forced drying regimes

the deeper lines, indicating, again, the much larger residual moisture and lower concentration gradients at depth in the latter slab.

Finite-element modelling of covering a slab
Once the finite-element model is satisfactorily calibrated to predict drying until 75% RH is observed at the surface, it is then possible to modify the top boundary to mimic an impervious condition with the application of a vinyl. With this boundary, fresh analyses can be run in which the initial RH condition through the concrete is re-set to be that when 75% RH is achieved on the surface. For instance, the RH profiles at 90 and 45 d in Figures 6 and 7 are input as the initial conditions. By running a simulation of how the RH distribution changes when the floor covering is applied (Figures 8 and 9), a good understanding of the next phase of moisture migration behaviour may be had.

As may be observed, the RH on the surface now increases for the first time as the residual moisture deep in the concrete continues to diffuse upwards under the RH gradient set up in the concrete at the point of covering. The process continues, increasing surface RH slowly (as the (b) diagrams indicate) until eventually, in theory, overall RH equilibrium is reached under the covering. The magnitude of this long-term equilibrated residual RH is determined by the initial shape of the RH profile and the maximum RH at the bottom upon sealing. In addition, as a consequence of
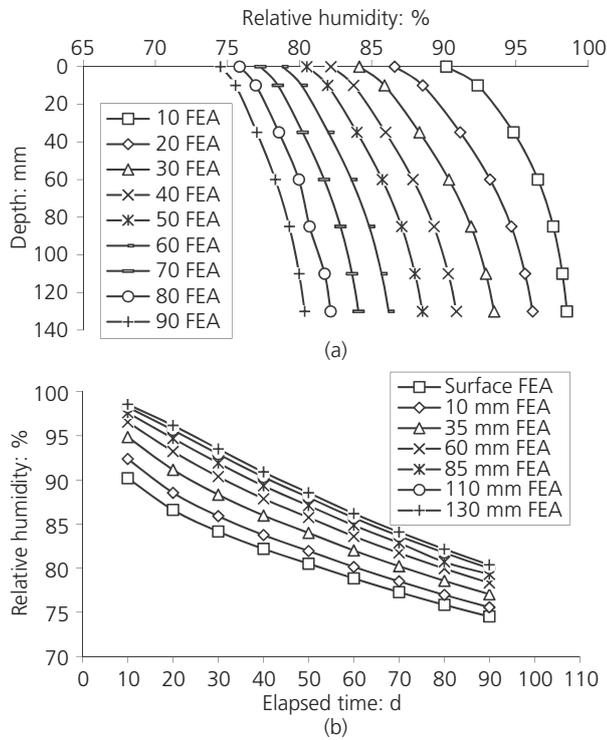
Figure 4. Calibrated diffusion model for different w/c ratio slabs

Figure 6. Simulation of drying in laboratory over first 90 d:
(a) with time over depth; (b) with depth over time (FEA: finite-
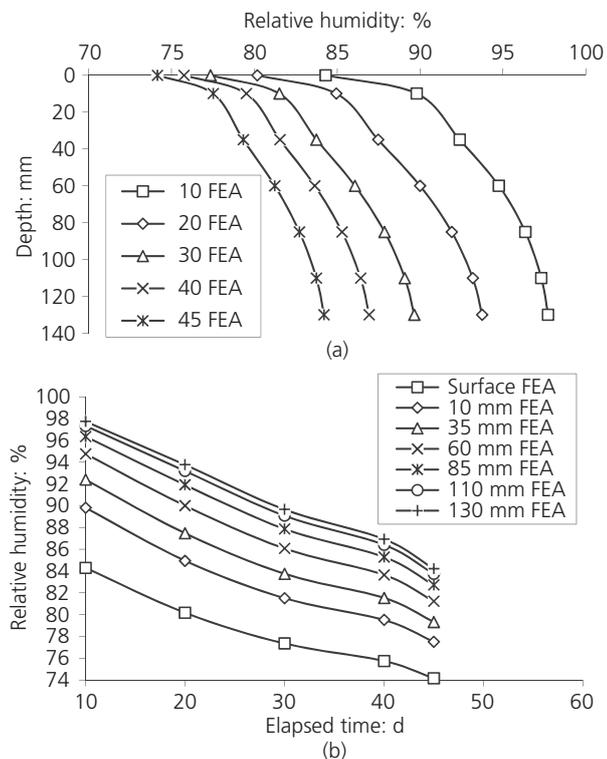element analysis)

Figure 7. Simulation of drying in control room over first 44 d:
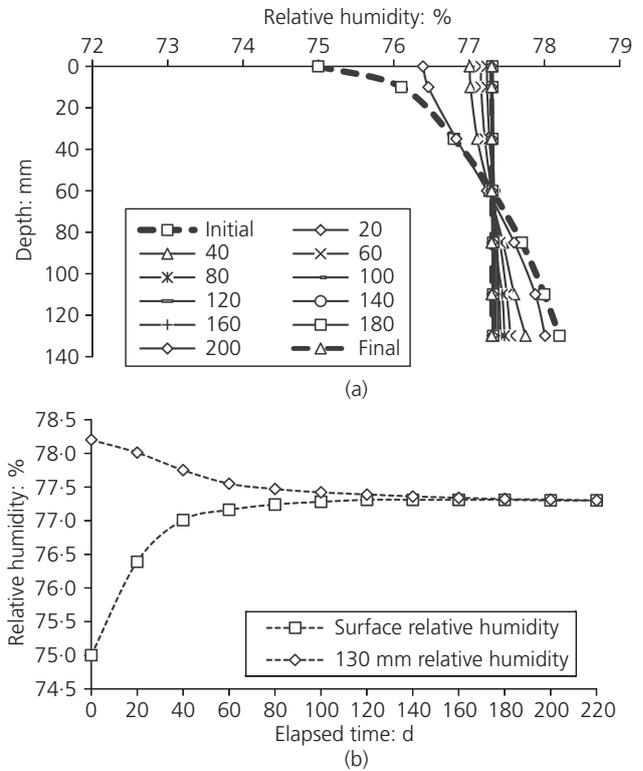(a) with time over depth; (b) with depth over time

Figure 8. Redistribution of RH: (a) over depth; (b) over time at the
extremes of depth in the laboratory-dried specimens using finite-
elements

the different drying regimes, the starting RH distributions will
vary. In the natural drying case (Figure 8), the final RH through
the depth (at approximately 160 d) is 77·5% RH, which is about
two-thirds of the difference between the initial top (75%) and
bottom (78·3%) RH values. In the forced drying case (Figure 9),
however, the long-term equilibrium value is about 82% at 400 d;
this is approximately, again, two-thirds of the difference between
the top (75%) and bottom (85·3%) RH values. The duration
before equilibrium is reached is not precise, nor does it matter
particularly except to illustrate that floor coverings can fail at
many months and perhaps even years after covering; this is well
known to be the case in practice.

As moisture moves upwards underneath the covering during
equilibration, a vapour pressure also develops. In addition,
moisture and dissolved salts can accumulate and interact with the
glue to precipitate the types of problems described earlier. The
greater the average residual moisture, the more likely this will
occur and it clearly is more likely to occur when accelerated
drying has taken place, because the long-term equilibrium RH
below the surface can be sufficiently high to initiate the issues
described above at some point.

Of particular note in Figures 8(a) and 9(a) is the fact that at
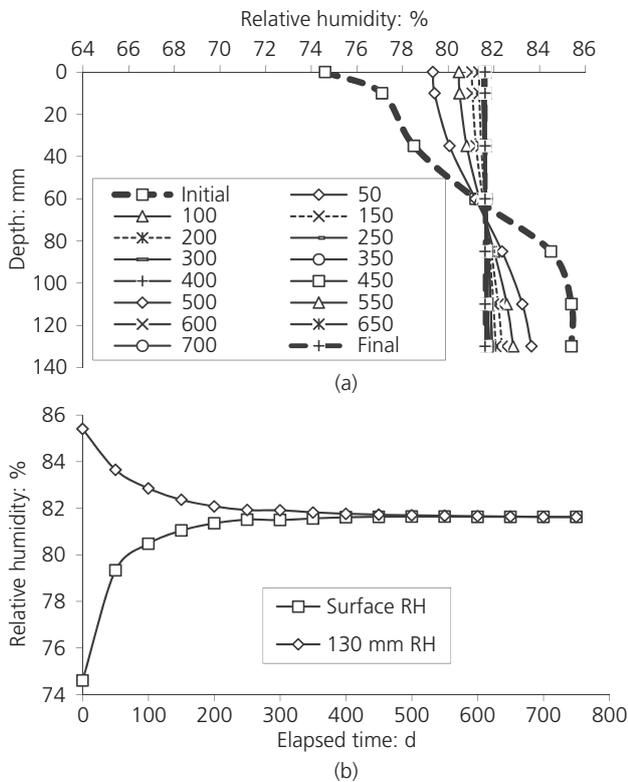approximately 60 mm (that is at 40% of the slab depth), there is a

Figure 9. Redistribution of RH: (a) over depth; (b) over time at the extremes of depth in the control-room-dried specimens using finite-elements

Figure 10. Comparison of finite-element predictions and actual RH redistributions on covering the slabs which were dried in the laboratory

stationary point where the RH during the equilibration process does not noticeably change. At this point, the long-term equilibrium RH, following redistribution, can be identified as the fulcrum point between RH increasing in the upper part of the slab and decreasing in the lower half. This phenomenon, if it is consistent, has practical significance as it suggests that before covering a slab, one should measure the RH at 40% of the slab depth (for unidirectional drying) as it will provide a reasonably accurate prediction of the long-term equilibrated RH through the slab. This makes it possible to evaluate if the likely ultimate RH just below the surface is safe. This adds further credence to the recommendation (ASTM F2170–02, ASTM, 2002) that RH should be measured at 20% and 40% of the slab depth for two- and one-way drying respectively.

Experimental results of long-term equilibrium RH below surface

Although these finite-element simulations and predictions are idealised (and dependent on the calibrated diffusion model and the initial RH distribution on sealing), they can still be compared to the actual below-surface behaviour of the slabs in this testing programme (for example, as shown in Figures 10 and 11). Good agreement is seen to be achieved between the actual and predicted behaviour of the moisture distribution both with depth and over time. Of course the nature of the external drying
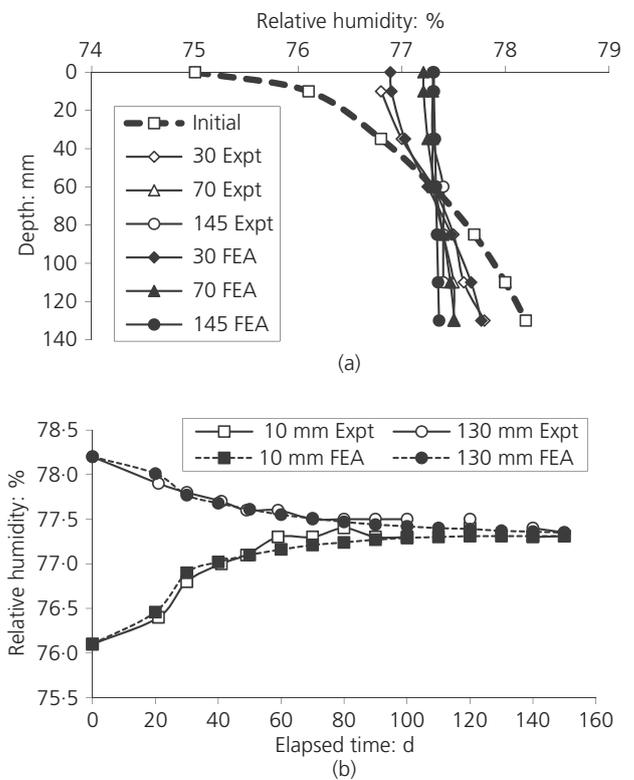
environments the slabs were subject to has no effect on their behaviour, but does affect the second phase initial conditions and thus the subsequent moisture gradients.

Figures 12 and 13 give the actual measured RH readings through the depth with time for six slabs, for three w/c ratios in each environment, after the floor coverings were applied when 75% RH was reached on the surface. Again, some minor experimental variations are evident, but the general trends are clear. There is a distinct fulcrum point, as predicted by the finite-element analysis, at 60 mm, or 40% of the slab depth. Table 2 summarises the relevant data from these profiles, from which it can be observed that, generally, it takes much longer for the accelerated drying specimens to reach long-term equilibrium (i.e. when a uniform RH through the depth exists). It, therefore, follows that covering issues can occur much later with artificially dried floors.

Furthermore, broadly, the value of the RH at 40% of the slab depth at covering, irrespective of the drying regime, is a good approximation as to what the long-term equilibrium RH will be. It may be considered to be a reasonable indication as to whether it is more or less likely that a covering may experience damages, other than the conventional threshold of 75% RH at the surface.
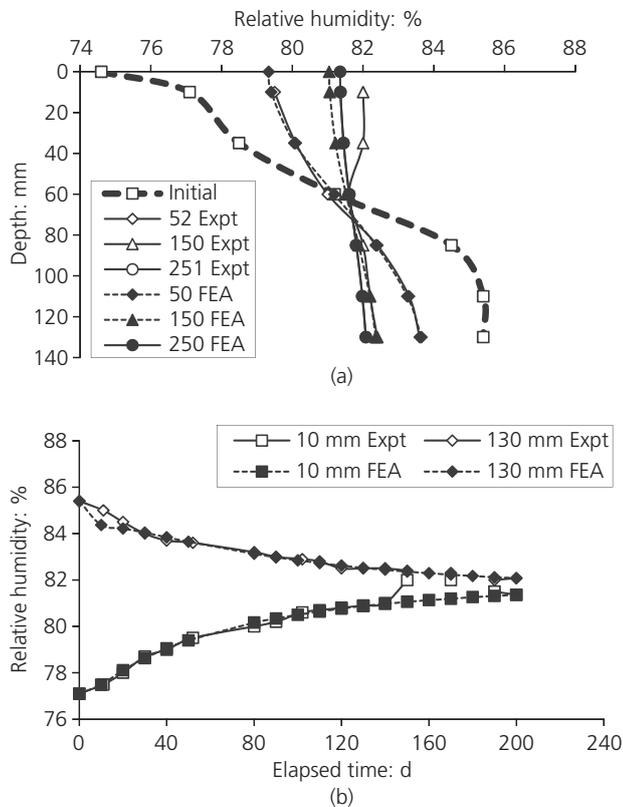
Figure 11. Comparison of finite-element predictions and actual
RH redistributions on covering the slabs which were dried in the
control room

Figure 12. RH profiles over time in the laboratory for the three
w/c ratios after covering: (a) w/c = 0·4; (b) w/c = 0·5;
(c) w/c = 0·6

Finite-element simulations of enhanced drying

Although the 75% RH surface threshold when drying naturally
has been used successfully for many years, the penchant for
accelerated drying to achieve this surface requirement is more
likely to increase the risk of damage due to much higher long-
term RH values below a covering. However, if the forced drying
regime duration was extended such that surface RH values lower
than 75% RH (and thus lower RH values at 40% depth prior to
covering) were sought, then the long-term RH could be manipu-
lated such that the risk of flooring failure is lower in such cases.

Using finite-element simulations of different durations of acceler-
ated drying before covering and simulations of the subsequent
RH re-distribution after the slab is sealed, plots of surface RH on
covering against long-term equilibrated residual RH can be
established for any drying environment. For example, in Figure
14 for the 150 mm thick slab in the laboratory and control room
environments with a w/c ratio of 0·5, the results seen earlier in
Table 2 are reproduced. As can be observed, when the surface
RH reaches 75% on initial drying, the long-term RH values for
the laboratory and control room are, respectively, 77·5 and 82%.

Alternatively, if a long-term equilibrium RH of 75% is desired,
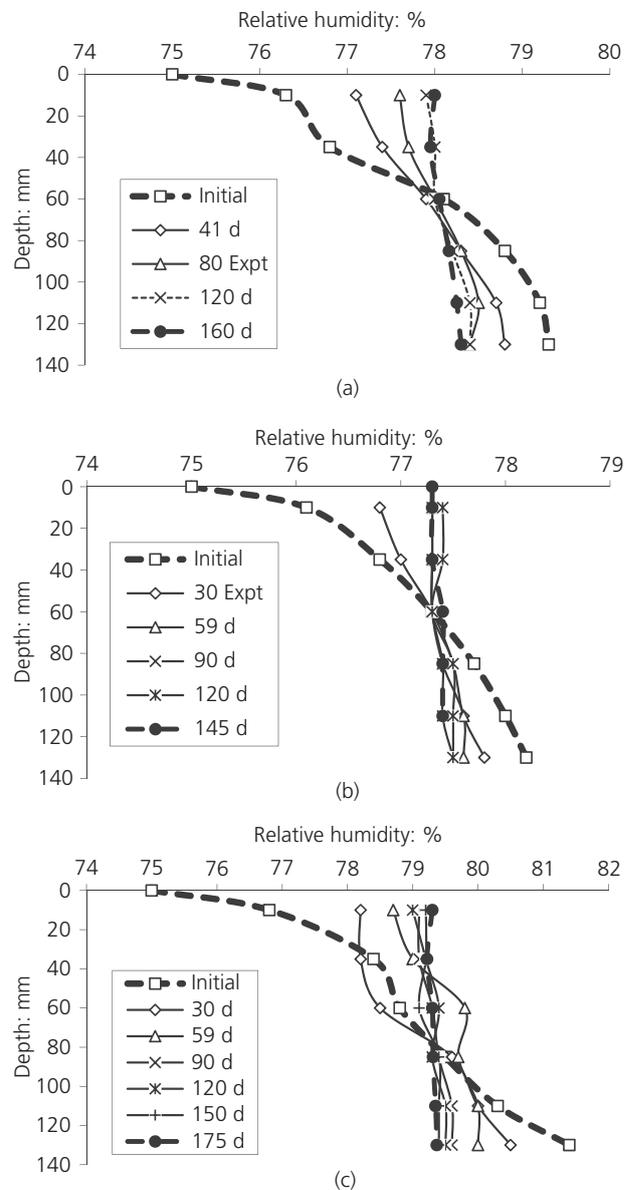then the graph in Figure 14 indicates that the surface RH at

sealing should be approximately 72·5% and 68·5% for the
laboratory and control room respectively. Note that the forced
drying requirement is more onerous as the relative residual
moisture deep in the slab is greater, as explained previously.

If either of these two points were to be selected for sealing the
slab, it is important to have an estimate of how long it is expected
that it will take to reach this new required surface RH prior to
sealing. Again, using a number of finite-element simulations, it is
possible to generate curves of surface RH against time to achieve
this new 'safe' surface RH value upon sealing (Figure 15). The
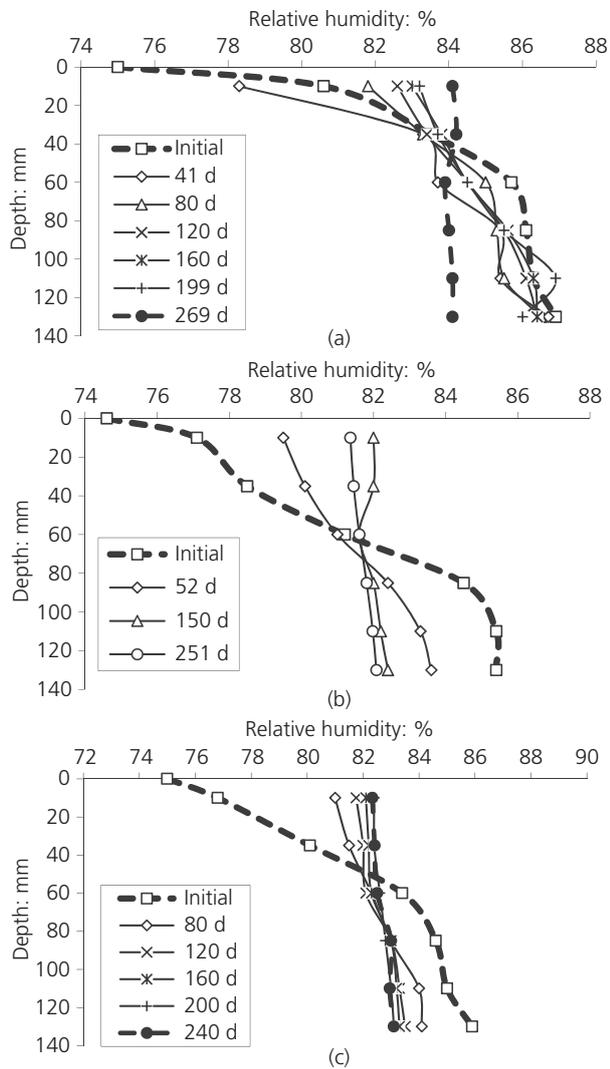graph suggests that it would take approximately 110 and 65 d in

Figure 13. RH profiles over time in the control room for the three
w/c ratios after covering: (a) w/c = 0·4; (b) w/c = 0·5; (c) w/c = 0·6
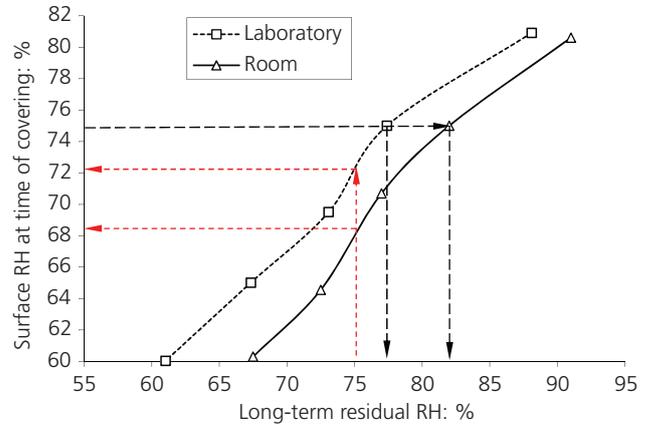

Figure 14. Relationship between RH when sealing and long-term
equilibrium RH for the laboratory and control room drying
regimes, with w/c = 0·5 and slab depth of 150 mm

the laboratory and control room respectively to reach these levels
of dryness. These suggest that an additional 20 and 19 d of
drying in the laboratory and control room respectively are
required to achieve a safer long-term equilibrated RH through the
slab. Clearly a 65-d accelerated drying time to reach 68·5% on
the surface is preferable (and safer) to a 90-d natural drying time
to reach the currently specified 75% RH on the surface.

While it is reasonable to employ accelerated drying methods for
longer than the 45 d it took to reach 75% RH on the surface
(which led to a significantly more risky 82% long-term RH under
the covering), it is hardly necessary to insist that a long-term RH
of 75% is required in an enhanced accelerated case. This is
because the naturally dried 75% surface case does not achieve
this level of long-term RH (77·5% in fact) and practice shows
this is not an unreasonable risk.

	w/c = 0·4	w/c = 0·5	w/c = 0·6
Natural drying			
RH at equilibrium: %	78·0	77·5	79·5
Approx time to reach equilibrium: d	160	145	175
Depth of balanced point: mm	57	60	80
Balance point as % of slab depth: %	38	40	53
Forced drying			
RH at equilibrium: %	84·5	82·0	82·5
Time to reach 75% on surface: d	269	251	240
Depth of balanced point: mm	43	62	56
Balance point as % of slab depth: %	29	41	37

Table 2. Actual long-term equilibrium RH after covering slabs,
approximate time to reach this threshold for natural and forced
drying regimes for slabs of different w/c ratios and percentage
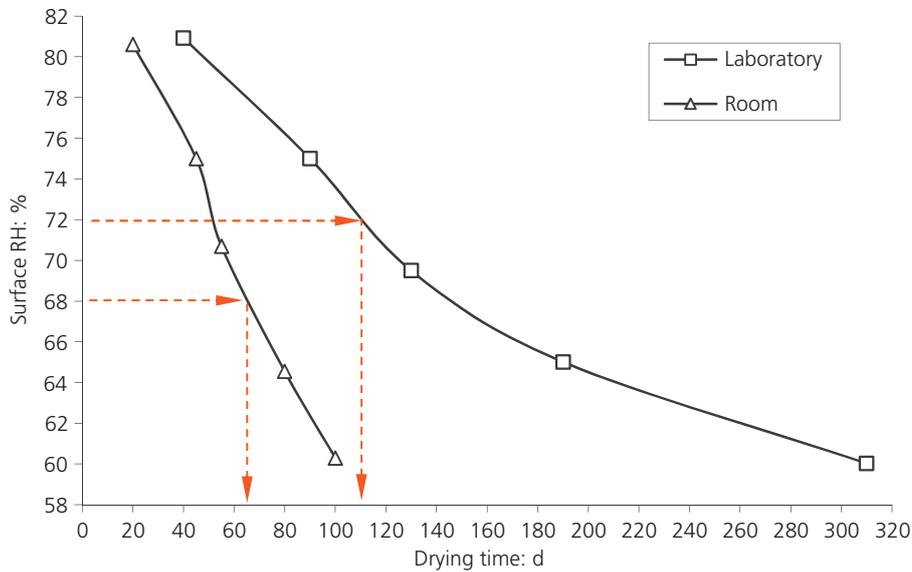balance points

9

Figure 15. Finite-element predictions of the drying time required to reach different levels of surface RH for the laboratory and control room drying regimes, with w/c = 0·5 and slab depth of 150 mm

Figure 16 shows what levels of accelerated drying are necessary in order to deliver a predicted long-term RH of between 75 and 80% for a w/c of 0·5 and depth of 150 mm, as per the BS 8203 limits. From the diagram, the predicted surface RH required to achieve these upper and lower bounds in this accelerated environment should range between 74% and 68·5% respectively. From Figure 15, this suggests that the drying times are about 65 d to reach 68·5% RH and 50 d to reach 74% (recall that it took 45 d to reach 75%). It is suggested that the level of risk which the engineer will accept will determine how long accelerated drying continues prior to covering and these values indicate what some

of the choices are for this specific case. Similar simulations are possible for different w/c ratios and slab depths for one- or two-way drying.

Finally, when a given long-term RH is selected and the subsequent time to achieve this has been estimated, it is also advisable to measure on site the actual RH at 40% of the slab depth (assuming one-way drying) using the hand-held humidity probe over a number of locations on the slab under review to confirm the actual state of drying prior to covering on site.

Table 3 shows the summary data for the 0·4, 0·5 and 0·6 w/c slabs where, although some minor anomalies exist due to testing and sample variations, the long-term 75–80% thresholds durations are broadly 50–60 d, 50–65 d and 55–75 d respectively for a 150 mm deep slab in the extended accelerated environment.

Conclusion

This paper has demonstrated the significant benefits of enhanced accelerated drying such that the long-term equilibrium RH below an impermeable covering is such as to make a covering failure (in terms of blistering, rising tiles, etc.) less likely than would be the case if the current requirement for a surface 75% RH were to be adhered to. This is achieved by drying at an accelerated rate for longer than normal and yet still making significant time savings compared to conventional natural drying before covering, which is the current practice.

The suggested procedure for delivering safer and faster drying of CEM I concrete slabs is, therefore, to input into an appropriate
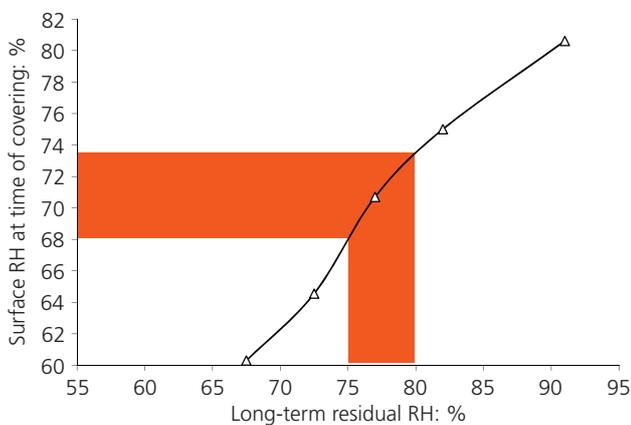

Figure 16. Required surface RH readings to achieve a long-term RH below the covering of 75 and 80% RH for a forced drying regime on a slab of depth 150 mm with w/c = 0·5

Time: d	w/c = 0·4	w/c = 0·5	w/c = 0·6
75% on surface on sealing	42	46	47
75% long term on surface	60	65	75
Extra time for enhance drying	18	19	28
Original laboratory drying time to 75%	82	90	96
Time saving if enhance accelerated drying to 75% long term	22	25	21
75–80% long-term drying	50–60	50–65	55–75

Table 3. Drying time (d) and consequences due to enhanced drying

finite-element model the slab depth, appropriate boundary conditions, material diffusion and evaporation models depending on the w/c ratio and apply suitable ambient environmental conditions as anticipated. Through simulation, this will provide an accurate estimation of the most appropriate time to cover the slab and predict the long-term RH under the covering so an assessment can be made of the risk or likelihood of impermeable floor covering serviceability issues.

Having predicted the amount of drying time required to achieve a 'safe' RH before sealing, a hand-held RH probe should also be inserted into a number of pre-drilled holes to a depth equal to 40% of the slab thickness prior to covering to confirm instantaneously what the approximate long-term equilibrated RH is likely to be.

If finite-element analysis is not an option or the calibrated concrete diffusion and evaporation models are not available, then readings of the actual values of the RH at 40% depth can be taken regularly in the early life of the slab to enable the trend in RH values with time to be established. This will allow an extrapolation to be made as to when the slab will be sufficiently dry at this depth to seal safely, irrespective of the drying regime employed. This technique has been made more practical because hand-held readings take just a few minutes; it would have been much more cumbersome when standard surface hygrometer and VET tests were available, both of which are slow and misleading, as the surface RH does not reflect what the residual RH distribution is, which is one of the principal factors that determines the risk of a covering failure.

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