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Requirements for Test Series for Relative Humidity Measurements to Calibrate Drying Time Simulation Model



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ABSTRACT

There is a great need for an easy-to-use tool to simulate drying of concrete floors. In order to model practical situations, the tool should take into account changing conditions, especially wetting at worksite, but also temperature. For this purpose, a simulation program was developed for drying time estimations for concrete floors, which was published in 2021 and is named as the “by2020 Concrete drying time estimate”. This study presents the results of the laboratory test series conducted to calibrate the drying time estimations of the by2020 software. As all possible scenarios for practical situations were not possible to study in the test series, results from the literature were partly used for calibration and validation of the tool. A methodology for test series for calibration of the drying time estimation model is proposed based on this study. It was found that a model suitable for practical applications can be implemented based on relative humidity measurements only. However, the tests series of relative humidity measurements should take into account the influence of various factors such as wetting period and different temperature conditions.

Key words: Drying of concrete, drying experiment, drying time estimation, model calibration, model validation.

1. INTRODUCTION

Drying of concrete and its prediction is an essential but very challenging task for construction. Especially in the Nordic countries the weather varies, and temperature (T) can be so low that without additional heating drying does not progress. Another important factor is wetting during construction. Especially in the case of wide-frame multi-storey buildings, concrete floors can get wet during construction and remain wet for long periods of time.

In practice, contractors may have their own experience-based calculation models for estimating drying of concrete, however, an estimation might often be made only based on casting thickness. On the other hand, there is a need for a general assessment to which the different parties could commit, as differences of opinion on sufficient drying time can vary significantly between contractors, consultants and the builder. To conduct more accurate estimates, a calculation model is required that considers the practical conditions and the schedule as realistically as possible. For this purpose, it was decided to develop a simulation program for drying time estimations for concrete floors, which was later published in 2021 and is named as “by2020 Concrete drying time estimate” (Owned by the Finnish Concrete Association [1]).

Several models to assess drying of concrete have been published. Bazant-Najjar model [2] is extensively cited (> 600 times) and applied in the fib Model Code 2010 [3]. The model takes into account self-desiccation of concrete. Moisture transfer in concrete is modelled with a single potential using diffusivity, which is an s-shaped function in the original model that depends on relative humidity (RH). For example, Kim and Lee [4] applied the Bazant-Najjar model [2] and carried out laboratory tests for drying in constant T and RH conditions to validate the model. Drying experiments were executed with 100 x 100 x 300 (mm) rectangular test blocks, which

were post-treated in water immersion for 3 and 28 days. After that, one 100 x 100 surface were left open, and the others were sealed with paraffin wax. Measuring pipes were installed after casting in drilled holes of depth 30, 70 and 120 mm from the open surface. Self-desiccation was determined by fully sealed 100 x 100 x 100 (mm) test cubes and the measurement being carried out using the borehole method. In both cases, two parallel test specimens were used for measurements. A Vaisala HMP44 probe and a Vaisala HMI41 indicator were applied to measurements and readings were taken in time intervals. Efforts have been made to further develop and to generalize the model. Rahimi-Aghdam et al. [5, 6] have presented the calculation methods for parameters based on the water-binder ratio (w/b) of concrete and dependent on the degree of hydration. The model was tested against the cited data from Kim and Lee [3] and Jiang et al. [7] where test blocks were 100 x 100 x 300 (mm) and from Arfvidsson et al. [8] in which test slab dimensions were 500 x 500 x 70 (mm).

The best reference case for building up a drying time estimation tool comes from a simulation software TorkaS, developed in Sweden, which is based on decades of studies to understand the moisture phenomena of concrete and extensive laboratory tests have been carried out to determine the calculation model and concrete properties of the program [9]. The material and moisture transfer model for concrete developed by Arfvidsson and Claesson [10] is based on Kirchhoff's potential for moisture transfer modelling and the one key feature they present, is the numerical simplicity of the method, which makes the simulation efficient. In determining the properties of concrete, the results of previous studies have been used in terms of moisture transfer properties from Hedenblad [11] and for self-desiccation and sorption from Norling Mjörnell [12]. For validation of TorkaS program, concrete cylinders ($d = 300$ mm and $h = 180$ mm) were utilized in two-way drying test, from which the measurement was carried out using measuring tubes installed from different depths on the sides [13]. Similar type of concrete cylinders have been used in the comparative study related to the TorkaS program by Johansson [14], who conducted several tests on the influence of various factors on drying of concrete. For example, the effect of the binder type and w/b ratio, wetting from rain after casting, wetting later during construction and the effect of levelling were investigated. Drying specimens in constant T and RH were post-treated in wet for 2 weeks, followed by another 2 weeks covered with plastic. Measurements were conducted with continuous Humi-Guard sensors 1 month after casting. Specimen in testing the effect of the levelling was measured with Vaisala HMP44 probes so that the probes were installed in the measuring tubes approximately 1 week after casting and the probes at the measurement depth of 15 mm remained in place during the entire trial period. Due to the limited number of sensors, they moved the sensors between specimen at the measurement depth of 48 mm according to a predetermined measurement schedule. To determine self-desiccation Johansson [14] used one-liter tin cans. One third of the volume was poured with concrete and the can was sealed with cover. The measurement of RH from the airspace was carried out through the cover with a probe sealed from ambient air.

This study presents the results of the by2020 software laboratory test series. The goal of the by2020 software development project was to implement a concrete material model based on existing research data and to calibrate the results based on practical measurement results from

building sites provided by construction companies. It became clear soon that the construction sites would not provide good enough data, so the laboratory test series was launched on a fast schedule. The laboratory measurement results are compared with the estimates calculated with the by2020 software. Since it was not possible to examine all the perspectives required for the examination of the practical situation in the test series in question, the reference material used for the calibration and validation of the model from other studies has also been discussed. The material model used in the software is presented only in terms of main principles since the data is not publicly available for commercial matters. The main objective of this study is to propose improvements for the test series for calibration of drying time estimation model for concrete floors.

2. MATERIALS AND METHODS

2.1 Relative humidity measurements

There are basically two *RH* measurements methods used in the Finnish practice, the borehole and the sample piece method [15], which are also described test methods for measuring relative humidity in, at or from mineral substrate in SFS-EN 17668:2022 [16] as hygrometer sleeve method and hygrometer sample method respectively. An empirical approach to the uncertainties of different *RH* measurements is shown in Figure 1 and states that, regardless of the method of measurement, the error can be quite large if measurements have not been carried out carefully. In addition, there are methodological uncertainties. Guideline [15] also presents the evaluation criteria for determining the total measurement error. According to the instructions, at the best in very stable conditions, performing the measurements with special care and using particularly precise calibrated probes a total measurement error of $\pm 1\%$ *RH* can be achieved. In practical measurements it can often be assumed to achieve a total measurement error of only $\pm 3\%$ *RH*, although this already requires quite stable conditions and careful measurement with calibrated measuring instruments.

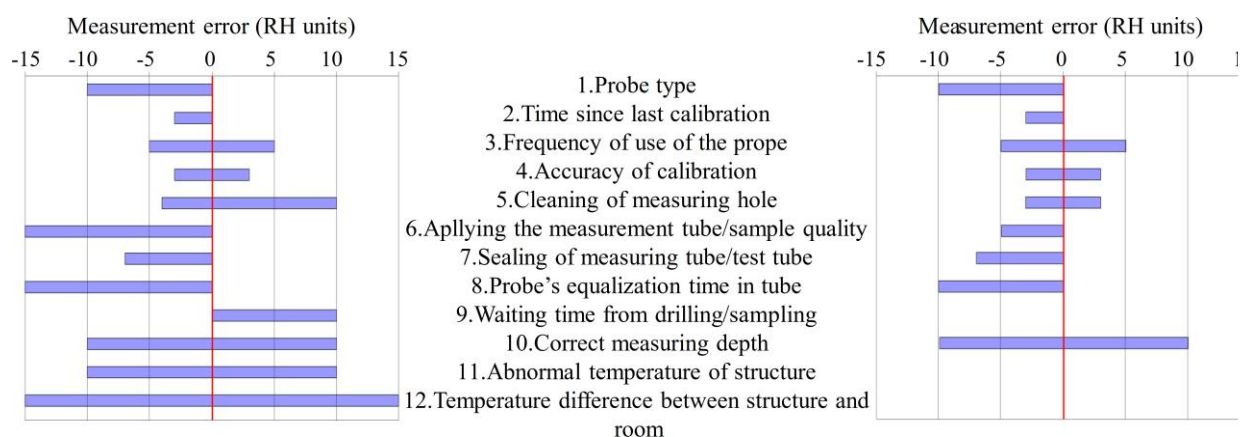


Figure 1 – *RH* measurements. Adapted from RT 103333 Betonin suhteellisen kosteuden mittaust.

The new guideline for measuring *RH* in concrete [15] also allows continuous measuring. However, the accuracy of continuously operating measuring instruments has been uncertain, and

shortcomings have been identified in reliability of different systems. The guideline requires that measurement equipment suppliers must demonstrate reliability of the system. In practice, sufficient drying is still ensured either with a borehole or with a sample piece measurement, even if continuous measurement is in use.

Either a borehole method or measuring through measuring tubes installed in casting have been mainly utilized in drying studies. The sample piece measurement has apparently not been widely used other than to determine self-desiccation, for which there is also the Nordtest Method [17]. From the point of view of the study of the test specimens, the most obvious difference between the measurement methods is that the borehole measurement interferes the concrete pore structure or, at least disturbs moisture transfer if tubes in casting are utilized. In the sample piece measurement, the test specimen is practically destroyed in the measurements. For laboratory measurements, the borehole measurement method could be used, with the tubes installed on the test pieces before casting as Johansson [14]. This is associated with the risk of concrete drying through measuring tubes and its interfaces especially when conducting reasonably long-term drying tests (180-360 days).

2.2 Specimen preparation and drying test procedure

The most significant criterion for the test series was equivalence in terms of practical situations, especially considering wetting during construction. Three different scenarios were examined, which were self-desiccation, drying under standard conditions and getting wet after casting. It was estimated that the short-term wetting period has only minor effect on drying, and therefore a wetting time of 25 days was chosen. The effect of the time of wetting was compared, which represent assumed worst case scenario of wetting during the installation phase of the concrete frame, when the unfinished structure is not yet protected from the weather. The test sets were:

1. Specimen for self-desiccation measurements
2. Specimen for constant drying 20°C / 50 % *RH*
3. Specimen for drying – wetting – drying procedure (placed in 20°C / 50 % *RH*)
 - a. 10 days of drying – 25 days wetting – drying
 - b. 25 days of drying – 25 days wetting – drying

The implementation and the uncertainties of the measurement of *RH* presented in Section 2.1 were taken into account when planning the preparation of test specimens. Concrete cylinder test specimen were produced by casting in 1 litre tin cans, which were sealed for 7 days. Specimen for self-desiccation tests remained sealed and were placed in a climate room at 20 °C and 50 % *RH* conditions. Specimen of sets 2 and 3 were treated for drying tests as shown in Figure 2. It was found that the upper part of the tin can is quite convenient to cut and pull the edge open just below the level of the upper edge of the concrete. After grinding the surface, the interface between the tin can and concrete was carefully sealed. The *RH* measurements were carried out with a sample piece method according to Figure 3. The sample pieces are taken as quickly as possible using a hammer. The grains should consist mainly of cement paste and no fine matter should be collected in the sample tube. Measurements were made frequently at the beginning of the series. The total duration of the measurements was nine months and total number of specimens was 180.

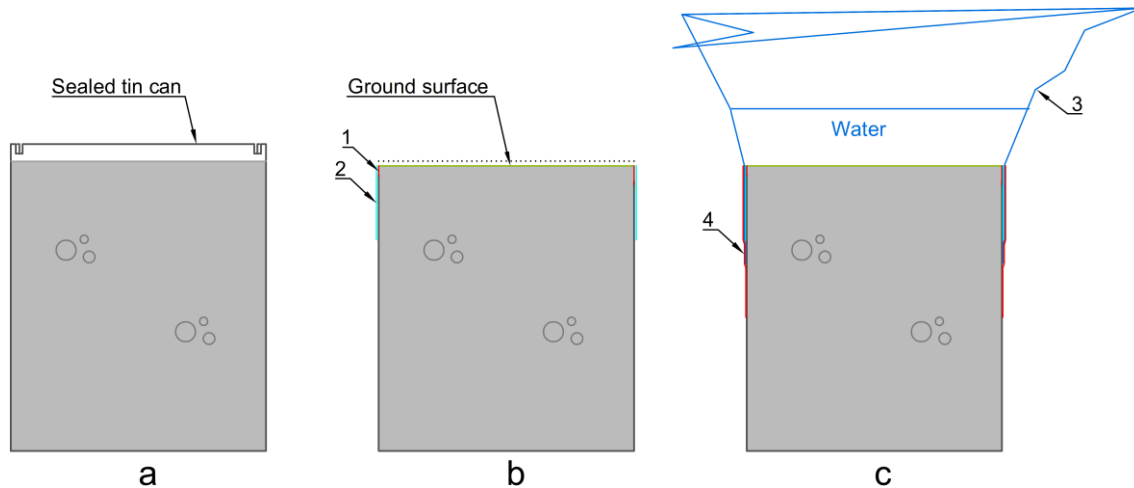


Figure 2 – Specimen types. 1. Epoxy resin. 2. Aluminium tape. 3. Sealed plastic bag filled with water and 4. Sealing tape.

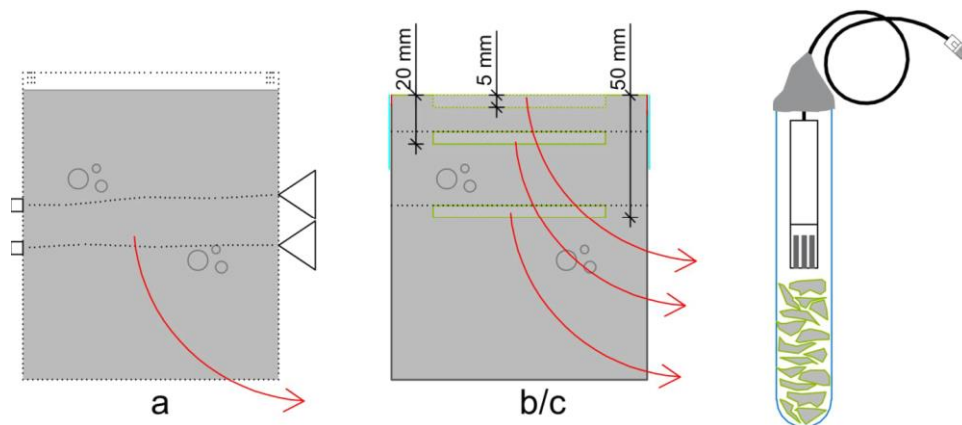


Figure 3 – Principle of RH measurements in sample piece method.

The result of self-desiccation was calculated as an average of six measurements from two test specimen or an average of three measurements from one test sample (excluding the last measurement at approximately two years of age, which is the result of only one measurement per sample). For determination of the humidity distribution in test sets 2 and 3, two samples were taken from the test specimens at each depth and the result is presented as their average. In addition, the specimen was weighted during the test period in connection to the *RH* measurements. The area of the open surface was calculated from the scanned image of each sample.

2.3 Tested concrete grades

The concrete specimen tested were produced from two different suppliers. Concrete (A) was implemented in the supplier's laboratory, manufactured by a laboratory technician, and (B) in a concrete supplier's production mixer. In the view of the suppliers, tested concrete grades are common grades suitable for concrete floors, apart from concrete with the highest *w/b*, which is rare in practice. The studied grades of concrete are presented in Table 1.

Table 1 – Tested concrete grades.

Sample	General information		Binder		ρ_{dry}^*	w/b^*
	Strenght, Slump, D_{max}	Type	[kg/m ³]	[kg/m ³]	[-]	
A1	C35/45, S3, 16	CEM II/B-M (S-LL) 42.5 N CEM I 52.5 R	282 188	2190	0.44	
A2	C30/37, S3, 16	CEM II/B-M (S-LL) 42.5 N CEM I 52.5 R	293 32	2139	0.59	
A3	C25/30, S3, 16	CEM II/B-M (S-LL) 42.5 N CEM I 52.5 R	269 30	2090	0.70	
B1	C35/45, S5, 16	CEM II/B-M (S-LL) 42.5 N CEM I 42.5 R	325 82	2225	0.44	
B2	C30/37, S5, 16	CEM II/B-M (S-LL) 42.5 N CEM I 42.5 R	244 60	2169	0.58	
B3	C25/30, S5, 16	CEM II/B-M (S-LL) 42.5 N CEM I 42.5 R	207 51	2197	0.70	

*Based on recipe

The castings of the test pieces were carried out for concrete (A) in the laboratory of the supplier and vibrating table, after which the specimens were sealed and transported to the research laboratory. On the other hand, fresh concrete (B) was transported to a research laboratory to be cast into test specimens. The vibration was performed with a setup similar to a vibrating table. The surface of both concretes was still trowelled before the pieces were left in the condition room.

2.4 Moisture transfer model in by2020 software

Moisture transfer in concrete is commonly modeled as either pure water vapor transfer [18], diffusivity of liquid water [2] or as multiphase with models describing moisture transfer by diffusion, as well as in liquid form [19-22]. When developing the software, it was decided to select equations for describing moisture transfer as in [22], based on positive experience from study [23]. The governing equations are as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot [k \nabla T + L_v \delta_p \nabla (\phi p_{\text{sat}})] + Q \quad (1)$$

$$\frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial t} = \nabla \cdot \left[\frac{\partial w}{\partial \phi} D_w \nabla \phi + \delta_p \nabla (\phi p_{\text{sat}}) \right] + S \quad (2)$$

where ρ is density [kg/m³], C_p specific heat [J/kg K], t time [s], k thermal conductivity [W/(mK)], L_v latent heat of evaporation [J/kg], δ_p water vapor permeability [s], ϕ relative humidity, p_{sat} saturation pressure [Pa], Q heat source from hydration [J/kg], $\zeta = dw/d\phi$ moisture storage capacity [kg/m³], $\zeta_T = dw/dT$ temperature dependent moisture storage capacity [kg/(m³K)], w water content [kg/m³], D_w liquid water diffusion coefficient [m²/s], S moisture sink from hydration [kg/(m³s)].

The coefficients of moisture transfer D_w and δ_p are modelled as functions of degree of hydration, T and RH including several model parameters which are not presented in more detail. In determination of the moisture transfer coefficients, material tests have not been conducted. The

parameter values have been estimated by experimentally determining the ranges for the parameters, taking into account the w/b .

Along with moisture transfer coefficients, determination of sorption is one of the key issues affecting the simulation result. In the model the w is modified from Norling Mjörnell [12] and Di Luzio and Cusatis [24]. The utilized model is described in Sekki et al. [25], however, the model parameters are not presented in more detail. The temperature dependence of RH of the pore air in concrete is not taken into account. If the aim were to model RH realistically, when T at the time of the examination deviates significantly from the recommended T for measurements (17-24°C [15]), the model should have w as temperature-dependent property, in which case the models [26-27] could be applied. When the temperature dependence of sorption is not considered, it should be noted that RH of the calculation illustrates RH reading at the reference T . Thus, when comparing a practical continuous measurement with a calculation, for example, at a significantly lower T , there may be a significant deviation between the results, because of the T difference.

3. RESULTS AND DISCUSSION

3.1 RH measurements results

The results of the RH measurements in the test sets 1-3 are shown in Figures 4-7. Solid lines show the results of the estimate. In Figures 4-6 colours/marker represent the measuring depths: blue/solid square = 50 mm, green/square = 20 mm and red/circle = 5 mm.

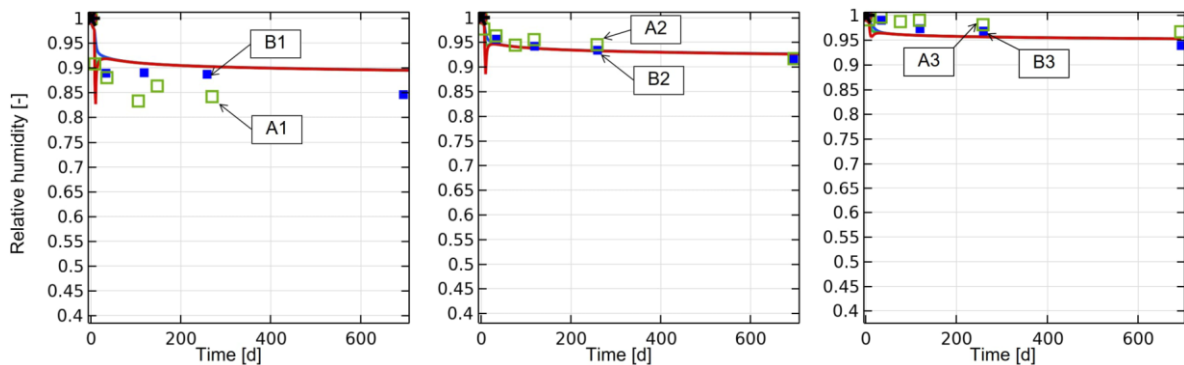


Figure 4 – Self-desiccation.

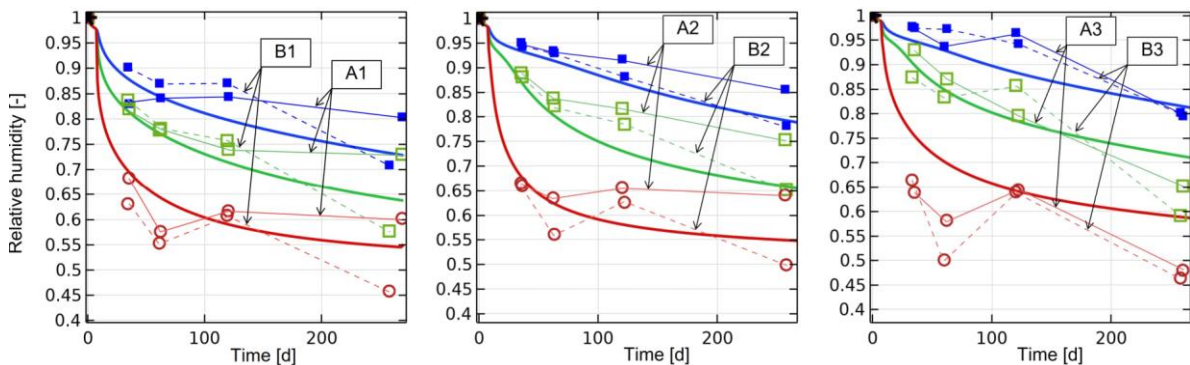


Figure 5 – Constant drying at 20 °C and 50 % RH.

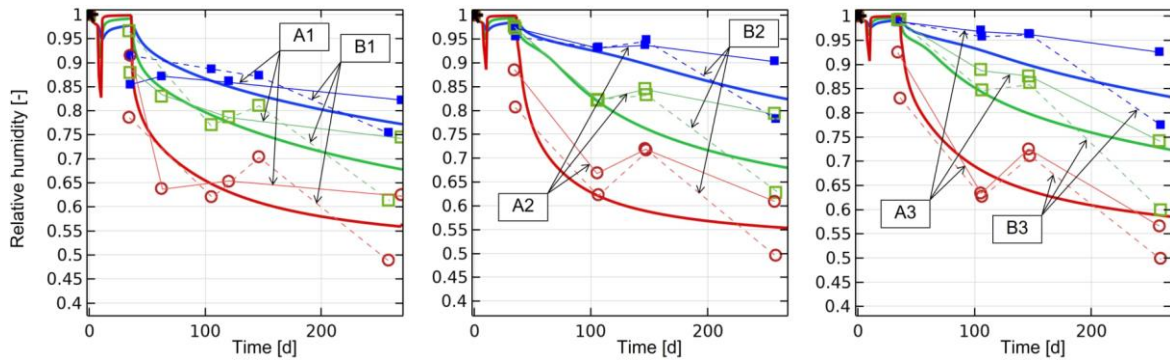


Figure 6 – 10 days of drying – 25 days wetting – drying at 20 °C and 50 % RH.

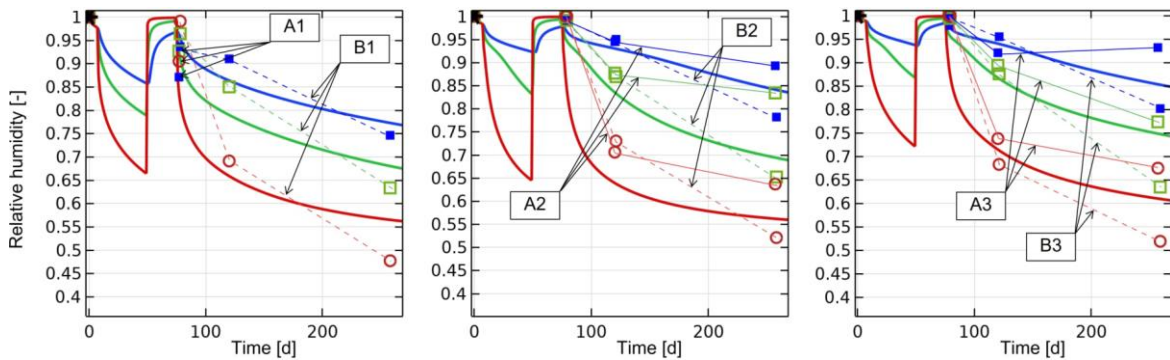


Figure 7 – 25 days of drying – 50 days wetting – drying at 20 °C and 50 % RH.

3.2 Analysis of results

In the self-desiccation test, samples A1 and B1 ($w/b = 0.45$) clearly dried to lower RH levels than concrete samples with higher w/b ratio. In addition, the greatest deviation in results was observed between concrete samples A1 and B1 compared to those with higher w/b ratio. At the age of 270 days, A1 had reached the 85 % RH , while B1 was at 89 % RH , which suggests that the amount of cement/slag per volume unit also has an effect in self-desiccation in addition to w/b ratio. In the results of A2 and B2 ($w/b = 0.60$) there were no significant differences between A and B specimens even in the long term. At 270 days, A2 and B2 are at 94 % RH ending up to level 92 % RH . Self-desiccation for A3 and B3 ($w/b = 0.70$) is negligible. RH was relatively high 98 % RH at 270 days and ended up to approximately 95 % RH in two-year period. The standard deviation in self-desiccation RH measurements averaged 0.6 percentage points in RH varying between 0.2 and 1.1. The greatest deviation, 1.1 was found with the A1 specimen, for which there were two specimens, the RH difference measured between the specimens averaged 1.5 points in % RH . This highlights the sensitivity of sampling to the time the measuring tube is kept open when the sample is crushed. For example, the A1 result at 100 days, which is abnormally low, may be caused by drying of concrete during crushing. The result in question is the average of three measurements from a single sample.

Based on a comparison of the time of wetting, no significant difference in final RH was observed in the test series 3. In contrast, the effect of getting wet gives a twofold result. In the case of A concrete samples, the difference to the standard drying situation is significant, increasing with the increase in the w/b , but in the case of B concrete samples, there is almost no difference at all.

Between A and B concrete samples, an indication of difference in moisture transport properties can be observed. Taking into account all the experiments, the drying of A concrete sample is slower than that of B. This refers to the higher water vapor permeability of B concrete samples. Due to an incorrect configuration of the monitoring device in the condition room, the measurement results are not available. Throughout the measurement period, the condition room was regulated at 20°C / 50 % *RH*. However, it is likely that the equipment has not been able to maintain constant *RH*, a fact that is indicated, for example, in the latest measurements, some below 50 % *RH* and at 120-145 days humidity of the surface part has increased from previous measurements. The deviation upwards is observed especially in the results of the surface part, but also at a depth of 20 mm in the B2 and B3 specimens. This is in line with the fact that, especially with regard to final drying, drying of the concrete of supplier B is fast and, therefore, transfer of moisture is also faster, which is observed as an *RH* increase when the condition changes. In addition to this, the noticeable difference in drying after the wetting period indicates a difference in moisture transport properties.

To have more information of the microstructure of the specimen, thin section analysis was conducted. One test specimen per concrete grade was examined from 25 mm wide sample from open surface to a depth of 75 mm (25x75 mm). The preparation and examination method of the thin section samples is presented in the standards ASTM C856/C856M-20 [28] and NT Build 381 [29]. The samples were examined with a Nikon E600 polarization and fluorescence microscope. The result showed that the concrete samples B2, B3 and A3 had a slightly less dense structure at most 20 mm of depth. Although the sample size is small, the result suggests that B test specimens might have a higher moisture transport coefficient near the surface. On the other hand, the thin section results are also in line with the fact that the A3 concrete sample behaved similarly with B3 in constant condition drying tests. However, after getting wet, drying of A3 and B3 concrete samples differed significantly from each other, which indicates that there are differences in moisture transfer properties not only in terms of the surface structure of the test specimens.

The results of *RH* measurements and thin section samples suggest that there would be a difference between A and B concrete samples in terms of moisture transport properties. In addition, an indicative calculation of the moisture transfer coefficient for the concrete grades, which is shown as relative water vapor resistance μ in Figure 8, was conducted based on the measurements of *RH*. The tin can method presented by Nilsson [30] was applied in the calculation, with the exception that the result was calculated on the basis of the last measurement interval of the drying specimen in constant conditions, when Nilsson suggests that the closed tin can should be opened at approximately 100 days of age, after which the measurements begin. The material model of the by2020 software was used to estimate the *RH* dependent moisture content for the calculation. Based on the results, there is also a partial indication that there is a difference in moisture transport properties between samples of different *w/b*. In particular, the water vapor resistance of A1 is clearly higher compared to that of B1 sample. The result of A3 sample corresponds to the thin section result indicating a less dense structure near the surface and therefore sample A3 has a lower water vapor resistance. In contrast, there is only a minor difference in the moisture transfer properties of A2/B2 concrete sample, based on the calculation.

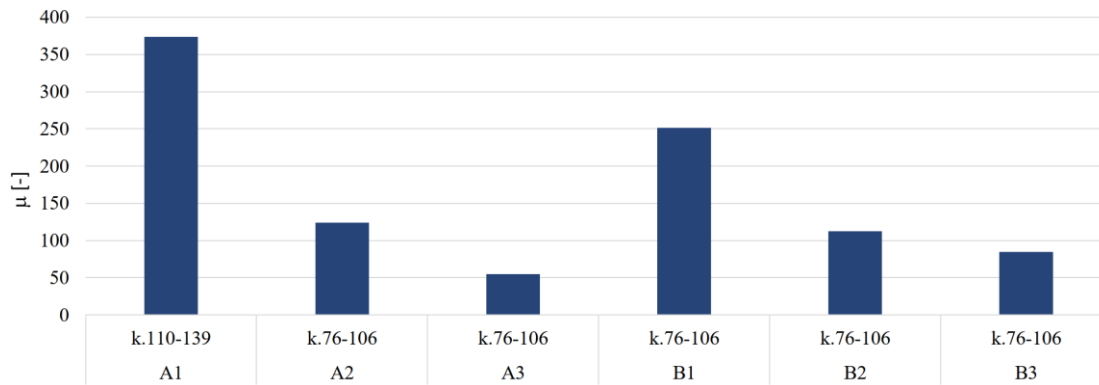


Figure 8 – Indicative relative water vapor resistance of concrete samples calculated from the last measurement interval of the drying specimen in constant conditions.

When comparing the order of magnitude of the results between different w/b ratios, it should be noted that the results reflect different forms of moisture transfer depending on different w/b. 50 % *RH* was used as the ambient condition in all calculation cases, but based on *RH* measurements, self-desiccation determines *RH* of the inner parts of the concrete, which varies depending on the concrete grade being for w/b 0.45: A1 = 87 and B1 = 89 % *RH*, w/b 0.60: A2 = 96 and B2 = 95 % *RH* and w/b 0.7: A3 = 99 and B3 = 98 % *RH*. Thus, the result of w/b 0.45 represents the pure water vapor resistance, while w/b 0.6 and 0.7 rather represent the resistance to moisture transport, taking into account transfer as water vapor as well as liquid.

When considering the results overall, it should be noted that moisture transfer is influenced by the assumption of the sorption properties of concrete. In the calculation of the moisture transfer properties, for both concrete samples A and B the same sorption properties were assumed for the respective w/b ratio. In reality, a significant difference in drying as measured in *RH* can be caused by the different sorption properties of concrete grades, which is determined by the pore structure that is formed in practice. The pore structure in turn is influenced by the properties of binders and, on the other hand, by concrete casting and post-treatment.

4.2 Analysis of the implementation of measurements and tests

The preparation of test specimens probably caused some of the observed differences between A and B concrete samples. On the other hand, the result represents extremes in practice, when the same grade of concrete, so to speak, can be cast and vibrated more or less dense, which produces a different pore structure in the concrete. Thus, the result also provides an explanation but not a direct solution to the problem encountered in practice on construction sites regarding drying of concrete; From time to time, there are cases in which the construction site management gets frustrated when the concrete does not seem to dry out at all. In this case, it may simply be a matter of the problematic area being wetted at the frame stage, and the considered concrete is not particularly quick-drying due to the supplier's recipe, as well as casting, vibration and post-treatment. In practice, this could be avoided by preventing wetting of concrete during work and with well controlled casting of concrete. However, when considering laboratory tests, these deviations should also be avoided and it is necessary to make castings in the moulds immediately

after the preparation of the concrete and to vibrate the moulds with a vibrating table, after which the concrete should be allowed to set and strengthen before moving to the condition room. Trowelling of the surface is probably not necessary, but the operation removes the need for heavier grinding of the surface.

The applied sample piece *RH* measuring method involved a fairly large number of specimens. The initial phase of the tests is laborious when the test pieces are finalized. After this, however, testing is quite straightforward. Compared to measurements, where measuring tubes are already installed in the mold, this method is, however, easier in the casting phase. In addition to this, during the drying phase there is no uncertainty on the possible effect of the measuring tubes on the measurement result. Although, a large number of specimens requires precise organization. The guidance of the measurements partially failed in these tests and resulted in wrong number of pieces being measured and partial loss of the results. These mistakes can be avoided with better advance planning.

The results may include single measurements in which the measurement error causes a deviation, such as possibly the A3 sample measurement at 120 days in a constant condition drying test. Systematic occurrences of ‘deviations’, such as the results of the last measurements, in which B concrete samples dry to a lower level, cannot be explained by the measurement error, since the last measurements were made by the same surveyor. It is indisputable that, in the case of measurements of otherwise identical test specimens, the test specimens of another supplier must have been systematically measured differently. Therefore, the results must be understood as the situation is in practice; The concrete grades in practice may differ significantly in terms of properties that affect drying, although the water-to-binder ratio is the same.

4.3 Calibration and validation of the simulation model

When calibrating the simulation model to the measurement results, an attempt could be made to determine the deviation of the drying curves from the measuring points using the parameter estimation [23]. Another aspect of calibration is to compare the estimate and measurement results according to the most frequently applied limit values in practice, meaning that when relative humidity at 50 mm measurement depth is below 85 % *RH* and at 20 mm below 75 % *RH*.

Due to the differences between the concrete samples, the measurement results are not the best possible baseline in terms of model calibration. However, in the short term (< 120 days), no significant difference was found between the concrete samples of different suppliers, which eases the calibration process of the model to some extent. In addition, since the goal was to assign one concrete sample per different *w/b* ratio to the by2020 software, the solution was to aim for the average of the final results in estimation, which might correspond to the average situation in practice moderately well. The calibration was conducted based on a qualitative assessment and no deviations to the measurement points were set as criteria and parameters were selected using a trial-and-error method.

The trial-and-error method is quite laborious, and the parameter estimation method could be considered in possible further studies. However, the benefit of the trial-and-error method is getting more aware of the influence of parameters on the result. Regarding the selection of parameters, it was found that very different combinations of material model parameters can be selected and yet achieve a result that corresponds well to the measurements under constant drying conditions. On the other hand, all of the parameter combinations did not produce an acceptable result in the wetting situation. In an effort to model a practical situation in which the structure may get wet, it is important to carry out measurements also at wetting situations and calibrate the model to these results as well.

The success of model calibration could be assessed by the separate data defined for the validation of the corresponding models. Since this kind of data is not available, the performance of the model was studied on a more general level by comparing the estimate given by the by2020 software with the data from separate studies with slightly different test setups and concrete grades.

Since the by2020 software aims to describe practical situations as realistically as possible, the role of temperature in terms of drying cannot be ignored. Regarding the temperature dependence of concrete drying, in comparison with previous tests, it was found that a temperature-dependent factor must be taken into account in the determination of moisture transport coefficients, so that the result reflects practice more accurately. Sekki et al. [27] has gone through the test series in more detail also in terms of determining temperature dependence of RH in the concrete pore. The estimates of the by2020 software were calibrated against the data from drying in different temperature conditions and the temperature-dependent moisture transfer coefficients were determined. The results for concrete grade w/b 0.45 are shown in Figure 9. The main consideration is that in cool conditions at a temperature of 5°C, drying is slow. On the other hand, drying at a higher temperature of 30°C compared to reference temperature 20 °C is not significantly faster, except for the surface part of the structure.

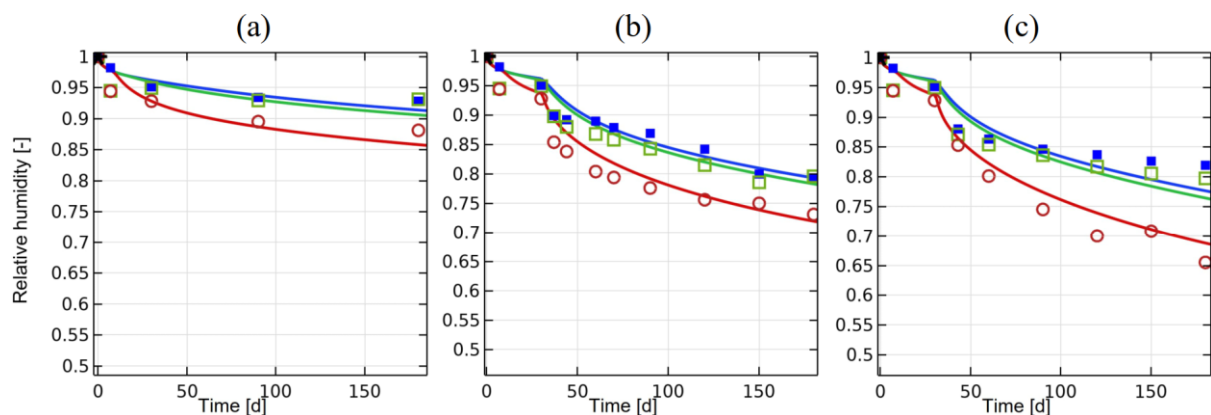


Figure 9 – 100 mm thick slab drying from one surface ($w/b = 0.45$). Drying at (a) constant 5°C, (b) 30 days at 5°C and then at 20°C and (c) 30 days at 5°C and then at 30°C. Colours represent the measuring depths: blue = 100 mm, green = 70 mm and red = 30 mm. Data points are from Sekki et al. [27].

The data by Johansson [14] for tests with concrete specimens with and without levelling were utilized for validation. The results in figures 10-12 show that the estimate of drying calculated

with the by2020 software in constant condition 20°C and 60 % RH is promising compared to measurements. The greatest difference between simulations and measurements was observed with $w/b = 0.55$ concrete grade. In the by2020 software, $w/b = 0.55$ is defined as a faster-drying concrete grade, thus the results are not completely comparable (although the difference is in the right direction). The effect of levelling in the estimation is also, for the most part, very close in magnitude to the measured values. However, there can be significant differences in terms of effect of levelling depending on the product used, which Johansson [14] also points out. Taking into account the effect of the generic so-called universal screed specified in the by2020 software in the estimate can be considered suitable for practical assessment.

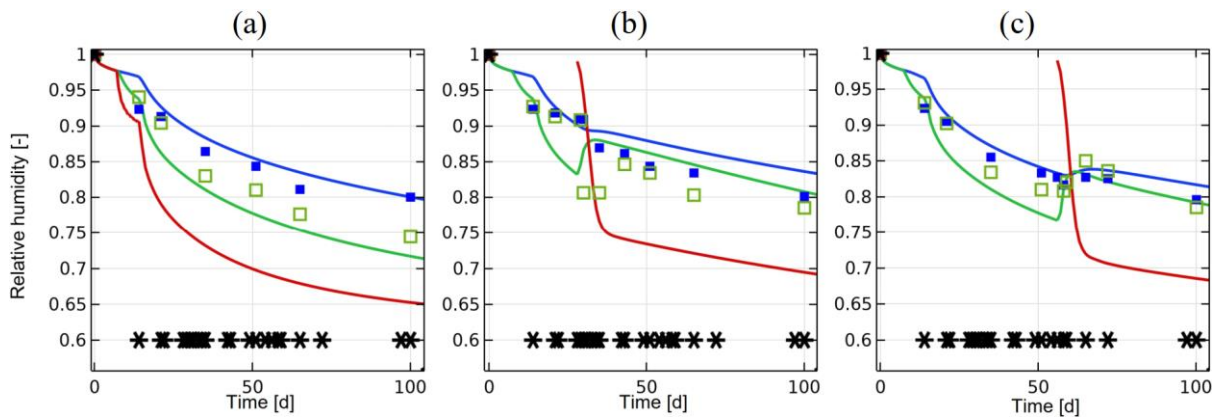


Figure 10 – $w/b = 0.45$, 180 mm thick slab drying from one surface. Drying at (a) constant 20 °C and 60 % RH, and 10 mm thick levelling installed at age of (b) 28 days and (c) 56 days. Colours represent the measuring depths in concrete: blue = 48 mm, green = 15 mm. Red = 5 mm in levelling/concrete. Asterisk indicates ambient RH. Data points are from Johansson [14].

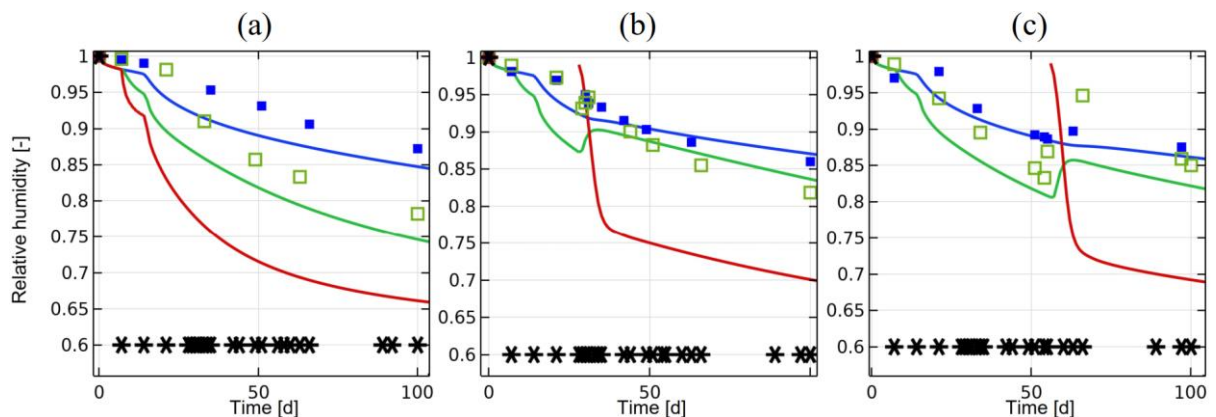


Figure 11 – $w/b = 0.55$, 180 mm thick slab drying from one surface. Drying at (a) constant 20°C and 60 % RH, and 10 mm thick levelling installed at age of (b) 28 days and (c) 56 days. Colours represent the measuring depths in concrete: blue = 48 mm, green = 15 mm. Red = 5 mm in levelling/concrete. Asterisk indicates ambient RH. Data points are from Johansson [14].

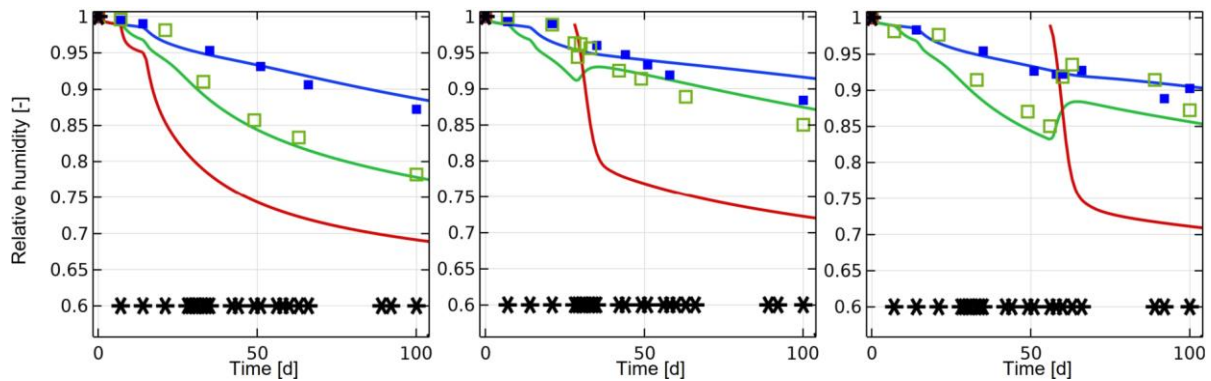


Figure 12 – $w/b = 0.70$, 180 mm thick slab drying from one surface. Drying at (a) constant 20°C and 60 % RH, and 10 mm thick levelling installed at age of (b) 28 days and (c) 56 days. Colours represent the measuring depths in concrete: blue = 48 mm, green = 15 mm. Red = 5 mm in levelling/concrete. Asterisk indicates ambient RH. Data points are from Johansson [14].

Another perspective of model validation has been presented by Sekki et al. [31], where a feature in the by2020 software has been studied, which can be used to examine the change in humidity distribution after coating the structure. Drying of the concrete test specimen had been monitored until coating, after which 3 mm levelling and coating, a vapor tight plastic carpet, were applied. RH measurements had been performed in different stages and RH under the coating had been monitored for maximum of three years. The observation was that the by2020 software can predict quite promisingly the highest RH level formed under the coating. Although, there is some difference compared to the results in the final state as shown in figure 13, the highest estimated RH level is decisive in terms of risk analysis, and therefore the estimate can be considered appropriate.

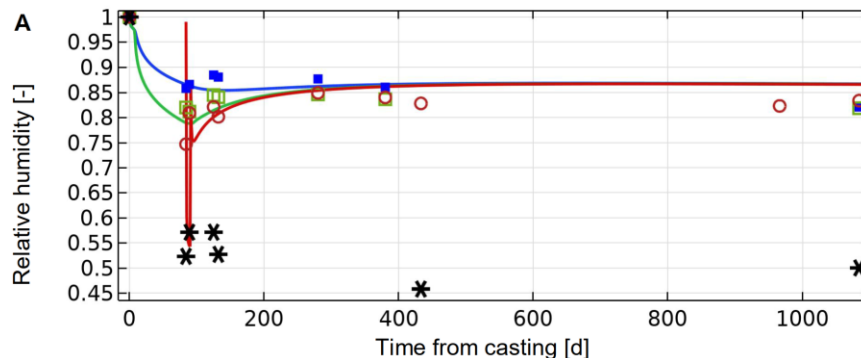


Figure 13 – 280 mm thick slab with 3 mm levelling drying from one surface ($w/b = 0.45$). Coated with plastic carpet ($s_d \sim 80$ m). Colours represent the measuring depths: blue = 70 mm, green = 28 mm and red = surface. Asterisk shows the ambient RH condition during test. Reproduced from Sekki et al. [31].

It is perhaps surprising that the results given by the by2020 software are reasonably comparable to Swedish tests where the binders (CEMII/A-LL) differ from binders used in concretes of this study (CEMII/S-LL+CEMI). Nevertheless, parallel experiments are required since changes in binders and recipes will be more radical in future, because efforts are being made to reduce the amount of clinker by supplementary cementitious materials (SCMs) to lower the carbon footprint of concrete.

5. CONCLUSIONS

The aim was to create a practical tool that is easy to use and that can be used to assess drying of concrete with sufficient accuracy. The approach in the by2020 software is not particularly scientific. The proportions of the components of concrete cannot be specified in detail, but the concrete is only described by using the w/b ratio as qualifier. For the calibration of the model from this perspective, concrete grades representing common floor concrete from two suppliers with different w/b ratios were selected for tests to determine data sets of *RH* during different drying situations. A comparison with the results of a Swedish study suggests that the approach is successful and allows the broadened utilization of by2020 software also outside of Finland at least to some extent. However, further research is required to determine more precisely which concrete grades can be simulated with confidence.

Calibrating the model to obtain an exact fit in terms of *RH* distribution is probably impossible. Especially obtaining a very close fit in practical conditions each time is hardly possible. However, calibrating the model with two different depths is essential, so that the *RH* distribution is more realistic. Thus, the evaluation depth closer the surface could also be used in the evaluation of adequate drying.

If the results of the by2020 software are taken as a reference point, very different measurements and test arrangements can provide reliable data on concrete drying and moisture behaviour. Regarding the measurement and experimental arrangements carried out in this study, pros and cons could be observed compared to other possible methods. Considering *RH* measurements using the sample piece method, the possibility of error is mainly due to operation of the surveyor, because the drying of a test specimen is not disturbed by measuring tubes or drilling. The main uncertainties are the measurement depth, the correct sample volume (no fine matter allowed) and the opening time of the sample. Other perspectives on the implementation of the test are presented below as recommendations taking into account that efforts are being made to describe the practical situation as well as possible.

Test specimens:

1. One-liter sealable tin cans are used as molds
2. A recommended method is to cast concrete into molds immediately after preparing the concrete mix and vibrate the molds on the vibrating table. Surface rubbing is not necessary, but in this case, a heavier diamond grinding of the surface is likely to be required.
3. The upper part of the tin can is quite convenient to cut and pull the edge open just below the level of the upper edge of the concrete.
4. After grinding the surface, the interface between the tin can and concrete is carefully sealed.

Drying and wetting tests conditions:

1. Different thermal conditions
 - a. Constant reference condition 20°C and 50 % *RH* (or 60 % *RH*).
 - b. Constant conditions below reference 5 to 10 to 15°C and 60 % *RH*.

- c. Constant conditions above reference 25 to 30°C and 50 % *RH*.
 - i. Additional, since temperature dependent coefficients in literature seem to predict more accurately the effect of temperature above the reference temperature 20 to 23°C [27].
2. Wetting during the drying period
 - a. 1-month constant wetting starting from 2 to 4 weeks from casting and continuing with constant drying conditions.

Relative humidity measurements:

1. Sample piece measurement is a suitable method for tin can specimen.
2. When determining the distribution, 3 measurements per measuring depth and two measurement depths in addition to the surface are recommended (the surface is not always necessary).
3. Sample piece method is suitable method for self-desiccation specimen. 3 measurements per sample are recommended.
 - a. Sample piece measurement is quite laborious, the [14] measurement method is possibly a suitable option.

Additional tests which are suitable with tin can test specimen:

1. Determination of temperature dependence *RH* in concrete pores [27, 32].
2. Determining the amount of water that evaporates or is absorbed during wetting by weighing the specimen.
3. Determination of moisture transport properties as proposed by Nillson [30].
4. Effect of coating. Closing the open surface after drying period with material with known water vapor resistance factor and determining the long-term *RH* development under the surface material. So-called incision/slit *RH* measuring method can be utilized by using thin probe which is described in [15, 31].

In practice, *RH* is measured, because it has a link to the essential damage mechanisms of surface materials. Therefore, measuring the effect of wetting in *RH* is more important than determination of the amount of immersed water or the capillary properties of concrete. Thus, in our opinion, the implementation of a model suitable for practice can be done purely on the basis of *RH* measurements, but the design of the test series should take into account the influence of various factors on *RH* of the concrete pores.

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