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Measurement and modelling of the moisture distribution in early-age concrete in the joint of composite beam and hollow core slab

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Abstract. The building moisture in concrete can damage the surface material if applied too early before the excess moisture has dried out. The composite beam forms an abnormal structure at the joint of the hollow-core slab, in which the thickness of the structural concrete is almost the thickness of the entire slab. For this reason, the joint of the beam and hollow core slab must be taken into account when assessing the adequate drying of concrete structures. The considered composite beams are steel casing beams, which are casted full of concrete. To achieve a composite structure, there are holes in the sides of the casing, through which moisture from the concrete transfers to the surrounding structure. However, the drying of the concrete inside the beam is significantly limited. The level of relative humidity of the concrete inside the beam remains moderately high for a long time, depending on the quality of the concrete and, consequently, the self-desiccation of the concrete. When using concrete with a low water binder ratio, drying occurs at a level of about 85%RH as a result of self-desiccation. In the study, relative humidity in the joint was measured continuously and with instantaneous measurements. The relative humidity in the joint concrete was also monitored after the surface structure layers were installed. In addition, humidity was measured from below the surface material and continued until equilibrium was reached. The structure was simulated as a 3D model and studied using a concrete material model which takes into account the self-desiccation and the thermal dependence of the sorption. A good agreement was found to describe the effect of temperature changes on the relative humidity of concrete that can be observed in continuous measurement. In addition, a suitable prediction of relative humidity below the surface material can be achieved based on modelled relative humidity distribution before the installation of the surface structure.

1. Introduction

Drying of concrete slabs is one of the most important phases of construction project that determine the schedule. Therefore, drying time estimations of concrete structures are necessary to ensure a realistic time table for finishing the concrete floors. An overly optimistic schedule estimate can cause pressure during the project to install surface materials too early when concrete is excessively moist. As a quality management method relative humidity is measured to ensure adequate drying of concrete [1]. In practice, on every building site, the concrete slabs must be measured and the set limit values reached before applying the surface materials. In order to ensure sufficient drying with measurements, it is necessary to choose the structures and the details that must be taken into account in the measurement plan. The structures that differ in terms of drying, such as thicker parts of the slab or structural parts in which drying is limited by a vapor tight layer, must take into account.

The studied composite beam forms an abnormal structure at the joint of the hollow-core slab, in which the thickness of the structural concrete is almost the thickness of the entire slab. For this reason, the joint of the beam and hollow core slab must be taken into account when assessing the adequate drying of concrete structures. The considered composite beams are steel casing beams, which are casted full of concrete. To achieve a composite structure, there are holes in the sides of the casing, through which moisture from the concrete transfers to the surrounding structure. However, the drying of the concrete inside the beam is significantly limited. The level of relative humidity of the concrete inside the beam remains moderately high for a long time, depending on the quality of the concrete and, consequently, the self-desiccation of the concrete. When using concrete with a low water to binder ratio (w/b), drying occurs at a level of about 80-90 %RH as a result of self-desiccation [2].

In this study, relative humidity in the joint concrete was measured continuously and with instantaneous measurements. Relative humidity in the joint concrete was also monitored after the surface structure layers were installed. Measuring continued until equilibrium below the surface material was reached. In addition, the structure was simulated as a 3D model and studied using a concrete material model which takes into account the self-desiccation and the thermal dependence of the sorption. The utility of continuous measuring compared to instantaneous measurements was studied. In addition, the applicability of the simulation model was evaluated. On a general level, the aim was to get more information about the long-term moisture behavior of the studied composite structure.

2. Material and methods

2.1. Investigated structure

Two composite beam and hollow core slab (HC) assemblies were studied (Figure 1). ORIG-1 was Deltabeam D50-500 with elevated bottom flange and ORIG-2 was Deltabeam D32-400. Thickness of the HC were 320 mm in both cases. Deltabeams and joint of the beam and hollow core slabs are cast in-situ. Heating cables are applied to speed up drying. After concrete of the joints is adequate dry, the levelling compound is applied, and depending of the levelling compound the flooring material is installed the specified time or when the excess moisture of the levelling compound has dried on target level.

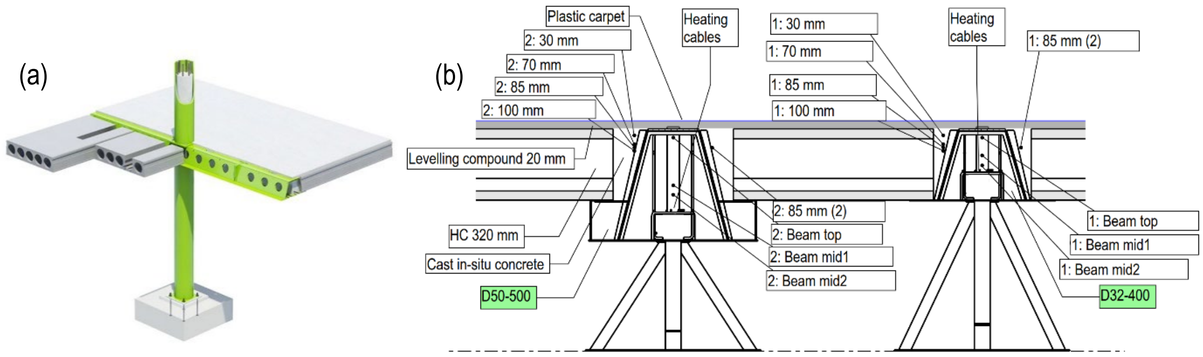

Figure 1. (a) Visualisation of the Deltabeam + Hollow core slap composite floor (peikko.com). (b) Sections of the studied structures with measurement points.

Cast in-situ structural concrete was ready mixed C35/45 (CEM II/B-M42.5) with maximum aggregate size of 8 mm. The water to binder ratio (w/b) was 0.4. Consistency class S4 is conducted by using workability enhancing admixture Sika Visco Flow MR-1. Admixture for freeze-thaw resistance Sika Air-Pro V5 was also used.

Levelling compound Ardex K 70 NEW was used and primer Ardex P 51 applied. The levelling is applied at 190 days from casting. According to the product information the installation of the finishing material (plastic carpet) can be applied after 24 hours if levelling thickness is 20 mm, as in studied structure.

2.2. Relative humidity measurements

Borehole measurements according to [1] using capacitive sensors (A), Vaisala HMP40S. Measuring point locations are on the joint, however, not accurately reported. Continuous measurements were conducted using pressure measuring based Matolog sensors (B) that represent a new type of technology in concrete moisture and relative humidity measuring. Measuring depths for borehole method were 30 mm; 70 mm; 85 mm and 100 mm from the concrete surface. Measuring devices of the continuous measurements were placed before casting near the web hole of the beam. Measuring points are shown in figure 1. So-called incision/slit method with thin probe were used for measuring RH under the plastic carped. Method is described in [1].

2.3. Simulation model

The model used in the study for early-aged concrete, which also describes the temperature dependence of the relative humidity in concrete pores, is presented in detail in [3].Governing equations for the heat and mass balance shown below, includes the additional temperature dependent moisture storage capacity (ξ_T) which is produced by the temperature dependence of sorption (TDS).

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

$$\xi \frac{\partial \phi}{\partial t} + \xi_T \frac{\partial T}{\partial t} = \nabla \cdot \left[\xi D_w \nabla \phi + \delta_p \nabla(\phi p_{sat})\right] + S \tag{2}$$

where T is temperature [K], ρ density [kg/m^3], C_p specific heat [J/kgK], 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 [J/kg], $\xi = dw/d\phi$ moisture storage capacity [kg/m3] (in which w water content [kg/m^3]), $\xi_T = dw/dT$ temperature dependent moisture storage capacity [kg/m3K], D_w liquid water diffusion coefficient [m^2/s], S hydration moisture sink [kg/m^{3}s].

Material parameters for concrete are also adopted from [3] using the parameters of concrete A (w/b = 0.45). Parameters estimated for the other materials are listed in table 1 indicating the order of magnitude of the parameters. Most of the material's properties are set as humidity-dependent between 0-100 %RH.

Table 1. Material properties in model.

Material	C_p [J/(kgK)]	k [W/(mK)]	ρ [kg/m^3]	D_w [m^2/s]	δ_p [s]	w [kg/m^3]	
Structural steel	475	44.5	7850	-	-	-	[4]
HC-slab	850	50 %RH: 1.6 100 %RH: 2.6	2300	50 %RH: 5.6e-11 100 %RH: 9e-9	50 %RH: δ_{air}/150	50%RH: 43 90%RH: 85 100%RH: 110	[a]
Levelling compound	850	1.6	1890	0	50 %RH: δ_{air}/45 100 %RH: δ_{air}/18	50%RH: 13 90%RH: 70 99%RH: 91	[5] [6] [7]
Hollow section	1005	0.02	1.25	0	δ_{air}[b]	0.15	[a]
Plastic carpet	-	-	-	-	7.9e-15	-	[a]

[a] estimate

[b] water vapor permeability of still air

The simulations were performed using a finite element method based software COMSOL Multiphysics 6.0. Simulation was executed in two phases. First phase started form “casting” the cast in-situ concrete. Boundary conditions T/RH are shown in figure 2 (a). Last values were used s constant for extrapolation. Two line heating source were set to 40 W/m and controlled by the valve shown in figure 2 (b) based on the experimental. Second phase started from 190 days form casting, when levelling compound layer was added into simulation model. Effect of the installation of the finishing material was modelled by changing the moisture transfer coefficient of the surface from open boundary to match the water vapor resistance of the plastic carpet. The change was implemented after 24 hours from the beginning of the second phase. Initial RH for cast in-situ concrete and levelling compound was set to 99.9 %RH and 92 %RH for HC.

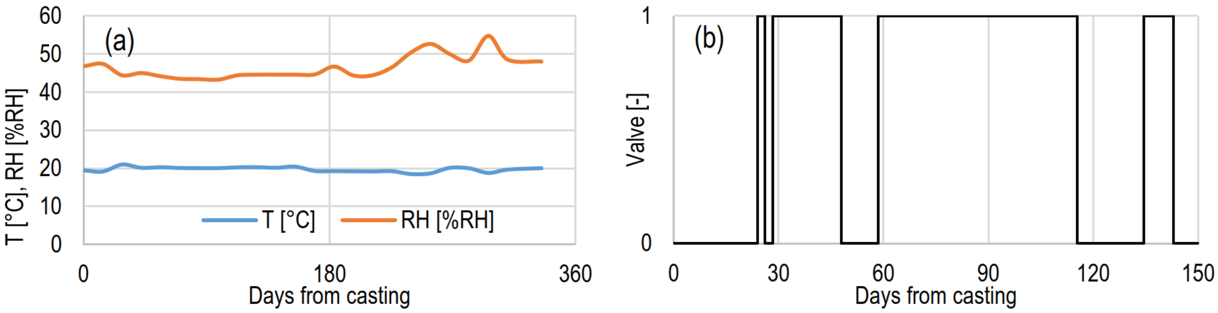

Figure 2. (a) Measured T and RH boundary conditions. (b) Operation valve of the heating cables.

Model geometry is shown in figure 3. The smallest possible symmetry was modeled excluding HC, which was modeled to a sufficient length based on experience. Thus, symmetry boundary is set on sides. Results for comparison are taken in different depths in concrete 30 mm; 70 mm; 100 mm and in upper part of the levelling (‘L top’ in results = 1 mm from upper surface of the levelling) from the cut lines 1-3 and from the middle point of the beam (cut point 4).

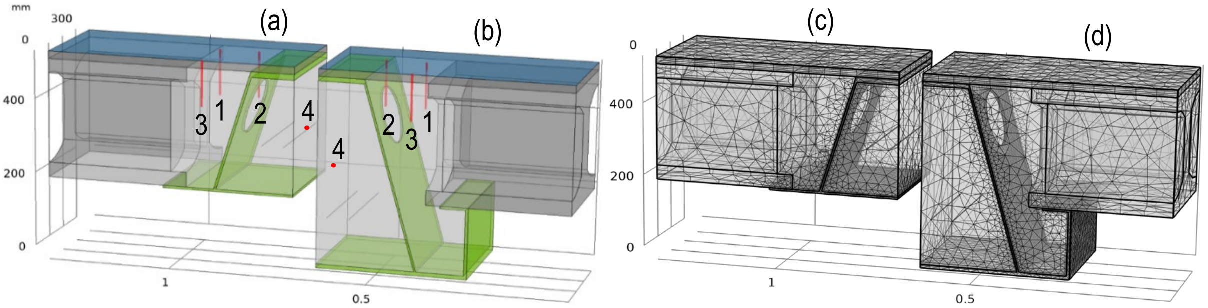

Figure 3. Model geometry showing cut lines 1-3 and cut point 4 (a) D32-400 and (b) D50-500 and mesh (c) D32-400 and (d) D50-500.

Three-dimensional simulation models consisting of D32-400: 33430 domain elements, 7182 boundary elements, and 723 edge elements and D50-500: 65678 domain elements, 11405 boundary elements, and 940 edge elements with quadratic shape functions were found to give adequate accurate results. The CPU time for first phase was approximately 3-8 h and second phase 1-3 h with a laptop computer equipped with an Intel(R) Core(TM) i7-8850H CPU, 2.60 GHz and 32 GB of memory.

3. Results and discussion

Results are shown in figures 4-6. Number in the beginning of the labels represents the cut line number shown in figure 3. The second number is the measuring depth in mm. The same applies to experimental results, presented number is the measuring depth in mm. Experimental results in cut point 4 is labeled as exp Beam.

Comparison of the temperature in continuous measurements and model are shown in figure 4.

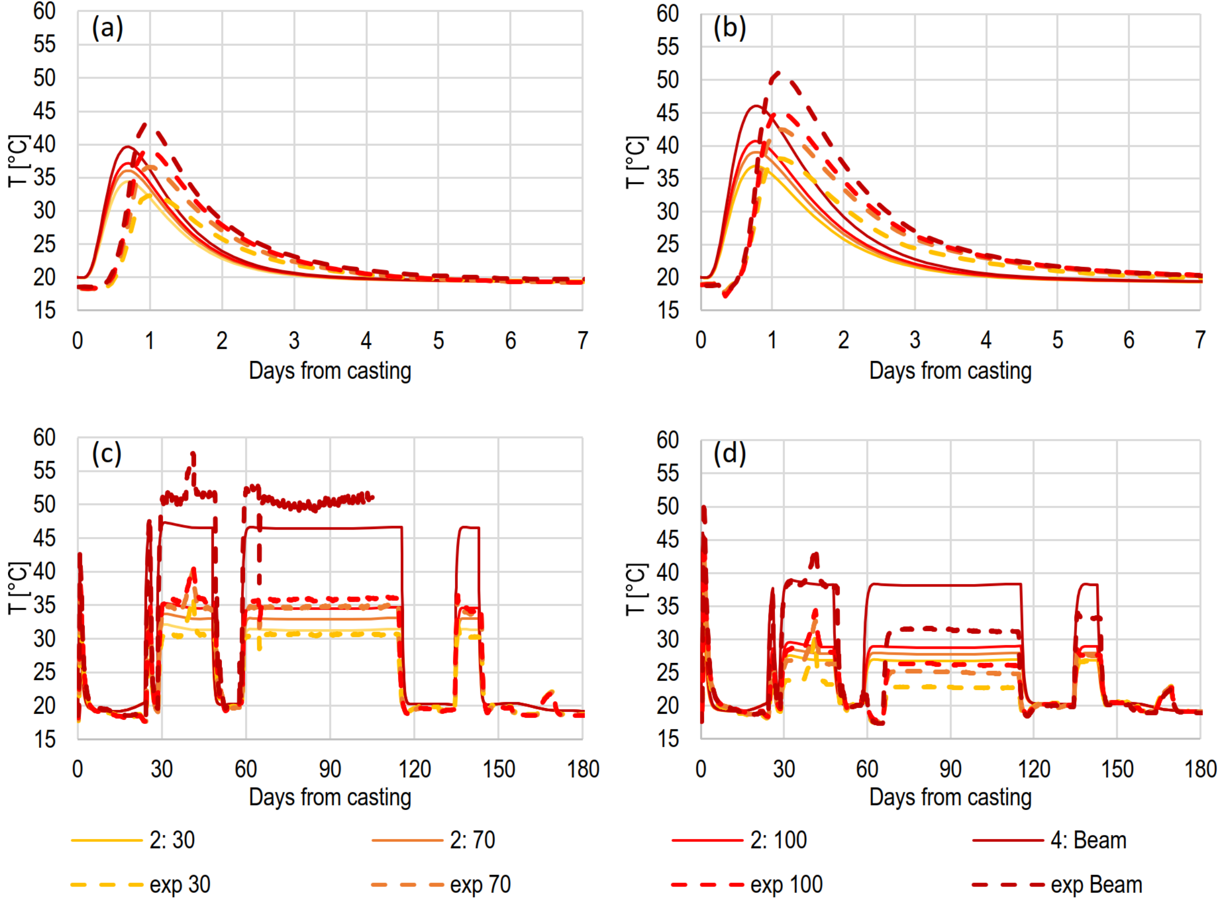

Figure 4. Measured and simulated temperature comparison. Temperature development of hydration (a) D32-400 and (b) D50-500. Temperature during drying period (c) D32-400 and (d) D50-500.

The modeled temperature change is moderate close to the measured temperature during hydration. However, the temperature change in the initial phase shows that the starting point of the model is not quite synchronized with respect to the measurements. The modeled temperatures are slightly lower, which is an acceptable deviation, because in the model the concrete w/b is slightly higher than in experiment.

During the drying phase, the model and measurements correspond moderate well to each other during the first heating cycle. Overall, the results of D32-400 are more suitable during heating.

The temperature readings during the borehole measurements were also compared to continuous measurements. The comparison indicated that the continuous measurement systematically shows a one degree lower temperature than the borehole measurement. For this reason, a temperature correction was implemented to RH results of the continuous measurements. Corrected RH_2 was calculated as $RH_2 = v_{sat}(T_1)RH_1/v_{sat}(T_2)$, where $v_{sat} = 4.85 + 3.47(T/10) + 0.945(T/10)^2 + 0.158(T/10)^3 + 0.0281(T/10)^4$, T_1 is the measured T and T_2 is the corrected temperature $T_2 = T_1+1$ °C. The average effect of the correction on the measurement result was -4.2 RH-percentage points. Comparison of the measured and simulated RH are shown in figure 5 and 6. For continuous measurements, the corrected result is presented.

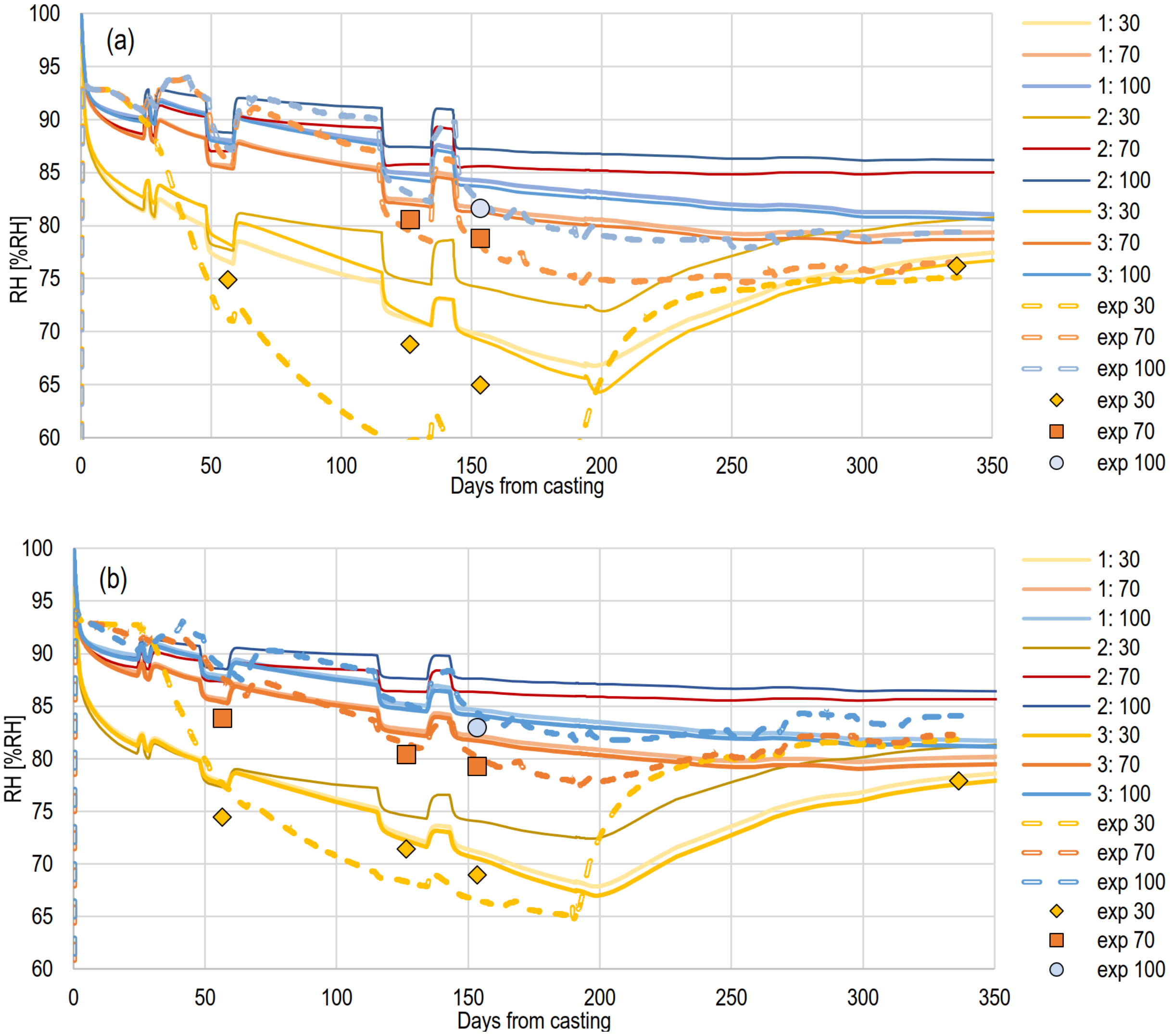

Figure 5. Measured and simulated RH comparison (a) D32-400 and (b) D50-500.

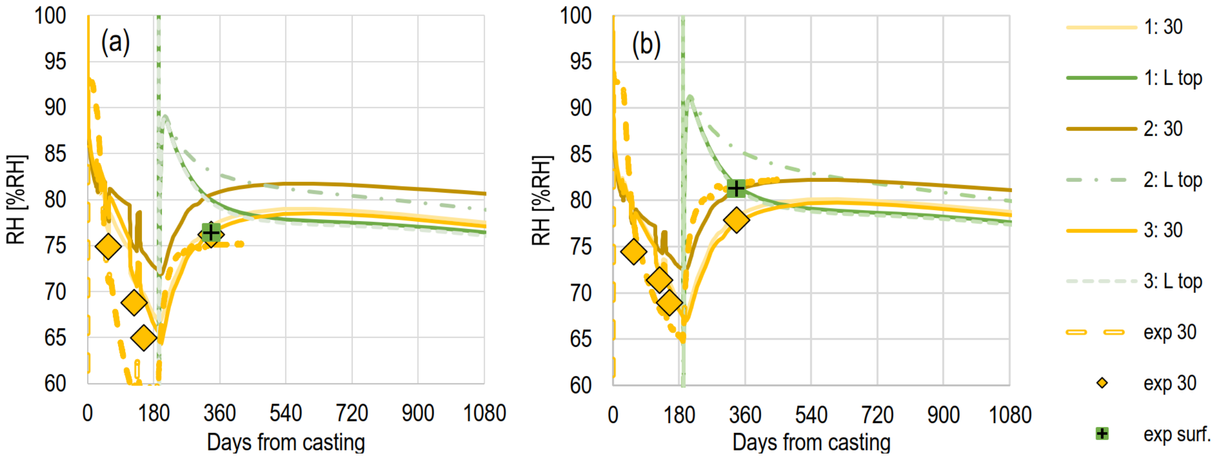

Figure 6. Measured and simulated RH comparison near the surface (a) D32-400 and (b) D50-500.

The results of the model shows notable difference between locations 1-3. Considering the variability of the results, the experimental and model results correlate each other quite well. Since the desired measurement points were near the web hole, the measurements should match the result of the point 2. However, the modeling deviates the most when compared to point 2. The higher w/b of the concrete in the model might be one of the explanatory factors. Thus, the self-desiccations of the modeled concrete is lower than in the concrete of the experiment, which distorts the result due the overestimated moisture transferred from the inside of the beam, especially near the web hole. Results shows that the modeling result remains on average about 5 percentage points higher during the drying period excluding D32-400 results in 30 mm depth which are up to 10 units higher at 155 days. Part of the deviation can be explained by the location of the measuring point in relation to the borehole.

The comparison between the measurement methods and the model at different points in time is summarized in table 2. The results shows that two different measurement methods gives comparable results. At a depth of 30 mm at 155 days, the difference is the largest, which may be caused by cracking forming at the continuous measuring device. However, after the installation of the surface material, the results of the continuous measurement rises to the level of the borehole measurement or even above, which can be caused by the greater water absorption of the cracked concrete and/or the redistribution of moisture around the cracked area. With deeper measuring depths, there is considerably less deviation between measurement methods A and B at the time points examined, of the order of +/- 1% unit.

Table 2. Summarized result comparison between measuring methods and model.

	D32-400 [%RH]				D50-500 [%RH]			
	(155 d)		(335 d)		(155 d)		(335 d)	
	A-B	model	A-B	model	A-B	model	A-B	model
L top	-	-	76,5	79,5…83	-	-	81.5	81.5…85.5
30 mm	65-59	69…74	76-75	76…80	69-66.5	70.5…74	78-82	77.5…81
70 mm	79-78	81…85.5	-	-	79-80	81.5…86.5	-	-
100 mm	81.5-82.5	83.5…87	-	-	83-84.5	84…87.5	-	-

According to the study, in-situ concrete casting of the beam and the thicker concrete in joint has a significant effect on the RH level under the carpet. However, in the examined situation the measurement conducted on the near of the concrete surface and under the carpet stays below the considered critical level of 85 %RH.

There are no considerable risk because of the RH of the joint and in-situ casting concrete of the beam to the surface material in the studied situation. However, the results cannot be applied to other somewhat similar structures, because the solutions differ from each other in terms of geometry. Based on the results, the applied model can be utilized in similar cases to examine the moisture risk due to the cast in-situ concrete of the beam.

4. Conclusions

A good agreement was found between continuous and with instantaneous measurements. It was found that when measuring RH, it is very important that the temperature measurement accuracy of the measuring device is sufficient. Comparing the measurements to the simulation, an appropriate correspondence was found. The model should generally be on the safe side. On the other hand, when modeling the early-age drying of concrete the material model should describe the moisture properties and self-desiccation of applied concrete as accurate as possible. Especially in the case of limited drying of the concrete in composite beams, the effect of poor estimate of self-desiccation can be significant. Part of the deviation noted in the study between measurements and model is probably due to some degree lower self-desiccation. The study utilized a simulation model that takes into account the temperature dependence of sorption. The effect of temperature changes on the relative humidity of concrete observed in continuous measurement were comparable to model.

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