LOSS OF MOISTURE FROM CONCRETE – MODEL vs. REALITY

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Abstract

Curing of concrete, as an operation preventing concrete from essentially cracking and comprehensively decrease in performances, definitely belongs to the most difficult operations in terms of correct design and schedule especially when dealing with large flat constructions like paving, bridge decks or floors. The biggest issue is to prevent concrete from water loss or supply curing water and cover already lost. When perfect curing is needed, the only option is relay on supply curing water from either outside (conventional curing) or inside (internal curing) of concrete. What is the essential assumption for right working of curing is that supplied water must cover the actual consumption and we all do know that it barely could be assumed to be stable in time. The „loss“ of physically bound water can be divided into chemical consumption due to running hydration and water evaporation due exposure of concrete. This paper deals with preliminary results of laboratory tests simulating various exposure conditions (and curing methods) measuring watter loss from concrete in comparison with worldwide used Menzel´s model.

Keywords: concrete, curing, evaporation, temperature, relative humidity, wind velocity

Introduction

Loss of moisture to the ambient environment can be simplified as water evaporation from the surface. Seemingly static system actually is dynamic. The unstationary moisture field is determined by changing concrete surface in direct contact with ambient environment, by changing moisture of cement paste (degree of capillaries´ saturation with porous solution) and falling moisture gradient, raising density of setting and hardening cement paste (raising diffusion resistance). The time behaviour of moisture loss to the ambient environment, in terms of intensity, is divided into three phases. The first one is represented by evaporation of so called bleed water from concrete surface (Menzel 1954). Gradually the evaporation zone moves deeper into cement paste (phase II). Between II. and III. phase, there is clear fall of evaporation intensity. In the 2nd phase the initially fully saturated capillaries are emptied what invoke capillary stresses expressed in cement paste. If the system, in meantime, starts to set, vertical deformations or collapse of system is restricted somehow. That generates non-directional stresses. The evaporation zone moves even more deeper into cement paste (3rd phase) and due to increasing of depth of evaporation and raising density of cement paste, there is noticeable fall of evaporation rate (Menzel 1954, ACI 301-05 (2005), ACI 308R-01 (2003), Hover (2006)).

There exist couple more or less know models of water evaporation. In general and widely used one was presented already in 1954 by Menzel. The model (formula 1 and figure 1) describes an intensity of water evaporation E_E (kg/m^2.hod) from open water level as a function of several driving factors of ambient environment, surface temperature T_C (°C); ambient temperature T_{AMB} (°C); relative humidity RH (%) and wind velocity v_W (km/h). It is obvious that validity of this model is markedly limited in time to short period close to finishing of surface when bleed water is to be evaporated (Al-Fadhala (2001)). Intensity of water loss from concrete surface is dependent on intensity of water segregation, boundary conditions, surface texture and concrete curing (Al-Fadhala (2001), Schindler (2003), Rochefort (2000)). The model is suitable for calculation of water loss just at very early age of concrete and often is associated with plastic shrinkage. In case of real applications in experience, this (based on its nature) stands on safety side. That means that curing water needed (according to model) to replace the amount of water evaporated will, already after start of 2nd phase, markedly exceed the requirements. Moreover, the model offers just framework information on how the individual factors contribute to water loss from concrete surface. The model does not consider a cooling effect of water evaporation and either to this suffers strong uncertainty which (according to Al-Fadhala (2001)) reaches ± 25 % at E_E up to 1,0 kg/m^2.hod and at higher values systematically shows higher values by roughly 50 %.

$$E_E = 5 \cdot \left(\left(T_C + 18\right)^{2,5} - \left(\frac{RH}{100} \cdot \left(T_{AMB} + 18\right)^{2,5} \right) \right) \cdot \left(v_W + 4\right) \cdot 10^{-6} \qquad (1)$$

where: E_E is intensity of water evaporation (kg/m^2.hod)
T_C is temperature of concrete surface (°C)
RH is relative humidity of ambient environment (%)
T_{AMB} is temperature of ambient environment (°C)
v_W is wind velocity (km/h).

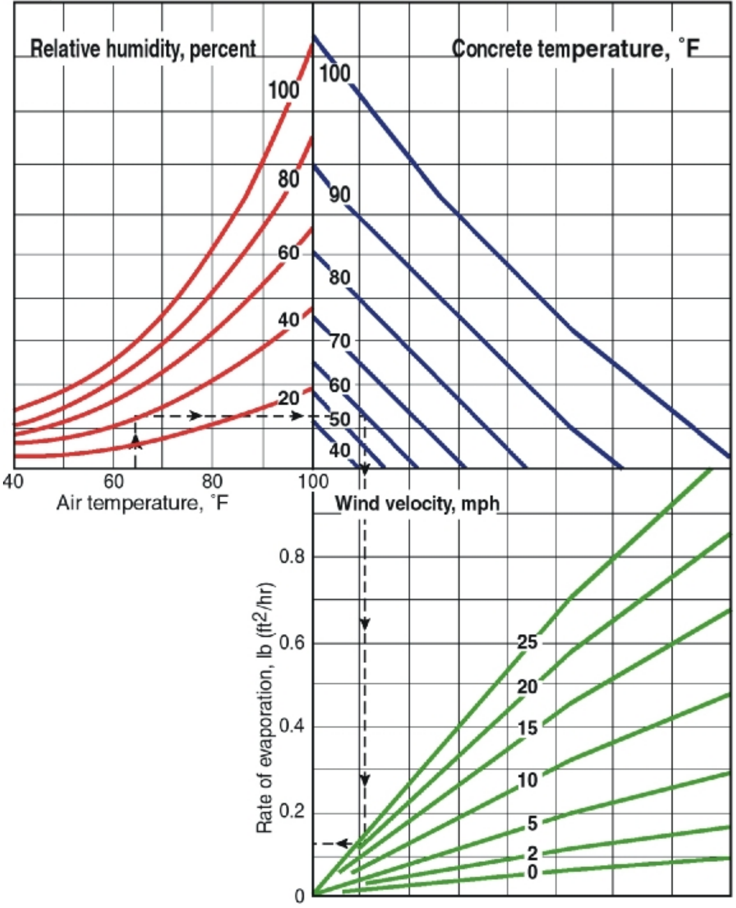

fig. 1 Model of water loss (intensity of water evaporation) according to Menzel (ACI 308R-01 (2003), Briatka (2011))

With time, the model needs some modification. One of possibilities is to incorporate, already mentioned, time-dependent intensity of water segregation. After all this lead to formula 2 (Al-Fadhala (2001), Schindler (2003)) for calculation of intensity of water evaporation from concrete E_C (kg/m^2.h), where there come into the concrete age t (h) and time constant a (=3,5 h. for concrete). The formula 2 may be understood just as a platform for given concret composition as quantification of water segregation from concrete hasn´t been performed. Based on previous experiences with hot weather conditioning of concrete, there was suggested new so called Mix design model (formula 3) just for design of curing.

$$E_C = E_E \cdot e^{-\left(\frac{t}{a}\right)^{1,5}} \qquad (2)$$

where: t is age of concrete (h)

a is time constant (=3,5 of concrete).

$$E_E = 0{,}2373 \cdot \left(\frac{1}{t^{0{,}5411}}\right) \qquad (3)$$

where: t is age of concrete (h).

The informative comparison of existing models shows figure 2, from where it´s clear that Menzel´s model gives constant intensity of evaporation regardless of rheology. With respect to found inaccuracy and by comparison to real, measured run it can be stated that it characterizes loss of water at very early age quite good. Other two models according to Al-Fadhala and (empirical) Mix Design take into account changes in concrete structure related with hydration. They, however, do not cover certain age, during with the intensity of water loss from concrete surface equals to or at least is close enough to intensity calculated according to Menzel´s model (valid for open water levels). This period refers to 1st phase of evaporation when intensity of moisture transfer from cement paste to the surface (intensity of water segregation) equals to intensity of evaporation as described Menzel. As can be seen in fig. 2, by shifting of both alternative models to age around 6 hours we can obtain more realistic model. Here, it must be emphasize that Al-Fadhala´s model needs some modification at early age, namely by increasing of evaporation intensity as shown in real measurement.

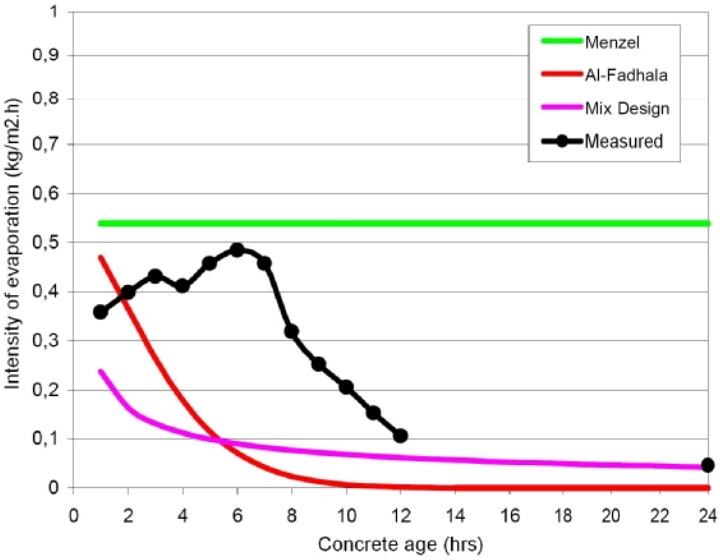

fig. 2 Comparison of several models and real measured data at (T_{AMB}=35 °C; T_C=40 °C; RH=50 % a v_W=3 km/h; w/c=0,42)

Methodology and testing apparatus

Measurement of moisture loss from concrete to ambient environment were performed in the environmental chamber, in which three parameters were controlled – temperature, relative humidity and wind velocity (fig. 3).

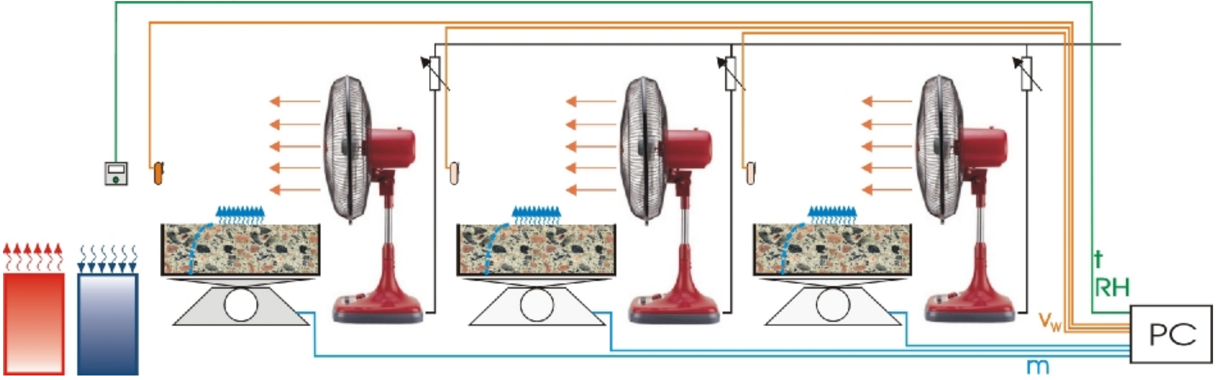

fig. 3 Sketch of measurement and conditioning apparatus

Loss of moisture was monitored by change of absolute mass of concrete specimens (blocks). Data were captured by regular weighting each 1 hour up to age of around 48 hours.

Reproducibility of the tests needed a regulation of the conditioning parameters (T, RH, v_W). Two of them – temperature and wind velocity are independent parameters. Relative humidity, however, is dependent parameter. It relates with temperature. With raising temperature proportionaly raises also capacity of the air to absorb moisture. Due to that, parameters were controled separately, as follows.

Required temperature in conditioning chamber was ensured by electric heating fan controled with mercury thermostatic trigger placed at the same heigth as the samples. Construction possibilities and needed accuracy (temperature hysteresis) using two different thermostatic triggers allowed to get accuracy in temperature from 15 °C up to 35 °C with hysteresis ±1 °C and from 35 °C up to 55 °C with histeresis ±2 °C.

Relative air humidity was ensured by two means. Moisture was releasing from open water level, from testing specimens and from air humidifier. Regulation of relative humidity was performed by condensing dehumidifier allowing regulation at 90; 80; 70; 60 and 50 % levels with histeresis ±5 %. Even level of 30 % was reached during trial run.

The air flow simulating real wind was ensured using axial fans (one for each individual specimen see fig. 4). Regulation was performed by placing the rheostats into the circuits and that way controlling speed circumferentical speed of the air wings. Regarding that actually wind velocity should had been regulated, this parameter was measured. There was used the anemometer with range 2 – 130 km/h and accuracy ±5 %.

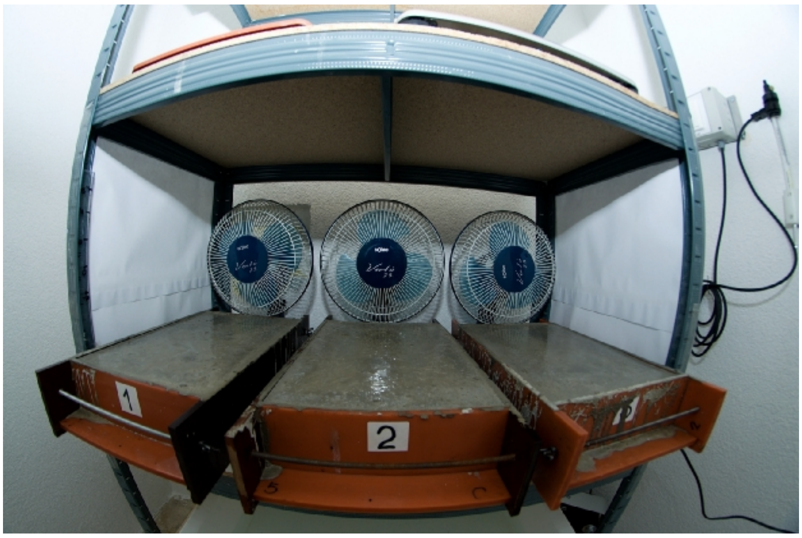

fig. 4: Axial fans regulated by rheostats

Combinations of exposure

Measurement of water loss from concrete was designed at real combinations of boundary conditions simulating common parameters of ambient environment during hot weather concreting. The trial run of the environmental chamber shown real possibilities in terms of relative humidity as a dependent parameter. At high temperature (above 30 °C) it was difficult to keep higher relative humidity (above 50 %). That was the reason of slight modifications in combinations of boundary conditions, as shown in table 1.

Tab. 1: Exposure combinations

Number of combination	WATER			w/c=0,42 REFERENCE		
	T (°C)	RH (%)	v_W (km/h)	T (°C)	RH (%)	v_W (km/h)
1	20	70	3	20	70	3
2	20	70	12	20	70	12
3	20	50	3	20	50	3
4	20	50	12	20	50	12
5	35	50	3	35	50	3
6	35	50	12	35	50	12
7	35	30	3	35	30	3
8	35	30	12	35	30	12

Used materials and mixture compositions

The test were performed using ordinary portland cement CEM I 42,5 N with specific gravity of 3077 kg/m^3. Chemical shrinkage of this cement was 7 % and fineness according to Blain was 344,77 m^2/kg. The aggregate for concrete was used natural gravel of fractions 0/4; 4/8 and 8/16. There was also used water reducer Berament HT2 based on polycarboxylates. Used mixture composition is shown in table 2.

Tab. 2: Mixture composition

Compound	Composition (kg/m^3)
CEMENT	456,335
WATER	220,101
AGGREGATE 0/4	809,603
AGGREGATE 4/8	507,050
AGGREGATE 8/16	338,033
WRA	1,751

Samples preparation

Before mixing as such, all aggregate was oven dried and cooled down to room temperature. Mixing was performed in normal laboratory pan mixer after doseshas been batched. Always the same mixing sequnce was strictly kept. Firstly the fraction 0/4, 4/8 and 8/16 mm were poured into the bowl. Subsequently the cement was added and dry batch let be mixed up for approximately 15 seconds. After this period water was slowly poured in and mixture was mixing for 30 seconds, after which a 30 seconds long break followed and then mixing proceeded with 15 seconds long period again.

Subsequently the fresh concrete was filled into the forms (see figures 5 and 6) and compacted. Then the surface was troweled and finished. Immediately after this point the samples were put into the environmental chamber where they were exposed to simulated hot weather curing.

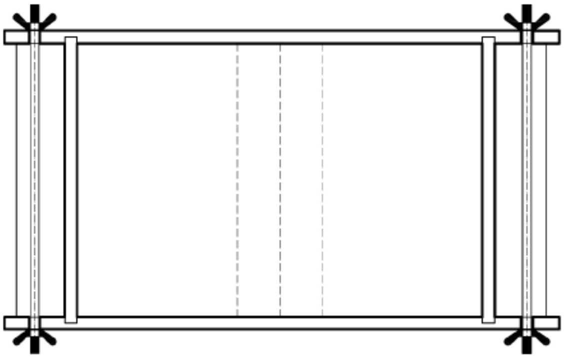

fig. 5: Top view of the form

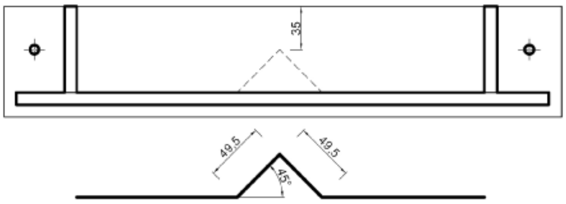

fig. 6: Cross-section of the form

Measurement

By measurement of actual weight all n specimens at time t_j and comparison with weight at time t_{j-1} (according to formula 4), the average intensity of evaporation $E_E(t_j)$ at t_j was calculated. The intensity of water evaporation is an indicator of susceptibility of concrete to water segregation (bleeding), dynamics of moisture transfer in the system and density of forming solid phase.

$$\overline{E_E(t_j)} = \frac{\dfrac{\sum_{i=1}^{n} m_i(t_j)}{n} - \dfrac{\sum_{i=1}^{n} m_i(t_{j-1})}{n}}{A\cdot(t_j - t_{j-1})} \qquad (4)$$

where: $E_E(t_j)$ is intensity of water evaporation at time t_j (g/m^2.hod),
m_i is weight of specimen i (g),
n is number of specimens (-) and
A is surface area (m^2).

Numerically, using formula 1 and 3, an anticipated Manzel´s mix design model´s intensity of water evaporation from open water level was derived.

By integration of derived time behavior of water evaporation intensity was (according to formula 5) obtained a cumulative amount of evaporized water till time t_j.

$$\Delta m(t_j) = \Delta m(t_{j-1}) + \sum_{j=0}^{j} \left(E_E(t_j)\cdot(t_j - t_{j-1})\right) \qquad (5)$$

where: $\Delta m(t_j)$ is overall change in mass up to time t_j (g) and
$E_E(t_j)$ is intensity of water evaporation at time t_j (g/m^2.hod)).

The curves of amount of evaporated water catch the deviations from uniform water loss represented by Menzel´s model.

Results and discussion

A comprehensive review of concrete (with w/c = 0,42) behavior in terms of wtaer evaporation when exposed to action of ambient environment is presented in figures 7-15. In those plots there are also incorporated predictions of water evaporation calculated following Menzel´s model and reale measured intensity of water evaporation from open water level exposed to the same environment.

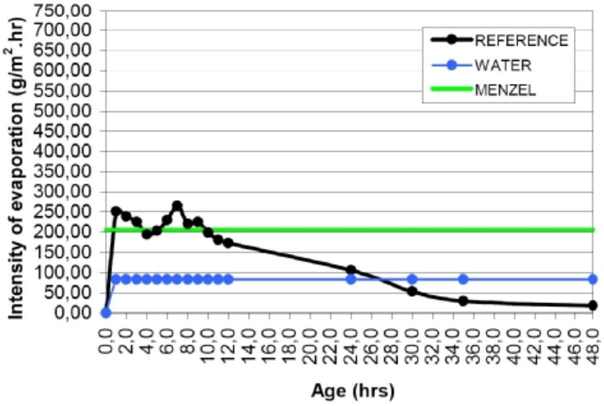

fig. 7: Intensity of evaporation at T=20 °C; RH=70 % and v_w=3 km/h

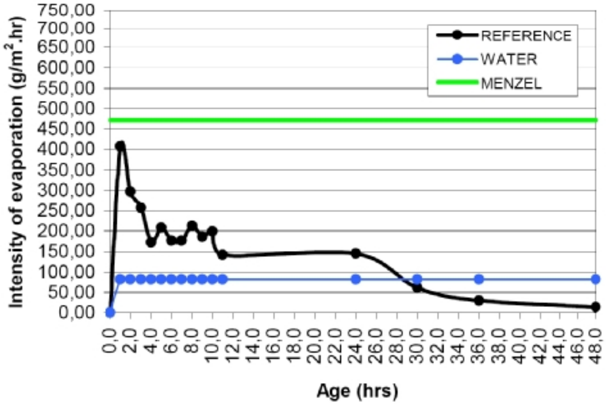

fig. 8: Intensity of evaporation at T=20 °C; RH=70 % and v_w=12 km/h

Figure 7 shows the water loss at the most favorable boundary conditions (quite low temperature, quite high relative humidity and almost no air circulation). When increasing wind velocity from 3 km/h up to 12 km/h we can observe dramatic acceleration of water evaporation especially at very early age when there is enough bleed water on the surface. As can be seen from both plots in figs 7 and 8, Menzel´s model overestimate intensity of water evaporation either from open water level. If we want to describe water loss in relation to hydration (and take fig. 7), it´s obvious that at the very beginning bleed water is to be evaporated. Then rate of water segregation from concrete falls. Around 5th or 6th hour intnsity raises due to synergic effect of increased surface temperature (because of decreasing heat consumption for evaporation in previous hours) and increase of hydration heat lyberation (initial setting stated at 215 mins). At arund 9th hour intensity of evaporation slightly falls again waht is assigned to slow down of hydration and to densification of the matrix.

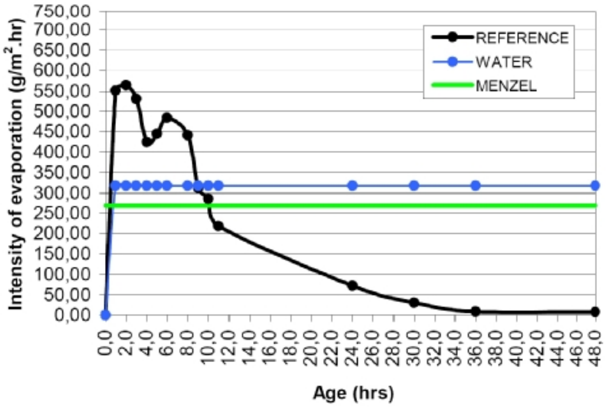

fig. 9: Intensity of evaporation at T=20 °C; RH=50 % and v_w=3 km/h

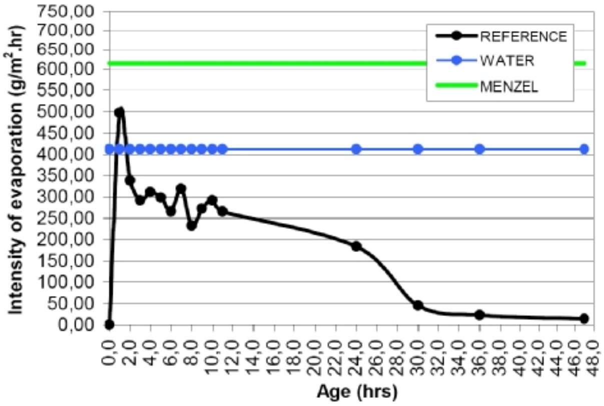

fig. 10: Intensity of evaporation at T=20 °C; RH=50 % and v_w=12 km/h

The environment in action in figs 9 and 10 can be described as moderate and normal for daily concreting jobs. Intensity of water evaporation from open water level dramatically raised up tu 3-4 times higher values when RH falled to 50 %. It´s logical as lower relative humidity of the air at almost constant air temperature indicates higher capacity to absorb water vapor. As can be seen from comparison of figs 10 and 9 or (8 and 7), increase of wind velocity causes strong increase of evaporation rate at very early age followed by deep fall when bleed water is no longer available and rate of water segregation does not cover demand of evaporation.

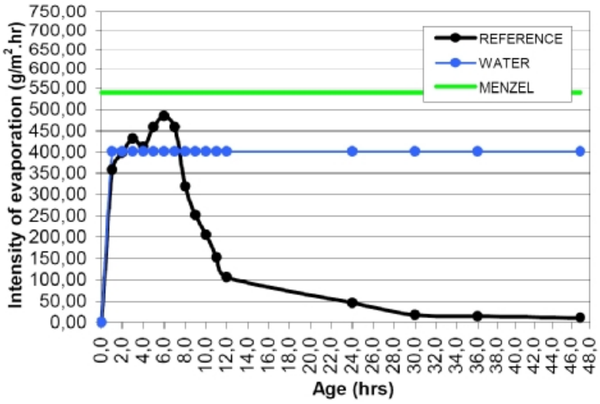

fig. 11: Intensity of evaporation at T=35 °C; RH=50 % and v_w=3 km/h

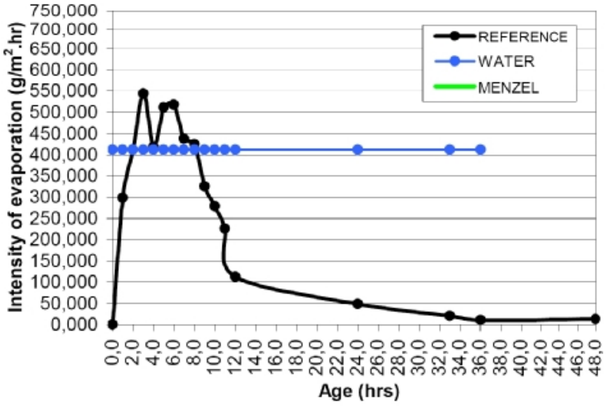

fig. 12: Intensity of evaporation at T=35 °C; RH=50 % and v_w=12 km/h

Figures 11 and 12 present water evaporation at normal boundary conditions typical for hot weather concreting. When compare predicted evaporation by Menzel´s model in fig. 10 and 11 we derive that T=35 °C; RH=50 % and v_w=3 km/h is little less sever for concrete than T=20 °C; RH=50 % and v_w=12 km/h. Out of this flows that the main driving force of water evaporation is just wind velocity. Approaching more severe conditions the phases of hydration and water evaporation are getting shorter and shorter what is in accordance with e.g. strength gain.

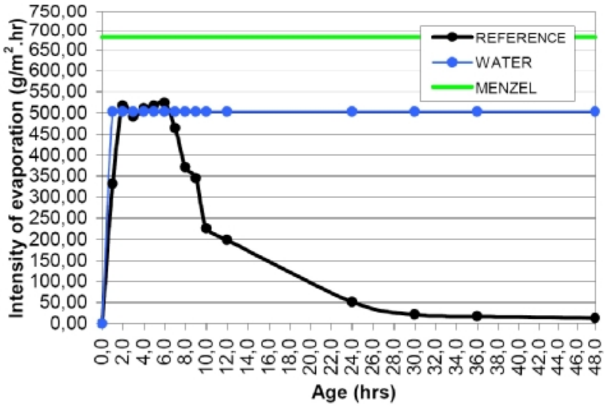

fig. 13: Intensity of evaporation at T=35 °C; RH=30 % and v_w=3 km/h

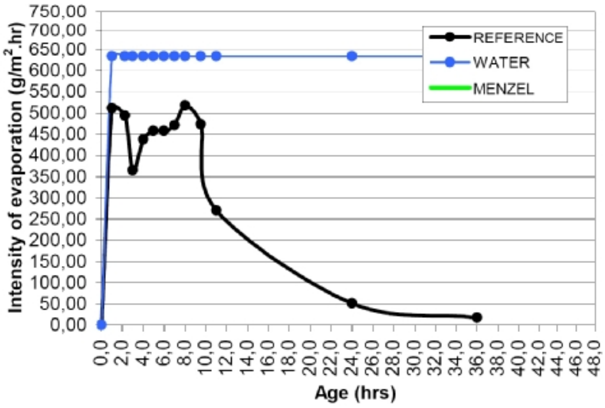

fig. 14: Intensity of evaporation at T=35 °C; RH=30 % and v_w=12 km/h

In figurs 13 and 14, there are shown runs of water loss at extremely severe boundary conditions. The predictions using Menzel´s model are far far away from reality especially when expose the samples to higher air circulation. Decrease of RH down to 30 % caused higher intensity of water evaporation (roughly +25 %) at 2nd hour (in comparison with fig. 11).

Conclusions

There in fig. 15, it can be seen the cumulative water loss from reference concrete (w/c=0,42) with predicted water loss according to Menzel´s model separately for most favourable (min) and most severe (max) boundary conditions. The Menzel´s model has got markedly limited validity and is suitable primary for mild environment (eg. T=20 °C; RH=70 %; v_W=12 km/h) but only in medium-terms.

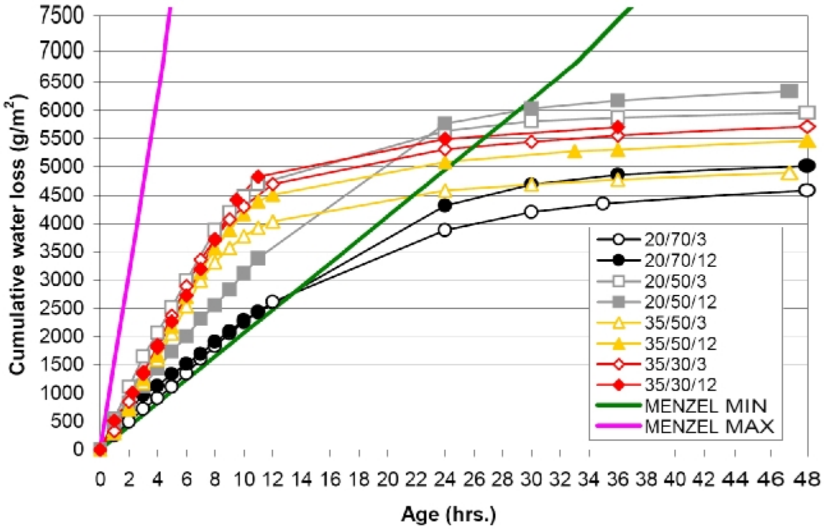

fig. 15: Cumulative water loss at different boundary conditions

Within severe boundary conditions the model merkedly overestimate loss of water what, on the other hand, is on the safety side. The differences in total amount of evaporated water are to be shown with respect to wind velocity, relative humidity and temperature. The total diference between the highest and lowest water loss was found around 100% – well readable at 9th hour of age. Up to this time the cumulative water loss seems to be almost linear. Later, slight deformations caused mailny due to residual moisture in concrete (creating potential to proceed in evaporation) and concrete structure (strongly influenced by hydration rate). The ratio of total cumulative water losses at various combinations of boundary conditions (at age higher than 9 hours) cannot be assumed to equal to that one at e.g. 9th hour. The cumulative water loss from concrete is quite good expressed by exponential function in format according to formula 6.

$$y = a \cdot \left(1 - e^{-b \cdot x}\right) \qquad (6)$$

where: y is overall water loss from concrete (g/m^2) and
x is age of concrete (hrs).

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