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DRYING OF LIGHTWEIGHT CONCRETE PRODUCED FROM CRUSHED EXPANDED CLAY AGGREGATES

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ABSTRACT

When crushed lightweight aggregates are used in lightweight aggregate concretes very small water amounts evaporate from the concrete even in a dry environment. It is shown that a large portion of the free batch water is absorbed into the pore structure of the crushed aggregates. The relative humidity in concrete pore structure diminishes faster than in normal weight aggregate comparison concretes. Lightweight aggregate concrete is drying internally and therefore the structure thickness has a minor effect on concrete drying times. The exceptional drying properties of lightweight concretes produced from crushed aggregates enables a fast execution of the floor covering works without time consuming drying operations.

Introduction

Lightweight aggregate concretes are naturally utilised in structures in which major part of the total load is caused by the dead weight of concrete. The most common lightweight aggregate type is produced from expanded clay. If only expanded clay aggregates are used fresh concrete properties are impaired and segregation problems are noticed. Reason for this is the lack of aggregate particles having a diameter below 1 mm. Part of the fresh concrete problems can be eliminated by using also normal weight fine aggregates but this decreases the obtainable strength density ratio. When the round expanded clay lightweight aggregates are crushed the whole continuous grading curve can be produced by mere lightweight aggregates and no normal weight aggregates are needed [1].

When lightweight aggregates are crushed the cracks propagate through the largest pores and this homogenizes the particles and increases the density of the crushed product. Even though the strength of the crushed aggregates is higher compared to uncrushed round lightweight aggregates the water and the binder amounts in concrete have to be increased. The crushing expenses are compensated by the density increase. The cost of the lightweight aggregates is relative to density and thus crushed aggregates have about the same price as normal rounded lightweight aggregates at the same density level.

A potentially interesting application for crushed lightweight concrete is a composite structure in which corrugated steel plate functions both as a form and tension reinforcement. Lightweight aggregate concrete is cast on the corrugated steel plate and concrete carries the compression stresses of the cross section. The functional problem in this kind of a structure is the long drying time because concrete dries only in one direction and the needed drying time is four times compared to a similar slab which can dry into two directions. Similarly, there exists no data how fast lightweight concrete produced by crushed lightweight aggregate actually dries.

Research Significance

Even with the contemporary rather slow building speed the slow drying rate of concrete floors governs the obtainable building time in Nordic countries during wintertime. When building speed is enhanced the situation becomes even more critical because the floor covering works cannot be started before the relative humidity in concrete pore system has decreased to 80-90 % depending on the floor cover type. With normal concrete types this can take at least 6 weeks or even longer than 6 months depending on the drying environment. When crushed lightweight aggregate concrete is used in composite floors the drying rate of the floor becomes a decisive factor which is on the critical path of the building process.

Materials and Test Methods

In the research project drying of three lightweight aggregate concretes and two comparison concretes which were produced by normal aggregates were studied. The main goal in the research project was to compare the drying rate and feasibility of lightweight and normal aggregate concretes in slab constructions. The composition of the test concretes was intentionally selected versatile so that a broad drying rate spectrum could be analysed. The composition and main fresh and hardened concrete properties of the test concretes are presented in Table 1. All test concretes were designed to be pumpable and the lightweight aggregate concretes (LWAC) were aimed to have a density of 1500 kg/m^3. Test concretes LWAC1 and LWAC3 possessed condensed silica fume 10% of the cement amount and their 28 day compressive strength values were 39.3 and 35.1 MPa in the average measured by 100-mm cubes. In test concrete LWAC2 the additional binder was fly ash and in addition to crushed lightweight aggregates one fourth of the aggregate amount comprised of normal weight aggregates #0...8 mm. It had a compressive strength of 19.5 MPa. Water reducing agents were used in the production of LWA concretes in order to decrease the batch water amount and thus to increase the drying rate of the concretes. Additionally, air-entraining agent was applied in test concrete LWAC3 to improve the permeability and in LWAC2 an additive based on methyl hydroxdiethyl cellulose was applied. This admixture improves the consistency and pumpability properties of fresh concrete and increases air content of the concrete.

The two comparison concretes had compressive strength values around 30 MPa. Test concrete NC4 was normal basic concrete in which normal weight granite aggregates were used and no admixtures were applied. The latter comparison concrete NC5 had a large entrained air content of 8 % and subsequently, larger cement amount and smaller water binder ratio.

In order to avoid producing mere labconcretes where especially the properties of lightweight concretes differ markedly from those produced by large mixers in practice the test concretes were produced in a ready-mix concrete plant. The lightweight concretes were produced in a 2 m^3 paddle mixer and the comparison concretes in a rotating drum mixer

TABLE 1
Composition and Properties of the Test Concretes

Test concrete	LWAC1	LWAC2	LWAC3	NC4	NC5
Cement content [kg/m³]	400	400	450	243	324
Silica fume content [kg/m³]	40	-	45	-	-
Fly ash content [kg/m³]	-	100	-	73	-
LWA # 0-3 mm					
volume %	65	75	50	-	-
[kg/m³]	333	370	286	-	-
LWA # 3-7 mm					
volume %	35	-	40	-	-
[kg/m³]	117	-	126	-	-
NWA # 0-8 mm					
volume %	-	25	-	55	65
[kg/m³]	-	370	-	1063	1159
NWA # 8-16 mm					
volume %	-	-	-	45	35
[kg/m³]	-	-	-	879	527
Water amount [kg/m³]	250	260	255	217	188
Superplasticizer [kg/m³]	8	8	8	-	-
Air-entraining agent [kg/m³]	-	-	0.09	-	0.58
Neptun [kg/m³]*	-	0.2	-	-	-
Water binder ratio	0.50	0.60	0.45	0.82	0.58
Slump [mm]	160	200	190	120	160
Air content [%]					
-before pumping	9	21	16	0.7	8
-after pumping	8	20	10	0.5	8
Density [kg/m³]	1558	1517	1503	2330	2107
Compressive strength 28d [MPa]	39.3	19.5	35.1	28.9	32.2

* An additive having a chemical composition of methyl hydroxdiethyl cellulose.

having a 5 m^3 batch volume. After the mixing the test concretes were placed into a truck mixer and pumped into the moulds. Slump, air content, and densities of the test concretes were measured before and after pumping during a time interval of 15 minutes after the mixing. The drying test samples were concreted into buckets having an average diameter of 200 mm and they could dry only into one direction. Eight 150 mm high and eight 200 mm high buckets were cast. Concrete was compacted by rod vibrators and the evaporation surface was levelled with a screed. The test specimens were covered with plastic sheets at the age of 2 hours. At the age of 2 days the specimens were transferred into a climate room having a temperature of 20°C and a relative humidity of 45%.

The relative humidity of concrete pore system was measured from two series of four test specimens having a height of 150 and 200 mm, respectively. The RH measuring device was HMP 36 by Vaisala and it was measured from a 20 mm diameter hole drilled into the concrete from the concrete surface, Figure 1. The depth of the hole was 40% of the sample thickness. Measuring time was 8 hours and the first measurement was performed at the age of two weeks. Thereafter measurements took place every two weeks in the beginning and later every four weeks until the age of the test samples was 126 days.

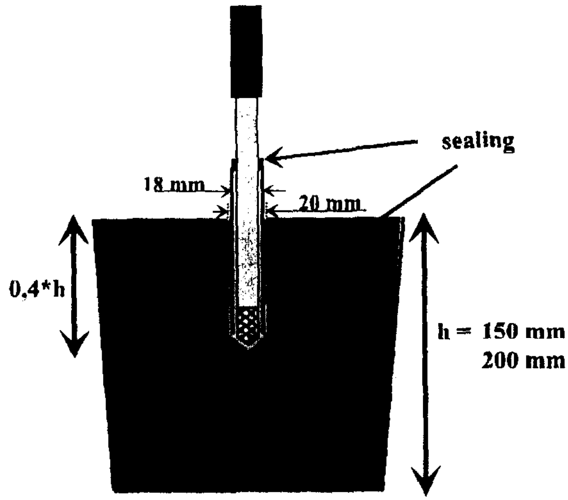

FIG. 1.
Relative humidity measuring method of the drying test specimens.

In order to measure the water amount evaporating from the test specimens a similar series of test specimens was weighed. The first weighing took place after the casting when the surface of concrete was levelled and the edges around the plastic tube mould were cleaned from concrete spatters. The second weighing was done at the age of two days, thereafter daily for a week and then once a week and finally once a month. After 126 days the test specimens were broken and concrete samples were taken from the middle part of the specimen in order to calculate the moisture content of concrete on weight basis from dried concrete samples at 105°C. Hence, the free water amount in concrete could be measured and

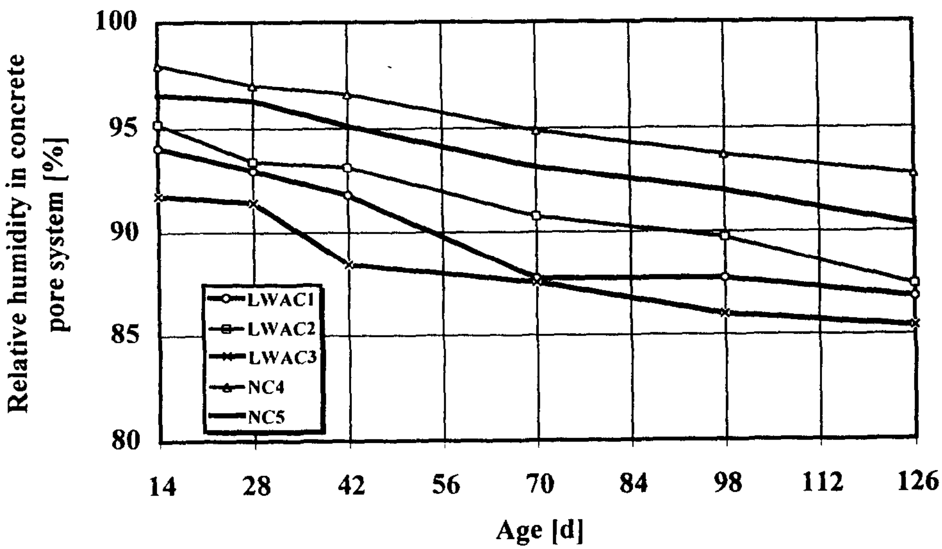

FIG. 2.
Relative humidity in concrete pore system of the 200 mm thick test specimens drying in one direction at 20°C temperature and RH 45%.

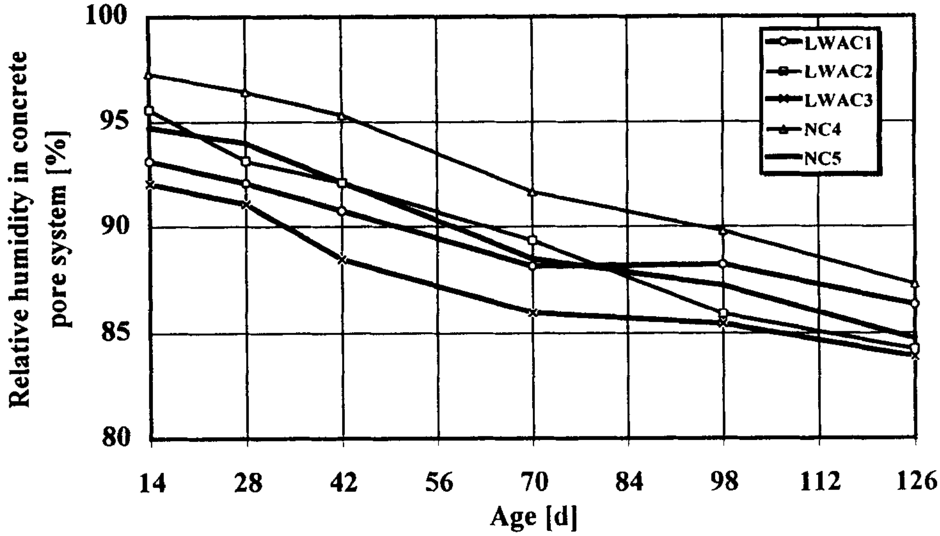

FIG. 3.
Relative humidity in concrete pore system of the 150 mm thick test specimens drying in one direction at 20°C temperature and RH 45 %.

after heating the samples to 550°C temperature the chemically bound water amount and hydration degree could be estimated.

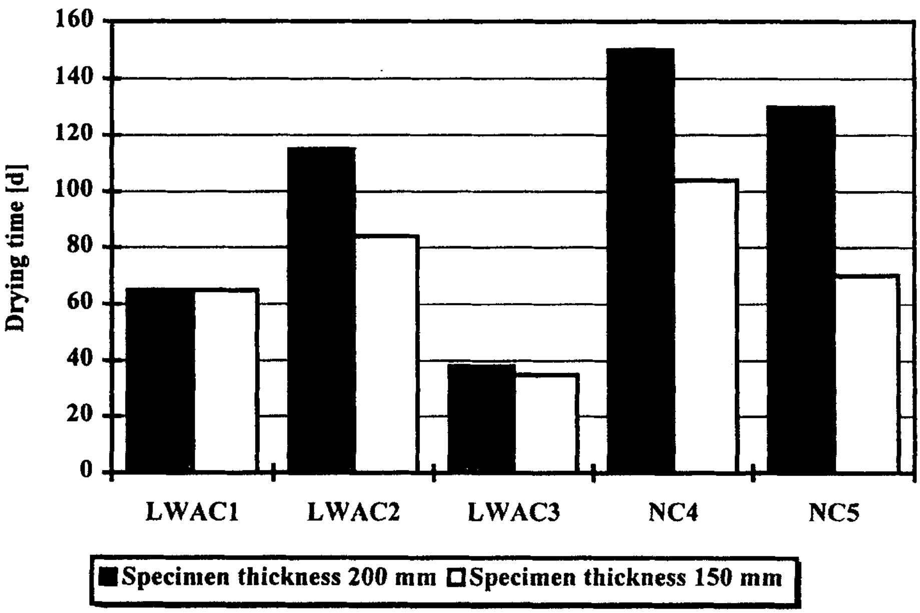

FIG. 4.
The drying times of the test specimens to the relative humidity of 90% when drying could take place only in one direction. Drying environment was 20°C temperature and 45% relative humidity in air.

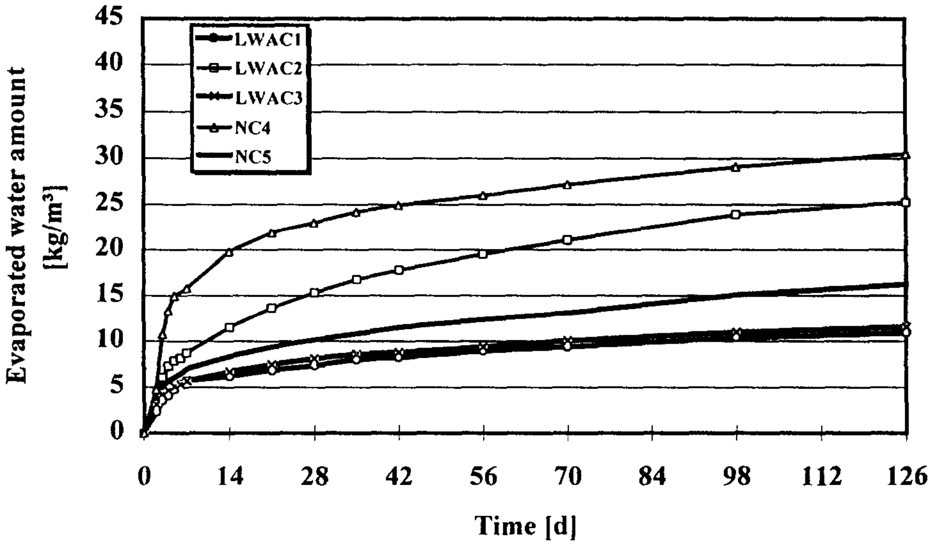

FIG. 5.
Evaporated water amounts of the 200 mm thick test specimens drying in one direction at 20°C temperature and 45% relative humidity in air.

Test Results

The results of the relative humidity measurements of the two types of test specimens are presented in Figures 2 and 3. The drying times to 90% relative humidity in concrete pore system is shown in Figure 4. The evaporated water amounts are presented in Figures 5 and 6.

In the relative humidity measurements of the concrete pore system the deviation of the test results was quite small. Every relative humidity result presented in Figures 2 and 3 is an average of 8 results measured from 8 different test specimens. The average of the standard deviations of all measurements in the 150 mm high specimens was 1.2 RH-percent units and 1.0 percent units in the 200 mm high test specimens.

Discussion

LWA concretes dried to 90% relative humidity in the concrete pore system remarkably faster than the normal aggregate comparison concretes. The air-entrained test concrete LWAC3 obtained 90% relative humidity value in concrete in 35 days and 85% relative humidity in 55 days when the specimen thickness was 150 mm. The air-entrained normal aggregate test concrete NC5 obtained the respective relative humidities in concrete in 55 and 100 days. The drying times for the normal unair-entrained test concretes NC4 exceeded the before-mentioned drying times markedly.

The difference between the drying times of LWA concretes and normal aggregate concretes increased with the specimen thickness. The drying times to relative humidity of 90%

in concrete of test concretes LWAC1 and LWAC3 where condensed silica fume was used were about the same for 150 mm and 200 mm thick specimens. The situation was quite opposite for normal aggregate concretes in which the larger thickness increased the drying times by 50 to 100 percent.

Drying of the unair-entrained test concrete LWCA1 measured by the relative humidity values in concrete pore system was slowed down at the age of 70 days while in all other test concretes the relative humidity values decreased also at later ages.

The evaporated water amounts of the LWA concretes were remarkably smaller compared to normal aggregate concretes. The water binder ratio of test concrete NC4 was higher compared to the other concretes and hence it also had the largest evaporation values. The water evaporation of test concretes LWAC1 and LWAC3 took mostly place during the first two week when the capillary pore system was still continuous. Thereafter evaporation slowed down.

The relative humidity values in the concrete pore system of lightweight test concretes LWAC1 and LWAC3 were very low even though the evaporation amounts were also very small. This can only be explained by self-desiccation in the binder paste or by water absorption into the crushed lightweight aggregates. Self-desiccation is caused by hydration reactions of the binders and these lightweight concretes were also produced with a larger binder amount than the normal aggregate comparison concretes. In order to find out the drying mechanism of the crushed lightweight aggregate concretes the samples taken from the middle parts of the test specimens were weighed in ambient temperature and after they were dried at 105 and 550°C temperatures. Due to the density differences of the test concretes the moisture content is presented as water amount per cubic meter concrete. The relative humidity amounts in lightweight concretes were remarkably smaller than in the comparison concretes. However, the free water amount of the LWA concretes was about 100 kg/m^3 larger than in the normal aggregate concrete NC4. This difference was caused by the free water

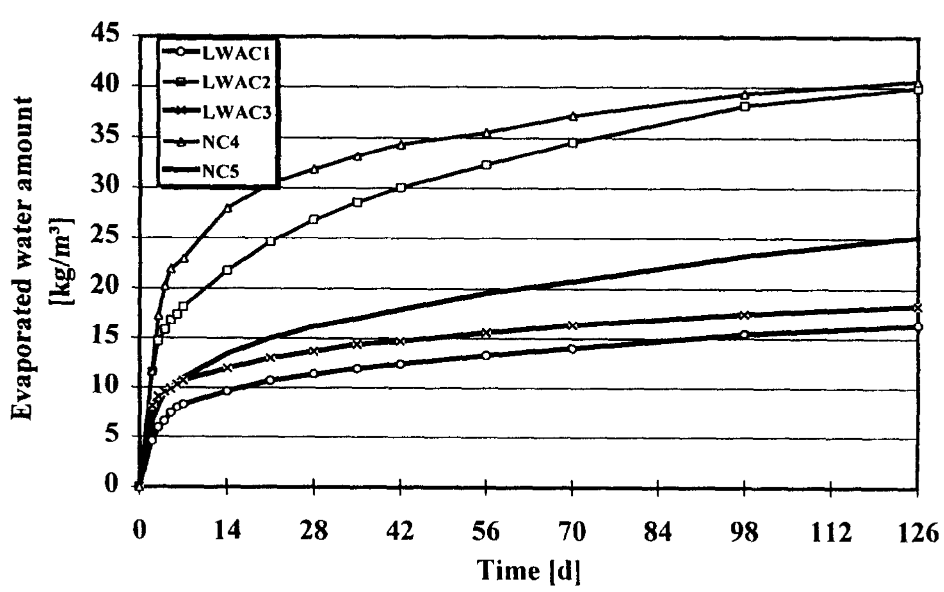

FIG. 6.

Evaporated water amounts of the 150 mm thick test specimens at 20°C temperature and 45% relative humidity in air.

absorbed into the lightweight aggregates. In normal indoor environment this absorbed water amount does not cause any harm to floor coverings but it will of course evaporate at 105°C.

Chemically bound water amount was calculated by weighing the samples at 550°C temperature. The distribution of water into the different concrete phases was then calculated by using data of the free water amounts and relative humidity of concrete. The calculation equations are presented in the following and it must by emphasized that they are of an approximate nature due to the inaccuracies in the desorption information of the binder paste of lightweight aggregate concretes.

The chemically bound water amount m_{cb} of concrete specimens in kg/m^3 *concrete* was calculated from equation

$$m_{cb} = \frac{w_{T105-550}}{m_{con105}} \cdot \rho_{con105} \tag{1}$$

in which $w_{T105-550}$ is the weight loss of concrete in the temperature range between 105 and 550°C. The dry weight of concrete at 105°C is represented by m_{con105} and ρ_{con105} denotes the subsequent dry density of concrete. Free water amount m_f of concrete in kg/m^3 concrete is obtained from equation

$$m_f = \frac{w_{T20-105}}{m_{con105}} \cdot \rho_{con105} \tag{2}$$

in which $w_{T20-105}$ is the weight loss of concrete in the temperature range between 20°C and 105°C. The gel and absorbed water amount m_{ga} in concrete where normal weight aggregates have been used can be calculated from equation (3)

$$m_{ga} = T(RH, m_w/m_b, \alpha) \cdot m_b \tag{3}$$

in which the desorption isotherm factor T being a function of ambient relative humidity RH, water cement ratio m_w/m_b, and degree of hydration α can be obtained from Figure 7. This equation will also be used to calculate approximately the gel and absorbed water amounts in the binder paste of concretes in which crushed lightweight aggregates were used. Then the relative humidity in concrete pore system measured from the holes drilled into the concrete specimens will be used as the relative humidity value. The weight of binder in kg/m^3 *concrete* is presented by m_b and weight of batch water in kg/m^3 *concrete* is denoted by m_w. In the calculations condensed silica fume (CFS) amounts and the fly ash (FA) amounts were multiplied with their subsequent efficiency coefficients when the total binder amount m_b was determined. The efficiency coefficient of CSF was taken as 2.5 and FA had a value of 0.3. These additional binders have also an effect on the isotherms of Figure 7 but this has not been taken into consideration.

The approximate water amount m_{LWA} absorbed into the crushed lightweight aggregates was calculated by equation (4)

$$m_{LWA} \cong m_f - m_{ga} \tag{4}$$

and the evaporated water amount m_e is obtained from equation

$$m_e = m_w - m_{cb} - m_f \tag{5}$$

The results of the calculations are presented in Table 2 and Figure 10.

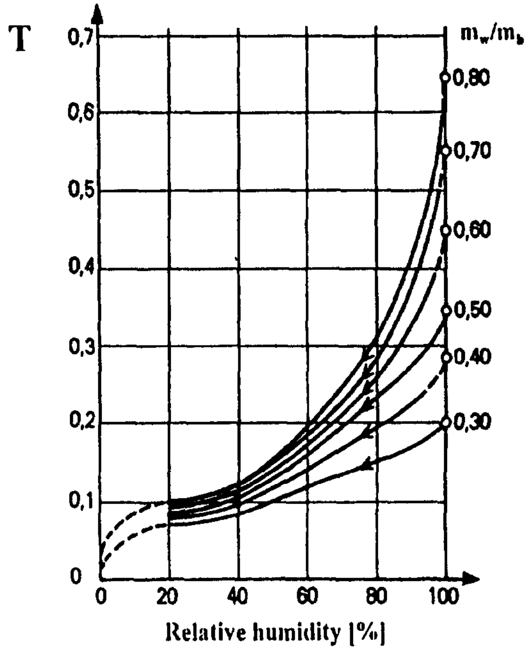

FIG. 7.
Desorption isotherms of concrete in which normal weight aggregates have been applied [2]. The hydration degrees α were 0.5, 0.6, and 0.8 for water binder ratios m_w/m_b 0.3, 0.4, and 0.5-0.9, respectively.

The results show that in the LWA concretes about one third of the free water amount is absorbed into the lightweight aggregates. Also the evaporated water amount of the LWA concretes is very small compared to the normal aggregate comparison concretes. Drying of the LWA concretes takes place inside the concrete when capillary water is absorbed into a large volume of porous aggregates and also a self-desiccation due to the larger binder amounts in the LWA concretes is responsible for a portion of the phenomenon. At 85% relative humidity of the pore system of LWAC3 the free water amount was rather large (195 kg/m^3 concrete) of which about half was in the crushed aggregates. The hydration degrees of the LWA concretes were low and therefore the self-desiccation of the hydration process

TABLE 2
The Distribution of the Batch Water Amount in Different Concrete Phases in the Test Concretes at the Age of 126 Days

Water content [kg/m^3]	LWAC1	LWAC2	LWAC3	NC4	NC5
Total batch water	250	260	255	217	188
Chemically bound water	52	58	55	40	51
Physically bound water	194	195	195	122	123
Absorbed water in the aggregates	64	66	66	-	-
Evaporated water	4	7	5	55	14

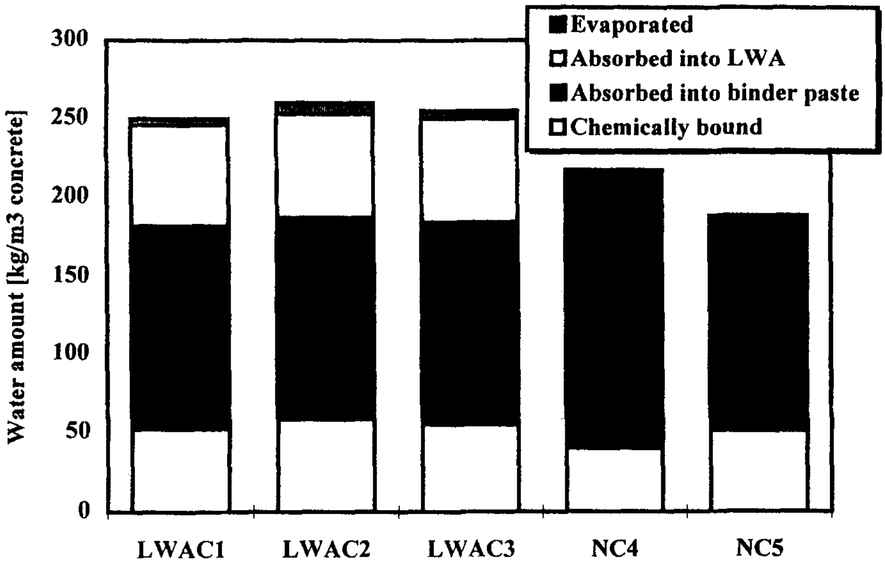

FIG. 8.
The distribution of water in the different concrete phases of the test concretes at the age of 126 days.

plays a minor role in the drying process. Because the drying of LWA concretes takes place inside the concrete the thickness of the test concretes had a much smaller effect on the drying time compared to normal aggregate comparison concretes.

The permeability of the LWA concretes was smaller compared to the comparison concretes due to the smaller water binder ratio and to the use of additional binders as CSF and FA. The denser transition zone between the binder paste and crushed aggregates could also decrease the permeability of LWA concretes. The use of air-entraining admixtures had a small effect on the evaporated water amount. As a matter of fact it diminished the evaporated water amounts in both concrete types.

The very small evaporated water amounts of the LWA concretes produced from crushed lightweight aggregates gives an advantage to these concrete types compared no normal weight concretes. Impermeable floor coverings can be detached on the concrete surface at a much earlier stage and the risk of unbonding of the covering due to the pressure caused by the evaporating water is eliminated. However, the large dormant free water amount in the porous aggregates of the LWA concretes can be a potential longterm risk if for example temperature gradients drive this absorbed water towards the impermeable floor cover.

Conclusions

1. When crushed light weight aggregates are used in LWA concretes very small water amounts are evaporated from the concrete. This enables a fast execution of the floor covering works without time consuming drying operations.
2. Large portion of the batch water is absorbed into the pore structure of the crushed lightweight aggregates. Despite of this the relative humidity in concrete pore system is diminishing faster than in normal weight aggregate comparison concretes.

3. Crushed LWA concrete is drying internally and therefore the structure thickness has a minor effect on concrete drying times. In normal concretes the drying times increase squared in relation to the structure thickness.

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