Curing of High Strength Concrete Using Lightweight Aggregates

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ABSTRACT

A technical solution for the still existing problem of curing high strength concrete is proposed. The new method uses a blend of aggregates containing lightweight aggregates. The prewetted grains become a water supply at the disposal of the hardening and drying cement paste, allowing a continuous hydration which leads to improved properties of the concrete.

KEYWORDS

high strength concrete, light weight high strength concrete, concrete aggregates

1. Introduction

An essential way to achieve the designed properties of concrete is avoiding water evaporation at the surface and supplying water from the exterior. If enough water were at the disposal of the cement paste for hydration to proceed, the concrete would achieve excellent properties. The traditional ways of curing often failed in practice. Even when meticulously performed only water evaporation can be reduced, but the water supply on the surface of vertical structural elements is still a technical problem. The time allocated for curing is a stagnation of building time increasing costs and efforts. The efficiency of modern technology like climb and slip forming is perturbed and the risk of damages caused by improper curing is still not eliminated. In case of high strength concrete (HSC) used commonly for vertical structural elements the problem increases. Due to a very low water cement ratio in combination with high cement content and the addition of silica fume the concrete shows a high compressive strength at early age, which makes an early form stripping possible.The high self-desiccation was the reason for using this concrete for self-desiccating slabs [1]. The very dense structure of high performance concrete might lead to the assumption that water evaporation is low and therefore water from the surrounding can penetrate only very slowly and not in a sufficient amount to achieve the interior of the member. So, curing can therefore be neglected. Saving the curing time would influence positively the construction costs. On the other hand when exposed to air water evaporation was observed [2] resulting in a considerable reduction of the compressive strength [3] and microcracks appear [4]. Own researches showed for HSC a failure of the traditional curing methods. Wet curing for a longer time- even submersing in water did not always influence positively the mechanical properties. Hence, the opinions and literature data about curing high strength are contradictory.

2. Theoretical Considerations

The main idea was to create in the concrete a water supply which is independent of the environment and which offers to the unhydrated cement water to continue hydration processes and to equalise the humidity content in cement paste during drying and hardening. Lightweight aggregates (LWA) generally can store a high amount of water. Their uniform distribution in the cement paste and a continuous transport of the water from the LWA to the cement paste transforms each grain of LWA to a water supply for the concrete surrounding it. The water transport in concrete is depending on the microstructure of the concrete and on the existent humidity gradient. As soon as hardening of concrete occurs, in the cement paste a system of pores develops. Silica fume concrete shows a refined pore structure with smaller radii than in normal concrete. The radii of these pores are smaller than the radii of the pores in the LWA, so that the requirement for water transport is the existence of a humidity gradient. During hardening and/or drying of concrete humidity gradients are distinguished on microscopical and macroscopical level. On microscopical level a shortage of water occurs due to chemical reactions. The capillary forces of the cement paste are high enough to absorb the water from the LWA grain and transport it to the „dryer“ cement paste where a reaction with the unhydrated cement takes place, forming $Ca(OH)_2$. After the reaction of $Ca(OH)_2$ with silica fume new hydration products of type calciumsilicate hydrate (C-S-H) are built, growing into the capillary pores, the available space, and into the micrcrocracks as well,

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making the structure of the cement paste more dense. As the C-S-H have a higher strength than $Ca(OH)_2$ has, the compressive strength increases. As the suction forces in the capillary pores are inversely proportional to the radius, the smaller the capillary pores of the cement paste get, the higher the suction forces in the smaller pores. Thus the difference in pressure (as the condition for water transport from the LWA to the cement paste) is given. This transport will stop when the relative humidity in the LWA and in the hardened cement paste are in equilibrium. This is a time depending transport of at the begin water and in the end vapour, with higher rate in the early age of concrete and lower at later age. On the macroscopical level the humidity gradient on the surface of a concrete member exposed to the environment is considered. The lower the relative humidity of the environment is, the steeper is the gradient between the surface layer and the more distant layer. Due to water evaporation the gradient increases and in the surface layer the moisture from the LWA will be transported to the cement paste faster than in the interior of the considered member. Because the water from the LWA is chemically bound, the structure on the surface is more dense, reducing the water evaporation and the diffusion process becomes slower. The surface of high strength silica fume concrete with a blend of aggregates being more dense than the traditional HSC, the exposure to dry environment at early age will not have a negative influence on its properties.

The task of the research was to transfer this idea into practice, developing a high strength concrete containing partly LWA which can be form stripped at early age and achieves improved properties without applying any curing.

3. Research Program

Material Properties and Optimisation Procedure

The optimisation was performed starting from a reference mix of high strength concrete containing : 450 kg/m³cement type CEM I 42.5 according to [6] , 30 kg dry mass of silica fume added as a slurry, 13,6 l/m³ superplasticizer (sulphonated naphthalene-formaldehyde condensate) and 1,75 l/m³ retarder. The normal weight aggregates (NWA) in amount of 1735 kg/m³ are dry rounded sand and gravel from the upper Rhine valley with a maximum size of 16 mm, separated in fraction as follows: 399kg/m³ fraction 0/2, 208kg/m³ fraction 2/4, 399kg/m³ fraction 4/8 and 729 kg fraction 8/16. The water/cement ratio was 0,33. The fresh density of this concrete was 2350 kg/m3 and the workability measured on the flow table ten minutes after mixing a10 >50 cm. The compressive strength Bc, 100, 28 =104 MPa was determined on 100 mm cubes at the age of concrete of 28 days. The cubes were cured according to DIN 1048 [7] which means 6 days submersed in water and 21 days at air by T= 20°±1C and 65% RH.

For the optimisation the cement and water content were kept constant while the normal weight aggregates were partly substituted by several types of expanded clay LWA, each replacing completely a certain fraction. As shown in Table 1 and Table 2 the LWA differed in grain size, strength, density, porosity and water absorption properties and hence moisture content.

Table 1: Properties of lightweight aggregates by sprinkling

Code	Grain Size [mm]	Dry Density [kg/m³]	Moisture [% by mass] after t/z hour of	
			Submersing*	sprinkling
A	0/2	1516	-	19,8
B	2/4	950	8,2	7,9
C	3/6	1300	11,1	16,3
D	4/8	930	11,8	12,5
E	4/8	1420	6,1	7,8

*declared by the producer

Table 2: Properties of lightweight aggregates wetted by submersing

Code	Grain Size [mm]	Dry Density [kg/m³]	Moisture [% by mass] after	
			t/z hour	24 hours
F	2/4	950	8,2	20,8
G	3/6	1300	-	11,6
H	4/8	930	11,1	18,3
I	4/8	930	11,1	16,5
J	4/8	1420	6,1	20,2

There are two main possibilities to introduce the LWA to the concrete mix: dry or wet. When introducing dry grains the water absorption of the LWA has to be known in advance and taken into consideration when calculating the water to be added. A disadvantage is, that the water absorption during mixing and hardening cannot be exactly determined. Additionally, the moisture absorption of LWA in fresh concrete differs considerably from the water absorption [8]. Considering that the water added suplimentarily to the mix is not absorbed by the LWA and can evaporate, the intended water reservoir cannot be achieved by this method.

Wetting can be done by submersing or by sprinkling for a given time. In this cases the moisture content can be determined in a simply way by drying, but one has no indication of the amount of water adhering on the surface of the LWA, which has to be considered by calculating the amount of water to be added. The water from the surface can be determined by the CM-Method commonly used to determine the moisture content of sand. As sprinkling the LWA for half an hour led to high scattering in the moisture content submersing for 24 hours was performed.

With the LWA shown in Tables 1 and 2 different concrete mixes were designed. Table 3 shows the type and the amount of the used normal weight aggregate and of LWA in % of the total volume of aggregates. 1 m^3 concrete contains 450 kg cement, 150 L water and 1,75 l retarder.

Table 3: Mix proportions per m^3 concrete

Mix	NWA		Aggregates Lightweight		Super-plasticizer	Silica Fume*
	[%] by	vol.	Type	Replaced Fraction	[l]	[kg]
I	75	25	A	sand	6,8	30
II	90	10	B	2/4	6,8	30
III	80	20	F	2/4	6,8	30
IV	90	10	C	3/6	6,8	30
V	80	20	G	3/6	6,8	30
VI	85	15	D	4/8	13,6	30
VII	85	15	J	4/8	13,6	30
VIII	85	15	E	4/8	13,6	30
IX	85	15	H	4/8	13,6	30
X	80	20	I	4/8	13,6	45

* dry mass of the slurry

The preliminary tests performed on 100 mm cubes cured in the folowing conditions: KK in air at temperatures T between 15°C and 25°C, relative humidity (RH) varying from 40% to 45%, KR in air at T=20°C, RH=65%, KL sealed in aluminum and polyamid foils and NK submersed in water for 6 days then in air T=20 °C, RH=65% showed for all mixes high compressive strengths.

Mix VII of the showed the best workability and a uniform distribution of the LWA in the cement paste. The LWA of type J has the advantage of a 115 MPa strength combined with a porosity of 50% and a water absorption of 20% of the dry mass when submersing. Figure 1 shows the pore size distribution [9].

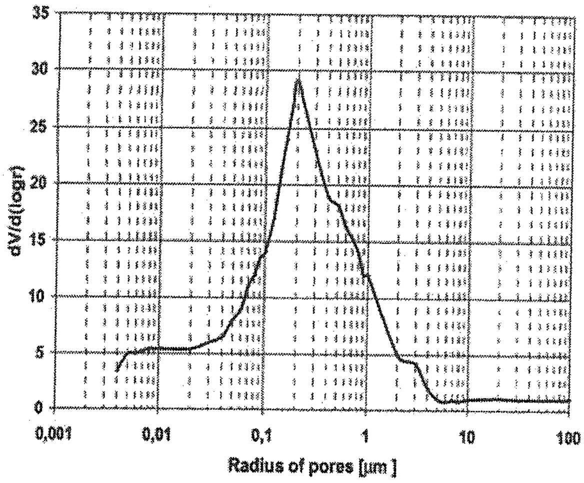

Fig. 1: Pore size distribution of lightweight aggregates type [9]

As by the reference HSC a relative high water evaporation was observed which should be covered as well by the water supply, the required amount of water to be stored in the LWA was of 47 l. It was necesary to replace completly the fraction 4/8 mm, which corresponds to 234 kg. The remaining aggregates are normal weight aggregates in amount of 1298 kg/m^3 separated in 471 kg/m^3 of fraction 0/2, 260kg/m^3 of fraction 2/4 and 567 kg of fraction 8/16. The amount of silica fume was increased to 45 kg dry mass /m^3. The dry density of the concrete is 2150 kg/m^3, the workability a10>50 cm and Bc,100,28 = 104 MPa.

Modelling the water transport in the cement paste

1. Water Transport within the Cement Paste

The results of the mercury intrusion are given as a differential distribution of the pore volume versus pore radius. Logarithmic scales are used. By plotting dV/d log r versus log r the area below the distribution curves correspond to pore volume. Using these curves the developed pore system of the cement paste can be defined by the equivalent pore radius [10] like shown in Equation:

$$r^2 eq = \left\{ \int_{r_{min}}^{r_{max}} \frac{dV}{d \log r} . r^2 . d \log r \right\} / \left\{ \int_{r_{min}}^{r_{max}} \frac{dV}{d \log r} . d \log r \right\} \quad (1)$$

The equation of the equivalent pore radius is relatively correct for concrete with pores of smaller radius [10]. Using the transport process in a single capillary pore of radius req the water transport of the pore system can be simplified modelled. Assuming a variation of the radii in the pore system with the tendency towards a greater number of pores with smaller radii, req is time depending req = f(t), being smaller with increasing age of concrete.When hardening of concrete starts the equivalent pore radius existing at early age of concrete can be considered the greatest equivalent pore radius req,max while at the age of concrete when all the water to be transported is used up, the smallest equivalent pore radius req,min dominates. In the meantime the number of pores is considered to be constant. At the beginning of hydration all capillary pores described by req,max are filled with water and due to the capillary pressure and the tension developed at the surface of the meniscus in the fluid a hydrostatic equilibrium is established. When hydration and/or desiccation occurs the pores become smaller achieving at a certain moment a pore radius req, t < req, max, and a difference in capillary pressure appears. At any time t the capillary pressure in the pores of radius $r_{eq,t}$ is given by: Water transport from lightweight aggregate to the cement paste for the concrete with lightweight aggregate an equivalent pore radius for the pore system of the LWA pores R eq,LWA can be described like in the equation (3) by adapting Eq.(1) and similar the capillary pressure PLWA in the pores R eq,LWA by Eq.(4). The number and size of the pores are constant in time.

$$R2eq,LWA = \left\{ \int_{R_{\min,LWA}}^{R_{\max,LWA}} \frac{dV}{d\log R}.R2.d\log R \right\} / \left\{ \int_{R_{\min,LWA}}^{R_{\max,LWA}} \frac{dV}{d\log R}.d\log R \right\} \quad (2)$$

$$P_{LWA} = \frac{2.\sigma.\cos\Theta}{R_{eq,LWA}} \quad (3)$$

To show the moisture transport from the LWA to the cement paste a model of two cylindrical pores in contact is used. The cement paste can be represented by a capillary pore of radius r eq(t) and the existing water supply of the considered lightweight aggregate by the equivalent pore radius $R_{eq,LWA}$. Figure 2 shows the different stages of water transport described in the following.

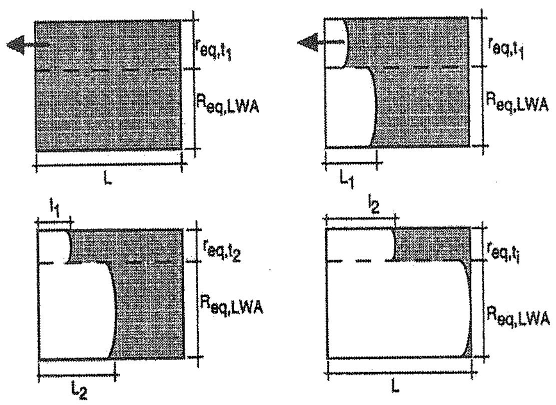

Fig. 2: Modelling the water transport from the LWA to the cement paste

When hydration proceeds, the smaller pore exerts suction forces in the greater pore $R_{eq,LWA}$ producing there a lower level of fluid, located at the distance L_1. The more the meniscus of the pore with radius $R_{eq,LWA}$ retreats, the higher is the capillary tension in the smaller pore. When this tension exceeds the friction forces in

$$m.(L_2 - L_1) = \frac{\sigma}{4\eta}.\left(\frac{1}{r_{eq(t)}} - \frac{1}{R_{eq,LWA}}\right).r^2{}_{eq(t)}.\pi.\rho_w \quad (4)$$

The smaller pores req(t), the meniscus change its position. The difference of the capillary pressures A P= PK(t) - PLWA makes the capillary transport on the distance L1 possible: a further transport of water is now possible only when the meniscus of the smaller pores shifts into position l1. The capillary transport for this distance:

When the meniscus of the greater pore is in position L, there is no pressure difference A P and the remained fluid in the smaller pore is used up either by capillary transport between pores of the cement paste (which can be described similarly) or by diffusion combined with condensation. Between the beginning until the end of hardening this difference is given by the Equation (5).

$$\Delta P = \frac{2.\sigma}{\left(\frac{1}{r_{eq,\min}} - \frac{1}{R_{eq,LWA}}\right)} - \frac{2.\sigma}{\left(\frac{1}{r_{eq,\max}} - \frac{1}{R_{eq,LWA}}\right)} \quad (5)$$

To make a simple calculation possible the assumption that the pores of the LWA and of the cement paste have the same length l which is known and the fluid water has a laminar flow through pores is necessary. As the length of the pores are not known with the aid of another modelling an idea of the distances on which the water has to be transported can be given, starting by the uniform distribution of the considered LWA of fraction 4 to 8 mm through the cement paste. In this modelling the volume of $1m^3$ concrete can be subdivided into a number n of identical spherical composite elements of radius RCE consisting of an aggregate of radius ra surrounded by a layer of cement paste having a constant thickness. In Figure 3 the modelling of the concrete using composite elements is given.

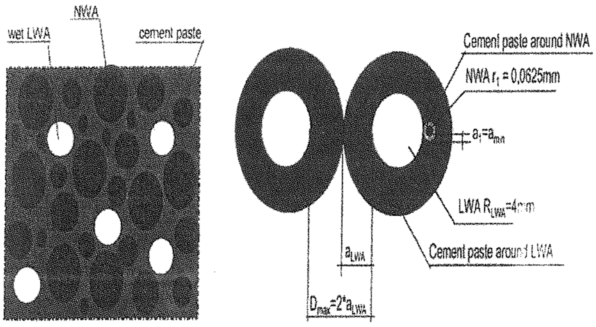

Fig. 3: Modelling of concrete and distances between the aggregates grains

For the total amount of the aggregate Z, the radius R_{CE} calculated from the following Equation (7) is given by the Equation (7):

$$\frac{1000}{n} = \frac{4}{3} R_{CE}^3 \qquad (6)$$

$$R_{CE} = \frac{10.r_a}{\frac{1}{3}.Z} \qquad (7)$$

In reality the total amount of aggregate contains grains of different fraction. Having a certain number i of fraction sizes of volume Bi according to Eq. (8) the radius Ri depending on Bi can be obtained. The difference of the radii Ri - ri gives the thickness of the layer ai which surrounds each grain of different size. The distance between two aggregates of the same size is two times the thickness of the layer. The calculation of the thickness of the surface layer and distances of grains of the same size are given in the following.

Table 4: Calculation of the thickness layer and distances between grains

Radius [mm]	Vol. Bi of	10/ (Bi) 1/3	Ri [mm]	ai [mm]	di [mm]
r_1= 0.0625	6.6	5.33	0.33	0.27	0.54
r_2= 0.125	26.4	3.36	0.42	0.29	0.59
r_3= 0.25	46.2	2.79	0.70	0.45	0.89
r_4= 0.5	6.6	5.33	2.67	2.17	4.33
r_5= 1.0	66,0	2.47	2.47	1.47	2.95
r_6= 2.0	92.4	2.21	4.42	2.42	4.85
r_7= 4.0	59.2	2.57	10.26	6.26	12.53
r_8= 4 LWA	165.0	1.82	7.29	3.29	6.59
R_9= 8.0	191.4	1.73	13.88	5.88	11,76

On the distance between two LWA grains other aggregate grain can be placed. Considering that every LWA grain is a water supply for the volume of cement paste surrounding it, the distance on which the water has to be transported can simplified be estimated by considering the limit states of maximum and minim transport distance. The longest distance D_{max} would be the most inconvenient case of transporting the water on the distance between two lightweight aggregates D_{max}= a_8. This would be the longest capillary pore, when assuming their linearity. The most detrimental situation for the concrete would be when a normal weight aggregate is positioned as near as possible to the LWA, being a barrier on the waters way through the cement paste. As the shortest way in this case is the thickness of the layer surrounding the smallest grain, this situation occurs when a aggregate of r_1 =0.0625 m is in the vicinity of a LWA grain. The thickness of the layer will determine the shortest length of a capillary pore being identical to the minimum length of D_{min}= a_1.

4. EXPERIMENTAL PROGRAM

On the concrete mix with lightweight aggregates macroscopical and microscopical investigations show the influence of autogenous curing and validity of the above shown modelling. On 100 mm cubes cured in different curing conditions the mass loss versus time was monitored and the compressive strength was determined. In Figure 4 the recorded mass change and the ratio of determined compressive strength to the characteristic compressive strength are shown.

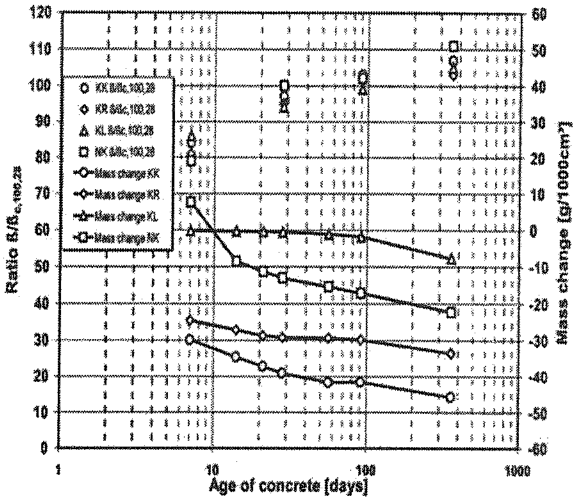

Fig. 4: Mass change and compressive strength of HSC with LWA

From fragments of the crushed cubes stored in the most unfavourable curing condition KK the physically bound water was eliminated by storage in an exsiccator.

Then they were crushed again and particles were picked out which contained only cement paste and sand, serving to determine the pore size distribution with mercury porosimetry shown in Figure 5.

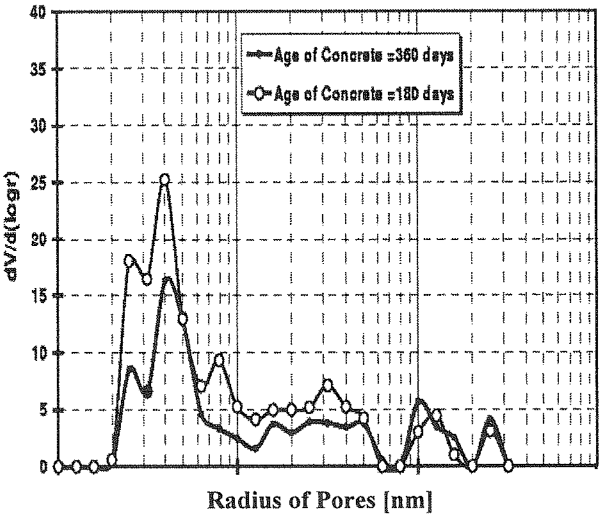

Fig. 5: Pore size distribution of concrete

The other part of the particle was hand milled and sieved through a sieve with a mesh size < 0.063 mm, obtaining samples rich in hydrated cement paste. The amount of chemically bound water and thus the degree of hydration was calculated on these samples like shown in Table 5.

Table 5: Calculation of the degree of hydration

Amount of water considered	Age of	
	180	360
Initial in concrete at t=0	150	150
Chemically bound when a=1	121	121
Total chemical bound determined by TG and DTA	82	100
Calculated degree of hydration a	0.67	0.82

The results of the simultaneously performed thermal gravimetry (TG) and differential analysis (DTA) are shown in Fig. 6.

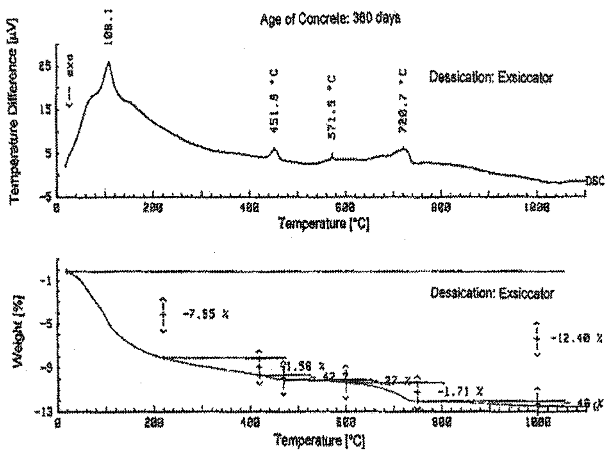

Fig. 6: simultaneously performed thermal gravimetry (TG) and differential thermal analysis (DTA)

On samples rich in hydrated cement paste X-ray diffraction was carried out. The obtained chemical composition at age of concrete 180 and 360 days are shown in Figure 7, for the reflecting angles of 9° to 23°.

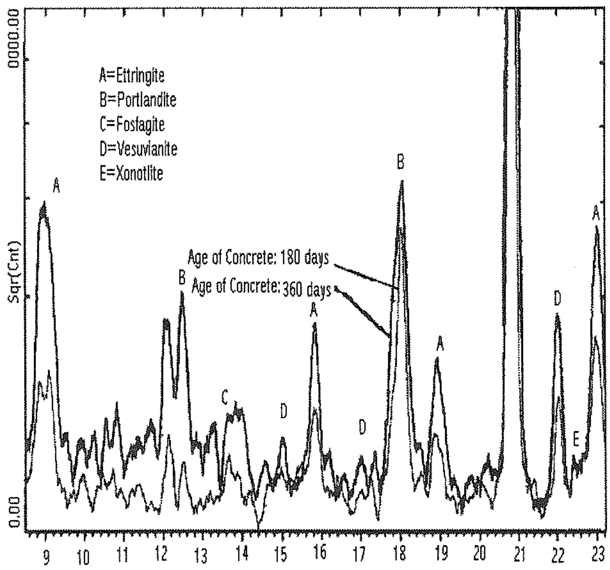

Fig. 7. X-ray diffraction, angles 9° to 23°, age of concrete 180 and 360 days.

5. Discussion

Regardless of the curing, a continuous increase in compressive strength with later age of concrete is recorded. The reason of increase in compressive strength independently of the environment lays in the more dense structure of the cement paste indicated by the porosity measurements, clearly showing a decrease of the total porosity with increasing age of concrete. Comparing the pore size distribution of the concrete at age 360 days with the age of 180 days a decrease of the number of pores with a great radius and an increase of the pores with smaller radius is observed (Fig.5). This refining of the pore system explains the decreasing porosity and leads to the presumption that water for hydration reaction was indeed available and chemically bound. The higher degree of hydration (Table 5)at later age of concrete confirms the chemical reaction of the supplementary water with unhydrated cement grains and by X-ray diffraction a higher amount of chemical compounds like calciumhydroxide and ettringite at the age of 360 days are detected (Fig.7). As $Ca(OH)_2$ results from the hydration of cement water had to be on the disposal of the cement grain. The X-ray diffraction shows also more C-S-H of the type afwillite at the age of 360 days, compared to the age of 180 days. The supplementary built C-S-H as well as the higher amount of Ca(OH)2 and ettringite are the result of supplementary hydration processes. These stays for the continuation of hydration processes from the age of 180 days to the age of 360 days. These aspects are confirming the theoretical assumption of ongoing hydration processes resulting in the predicted more dense structure at later age, due to the partial filling of the pores by additionally formed hydration products. The peak shifting in the curve of the pore size distribution into the direction of smaller pores stands for creating higher capillary pressure necessary for the water transport from LWA to the cement paste. From the mass loss of the cubes versus time a humidity gradient is shown. From the pore size distribution (Fig.5) and the mass loss (Fig.4) the transport conditions (increasing capillary pressure and existence of a humidity gradient) for the shown modelling are given. Compared to the conventional HSC containing only NWA the amount of chemically bound water is about 24 l per m^3 concrete higher [5] and represents only the half amount of the water stored initially by submersing in the selected lightweight aggregate. Hence this concrete has still a water supply at its disposal.

6. References

[1] Persson, B.S.M. Self-desiccating high-strength concrete slabs, In Proceedings Utilisation of High Strength Concrete, Symposium in Lillehammer, Norway, June 20-23, 1993, eds. I. Holland and E. Sellevold, pp 882889.

[2] Hammer, A.: The Maturation of Mechanical Properties of High Strength Concrete Exposed to Different Moisture Conditions. In: Proceedings Third International Symposium on Utilization of High-Strength Concrete, June 20-24, Lillehammer, Norway, 1993, eds. Ivar Holland and Erik Sellevold, Vol 2, pp 1084-1091.

[3] Weber, S. Reinhardt, H.W. Various curing methods applied to high- performance concrete with natural and blended aggregates. In Proceedings of Fourth International Symposium on the Utilisation of High Strength/High Performance concrete, Volume 3, Paris, May 29-3,1996, Editors F.de Larrard and R.Lacroix, pp 1295-1303.

[4] Guse,U. Dauerhaftigkeit von hochfestem Beton. DAfStb - Forschungs-kolloquium. Beitrage zum 32. Forschungskolloquium in Karlsruhe am 21.und 22.Marz 1996, pp 99-106.

[5] Weber, S. Nachbehandlungsunempfindlicher Hochleistungsbeton. Doctoral Dissertation, Stuttgart University, 1996.

[6] DIN EN 196 Teil 1," Zemente" (Ausgabe Marz 1990).

[7] DIN 1048, Prufverfahren fur Beton, Teil 5: Festbeton, gesondert hergestellte Probekorper. Ausgabe Juni 1991.

[8] Hennek, J. Liapor Franken, Private communication.

[9] Chelouah, A. Private communication.

[10] Reinhardt, H.W., Gaber, K.: Equivalent pore size characterising the pore size distribution of cement mortar. Ceramic Transactions, Vol. 16, ed.S.Mindess, Am.Ceram.Soc., Westerville 1991, pp 319-335.