PERMEABILITY, DIFFUSION, AND CAPILLARY ABSORPTION OF CONCRETE AT ELEVATED TEMPERATURE IN THE SERVICE RANGE

PERMEABILITÄT, DIFFUSION UND KAPILLARES SAUGEN VON BETON BEI MÄSSIG ERHÖHTEN BETRIEBSTEMPERATUREN

PERMEABILITE, DIFFUSION ET ABSORPTION CAPILLAIRE DU BETON SOUS TEMPERATURES MODEREMENT ELEVEES

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SUMMARY

Permeability, diffusion and capillary absorption represent the main mechanisms for water and water vapour transport in concrete. Up to present the relationship between temperature and the individual transport mechanisms is unclear. In the present work the influence of temperature was therefore examined at 20, 50 and 80 °C. The results show that an increase of temperature is always accompanied by an acceleration of the transport processes. For this purpose, concretes with different quantities of acrylate dispersion, high performance concretes with different types of cement and aggregates, and the French BPR were examined and compared with a reference concrete and among themselves.

ZUSAMMENFASSUNG

Die Permeabilität, die Diffusion, sowie das Kapillare Saugen stellen die hauptverantwortlichen Transportprozesse von Wasser bzw. Wasserdampf in Beton dar. Unklar ist hierbei noch der Zusammenhang zwischen der Temperatur und den einzelnen Transportmechanismen. In der vorliegenden Arbeit wurde deshalb der Einfluß der Temperatur bei 20, 50 und 80 °C untersucht. Die Ergebnisse zeigen, daß mit der Erhöhung der Temperatur immer auch eine Beschleunigung der Transportvorgänge einher geht. Dabei wurden Betone mit unterschiedlichen Mengen Acrylatdispersion, hochfeste Betone mit unterschiedlichen Zementarten und Zuschlägen, sowie der französische BPR untersucht und mit einem Nullbeton bzw. untereinander verglichen.

RESUME

La perméabilité, la diffusion et l´absorption capillaire représentent les principaux mécanismes de transport d´eau et de vapeur d éau dans le béton. Jusqu´ à présent, la relation entre la température et les differents mécanismes n´est pas encore déterminée. Dans l´etude présentée, l´influence de la température a été examinée à 20, 50 et 80 °C. Les résultats montrent qu´une augmentation de température est toujours accompagnée d´une acclélération des processes de transport. Les bétons éxaminées sont des bétons avec adjunction de différentes quantités de dispersion acrylate, des bétons à haute performance avec différents ciments et granulats, aussi que le BPR francais. Les résultats pour les differents bétons sont companés entre eux, aussi qu´avec un béton reference.

KEYWORDS: Permeability, diffusion, concrete, capillary absorption

1. INTRODUCTION

In the context of the BMBF Research project "hot water storage in high performance concrete tanks" the vapour behaviour of the concrete should be examined under simultaneous action of temperature and hydraulic pressure. The previous concept for the seasonal storage designated to line the concrete containers with an interior liner made of stainless steel with 0.50 mm thickness in order to prevent a moisture penetration of the thermal insulation. After the first storage tank in Rottweil was finished and the planning of the second one in Friedrichshafen was concluded, the following disadvantages of an interior liner made of stainless steel can be indicated: expensive and difficult to construct.

With a high performance concrete (HPC), higher values for the vapour diffusion resistance can be expected than for concrete with normal strength (normal concrete). Thus heat storages by HPC are conceivable without a stainless steel lining.

2. CONCRETE

The composition of the concretes investigated are shown in table 1.

Table 1: *Composition of the examined concrete*

Mixture	w/c ratio	Cement	Content [kg/m³]	Aggregate	Fly-ash [kg/m³]	Additive [kg/m³]
Mowi 45	0,45	CEM II 32, 5 A-L	330	AB 32	FA 30	Mowilith, 45
Mowi 30	0,45	CEM I 32, 5	330	AB 32	FA 30	Mowilith, 30
Ref.	0,45	CEM I 32, 5	330	AB 32	FA 40	-
35	0,33	CEM I 42,5	400	AB 16	-	MS, FM
36	0,33	CEM I 32,5	400	AB 16	-	MS, FM
37	0,33	CEM I 32,5 NW/HS	400	AB 16	-	MS, FM
40	0,37	CEM II 32,5 A-L	360	AB 32	FA 40	MS, FM
41	0,37	CEM II 32,5 A-L	360	AB 16	FA 40	MS, FM
BPR	0,17	Powder	900	-	Plastic.	-

MS: MICROSILICA, FM: SUPERPLASTICIZER

3. TESTING METHODS

3.1 Permeability

The permeability of the different concretes was tested with a special test cell made by the company Mess- and Feinwerktechnik Sommer (Schmidtheim), (see fig. 1).

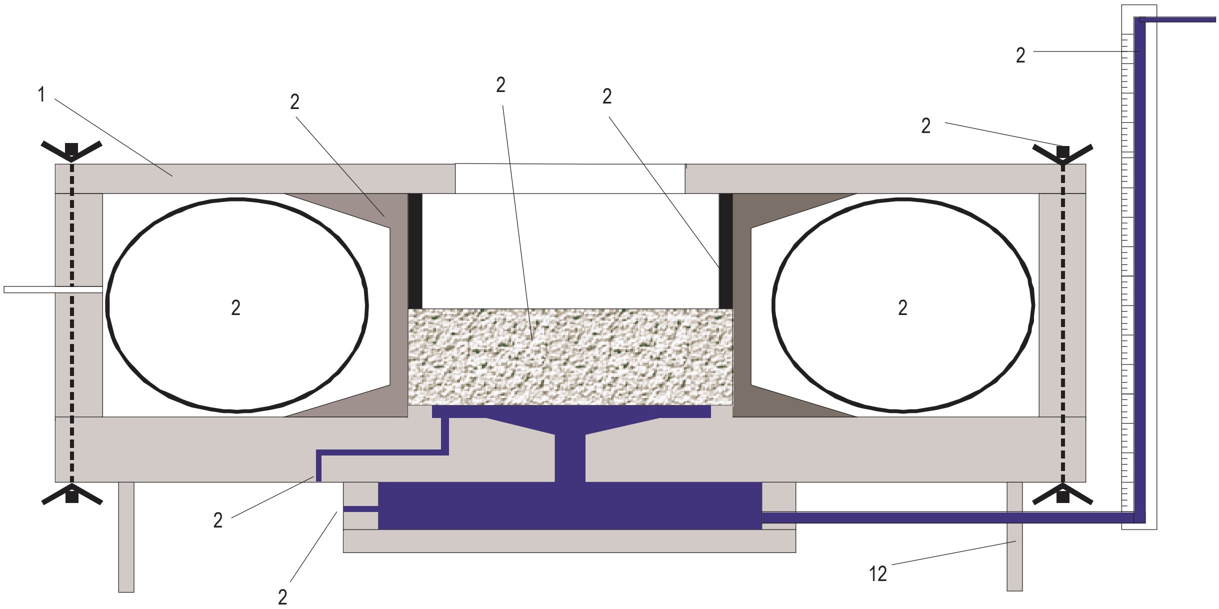

Fig. 1: *Testing cell for Permeability*

This permeability measuring system was modified at the institute of construction materials, so that it was possible to test concrete disks with a thickness of only 3 cm at a water pressure to 10 bar (100 m water column). The system consists of the test cell, the automatic controller unit, as well as the connecting devices (PU pressure hoses).

3.1.1 Specimens

The specimens were stored up to the test under water. The disks are three centimetres thick and have a diameter of 15 cm. Both flat sites were polished and coated on the lateral surfaces with epoxy resin (Sikafloor 370, Sika Chemie GmbH, Stuttgart).

3.2 Diffusion

The diffusion tests were performed according to the standardised procedures in DIN 52615. Both methods, the “dry-cup“ and the “wet-cup procedure” were examined, although the “wet-cup method” is the most important. To achieve the correct humidity, the salt solutions according to table 2 were used.

Table 2: *Salt solutions or drying agents*

	20 °C	50 °C	80 °C
0 -3 %	Silica gel	Phosphorpentoxide P_2O_5	Phosphorpentoxide P_2O_5
50 %	Natriumdicromate $Na_2Cr_2O_7 \cdot H_2O$	Natriumbromide NaBr	Natriumbromide NaBr
93 - 100 %	Amoniumdihydrogen-phosphate	Amoniumdihydro-Genphosphate	Amoniumdihydro-genphosphate

3.2.1 Specimens

In this work, specimens with a diameter of 10 cm and approx. 2 - 2.5 cm height were examined. Thinner specimens than the ones which are required by DIN, usually show larger diffusion coefficients, so that it can be assumed that the results, which were determined here, were considered to be on the safe side. When the specimens were installed, they were in moisture equilibrium.

3.3 Capillary absorption

Capillary absorption is dominant among the three mentioned transport mechanisms, because it causes the fastest transport of water. With the tests executed in this work, the uniaxial penetration behaviour by liquids, here water, into cylindrical concrete specimens was examined. Capillary absorption is described by the water absorption coefficient A. The basis of the procedure is DIN 52617: "Determination of the water absorption coefficient of building materials".

3.3.1 Specimens

The concrete specimens had a cylindrical form with a diameter of 15 cm and a height of approx. 12 cm. The CWA tests (capillary water absorption) were executed at three different temperatures, i. e. 20, 50 and 80°C.

First, the cylinders were dried at 60° C up to a constant weight. The temperature was intentionally limited at 60 °C in order to exclude a crystal change in the concrete structure. After attaining the constant weight the lateral surface of the specimens were coated with transparent epoxy resin (Sika floor 370, Sika Chemie GmbH, Stuttgart).

4. INTERPRETATION OF TEST RESULTS

4.1 Permeability

The analysis of the results takes place with the following formula:

$$k_w = \frac{V}{t} \cdot \frac{d}{A} \cdot \frac{1}{h_1 - h_2} \cdot \rho_w \cdot g \quad \text{[m/s]}$$

with

ρ_W = density of water, V = flow rate, d = thickness,
A = cross-section area, h_2-h_1 = pressure difference

4.2 Diffusion

In the stationary case, (constant concentration difference), Fick's first law applies:

$$\dot{m} = -D \cdot \frac{dc}{dx}$$

D is the diffusion coefficient, which is assumed constant over the regarded area. The concentration c (water vapour in air) is strongly influenced by temperature (see Table 3).

Table 3: *Saturation humidity content c_S [g/m³] and δ_L [kg/(mhPa)].*

T [°C[	c_S [g/m³]	δ_L [kg/(mhPa)]
0	4.84	6.58
20	17.3	7.07
50	83.0	7.64
80	293.3	8.21

A further characteristic is the resistance coefficient of water vapour diffusion µ. It is dimensionless and indicates the ratio of the vapour diffusion of an air layer and a layer of the considered material, both with the thickness of 1m thus $\mu = D_{air}/D_{mat}$. It is calculated as follows:

$$\mu = \frac{1}{d}(\delta_L \cdot A \cdot \frac{p_1 - p_2}{I} - s_L)$$

with:

p_1, p_2 water vapour partial pressures in [Pa]
I water vapour flow in [kg/h]
d medium thickness of the specimen in [m]

The diffusion transfer coefficient of water vapour of in air depends on both air pressure and temperature (see Table 2)

$$\delta_{\mathrm{L}} = \frac{0.083}{R_D \cdot T} \cdot \frac{p_0}{p} \cdot \left(\frac{T}{273} \right)^{1.81}$$

with:

R_D: gas constant of water vapour 462 Nm/(kg K)

T: temperature in [K]

p: medium air pressure: p_0: atmospheric pressure

4.3 Capillary absorption

The data are presented in diagrams, in which the abscissa (time) is given in a square-root-of-time scale. The dependence between the surface-related water absorption W and the square root of time t is approximately linear, so that the water absorption coefficient results from the gradient of the straight line.

$$A_t = \frac{\Delta W_t}{\Delta \sqrt{t}}$$

5. TESTING RESULTS

The following diagrams (fig. 2 and 3) describe the dependence of the permeability coefficient with on temperature. In fig. 4 and 5, the diffusion results are given. The capillary water absorption results are presented in fig. 6.

5.1 Permeability

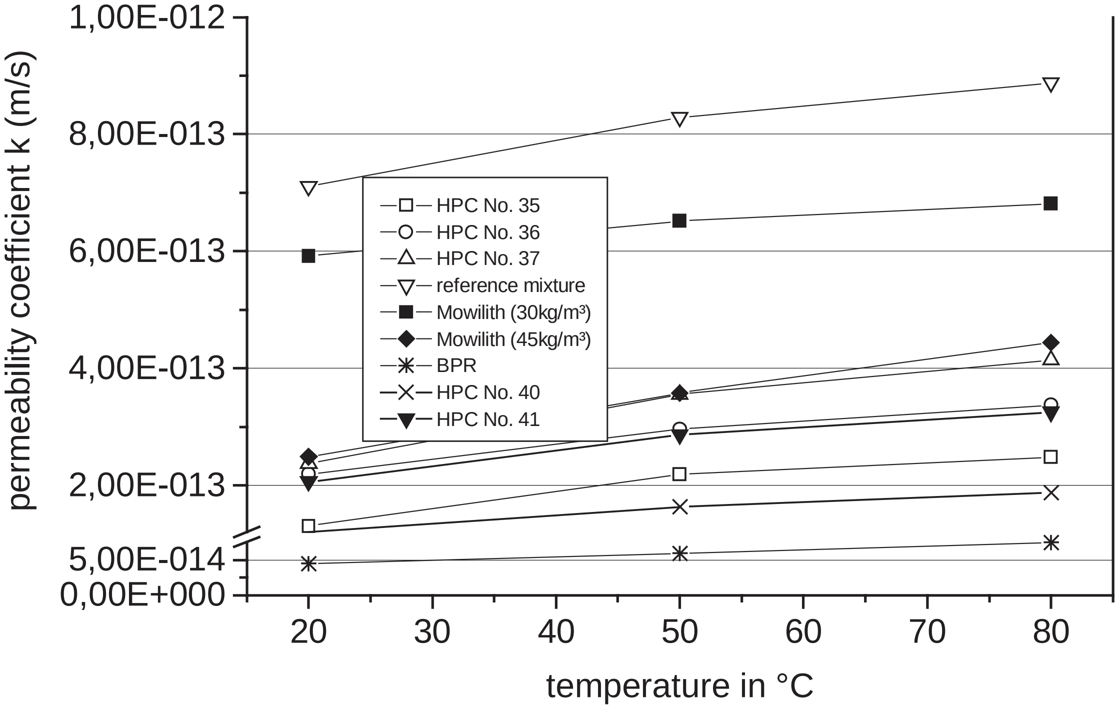

Fig. 2: *Permeability coefficient k [m/s] versus temperature (after one hour)*

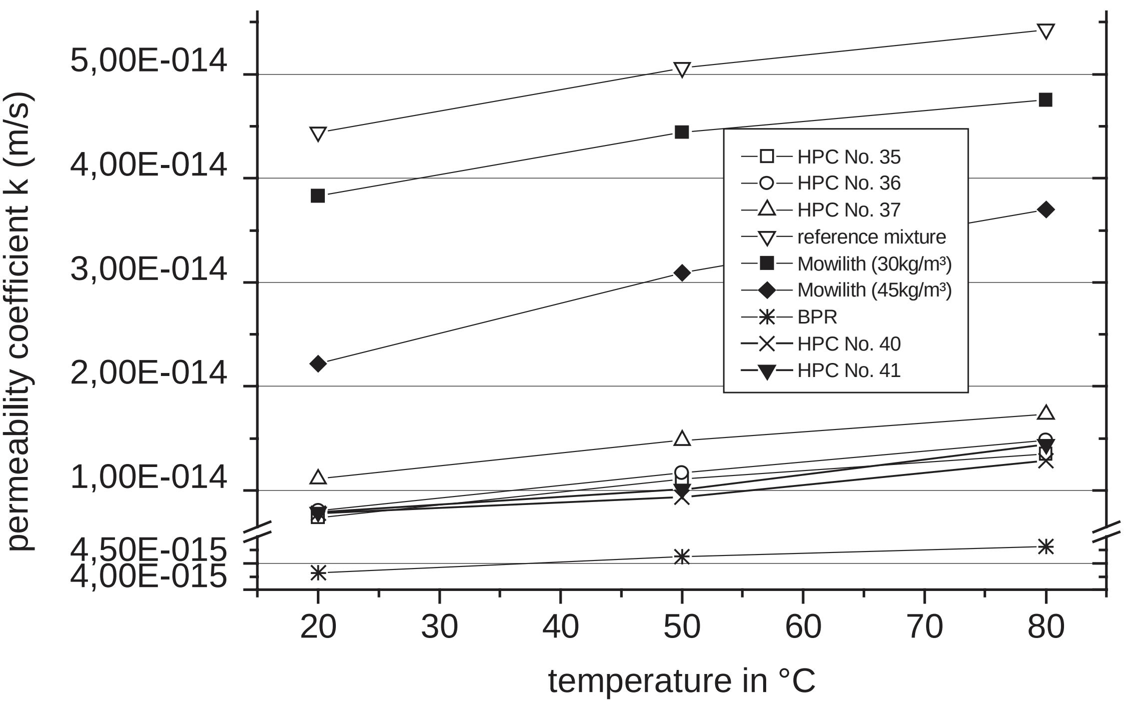

Fig 3: *Permeability coefficient k [m/s] versus temperature (after 48 hours)*

5.2 Diffusion

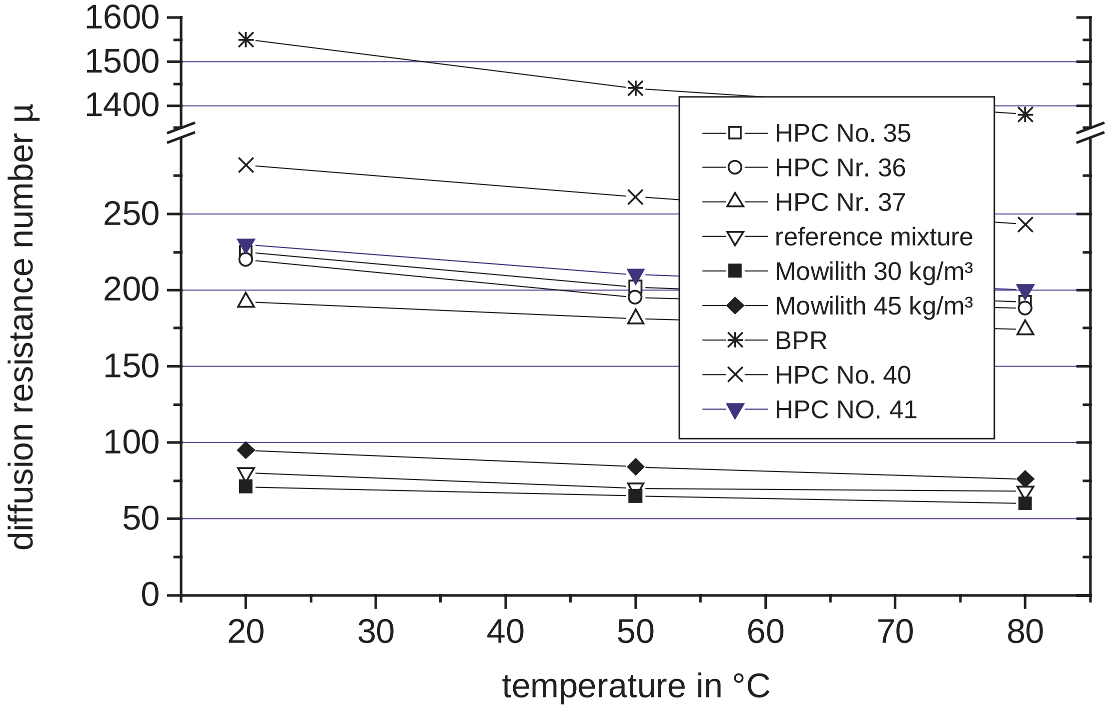

Fig. 4: *Dependence of the resistance number µ on temperature (50 - 93 % R.H)*

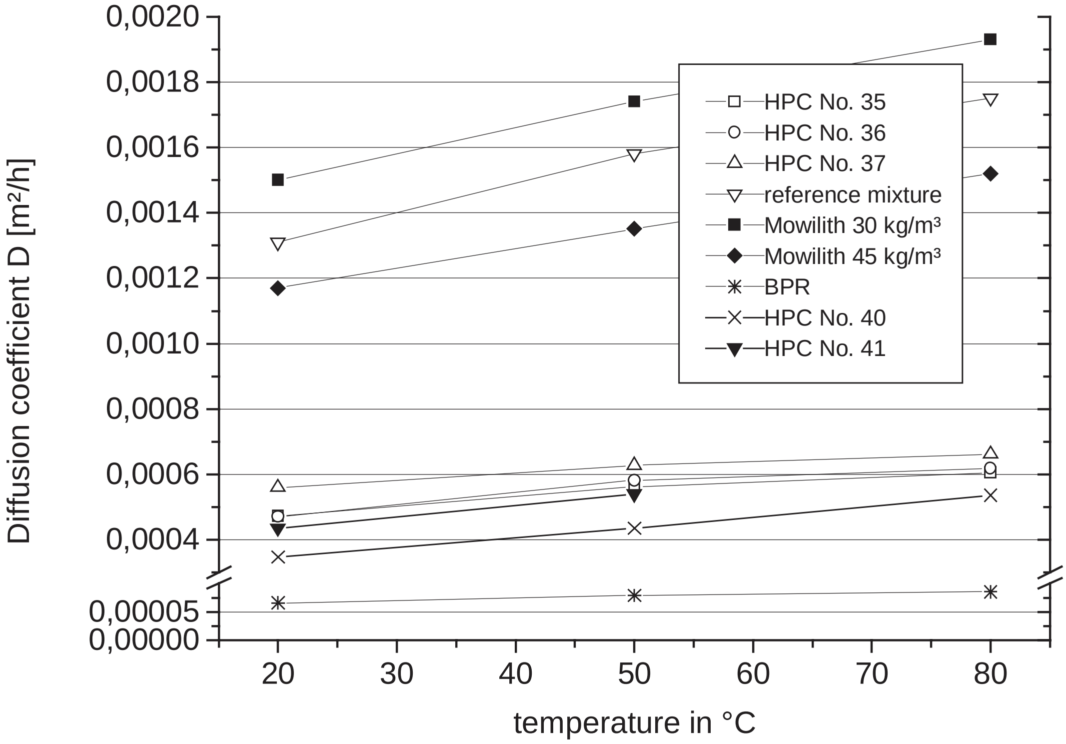

Fig. 5: *Dependence of the diffusion coefficient D on temperature (50 - 93 % R.H)*

5.3 Capillary water absorption

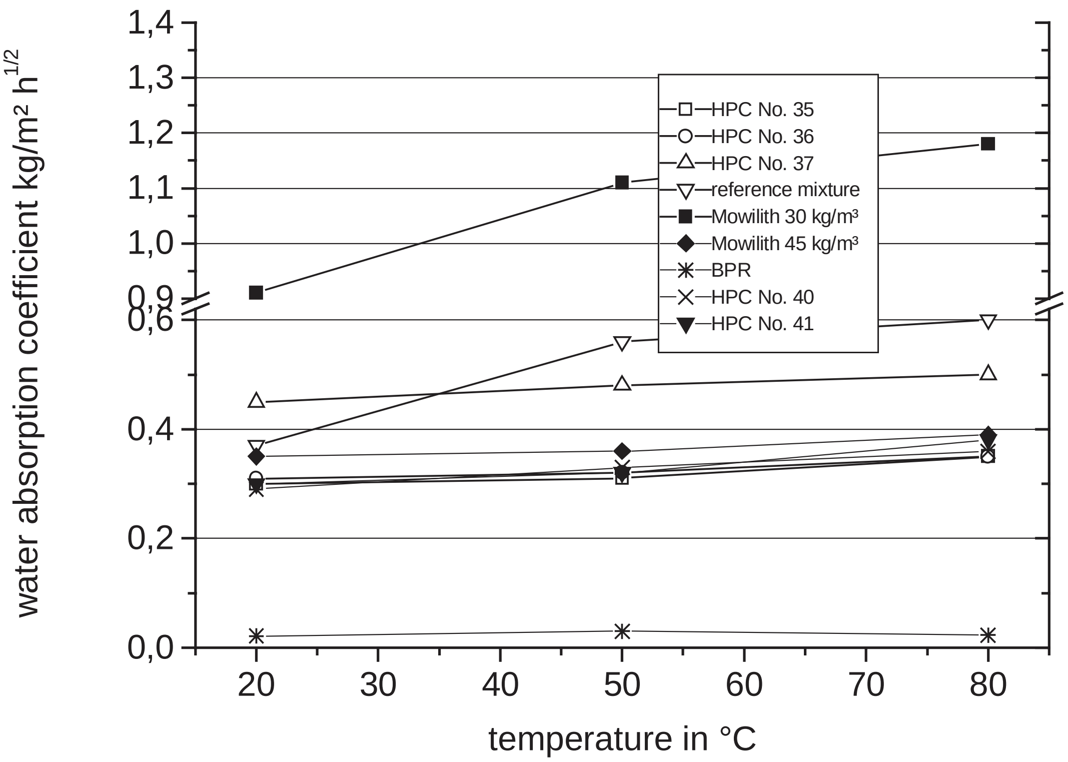

Fig. 6: *Dependency of the water absorption coefficient A from the temperature*

6. DISCUSSION OF RESULTS

6.1 Permeability

Fig. 2 clearly shows the increase of permeability with temperature. The increase amounts approx. 10 % between 20 and 50 °C and approx. 8 % between 50 and 80 °C. The effect of the Mowilith content on permeability can be clearly recognised. A higher content of Mowilith is related with a reduction of the permeability coefficient. The difference between normal concrete and high-performance concrete becomes again very clear.

The permeability behaviour changes with time. In figure 3, the permeability coefficient after 48 h was plotted. The permeability decreased to approx. a tenth of the values after one hour. They increase further approx. 10 to 20 % over the temperature range of 20 - 80 °C.

6.2 Diffusion

The most important concrete characteristic, apart from permeability, is diffusion. In fig. 4 the diffusion resistance numbers of the examined concretes are plotted together. Again the dependence of the transport processes on the temperature is shown. A reduction of the resistance number of approx. 10 - 20 % related to the temperature span of 20 - 80 °C can be read off clearly. For normal concrete, literature indicates values in the humid area procedure which are a third of those of the dry-cup procedures. According to DIN 4108, the values for the diffusion resistance number μ in the dry-cup-procedure are ranging between 70 - 150.

6.3 Capillary Absorption

Fig. 6 shows that the concrete specimen modified with 30 kg/m³ Mowilith has a very high absorption coefficient. The absorption coefficient is approx. 50 % higher than that of the normal concrete.

The values plotted, are the average values of three individual values. The high-performance concrete are situated with an A of 0,31 around approx. 11 % over the reference mixture.

Apart from the BPR, high-performance concretes are much less sensitive to temperature influences than e.g. the reference mixture or the 30 kg Mowilith mixture.

In contrast to the permeability or diffusion, the rise of the capillary absorption is almost linear with temperature.

7. CONCLUSION

The main conclusions are summarised as follows:

An increase of the transport processes with temperature increase is clearly shown. The different increase depends strongly on the kind of concrete.

- Concrete with Mowilith (30 kg/m³) is not suitable under the criterion of the increased strength and density with simultaneous price reduction. The physical properties differ only insignificantly from those of the reference mixture.

- However, concrete with Mowilith (45kg/m³) is suitable for the construction of heat storages under the criterion of increased strength and density at higher cost.

- All high-performance mixtures show very good results (density and strength). The concrete can be made without difficulties.

- The French concrete BPR represents the exception in this comparison. The density and the strength results are very good. However, the production requires much more know-how. With this concrete, the wall thickness of a storage tank could be substantially reduced.

8. REFERENCES

EIBL, J. U. HILSDORF, H. K.: *Permeabilität als Kennwert der Dauerhaftigkeit von Beton,* Schriftenreihe des Instituts für Massivbau und Baustofftechnologie, Heft 8, Karlsruhe, 1989

LUTZ, P., JENISCH, R., KLOPFER, H.: *Lehrbuch der Bauphysik,* Teubner-verlag, Stuttgart, 1989

REINHARDT, H.-W., FEHLHABER, T.: *Zum Eindringverhalten von Flüssigkeiten und Gasen in ungerissenen Beton*, DAfStb, Heft 445, Berlin, 1994

REINHARDT, H.-W., FREY, R.: *Untersuchungen der Dichtigkeit von Vakuum beton gegenüber wassergefährdenden Flüssigkeiten*, DAfStb, Heft 445, Berlin, 1994

BUSS, H.: *Aktuelles Tabellenhandbuch Feuchte, Wärme, Schall*, Weka-Fachverlage GmbH & Co. KG 1987