HEAT CURING OF SELF-COMPACTING CONCRETE (SCC)

WÄRMEBEHANDLUNG VON SELBSTVERDICHTENDEM BETON (SVB)

TRAITEMANT THERMIQUE DES BETONS AUTOPLAÇANTS (BAP)

Michael Stegmaier

SUMMARY

In precast production, heat treatment of concrete is of great significance for economic utilisation of operating resources. In this paper the effect of heat treatment on the mechanical properties of self-compacting concrete (SCC) is examined. For this purpose, different types of SCC ranging in strength classes from C20/25 to C70/85 were subjected to heat treatment of different intensity, corresponding to durable storage of three days at 20 °C, and compared to specimens stored under standard conditions to the same maturity. It was found that the $(w/c)_{eq}$-ratio of the concretes played an important role in achievable strength and that the strength is significantly influenced by the pore space.

ZUSAMMENFASSUNG

Bei der Herstellung von Fertigteilen ist für eine wirtschaftliche Auslastung der Betriebsmittel die Wärmebehandlung der Betone von großer Bedeutung. In dieser Arbeit werden die Auswirkungen einer Wärmebehandlung auf die mechanischen Eigenschaften von Selbstverdichtendem Beton (SVB) untersucht. Dazu wurden unterschiedliche SVB-Typen im Bereich der Festigkeitsklassen von C20/25 bis C70/85 mit verschieden scharfen Wärmebehandlungen auf eine Reife gebracht, die einer dauerhaften Lagerung von 3 Tagen bei 20 °C entspricht, und mit normgelagerten Proben der selben Reife verglichen. Dabei wurde festgestellt, dass der $(w/z)_{eq}$-Wert der Betone eine wichtige Rolle bei der erreichbaren Festigkeit spielt und dass die Veränderung des Porenraumes einen beträchtlichen Einfluss auf die Festigkeit hat.

RESUME

Dans la production du béton préfabriqué, le traitement thermique joue un rôle important dans l'exploitation économique des ressources. Cet article traite de l'influence d'un traitement thermique sur les propriétés mécaniques des bétons autoplaçants (BAP). Différents types de BAP, dont les classes de résistance allaient de C20/25 à C70/85, ont été soumis à des traitements thermiques d'intensités différentes jusqu'à obtention d'une maturité correspondant à une cure de 3 jours à 20°C, et ont été comparés à des échantillons de même maturité conservés selon les conditions standard. Il s'est avéré que le rapport eau/ciment équivalent joue un rôle important pour la résistance réalisable et que la résistance est fortement affectée par le volume des pores.

KEYWORDS: SCC, heat curing, maturity, compressive strength, splitting tensile strength, Young's modulus

OBJECTIVE

The effect of heat treatment on the mechanical properties of conventionally vibrated concrete is well known [1, 2]. Whether this knowledge can also be applied to SCC had been called into question when the code of practise on self-compacting concrete [3] was drawn up by the German Association of Structural Concrete (DAfStb). For this reason, heat treatment was not included in the first edition of this code. To close this gap, comprehensive investigations have been carried out, extracts of which will be described in the following [4]. In the new edition of the code, heat treatment has been included.

HEAT TREATMENT

Calculation of maturity

The maturity was calculated in accordance with the de Vree (CEMIJ) method [5], in which a cement-specific factor C is introduced. Based on the Portland cement clinker content, a C-value of 1,3 was assumed [6]. The calculation of the weighted increase in maturity per hour was performed using equation 1 [5]:

$$\Delta R_g = \frac{10 \times \left[C^{(0{,}1T_i - 1{,}245)} - C^{-2{,}245} \right]}{\ln C} \tag{1}$$

where:

ΔR_g = weighted maturity per hour

T_i = mean hardening temperature of the concrete during this hour [°C]

C = cement specific factor [-]

For determining a concrete's total maturity, the individual increases in maturity are added up in accordance with equation 2:

$$R_g = \sum \Delta R_g \times \Delta t_i \qquad [°Ch] \tag{2}$$

where:
ΔR_g = weighted maturity per hour
Δt_i = time interval observed, here 1 hour [h]

Heat treatment process and storage of the specimens

For performing the heat treatment the limiting values of the maximum temperature, the temperature during preliminary storage and the rate of heating and cooling given in the DAfStb code of practice on heat treatment of concrete [79] were employed. The procedure adopted for the different curing temperatures is summarised in Table 1.

Table 1: Temperature management for heat treatment with different maximum temperatures

		Maximum temperature T_{max}		
		40 °C	60 °C	80 °C
Preliminary storage time	[h]	3.0	3.0	1.0
Preliminary storage temperature	[°C]	30.0	30.0	30.0
Heating rate	[K/h]	10.0	10.0	10.0
Maintained at T_{max}	[h]	14.0	5.0	3.0
Cooling rate	[K/h]	10.0	10.0	10.0
Storage at 20 °C prior to testing	[h]	30.6	27.4	4.1
Total treatment time	[d]	2.1	1.8	0.8

Heat treatment of the concretes took place by hot-air method in two programmable heating cabinets and with steel forms with good conductive properties. Prior to filling, the forms in the heating cabinets were preheated to the preliminary storage temperature. To ensure sufficient air humidity during the heat treatment and to keep the specimens from drying out on their upper open side, containers filled with water were placed in the cabinets. The evaporating water was to ensure sufficient air humidity. The reference specimens not subjected to heat treatment were placed after manufacture in a climate chamber at a temperature of 20 °C and a relative humidity of 100 %. The heat-treated specimens were placed in the specific heating cabinets immediately after manufacture and the the heat treatment has been carried out. Subsequent storage after the heat treatment until testing took place in a climate chamber at 20 °C and a relative humidity of 100 %.

Mix compositions used

The following nomenclature was adopted to ensure clear identification of the concretes: "M" denotes the powder type, "K" the combination type and "S" the viscosity-agent type. The capital letter is followed by a number, which indicates the target strength (compressive strength measured on cubes with an edge length of 150 mm) of the concrete. The second number states the maximum temperature applied during the heat treatment and/or storage temperature. The third number stands for the aimed maturity in °C days (at storage at 20 °C). Accordingly, a sample marked M85-60-3, for example, identifies the specimen as being of powder type with a projected compressive cube strength of 85 N/mm², subjected to heat treatment at a maximum temperature of 60 °C in order to achieve a maturity that corresponds to a storage of 3 days at 20 °C.

Table 2: Mix compositions of the combination types investigated

Constituents	K25	K45	K65	K85
Cement type	CEM II/ A-LL 32.5R	CEM II/ A-LL 32.5R	CEM II/ A-LL 42.5R	CEM II/ A-LL 42.5R
Cement content [kg/m³]	240	300	350	500
Water [kg/m³]	170	166	170	185
Limestone powder [kg/m³]	316	104	79	0
Fly ash [kg/m³]	0	99	119	129
Sand [kg/m³]	746	775	751	705
Gravel [kg/m³]	878	900	873	819
Powder content [kg/m³]	569	516	560	643
Plasticizer content [% by mass of cement]	1.25	1.35	1.35	1.60
Viscosity-agent content [% by mass of cement]	0.20	0.10	0.10	0.10
$(w/c)_{eq}$ [-]	0.71	0.49	0.43	0.34

For the purpose of the investigations presented here, combination types and powder types ranging in strength classes from C20/25 to C70/85 were designed. In addition to these a viscosity–agent type of strength class C20/25 was included in the program. The exact composition of the SCCs investigated is summarised in Tables 2 and 3.

Table 3: Mix compositions of the powder types and the viscosity-agent type investigated

Constituents	M25	M45	M65	M85	S25
Cement type	CEM II/ A-LL 32.5R	CEM II/ A-LL 32.5R	CEM II/ A-LL 42.5R	CEM II/ A-LL 42.5R	CEM II/ A-LL 32.5R
Cement content [kg/m³]	240	300	350	500	240
Water [kg/m³]	168	166	170	183	192
Limestone powder [kg/m³]	338	134	66	0	145
Fly ash [kg/m³]	0	99	119	137	0
Sand [kg/m³]	752	763	751	705	815
Gravel [kg/m³]	856	887	873	819	928
Powder content [kg/m³]	594	545	548	650	402
Plasticizer content [% by mass of cement]	1.25	1.25	1.35	1.45	1.50
Viscosity-agent content [% by mass of cement]	0.00	0.00	0.00	0.00	0.45
$(w/c)_{eq}$ [-]	0.70	0.49	0.43	0.34	0.80

The $(w/c)_{eq}$-ratio given in Tables 2 and 3, was calculated with the following equation 3:

$$(w/c)_{eq} = \frac{w}{c+0.4f} \tag{3}$$

where:

w = water content [kg/m³]
c = cement content [kg/m³]
f = fly ash (f allowable $\leq$ 0.33 z) [kg/m³]

The water content of the superplasticizer was taken into account for the mixing water. The superplasticizer used is a product based on polycarboxylate ether (PCE) with a solids content of 35% (Woerment FM/BV 375). In addition, a stabilising admixture was added to the concretes of the viscosity-agent type and the combination type. The product used is a Woermann underwater compound (ST). This admixture is largely water insoluble and is characterised by a high swelling capacity. The raw materials basis are natural and synthetic polymers. The limestone flour used, Calcit MS 14, was obtained from the company Schön und Hippelein and has a $CaCO_3$ content larger than 99 %. Another admixture used was fly ash. Here, too, fly ash from Altbach power plant was constantly used to avoid fluctuations in the composition. The water used as mixing water originated from the city of Stuttgart.

SCOPE OF THE MEASUREMENT

The aim of the investigations presented here was to investigate the effect of heat treatment of different temperature on the mechanical properties of SCC. In order to be able to make the assessment, reference test specimens were manufactured of the SCC in addition to the specimens subjected to heat treatment. These specimens were stored in accordance with the standard at a temperature of 20 °C and a relative humidity of 100 % to the age of 3 days. With the aid of the heat treatments administered at various temperatures the concretes were brought to the same maturity as attained under durable storage conditions of 3 d at a temperature of 20 °C (1822 °Ch after the de Vree's method). All of the concretes described here are therefore of the same maturity, independent of the temperature applied for heat treatment, and can as such be directly compared with each other.

Fresh concrete tests

On the concretes manufactured, the typical fresh concrete test procedures for SCC were applied to determine the flowability (slump), viscosity (V-funnel test) and inclination to blocking (slump test with J-ring). The test procedure adopted is described in detail in [3, 8]. The SCCs inclination to sedimentation was assessed on the specimens for the splitting tensile strength. When the split specimens contained coarse aggregate also in the uppermost area of the cube, no inclination to sedimentation was in evidence. Apart from the special fresh concrete procedures adopted for investigating the SCC as described above, the fresh concrete air content was in addition determined on every SCC by the pressure equalisation method specified in DIN EN 12350-Part 7 and the temperature of the fresh concrete determined with a commercially available thermometer.

Manufacture of the concretes

In order to ensure an as good as possible comparability among the fresh concrete varieties, the same scheme was adopted for testing and manufacturing for all the concretes. Following fresh concrete testing, the test specimens for determining the mechanical parameters were manufactured. The forms were filled using a channel of 1.5 m length. In this way it could be ensured that the concrete would be able to adequately deaerate during the flow process. For practical reasons it was not possible to cast the test specimens in one batch for all temperature treatments. Every concrete variety had to be manufactured separately for every curing temperature. Testing for the rheological properties was performed only on the first batch of every SCC type; the air content and the fresh concrete temperature were determined in every casting process.

Determination of the mechanical properties of SCC

The compressive strength of the SCCs was determined as specified in DIN EN 12390-Part3 on cubes with an edge length of 150 mm and a loading rate of 0.5 N/mm²s. For determining the splitting tensile strength of the SCCs, cubes with an edge length of 150 mm were manufactured in accordance with DIN EN 12390-Part 6 and tested at a loading rate of 0.05 N/mm²s. The static Young's modulus was measured as specified in DIN 1048 Part 5 on cylinders of 150 mm diameter and a height of 300 mm.

TEST RESULTS AND DISCUSSION

Fresh concrete properties

The results of the SCC-specific fresh concrete investigations are summarised in Table 4. The fact that the slump measured with the J-ring is partly higher than without J-ring can be explained by the inherent scattering and is quite possible for individual values and the measuring accuracy employed for this procedure.

Table 4: Results of the fresh concrete tests

	K25	K45	K65	K85	M25	M45	M65	M85	S25
V-funnel time [s]	10.5	13.0	18.0	14.0	11.0	12.0	15.5	12.0	5.0
Slump [mm]	750	720	690	780	780	740	745	770	720
Slump with J-Ring [mm]	750	725	690	765	785	730	750	730	685
t_{500} [s]	5.0	6.0	10.0	8.0	6.0	7.0	6.0	8.0	4.0

The air contents and the temperatures of the fresh concretes measured on the SCC manufactured on different dates are presented in Table 5 and Table 6.

Table 5: Air contents of the fresh concretes for the different curing temperatures

	Air contents of the fresh concretes for curing temperature [°C]			
	20 °C	40 °C	60 °C	80 °C
K25	2.0	2.2	3.2	2.8
K45	0.8	2.4	2.2	0.7
K65	2.1	3.6	2.2	1.5
K85	0.7	0.8	0.6	0.6
M25	3.9	4.4	5.6	2.7
M45	1.9	2.0	1.8	0.6
M65	2.5	0.5	1.2	0.5
M85	1.3	1.8	1.4	0.7
S25	0.7	0.4	2.4	0.4

Table 6: Fresh concrete temperatures of the concretes for the different curing temperatures

	Fresh concrete temperature for curing temperature [°C]			
	20 °C	40 °C	60 °C	80 °C
K25	25.4	19.9	20.2	21.2
K45	27.9	20.1	21.2	20.7
K65	28.0	20.8	21.4	21.5
K85	26.6	20.8	22.0	22.5
M25	23.8	20.8	20.7	21.1
M45	25.0	19.5	20.1	21.4
M65	25.2	20.3	20.6	22.2
M85	24.0	21.8	19.6	21.9
S25	21.4	20.0	19.1	19.7

Mechanical parameters

The effect of the curing temperatures on the compressive strength of the combination types is presented in Fig. 1 and Fig. 2. The high-strength concretes K65 and K85 are hardly affected by the heat treatment. The low fluctuations at 40 °C and 60 °C in respect of the strength achieved under standard storage ranged within the possible scattering that is possible when measuring the compressive strength and can not be attributed to the heat treatment.

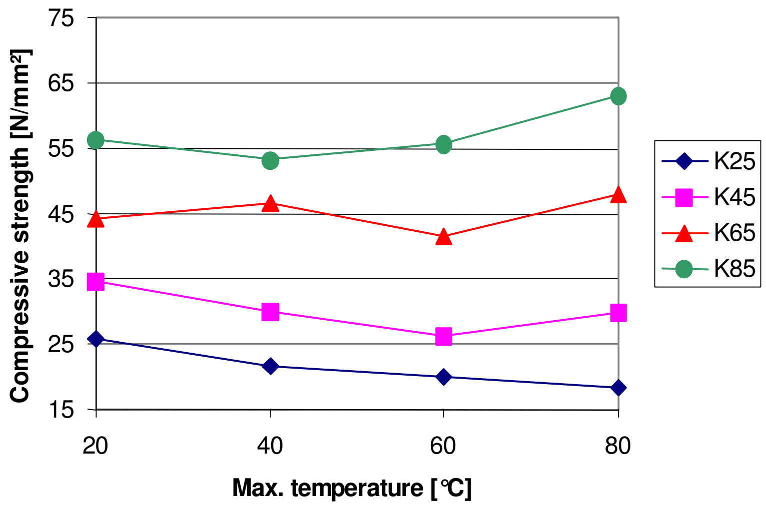

Fig. 1: Comparison of compressive strengths of the combination types at an effective age of 3 d and different maximum curing temperatures

At 80 ° the high-strength concretes K65 and K85 even reached higher compressive strengths compared to standard storage. The results obtained in mixes K25 and K45 present a completely different picture. Both SCCs exhibit up to a curing temperature of 60 °C a continuous decrease in compressive strength of approx. 22 % relative to standard storage. The loss in strength continues with K25 as the curing temperatures increases and reaches approx. 30 %. Combination type K45 shows at 80 °C again a higher compressive strength. This value, however, ranges about 13 % below the strength achieved with standard storage.

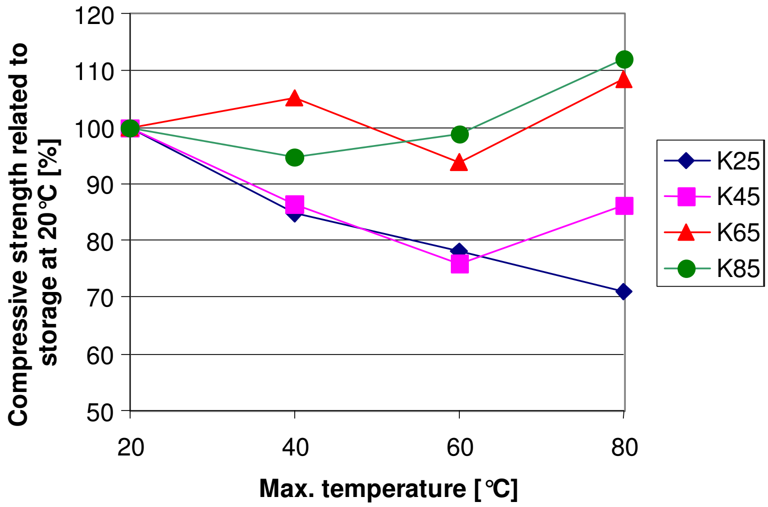

Fig. 2: Percentage difference in the compressive strength of the combination types related to standard storage at an effective age of 3 d and different maximum curing temperatures

The powder types investigated were observed to have a behaviour similar to the combination types. At a curing temperature of 40 °C, the compressive strength is lower by approx. 12 % for all powder types compared to standard storage at 20 °C. An increase in curing temperature to 60 °C leads for the M25 to a further loss of strength, while the remaining powder types experienced no further decrease in compressive strength. At 80 °C, all powder types exhibited once again a higher compressive strength than at 60 °C. The values of the high-strength powder types even surpass the values attained under standard conditions.

Viscosity-agent type S25 exhibits a comparatively poorer behaviour than combination type K25. The compressive strength of this concrete continues to decrease with rising curing temperature and ranks at 80 C about 32 % below the values achieved at standard storage.

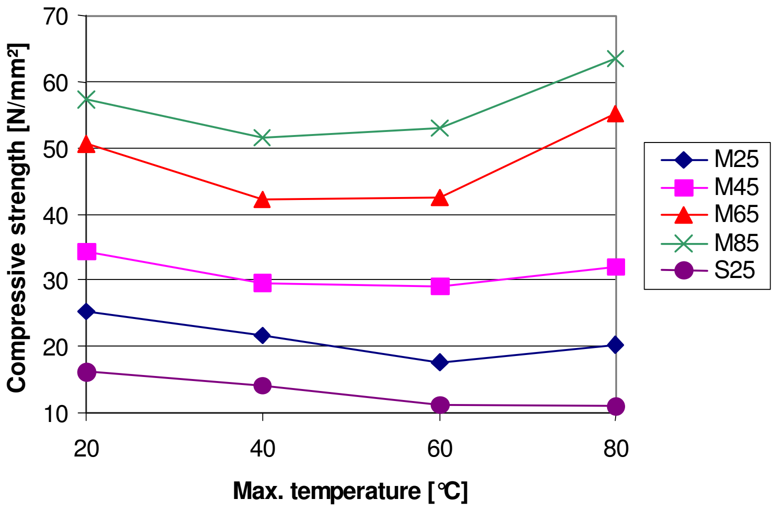

Fig. 3: Comparison of compressive strengths of the powder types and the viscosity-agent type at an effective age of 3 d and different maximum curing temperatures

With regard to the effect of the heat treatment on the compressive strength, the SCCs with a low $(w/c)_{eq}$-ratio are in general better suited for heat treatment than SCC with a high $(w/c)_{eq}$-ratio. In literature [9] the same observations are described also for vibrated concretes. At a comparable cement content and $(w/c)_{eq}$-ratio, the combination types are better suited for heat treatment, with regard to the compressive strength, than the remaining SCC types.

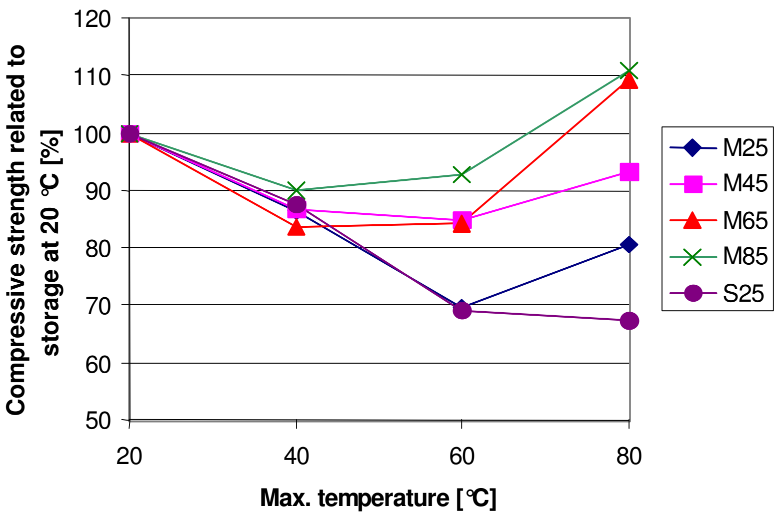

Fig. 4: Percentage difference in the compressive strength of the powder types and the viscosity-agent type related to standard storage at an effective age of 3 d and different maximum curing temperatures

All combination types, except for K45, show an approximately identical behaviour with regard to the influence of heat curing temperature on the splitting tensile strength (see Fig. 5 and 6). Up to a maximum temperature of 60 °C, the change in splitting tensile strength is insignificant compared to standard storage conditions. These deviations from standard storage lie within the possible scatterings for the determination of the splitting tensile strength. At 80 °C, a decrease in splitting tensile strength, in excess of the known scattering, is observed on all combination types. Concrete K45, in contrast, experiences a continuous decrease in splitting tensile strength with rising curing temperature. For the powder types, no such uniform behaviour is observed as for the combination types (see Fig. 7 and 8).

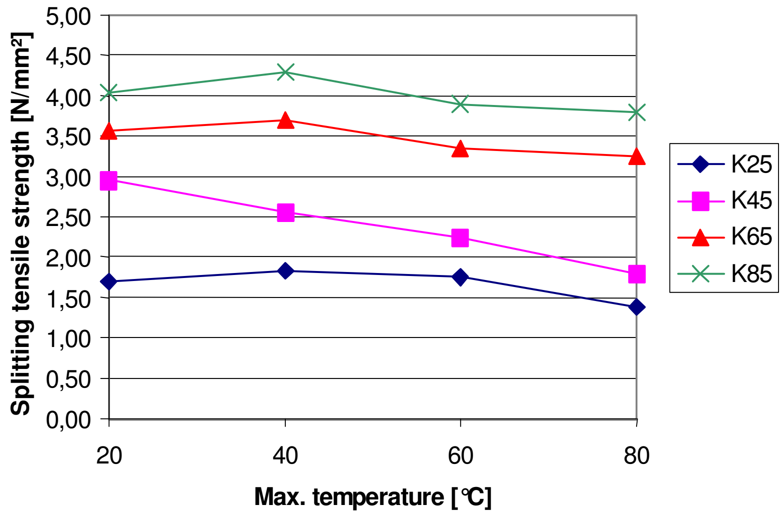

Fig. 5: Comparison of splitting tensile strengths of the combination types at an effective age of 3 d and different maximum curing temperatures.

The viscosity-agent type shows analogously to the compressive strength a continuous decrease in splitting tensile strength with rising curing temperature and achieves at 80 °C only approx. 60 % of the splitting tensile strength of the standard storage.

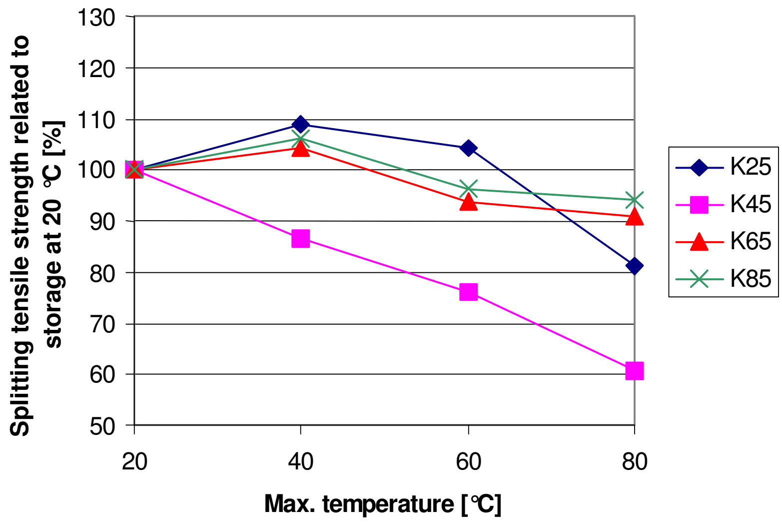

Fig. 6: Percentage difference in the splitting tensile strength of the combination types related to standard storage at an effective age of 3 d and different maximum curing temperatures.

For the splitting tensile strength, the effect of $(w/c)_{eq}$-ratio on the achievable strength compared to standard storage is not as pronounced as for the compressive strength. In general, however, the splitting tensile strength is not as markedly influenced as the compressive strength, independent of the strength class of the concretes. Only the viscosity-agent type is an exception to this.

Looking at the results of the Young's modulus measurements, it is clearly apparent that both the powder types and the combination types show hardly any difference in the values measured on the concretes of the strength classes C55/67 and C70/85. This came as a surprise, as the compressive strengths of some of the mixes of these strength classes clearly differ from each other.

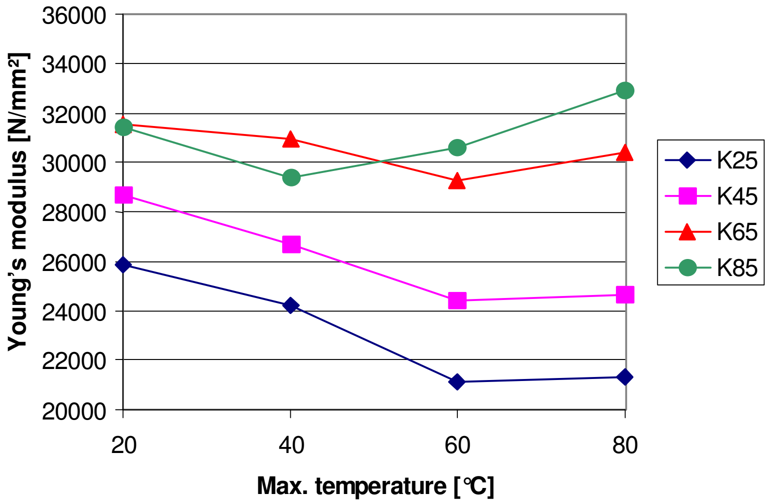

Fig. 9: Comparison of the Young's modulus of the combination types at an effective age of 3 d and different maximum curing temperatures.

The effect of the curing temperature on the Young's modulus is for the combination types essentially the same as for the compressive strength. On the concretes with low $(w/c)_{eq}$-ratio, the curing temperature effects hardly a change. The Young's modulus, in contrast, decreases compared to storage at 20 °C with the concretes with high $(w/c)_{eq}$-ratio with increasing curing temperature, with no difference between treatment at 60 °C and 80 °C. The difference in respect of durable storage at 20 °C is approx. 17 % for K25 and 15 % for K45.

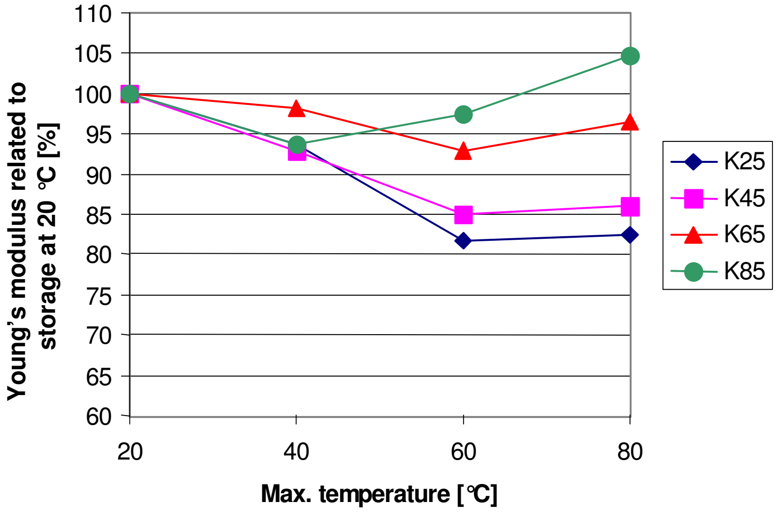

Fig. 10: Percentage difference in the Young's modulus of the combination types related to standard storage at an effective age of 3 d and different maximum curing temperatures

In the case of the powder types, the concretes with high $(w/c)_{eq}$-ratio were found to be equal in respect of the Young's modulus up to a temperature of 60 °C compared to storage of 20 °C and/or even somewhat better than the concretes with a low $(w/c)_{eq}$-ratio (see Fig. 11 and 12).

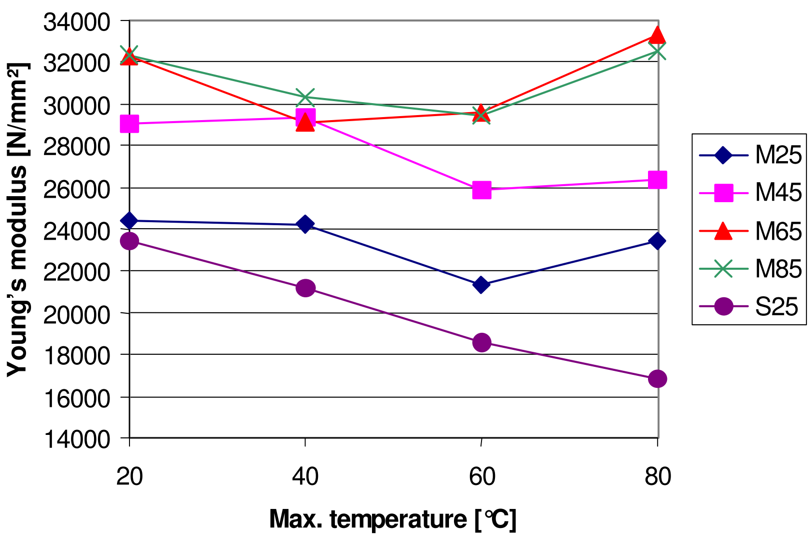

Fig. 11: Comparison of the Young's modulus of the powder types and the viscosity-agent type at an effective age of 3 d and different maximum curing temperatures

When the curing temperature is further increased to 80 °C, the reverse takes place, in that the loss in Young's modulus in the high-strength concretes with a low $(w/c)_{eq}$-ratio is less compared to normal storage.

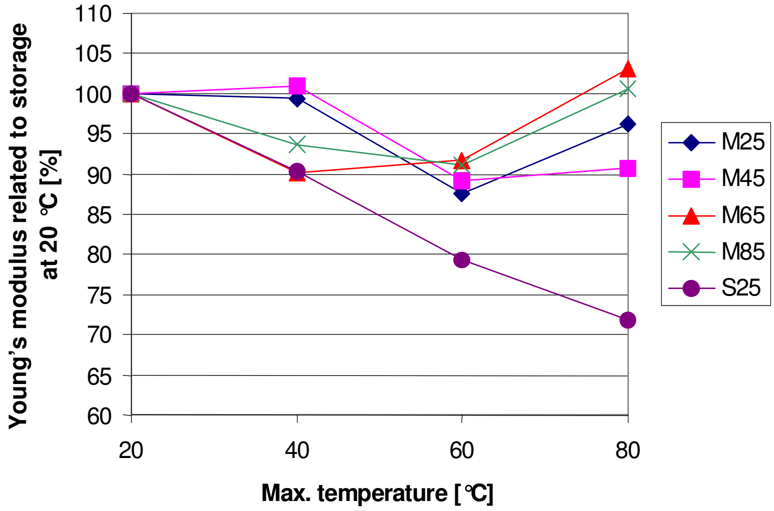

Fig. 12: Percentage difference in the Young's modulus of the powder types and the viscosity-agent type related to standard storage at an effective age of 3 d and different maximum curing temperatures

The viscosity-agent type, too, shows with regard to the Young's modulus, a definite dependency on the curing temperature. The Young's modulus decreases with increasing curing temperature of the heat treatment and lies at 80 °C at only approx. 70 % of the value achieved under standard storage conditions.

SUMMARY AND CONCLUSIONS

The objective of these investigations was to study the effect of heat treatment on the mechanical properties of SCC within the limits set by the DAfStb code of practice. With the aid of curing at different temperatures, various SCCs were brought to a maturity corresponding to a durable storage of the concretes for 3 days at 20 °C. On these concretes, the compressive strength, the splitting tensile strength and the static Young's modulus were determined and compared to reference concretes that had been stored for 3 days under standard conditions.

The concretes with a low $(w/c)_{eq}$-ratio, which are typically used in the precast industry, are hardly affected by the heat treatment as regards the compressive strength and the Young's modulus, related to the values of standard storage conditions. This applies independent from the curing temperature. The positive effect of low $(w/c)_{eq}$-ratio on heat treatment is also known for vibrated concretes [9]. A high $(w/c)_{eq}$-ratio leads in part to marked loss of strength, which in most cases increases with increasing curing temperature. For the splitting tensile strength, heat curing temperatures up to 60 °C can be regarded as uncritical. Beyond this temperature, strength losses compared to standard storage have to be reckoned with. When comparing different SCC types of identical strength classes for their suitability for heat treatment, the combination type can be said to be the most suitable. The viscosity-agent type of strength class C20/25 showed the highest loss of strength for all mechanical parameters and must be regarded as being unsuitable for heat treatment. Heat treatment influences the pore space of the concretes [10, 11]. This process, however, does not increase the total porosity. The cause of the loss of strength determined in testing as compared to strength after standard storage must, instead, be attributed to a change in the distribution of pore radii towards larger pores. That this is in fact the case could be shown by mercury intrusion porosimetry and helium pyknometry [10, 11]. The partly higher strength values measured on the mixes with a low $(w/c)_{eq}$-ratio subjected to heat treatment can be explained by the lower total porosity of these concretes compared to standard storage.

LITERATURE

[1] ALTNER, W.: *„Betonschnellerhärtung: Grundlagen und Verfahren“,* Düsseldorf: Beton – Verlag, 1981.

[2] NECK, U.*: “Auswirkungen der Wärmebehandlung auf die Dauerhaftigkeit von Beton“*. beton 38 (1988), H. 12, S 488-493

[3] DEUTSCHER AUSSCHUSS FÜR STAHLBETON (DAFSTB): *„DAfStb – Richtlinie* SELBSTVERDICHTENDER *Beton“,* Ergänzungen zu DIN 1045-2: 2001, Ausgabe November 2003.

[4] REINHARDT, H.-W.; STEGMAIER, M.: *„Wärmebehandlung von Selbstverdichtendem Beton“,* Abschlussbericht zum Forschungsvorhaben gefördert durch die Gips-Schüle Stiftung, 2004.

[5] DE VREE, R.T.; TEGELAAR, R.A.: *„Gewichtete Reife des Betons.“*, beton 48 (1998), H. 11, S 674-678.

[6] REINHARDT, H.-W.: *„Beton“*. In: Bergmeister, K., Wörner, H.-D. (Hrsg.): BetonKalender 2005 ; Teil 2., 94. Jahrg. Berlin: Ernst & Sohn, 2004, S.1-142

[7] DEUTSCHER AUSSCHUSS FÜR STAHLBETON (DAFSTB): *„DAfStb – Richtlinie zur Wärmebehandlung von Beton“,* September 1989.

[8] REINHARDT, H.-W. (HRSG.) ET AL.: *Sachstandbericht Selbstverdichtender Beton (SVB).* Deutscher Ausschuss für Stahlbeton (DAfStb), Heft 516. Berlin, Beuth Verlag, 2001.

[9] NEVILLE, A. M.: *"Properties of concrete",* 4th and final edition, Harlow : Longman Group, 1995.

[10] REINHARDT, H.-W.; STEGMAIER, M.: *"Einfluss der Wärmebehandlung auf die mechanischen Eigenschaften von SVB."* In: Betonwerk + Fertigteil-technik 71(2005), Nr. 5, S. 34-45.

[11] STEGMAIER, M.: *"Eigenschaften von wärmebehandeltem Selbstverdichtenden Beton"*, Dissertation, Universität Stuttgart, 2005.