New Results on Early-Age Cracking Risk of Special Concrete

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Abstract

The Center of Building Materials (cbm) at the Technische Universitaet Muenchen has many years of experience in the early-age cracking risk of concrete. So far most of the investigations have been focused on mass concrete with regard to its semi-adiabatic thermal behaviour – the development of uni-axial restraint stress during hardening has been determined in the cracking frame, simulating the centre of an approx. 50 cm thick concrete element.

New results on the early-age cracking risk of special concretes with regard to their specific conditions or composition that is different to that of ordinary mass concrete will be shown in this paper. These special concretes are self-compacting concrete, pavement concrete, high-strength concrete and in particular ultrahigh-performance concrete with a compressive strength of up to 200 N/mm^2 at an age of 28 days.

Furthermore, a test-based calculation method using the finite element method (FEM) was developed to predict, for example, the thermal restraint stress in concrete structures under various weather and curing conditions. The restraint stress distribution at any location in the concrete can be calculated realistically by applying appropriate rheological models for which “true values” of particular early-age concrete properties are required, which have to be determined experimentally.

1 General Purpose

Restraint stresses are generated inside a concrete element, if load-independent dilatation is obstructed. There is a high risk of cracking, in particular at an early age, when mechanical properties are developing quickly and comparatively large (restrained) dilatations occur. However, whether the resulting restraint stress in the concrete will indeed be able to achieve the tensile strength crucially depends on the concrete itself. Its composition is crucial both for the temporal development of thermal deformation, drying shrinkage or autogenous shrinkage as well as for the temporal development of the modulus of elasticity and the relaxation ability, which determine the degree to which dilatations are converted into stresses.

It is known that mass concrete may be effectively optimised in its composition with the objective of avoiding a cracking risk as a result of dissipating hydration heat. Tests carried out inside the Munich cracking frame /1/ have here for instance shown the favourable effect of composite cements. Other “special concretes” too need to be examined and assessed for their early-age cracking risk, in fact, each one under the special conditions constituted by its composition and area of application.

The different possible influencing parameters for the early-age cracking risk of the respective “special concretes” are so numerous that it is hardly possible to examine them exclusively by means of tests – for instance by means of cracking frame tests. A theoretical examination using a FEM-model on the contrary offers the opportunity to carry out parameter studies on different concretes in the intended static system and to avoid errors already during the planning phase.

2 Experimentally based method to calculate restraint stresses in early-age concrete

On behalf of the “Deutsche Forschungsgemeinschaft” (DFG), the cbm has developed a method to realistically calculate early-age restraint stresses in thick concrete elements /2/, /4/. It is essential in this regard that the non-linearity between temperature and stress development is taken into consideration.

The procedure followed during the experimentally supported calculation of restraint stresses in early-age concrete is depicted in figure 1.

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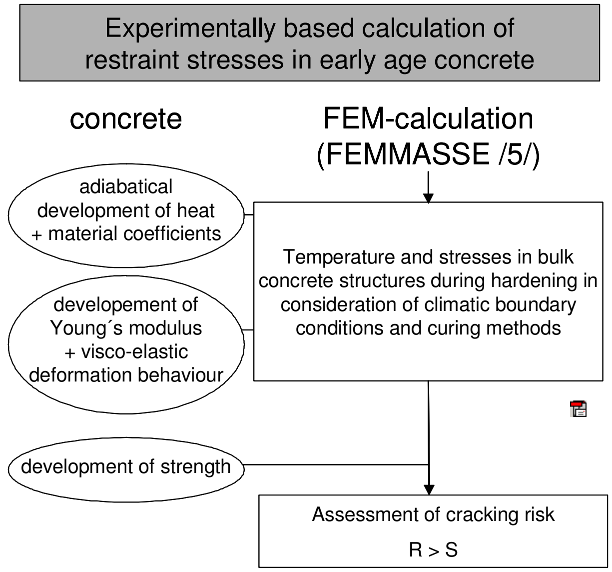


figure 1: Method for the experimentally supported calculation of restraint stresses in early-age concrete

In simple laboratory tests, experimentally determined material parameters of the concrete, which characterise the development of the thermal and mechanical properties of a concrete of a certain composition, and the boundary climatic conditions are used as input data for calculation.

The adiabatic temperature curve of the concrete is measured inside an adiabatic calorimeter. The results are used to draw up a function of released hydration heat. The development of the static modulus of elasticity is determined from a concrete age of 15 hours. The elastic-viscous deformation behaviour of the examined concrete is determined by means of creep tests at different load times. The rheological model of the Maxwell chain is used for the stress calculations /3/. The individual elements of the Maxwell chain may be derived from the results of the creep tests /4/.

For verification of the selected models, the centric restraint stresses at completely restrained deformation were measured inside the temperature stress testing machine (TST, compare figure 2) and parallel to that calculated using the Finite Element Method (FEM), here with the program FEMMASSE /5/. A concrete of strength class B35 was used for the studies. The cement was OPC (CEM I 32.5 R) and its content was 280 kg/m³, the fly-ash content 60 kg/m³. 168 kg/m³ of water were added, so that the water cement ratio was w/c = 0.60. Taking the fly-ash into account with a k-value of 0.4 the effective water binder ratio was w/(c + 0.4f) = 0.55.

In the TST it is possible to simulate storage conditions of a 1 m thick base plate, which is casted on a foundation in an undisplaceable manner and thus completely deformation-restrained. The concrete test piece has a length of roughly 1.30 m, a cross section of 150 · 150 mm² and is situated inside a temperature-controlled formwork. The prespecified temperature curve was beforehand calculated for a 1 m thick base plate at an ambient air temperature of 20 °C at a point 10 cm below the surface (using FEM). External boundary conditions were taken into account via the air temperature (T_{air} = 20 °C) and a convective heat transmission coefficient of α_K = 7,69 W/m²K. figure 2 shows the static system underlying these calculations.

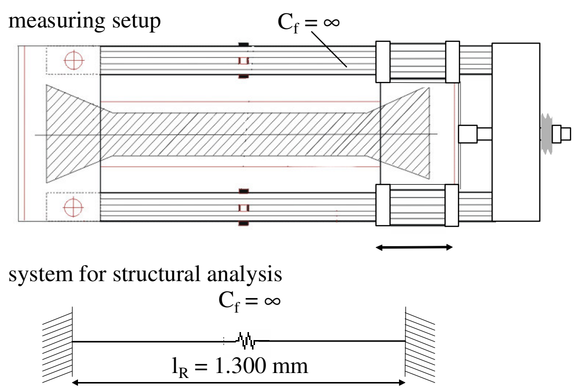


figure 2: Diagrammatic view of the TST and the associated static system (C_f: spring constant of a substitute spring, exercising the same lengthwise deformation restraint on the concrete test piece as the test facility, l_R: length of the concrete element)

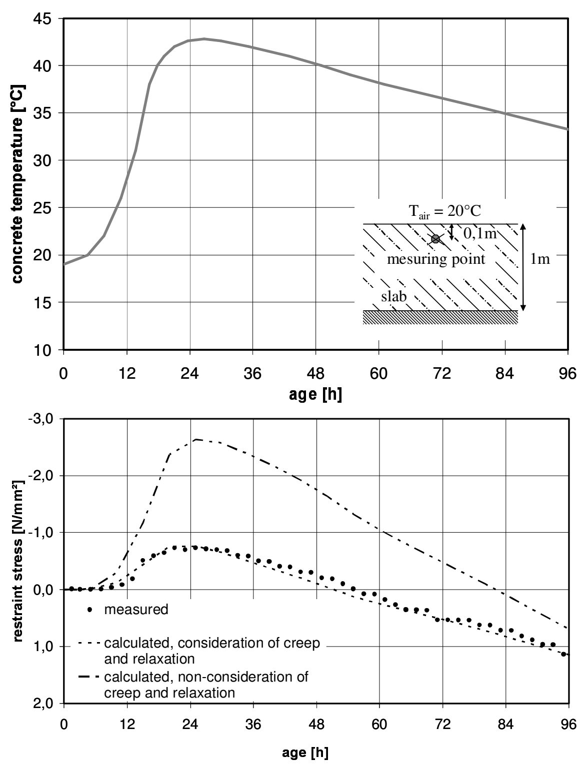


figure 3 Prespecified temperature curve and associated restraint stress development in the TST at complete deformation restraint; thermal stress measured and predicted according to the calculation method shown above, in comparison to the thermal stress when assuming a linear-elastic material behaviour

At the age of one day, the concrete reaches a maximum temperature of roughly 43℃ and then cools down again slowly, compare figure 3. The agreement of measured and calculated stress development, taking into consideration the elastic-viscous deformation behaviour of early-age concrete, is very good. To clearly show the influence of creeping and relaxation, the theoretical stress development has been specified without consideration of the elastic-viscous behaviour. Even if the development of the modulus of elasticity is taken into account, the result of the purely elastic calculation is a maximum compressive strain after one day of 2.64 N/mm²; the measurement however shows that roughly 70% of this stress will relax, which may be calculated by taking the creeping behaviour into account as a mechanical property.

3 Early-age cracking risk of special concrete

3.1 Uni-axial restraint stresses due to shrinkage

3.1.1 Drying shrinkage of self-compacting concrete

What kind of restraint stress development is to be expected for a self compacting concrete (SCC), depends - as has been clearly shown above - quite essentially on the ambient and storage conditions during hardening. According to current tests, no significant difference in temperature and stress development in comparison to ordinary vibrated concrete are to be expected for a SCC used as mass concrete /6/.

However, according to our own tests, the final shrinkage coefficients of SCC may be up to 50% higher than those for ordinary vibrated concrete, compare figure 4. This is why clearly higher shrinkage deformations may occur on thin SCC elements due to desiccation. Shrinkage was here measured on hollow concrete cylinders from an age of 24 hours and at an ambient humidity of 65 % r.h. Otherwise in case of a favourable composition or by using shrinkage-reducing agents, SCC may perfectly well equal the low shrinkage coefficient of vibrated concrete. For instance, the shrinkage coefficients of concrete with cement and limestone powder instead of fly-ash are clearly smaller, obviously because fewer gel pores are generated, which cause the shrinkage on release of water.

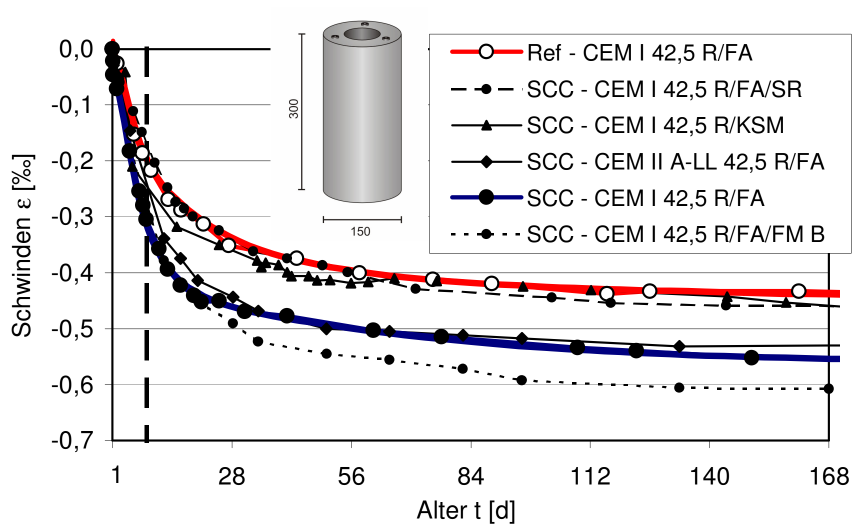


figure 4: Drying shrinkage of self-compacting concretes compared to vibrated concrete (Ref.)

table 1: mix design of the vibrated (Reference) concrete and of the reviewed SCC „CEM I 42,5 R/FA“

	Vibrated concrete	Self-Compacting Concrete
name	**Ref - CEM I 42,5 R/FA (OPC+PFA)**	**SCC - CEM I 42,5 R/FA (OPC+PFA)**
Content	[kg/m³]	
Cement	320	290
Fly Ash	60	260
Water	142	176
Superplastiziser	6,4	6,1
Stabilizer	---	0,3
Sand 0/2	793	664
Gravel 2/8	548	459
Gravel 8/16	548	459

After 7 days of desiccation, the SCC with Ordinary Portland Cement CEM I 42.5 R and fly-ash (/FA), which is unfavourable with regard to the shrinking behaviour, showed a shrinkage dilatation of roughly 0.3‰, while that of vibrated concrete is only roughly 0.2‰. The mix design of these two concretes is shown in table 1. The development of the modulus of elasticity of this SCC was only somewhat slower during the first three days; after that the curves run almost parallel /6/. However, based on creep measurements started at an age of 1 and 4 days, the specific creep at early ages was almost 40 % higher than that of the reference concrete. The equivalent higher relaxation ability of the SCC leads to a restraint stress which is hardly higher than that of the reference concrete, see figure 5, which shows the stress development calculated for a 7-day desiccation period in the TST using the FE-method (section 2).

However, in both cases the assumed longitudinal shrinkage would lead to high centric restraint stresses and to cracks, which can only occur on the periphery of a concrete element in practise. But these coefficients measured on thin-walled hollow cylinders are needed for using the calculation method demonstrated in section 2, which enables to calculate the distribution of shrinkage dilatations and restraint stresses across a component cross-section for any concrete element with practice-relevant moisture gradients.

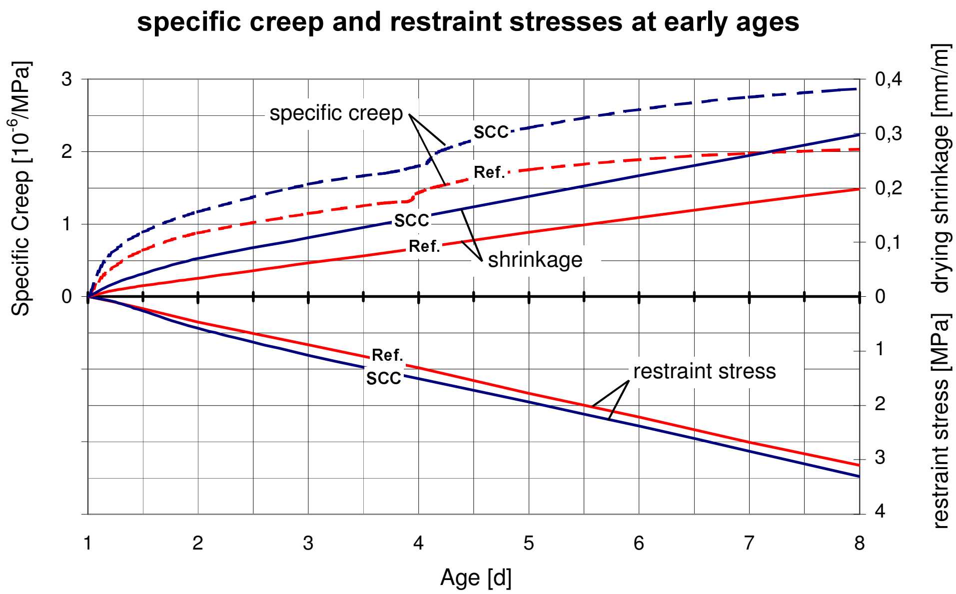


figure 5: Theoretical development of restraint stresses of a desiccating SCC in the TST with consideration of relaxation at early ages

3.1.2 Autogenous shrinkage of HPC and ultra-high performance concrete (UHPC)

Concrete of strength classes C55/67 to C100/115 – with cylinder compression strengths of at least 55 or 100 MPa – is designated as high strength concrete (HSC) in Germany. Ultra high-strength concretes have compression strengths of up to 200 N/mm² and even above that. All these concretes have w/c-ratios that clearly range below 0.40 and will thus show autogenous shrinkage deformations in the course of hardening. In Germany too, these concretes are often called (ultra-) high perf ormance concrete.

The autogenous deformation of concrete with low w/c-values is closely linked with hydration, because the chemical shrinkage and the resulting self-desiccation lead to a negative pressure between the solid matter. Measurements of autogenous shrinkage from approx. the end of solidification show that within the first 12 hours, already roughly 90% of autogenous deformation has occurred. /7/. Apart from the cement, the frequently used silica fume makes a considerable contribution to chemical and thus also to autogenous shrinkage in high-strength concretes due to its pozzolanic reaction with a volume contraction of roughly 20 ml per 100 g of reacted silica fume /8/ /9/.

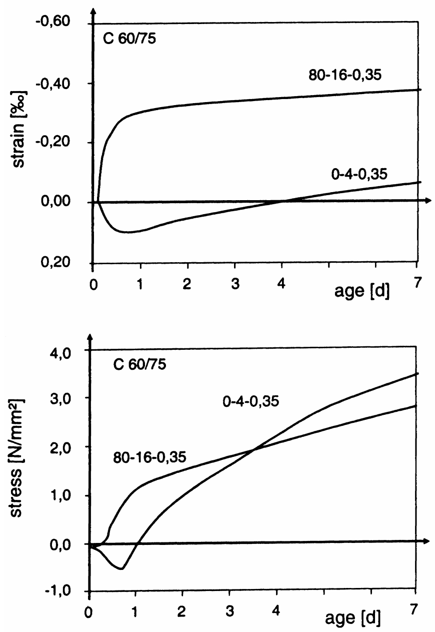


figure 6: Time history of free autogenous shrinkage and restraint stresses of two high-strength concretes (w/c = 0.35 and b = 450 kg/m³)

The extent of these resulting restraint stresses cannot be derived just like that from the final extent of free autogenous shrinkage /10/. The example in figure 6 rather shows that especially the time history of autogenous shrinkage is essential. A concrete, which shows a large amount of autogenous shrinkage on the first day but after that hardly shrinks at all, will after a few days have been "overtaken" with regard to the restraint stress development by a concrete the autogenous shrinkage of which only develops after approximately half a day, but from than on at a larger gradient. The autogenous shrinkage on the first day therefore only makes a small contribution to the overall restraint stress.

With regard to possible autogenous deformations and restraint stresses, UHPC with its high binder paste content of ≥ 600 l/m³, its low w/c-ratio < 0.30 and high silica fume content of roughly 30 M.% referred to the cement content, constitutes an extreme case. In particular so as to be able to take into consideration its high structural density when assessing the durability of UHPC, crack formation, for instance due to restraint stresses at an early age, must be completely ruled out. Schachinger has carried out extensive research with regard to concrete-technological influences on the development of shrinkage deformations and the resulting restraint stresses of UHPC [11]. Measurements under isothermal conditions (20 °C) were carried out from an age of 30 minutes; all measurements are referred to the condition at the end of solidification.

The recipes of examined concretes are shown in Table 2. A high intensity vacuum mixer was used for mixing. The 28d compressive strength of the reference concrete with OPC was about 15% higher than that of the blast furnace slag cement roughly 171 compared to 148 MPa.

Table 2: Investigated concrete mixes

Parameter	*Unit*	*Concrete I*	*Concrete II*
Cement type	*[-]*	*OPC: CEM I 42,5 R/HS*	*BFSC: CEM III B 42,5 NW/HS *)*
Binder paste volume	*[l/m³]*	*495*	*612*
Silica fume (sf)	*[wt.%]*	*18 – 22 – 26 – 30 (ref)*	*0 – 12 (ref) – 14 – 18*
w/c-ratio	*[-]*	*0.27 (ref) – 0.30 – 0.33*	*0.20 – 0.22 – 0.24 (ref)*

*) blast furnace slag content 70 % (ref) reference mixes of concrete I and II

The type of cement used essentially influences the autogenous deformation of UHPC. For instance, compared with concretes containing blast furnace slag cement (CEM III), concretes with Portland cement (CEM I) showed approximately double the shrinkage coefficient within the first day, even given a lower cement content. When the w/c-ratio of concretes containing Portland cement was changed from 0.33 to 0.27, the shrinkage coefficient was about 0.1‰ higher and already occurred after 12 to 15 hours. The same effect was achieved with a silica fume content, which at 30 M.-% ranged clearly higher compared to 18 M.-%. Even smaller was the difference for the concretes containing blast furnace slag cements. However, as expected, the concrete plasticizer substance used had a clear effect on early autogenous deformation. Apparently, a part of the early chemical shrinkage processes does not contribute towards autogenous deformation in case of late solidification.

Although the quality of the stress development curve corresponded to the autogenous deformation curve, the concrete containing blast furnace slag overtook the concrete with CEM I already on the second day, as the time-dependent increase of shrink deformations was here only clearly higher at a later stage, when the concrete already had a high modulus of elasticity, compare figure 7 at the bottom left. To be able to estimate relaxation, the theoretical stresses that result from calculations without taking into consideration the elastic-viscous behaviour may be used. Accordingly, for the reference concrete with Portland cement, after one day only roughly 10% and after 2 weeks only roughly 20% of the theoretical restraint stresses occurred. However, when the concrete plasticizer C was used to achieve a high early strength, the increase of the shrinkage coefficient after solidification was so steep, that the restraint stresses already at this early stage – after 6 and 7.5 hours – led to a separation crack, compare figure 7 on the bottom right.

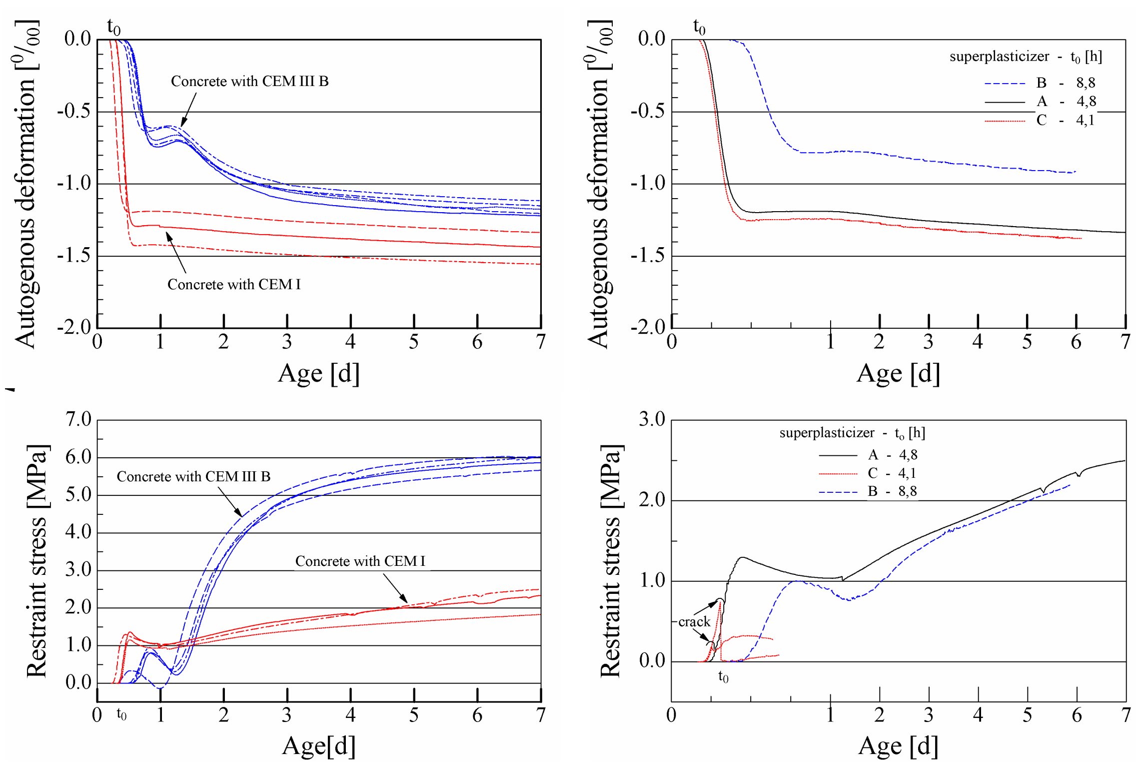


figure 7: Time history of autogenous deformation and the restraint stresses in dependence on the type of cement (left) and the concrete plasticizer substance

To assess the cracking risk, it is therefore necessary to bring into play the ratio of centric restraint forces and tensile strength. For normal and high-strength concrete it is stated that this ratio should not exceed roughly 70% over a longer period of time /12/ /13/. As is already known from normal- and high-strength concrete, the static modulus of elasticity of UHPC also develops faster than the tensile strength and the compressive strength, in this case particularly pronounced for the UHPC with CEM I. Correspondingly, the cracking risk of ultrahigh-strength concrete with Portland cement (CEM I) is particularly high on the first day, compare figure 8. Changes to the concrete composition, which only result in slightly increased deformation, will then however result in cracking.

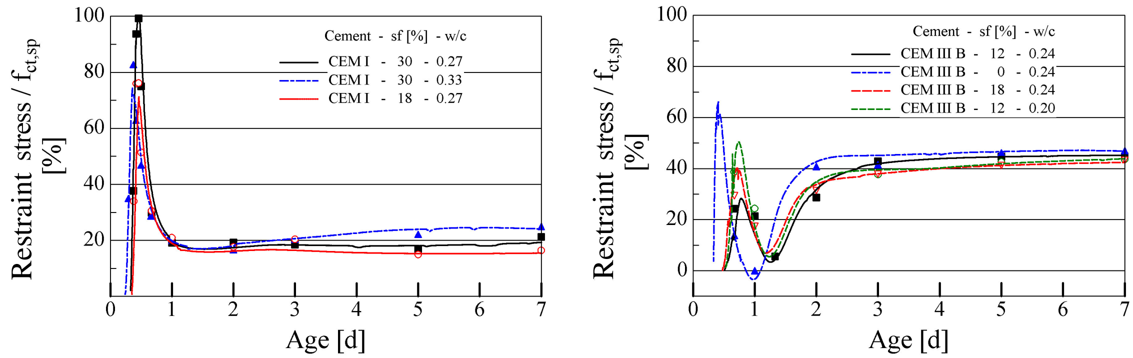


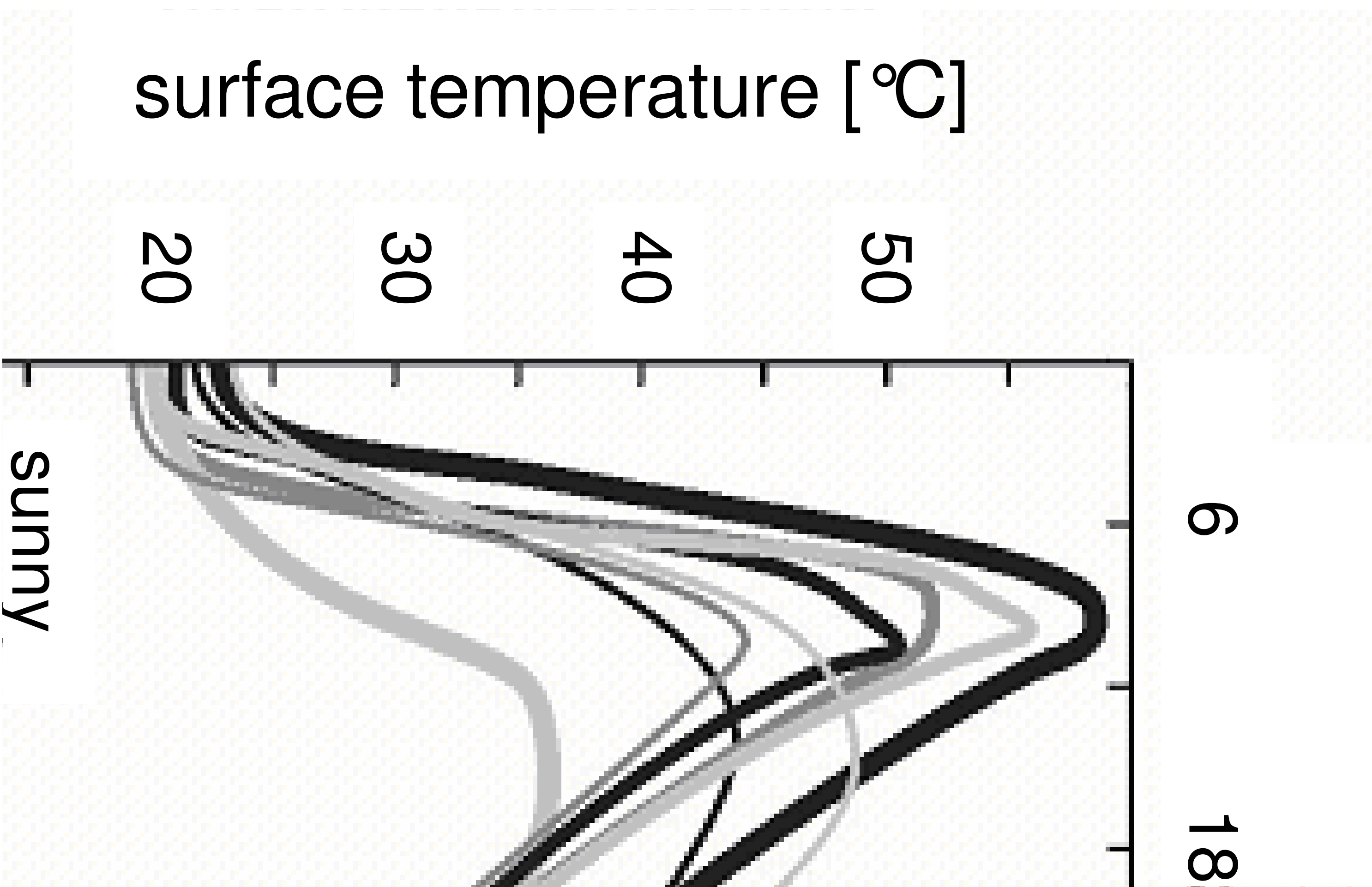
figure 8: Time history of the degree of stress due to restrained autogenous deformation of concretes with Portland cement (left) and blast furnace slag cement (right); isothermal storage at 20 °C

3.2 Bending restraint stresses due to thermal impact

3.2.1 Pavement concrete

As a rule, concrete pavement in Germany are unreinforced and are subdivided into slabs after fabrication by cutting transversal and longitudinal dummy joints. A cracking risk due to restraint stresses can thus essentially only occur up to when the dummy joints are cut due to restrained thermal dilatation, and in the case of high-strength pavement concrete additionally due to autogenous shrinkage. Drying shrinkage on the contrary is as a rule of no importance for the 26 to 30 cm thick concrete pavements.

In the cracking frame, it is only possible to measure centric restraint stresses. These could cause a cracking risk for concrete pavements under unfavourable, very summery conditions as a result of high hardening temperatures on the first day with subsequent cooling down during the night, before the transverse dummy joints have been cut. Such examinations with a “cyclic” temperature development in the concrete have been carried out in the cracking frame for a normal-strength and a high-strength pavement concrete /14/. Both concretes have been produced with 5% of air voids and the same cement CEM I 32.5 R. The high-strength pavement concrete, which develops a very high flexural strength (above 9 MPa), contained 432 kg of cement (c) and 18 kg of silica fume (s) per m^3 with a w/b-ratio of 0.30 and has in a similar composition been successfully used on a section of a German motorway.
Given the same external heat input on the first day, the maximum temperature increase of the high-strength concrete was hardly higher than that of normal-strength concrete, while with 36°C during the semi-adiabatic test (for massive elements as in figure 3), the maximum temperature increase of the normal-strength pavement concrete was still roughly 7 K smaller and was also reached later than that of high-strength concrete. The as expected higher cracking temperature of high-strength pavement concrete and thus the increased cracking tendency according to the criteria developed for mass concrete, can be put down to the higher modulus of elasticity, the lower relaxation ability and the additional autogenous shrinkage. With a tensile strength of roughly 3 MPa after 2 days, the cracking risk may be assessed to be only low.



surface temperature [℃]
20
30
40
50
sunny
6

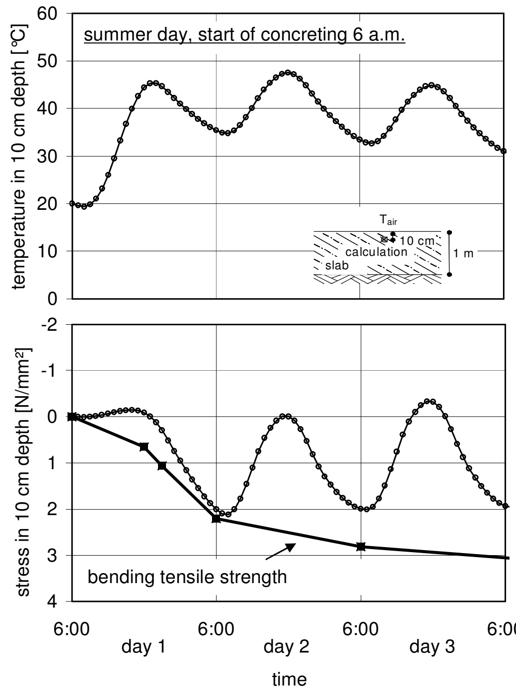


figure 11: *Development of stresses at a depth of 10 cm in a thick base plate during hardening. Reference calculation: summer day, start of concreting 6 a.m.*

For the critical time in the early morning of the day after fabrication, a cross section of stress distribution is additionally shown, compare illustration 14. The critical tensile stress at the „cold“ top surface is in this case made up in approximately equal parts by the activated bending tensile stress and the residual tensile stress. Looking at the associated temperature gradient it becomes clear that a large part of both stress portions, but above all the residual stress portion, may be put down to the unfavourable temperature gradient during hardening (hot at the top, compare for example the gradient after 12 hours), which has impressed on the element.

The temperature in a concrete slab crucially depends on its temporal development and distribution across the cross section at the time of day at which concreting is carried out. It is crucial in this regard to what extent the development of hydration heat overlaps with the influences that are subject to the time of day, inter alia air temperature and intensity of insolation. The central issue is here the separation of the maximum heating due to insolation and air temperature and the maximum hydration heat generation in the hardened concrete. The results of comparative calculations for different concreting times are depicted in figure 12. A base plate, which is concreted during the night (midnight) or even in the morning (6 a.m., compare figure 11), heats up by an approx. 10 K more during insolation in the near-surface area (here at a depth of 10 cm) during the first 16 hours than a base plate that has been concreted in the afternoon at 3 p.m. Cooling down during the first night causes in the elements that have been concreted in the early morning stress gradients with a critical tensile stress at the margin (see figure 13, left). Close to the surface, the concrete’s bending tensile strength is nearly reached. However, when concreting is started at noon and in particular at 3 p.m., the maximum restraint stress clearly stays below the bending tensile strength (compare figure 13, centre and right), because here the generation of hydration heat does not coincide with the strong heating-up from the outside and thus, a comparatively more favourable temperature gradient is impressed during hardening.

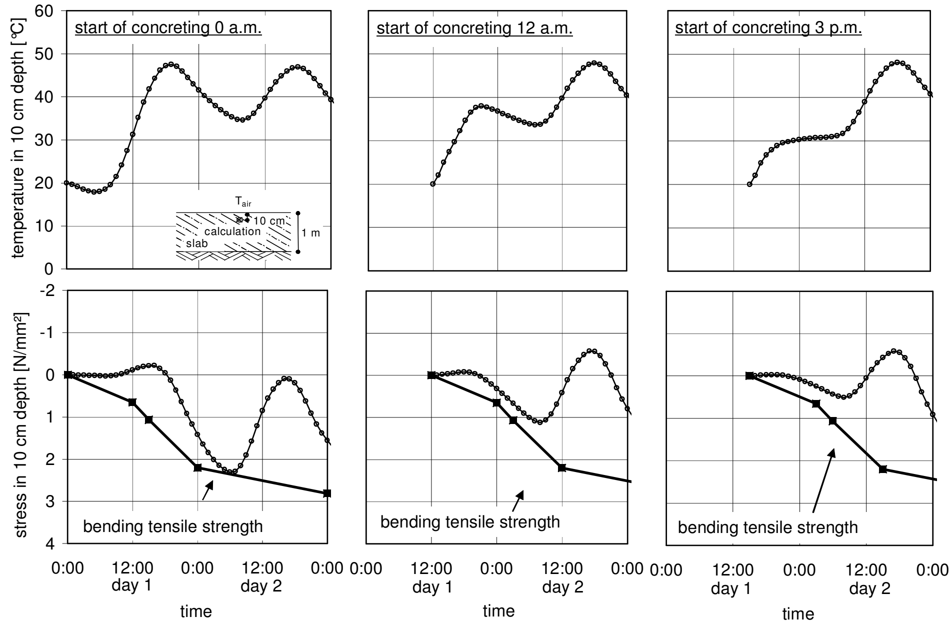


figure 12: *Development of temperature and stresses at a depth of 10 cm in a 1 m thick base plate. Start of concreting at midnight (0 a.m.), noon (12 a.m.) and in the afternoon (3 p.m.) in summer*

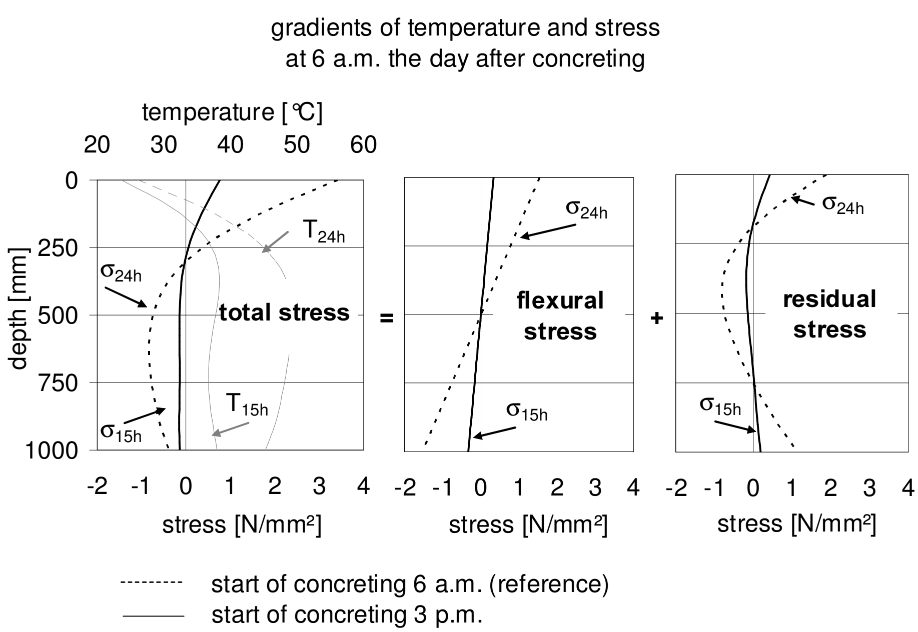


figure 13: *Comparison of stress gradients in a concrete base plate of 1 m thickness at 6 a.m. one day after fabrication with concreting start at 6 a.m. and 3 p.m. in summer*

In practical application, the stress calculations presented above permit a prediction of the restraint stresses as a result of temperature and the selection of suitable measures to reduce the cracking risk.

4 Discussion and Conclusion

Every type of concrete has to be examined separately under the planned boundary conditions during its hardening phase with regard to its early-age cracking risk. In particular the temporal development of the stress-causing dilatation and the mechanical properties determining the degree of conversion into stress and relaxation are decisive for the cracking risk.

Method for the theoretical determination of restraint stresses

With the demonstrated theoretical method to determine early-age restraint stresses it is possible to carry out parameter studies for every concrete on the basis of simple laboratory tests, which are for instance used to examine suitable protection or curing measures for unfavourable weather conditions. This facilitates purposeful and economic planning with regard to avoiding an early-age cracking risk. However, in order to depict the early-age behaviour of concrete as realistically as possible, the decisive mechanical properties of early-age concrete have to be determined beforehand by means of tests.

Special Concrete - SCC

Self-compacting concrete (SCC) with a comparatively high drying shrinkage showed roughly higher restraint stresses in comparison to ordinary vibrated concretes – above all because of also higher specific creep at early ages. Although "free" shrinkage dilatation was up to 50% higher during tests, it has also been possible to show that by purposeful selection of the concrete base materials, the degree of shrinkage is able to keep pace with that of vibrated concretes, for instance if shrinkage-reducing agents are added or also if low portions of cement and additional inert, flour grain sized agents (limestone powder) are used.

Special Concrete – UHPC

The relaxation ability of UHPC, which is very high during the first 12 hours, reduces the early-age cracking risk – despite the very high autogenous shrinkage of up to 1.5‰ after 1 day. The w/c-ratio and the silica fume content only had a minor influence on the development of restraint stresses in the UHPC. Of decisive importance were rather the types of cement and concrete plasticizer used because of their strong influence on the chemical processes and development of the mechanical properties during hydration. Observation showed that cracking risk exists within the first 15 h if Portland cement and a simultaneously high content of silica fume, and in particular if concrete plasticisers without retarding effect are used. There wasn´t any cracking risk when using blast furnace slag cement.

Special Concrete – Pavement Concrete

Ambient conditions are above all decisive to the temperature development of pavement concrete, less so the concrete composition. In case of strong radiation early-age heating can be very effectively achieved if a white-pigmented and thus reflecting curing agent is used. Of course, the development of restraint stresses essentially depends on the mechanical properties of early-age concrete. A favourable concrete composition may be demonstrated in the cracking frame.

High Strength Pavement Concrete: High-strength pavement concrete did show a clearly higher cracking tendency in the cracking frame than ordinary-strength pavement concrete. However, the extremely rapid strength development of high-strength pavement concrete at the same time means that there is only a small cracking risk, because in this case – even still during the heating phase - the concrete paving is relaxed by the cutting of joints long before a critical tensile load occurs.

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