Early-Age Cracking Risk and Relaxation by Restrained Autogenous Deformation of Ultra High Performance Concrete

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ABSTRACT

Ultra high performance concrete (UHPC) with 28 d compressive strengths up to 200 N/mm^2 contain high amounts of cement and silica fume at low w/c-ratios as well as highly effective superplasticizers. Such compositions enhance chemical and autogenous shrinkage. The development of stress due to restraint and thus the risk of cracking as well as the relaxation behaviour of UHPC was investigated under isothermal conditions (20 °C) using the rigid cracking frame. The elastic modulus, tensile splitting strength, free deformation and the stress induced by restraining the autogenous deformation were measured from initial setting up to an age of 28 days. The effect of cement type, w/c-ratio and silica fume content on the development of deformation and restraint stress due to hydration reactions and self-desiccation were investigated.
For Portland cement concrete at early ages between 12 and 15 h the risk of cracking was very high. At ages above 28 days the stress due to the restraint of the autogenous deformation was independent of the type of cement. The stress was about 40% of the splitting tensile stress. However, later crack formation and failure due additional stress at discontinuities (e.g. air voids, corners, notches) can not be excluded.

1 Introduction

The characteristic property of ultra high performance concrete (UHPC) is its high compressive strength with respect to its weight. Due to its low porosity and dense pore structure it can also be used successfully in aggressive environmental conditions (e.g. the substructure of the cooling tower CATTENOM [1] is made from reactive powder concrete).
It is well known that stress due to restrained autogenous deformation can develop in UHPC at early ages. In the worst case this leads to macro-cracks which increase permeability and therefore reduce the durability of the structure.
The reasons for deformation at early ages can be classified according to their origin:

- hydration heat
- chemical expansion
- chemical shrinkage
- autogenous shrinkage

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Especially the last two aspects have to be considered for high strength concrete. The first aspect applies to massive structures and is not considered in this paper.

2 Concrete Mixes, Treatment of Fresh Concrete and Specimens

Concrete Mixes

The concretes were made with different types of cement, w/c-ratios and contents of silica fume at constant binder paste volume (Table 1). The binder paste consisted of cement, silica fume, water and superplasticizer.

Table 1: Concrete mixes investigated

Parameter	**Unit**	**Concrete I**	**Concrete II**
Cement type	[-]	CEM I 42,5 R/HS	CEM III B 42,5 NW/HS (3)
Binder paste volume	[l/m³]	495	612
Silica fume (sf)	[wt.% of Cem.]	18 – 22 – 26 – 30 (2)	0 – 12 (1) – 14 – 18
w/c-ratio	[-]	0.27 (2) – 0.30 – 0.33	0.20 – 0.22 – 0.24 (1)

(1) reference mix concrete I
(2) reference mix concrete II
(3) blastfurnace slag content 70 %

Preparation of Fresh Concrete

The production of a pore-free fresh concrete with good flowing ability required a high standard of mixing technology for the low w/c-ratios and high powder contents of the mixes. A high intensity vacuum mixer (R02 Vac. Fa. EIRICH) was used which on account of its high mixing intensity, slanting mixing pot and ability to mix under reduced pressure had the following advantages:

- short mixing time
- effective mixing of small doses of additives
- homogenization of mix components with very different densities
- removal of air from the concrete while mixing.

Preliminary tests were performed to develop an optimal mixing procedure. This procedure was used for the production of all the fresh concretes. A total of 7.5 min was required to mix a batch of fresh concrete. This included a break of 3.5 min necessary to increase the effectiveness of the superplasticizer.

Specimens

In order to evaluate the mechanical properties it was necessary to make specimens of different geometry (Table 2). The specimens were cast immediately after mixing.

Table 2: Specimen geometry for different tests

Test	Specimen Geometry
Compressive strength	Prism (W/H/L = 40/40/160 mm) Cylinder (D/H = 50/50 mm)
Splitting tensile strength	Cylinder (D/H = 50/100 mm)
Static elastic modulus	Cylinder (D/H = 50/200 mm)
Autogenous shrinkage	Cylinder (D/H = 34/165 mm)
Restraint stress (centric tension)	Cracking frame Beam geometry (W/H/L = 50/35/420 mm)

The prisms (W/H/L = 40/40/160 mm) were only used to determine the compressive strength up to 1 day. The ends of the cylinders were ground coplanar before the tests.

3 Investigations

3.1 General

The development of the mechanical properties (compressive strength, splitting tensile strength and static elastic modulus), autogenous deformation and restraint stresses were investigated.
All tests were performed under isothermal (20 °C) and sealed conditions (no moisture exchange with the surroundings).

3.2 Mechanical Properties

The compressive strength, splitting tensile strength and elastic modulus were determined according to DIN 1048 T.5 [2]. The static modulus of elasticity was based on three consecutive loading and unloading cycles (lower stress = 0.5 MPa; upper stress = 1/3 of compressive strength at test time). The lower and upper stresses were kept constant for 30 s before and after third loading. However, to avoid deformation, the measurements at ages up to 1 day were carried out without the 30 s constant upper stress period.
As already known from normal and high strength concrete [3, 4], the static elastic modulus develops faster than the splitting tensile strength and the compressive strength (Figure 1).

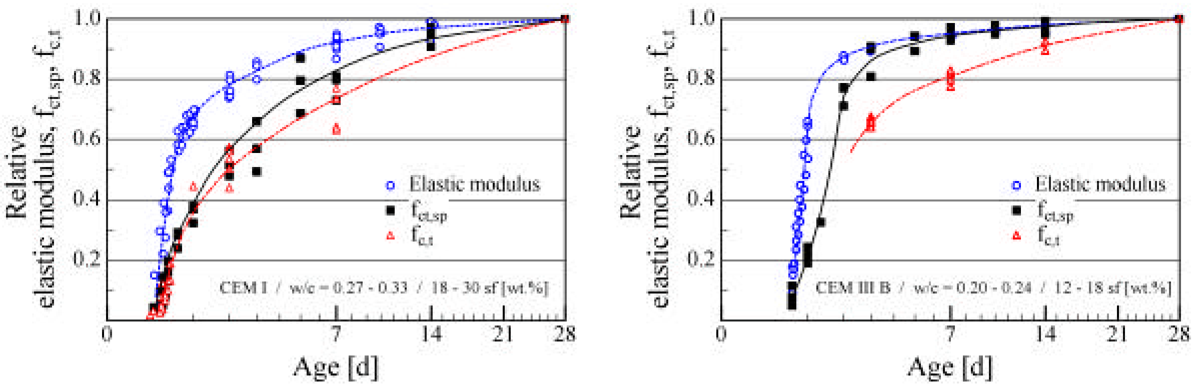

Figure 1: Development of mechanical properties (left: concrete with ordinary Portland cement; right: concrete with blastfurnace slag cement)

Compressive Strength

The 28d compressive strength of the initial concrete with OPC was about 15% higher than with the blastfurnace cement: roughly 171 compared with 148 MPa.
A decrease in silica fume content resulted in a loss of compressive strength only when the dosage was below the limiting value for a particular cement type. For OPC concrete this limit was found to be about 22 wt.% of cement. Owing to the range of binders investigated it was only possible to find an upper limit of 12 wt.% for the blastfurnace cement. Thus the 28 d compressive strength of the blastfurnace cement concrete without silica fume was very low at 111 MPa.
The effect the w/c-ratio on the blastfurnace cement concrete was more significant. The 28d compressive strength of the blastfurnace cement concrete with a low w/c-ratio of 0.20 was about 10% higher ($f_{c,t}$ = 165 MPa) than at a w/c-ratio of 0.24.

Splitting Tensile Strength

The 28d splitting tensile strength of all concretes was high at around 14 MPa. The splitting tensile strength of the concretes made with blastfurnace cement was observed to develop faster. After three days it was at roughly 12 MPa well above the strength of the OPC concretes, 8 MPa (Figure 2).
There was no obvious effect caused by the variation of the silica fume content and the w/c-ratio of both concrete types. The splitting tensile strength development tended to increase more slowly at higher w/c-ratios.

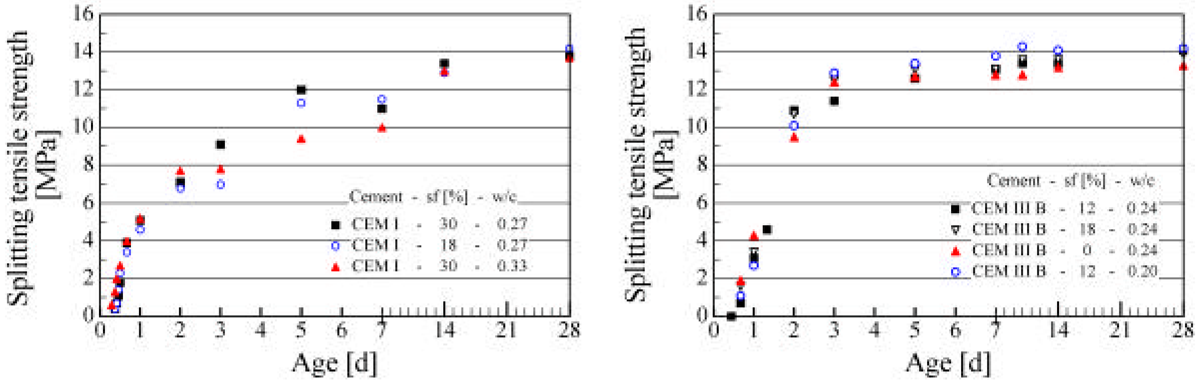

Figure 2: Effect of silica fume content (sf) and w/c-ratio on splitting tensile strength of the concretes with OPC (left) and blastfurnace cement (right)

Static Elastic Modulus

With the exception of the blastfurnace cement concrete without silica fume, the static elastic modulus of the concretes reached, independent of the cement type, about 45000 MPa after 56 days. The static elastic modulus of the blastfurnace cement concrete without silica fume was at 41000 MPa significantly lower. This seems to be caused by a disadvantageous pore size distribution of the hardened concrete. The static elastic modulus of the blastfurnace concretes developed somewhat faster than the Portland cement concretes (Figure 3).

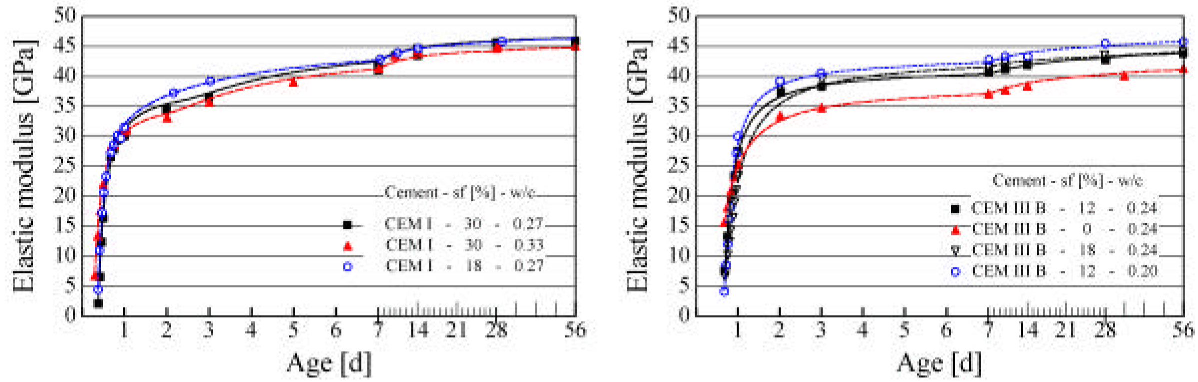

Figure 3: Effect of w/c-ratio and silica fume content (sf) on static elastic modulus of the concretes (left: OPC; right: blastfurnace cement)

The exponential function Equation 1 was fitted to the data for the elastic moduli in order to calculate theoretical stresses. As the curves in Figure 3 show, it was possible to obtain a very good fit of the experimental data with this function (Figure 3). The curves were calculated for time steps of 5 minutes.

$$E-Modul_{stat.} = \left(e^{-\frac{1}{t}}\right)^{f_I} \cdot b_I + \left(e^{-\frac{1,3}{t-a}}\right)^{f_{II}} \cdot b_{II} \qquad \textit{Equation 1}$$

where:	E-Modul $_{stat.}$	calculated static elastic modulus, time dependent
	β_I , β_{II}	factors dependent on concrete composition
	f_I , f_{II}	factors to specify velocity
	α	deceleration coefficient
	t	concrete age

3.3 Autogenous Deformation

To determine the free autogenous deformation, the length changes of the cylindrical specimens were monitored with transducers (one value per 5 min), see Figure 8. The measurements were performed under isothermal (20 °C) and sealed conditions. Restraint due to friction between the concrete and the plastic pipe containing it was prevented by inserting a teflon foil 0.25 mm in thickness. The temperature was recorded in the core of a reference specimen over the complete test period. The measurements started 30 minutes after the water was added to the mix.

In the following, the term autogenous deformation includes changes during the transition of the concrete from the fluid to the rigid phase where it is not possible to distinguish between chemical and autogenous shrinkage.

Due to intensive mixing and the initial chemical reactions, the temperature of the fresh concrete was between 28 to 30 °C. During the subsequent dormant period the specimens (small geometry) cooled down to room temperature (20°C) relatively fast.

At the beginning of the acceleration period after about 6 h for OPC and 9 h for blastfurnace cement, a temperature increase of at most 1.7K under isothermal conditions (20 °C) was observed (Figure 4).

The time shift of the individual hydration periods with respect to the values given in the literature [5, 6] is evidently due to the specific composition of UHPC (low w/c-ratio, high silica fume content, use of superplasticizer).

Since the coefficient of thermal expansion of concrete at ages up to 12 hours is not constant and the maximum temperature increase due to hydration is only 1.7K (isothermal conditions, small specimen), thermal expansion was not considered. However, a constant coefficient of thermal expansion of, for example, $\alpha_T = 1*10^{-5}$ 1/K, would increase the expansion by at most 1.5 % (Figure 4).

During the initial hydration phase a large contraction of the concrete was measured which ended after about 4 h. This was due to chemical shrinkage caused by the formation of ettringite and other early hydration products[7, 8]. Obviously, contraction also occurred as the fresh concrete cooled from about 30 to 20°C (see Figure 4).

To investigate this early contraction, the setting behaviour of one mix was examined with a Vicat needle apparatus. The initial and final set were found to take place about 2 h after termination of the early contraction (Figure 4), the time span being only 10 minutes. Furthermore, the time of setting coincided exactly with the temperature onset due to hydration. This corresponds to the beginning of the acceleration period, during which additional ettringite and a larger quantity of calcium silicate hydrates form which

involves a further volume decrease. At the same time portlandite is formed, which on its part reacts with silica fume and forms rigid CSH phases. This pozzolanic reaction also leads to a decrease in volume.
The contraction before setting is not considered in the evaluation of the autogenous deformation. The reference length is taken as the specimen length at the beginning of the temperature increase (t_0 in Figure 4).

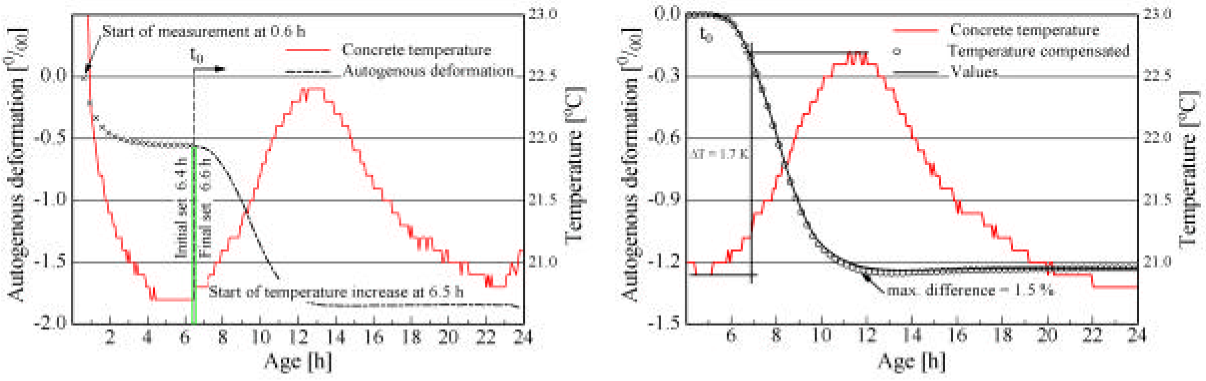

Figure 4: (left) Comparison of autogenous deformation, temperature development and setting (Vicat needle test); (right) effect of hydration heat on measured deformation

No significant dependence of the autogenous deformation on the silica fume content was observed for blastfurnace cement concretes. Obviously, this is due to the availability and/or amount of portlandite as a reactant for silica fume.
The blastfurnace cement concrete made without silica fume showed a smaller autogenous deformation than concrete containing 12 % silica fume (Figure 5). This confirms literature reports [9] which state that the reaction of silica fume with portlandite results in volume decrease.
During the first day, the autogenous deformation of OPC concrete made with 18 wt.% silica fume content was larger than for the concrete made with 30 wt.% silica fume. Afterwards the autogenous deformation developed in the same manner for both concretes. This was due to the higher cement lime content of the mix with less silica fume; the binder volume (water, cement, silica fume) of the two mixes was the same. According to Reschke [9] the shrinkage factor for the hydration of OPC (calculated for the clinker phases F_{CS}=0.1908) exceeds that of the pozzolanic reaction silica fume (F_{CS}=0.1021).
The cement type also had a significant effect on autogenous deformation. Thus despite lower cement contents, the contraction of OPC concretes was double that of the blastfurnace cement concretes; -1.3 ‰ compared with -0.6 ‰ up to 1d (Figure 5). This indicates that blastfurnace cement has a lower shrinkage factor than OPC.
Following the initial contraction (up to 20 h), all the concretes made with blastfurnace cement exhibited a slight expansion over the next 10 h. Afterwards the contraction continued. The reason for the expansion could not be established.
For both cement types the autogenous deformation was still in progress after 56 d, whereby the autogenous deformation of the OPC concretes was still significantly higher than for the slag cement concretes; -1.7 ‰ and -1.3 ‰, respectively (Figure 5).

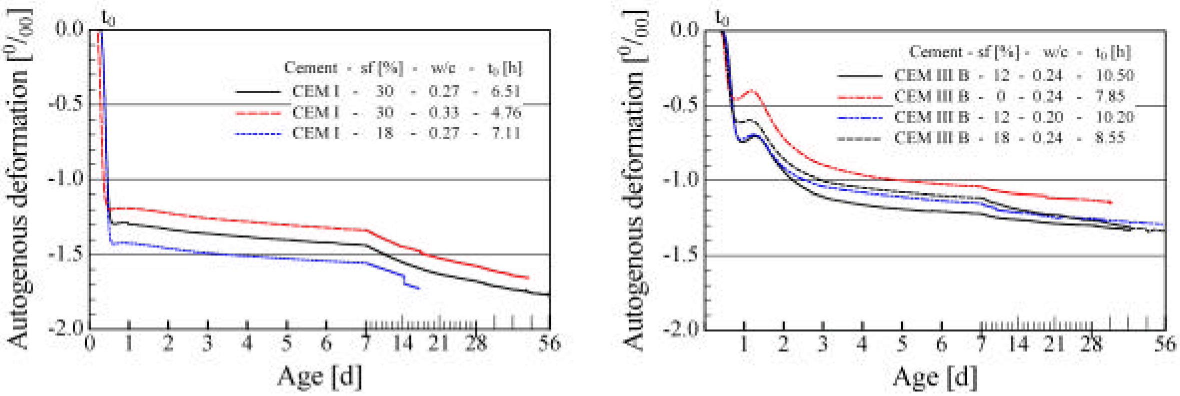

Figure 5: Autogenous deformation of the OPC concretes (left) and blastfurnace cement concretes (right) for various w/c-ratios and silica fume contents

3.4 Measurement of Restraint Stress

A rigid cracking frame was used to measure the stress due to the restrained autogenous deformation (one value every 5 minutes). The large contraction at early ages resulted only in low tensile stresses owing to the small elastic modulus and high relaxation ratio of the young concrete. The loss of stress due to slippage caused by shrinkage of the concrete was minimized by inserting steel bars perpendicular to the direction of measurement in the dovetails. In fact, no slippage occurred because no sudden changes in stress were observed.

Degree of Restraint

The degree of restraint in the cracking frame decreased from 100 % to about 80 % as the static elastic modulus increased to 45000 MPa after 28 d (Figure 6).

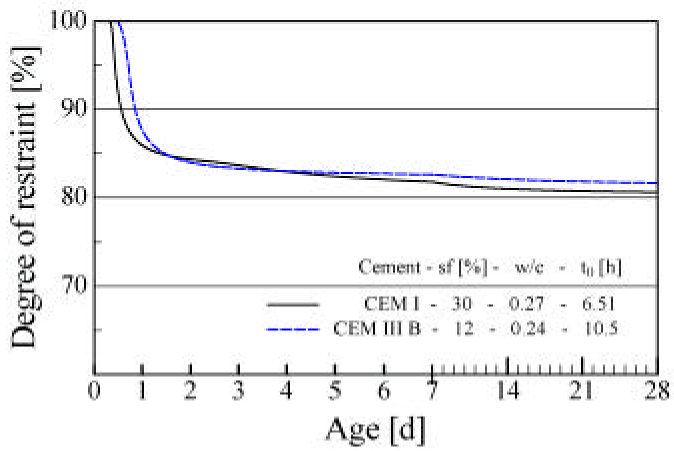

Figure 6: Time dependent degree of restraint in the cracking frame

A degree of restraint of 80 % corresponds roughly to that of a wall cast onto a foundation.

The qualitative development of restraint stress is analogous to the development of deformation strain. In spite of a low elastic modulus at early ages, the large initial contraction of OPC concretes resulted in an increase of restraint stress (centric tension) of 1.3 MPa after 12 h.

In the case of the blastfurnace cement concretes, the tensile stress increased only up to 0.9 MPa within 20 h. It then fell by about 66 % to 0.3 MPa during the expansion period (10 h) as elastic modulus increased (Figure 7).

During the following 1.5 days of hydration, the restraint stress of the blastfurnace cement concretes increased significantly faster and was at 5 MPa roughly three times higher than the stress developed with OPC. This was caused by the large autogenous deformation at high elastic modulus of the blastfurnace cement concretes.

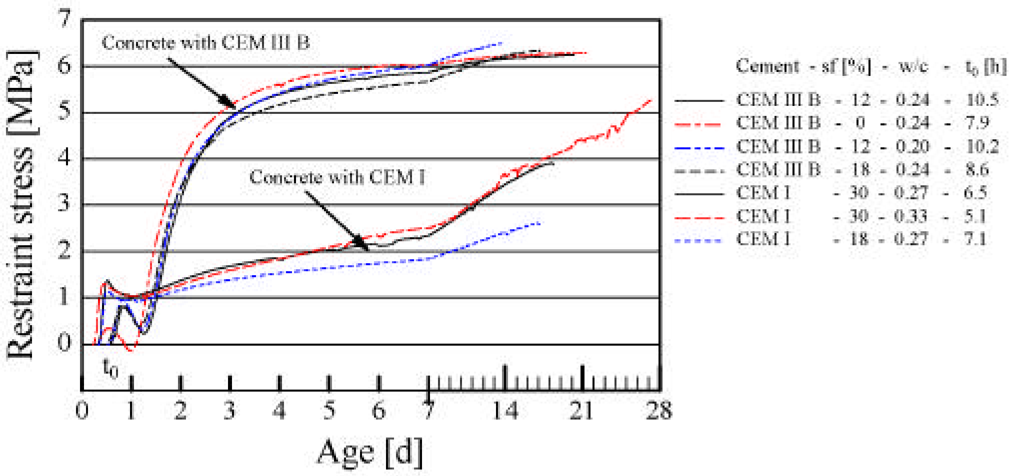

Figure 7: Centric tensile stress due to restrained autogenous deformation

4 Theoretical Stress Due to Restrained Autogenous Deformation

The restraint stress (without relaxation) was calculated from the free autogenous deformation, static elastic modulus and degree of restraint (δ), see equation in Figure 8.

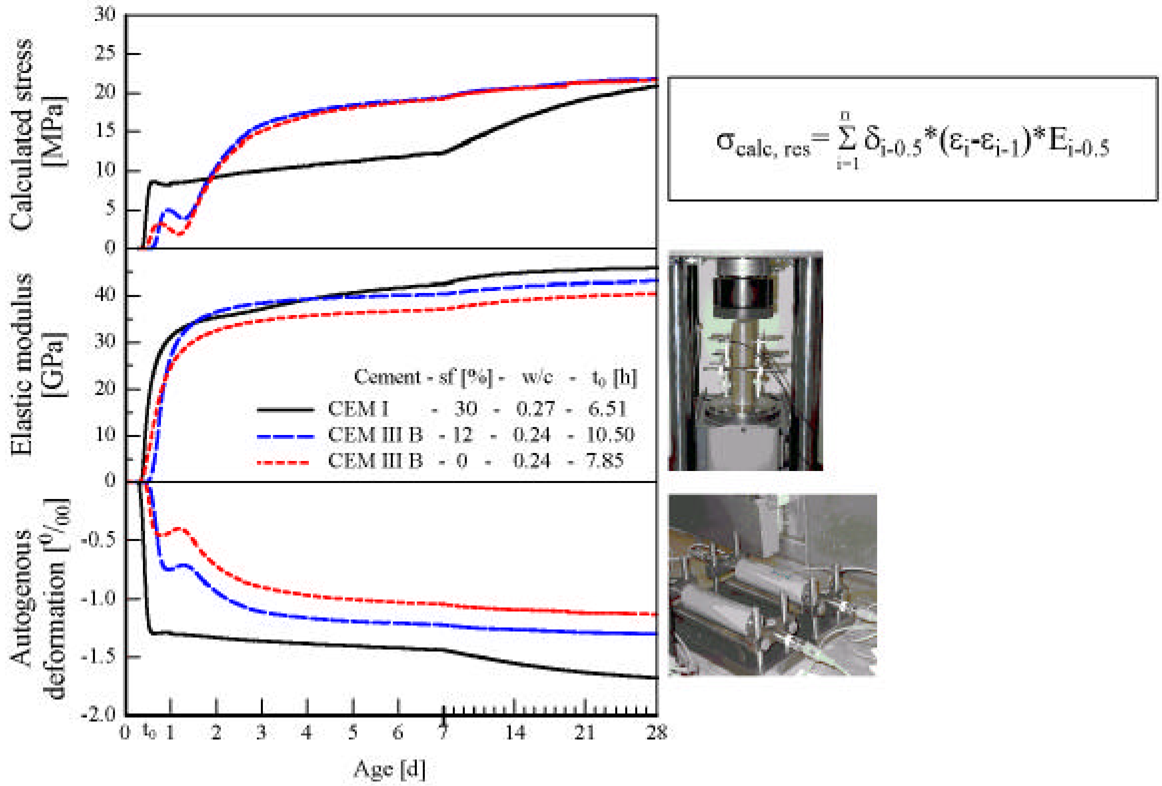

Figure 8: Calculated restraint stress of selected concretes (without relaxation)

As expected, the development of the calculated and measured restraint stress are qualitatively identical (Figure 7, Figure 8). The differences are due changes in the degree of load ($\sigma_{res.}/\sigma_{ct,sp}$) and relaxation with time.

5 Cracking Risk and Relaxation

<u>Cracking Risk</u>

If the large shrinkage deformation of high strength concrete is restrained by casting onto hardened concrete members or by the formwork itself in the case of filigree structures (degree of restraint ≥ 80%) the probability of cracking is high due to slower development of tensile strength compared with elastic modulus (Figure 1).

Bjontegaard [8] compared the tensile strength of concrete (w/c=0.4) which was loaded during hardening (cracking frame with moveable crossheads) with the strength of concrete which was not loaded. It was found that the tensile strength of the loaded concrete was about 20% lower. Moreover, other investigations [10] indicate that the tensile or tensile splitting strength decreases compared with the short-term value as the during of load becomes longer. Normal concrete loaded for 7 days had a tensile strength which was only 70 % of the short-term value.

According to investigations in [11] high-strength concrete is able to withstand stress at only about 70 % of the short-term tensile strength. Prolonged loading at higher stress values resulted in the initiation of micro-cracks at air-voids or sharp-cornered coarse aggregate. Failure finally occurred on account of the low late hardening of the high-strength concrete which meant that crack growth could not be inhibited.

The degree of load ($\sigma_{res.}/\sigma_{ct,sp}$) development for all the investigated concretes was calculated in order to evaluate the risk of cracking of UHPC. Figure 9 shows that the cracking sensitivity of OPC concretes within the first 12 to 15 h was very high (degree of restraint > 70%) whereas blastfurnace concretes were less vulnerable (25 to 35 %). Apparently, the critical loading period in the cracking frame was short enough not to lead to failure of concrete made with OPC. This period is almost identically to the dwell time of precast concrete in the formwork. However, these results can not be applied to practice owing to the elimination of temperature development (isothermal conditions 20°C) in the present experimental set-up.
At ages up to 1 d, the concretes with lower w/c-ratios and higher silica fume contents tended to result in higher degrees of load. After 3 d only a small effect was apparent.

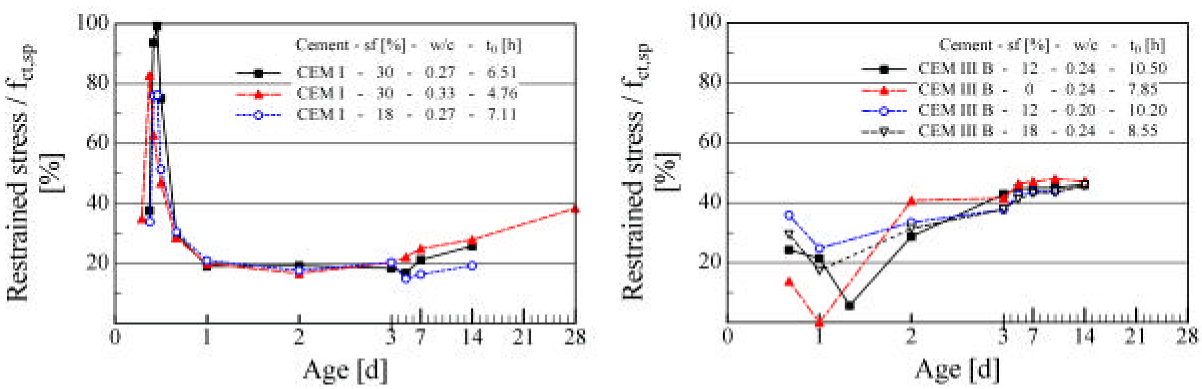

Figure 9: Development of degree of load due to restrained autogenous deformation of concretes with OPC (left) and blastfurnace cement (right)

If hardening occurred under the restrained conditions in the cracking frame, which corresponds to casting onto a hardened foundation, the degree of restraint for both concretes increased to over 40 % at higher ages. The superposition with discontinuity stresses, e. g. due to abrupt changes in thickness and edges, can result in an increase of the degree of load by up to 60 to 70 %. This can cause cracking at high ages on long-term loading (Figure 9).

Relaxation

Due to the changing ratio between the degree of load ($\sigma_{res.}/\sigma_{ct,sp}$) and the static elastic modulus during hydration it is not possible to draw quantitative conclusions on the relaxation behaviour as a function of time. It is possible, however, to describe relaxation qualitatively by comparing the calculated stress with the stress measured in the cracking frame.
For OPC concretes the difference between the calculated and measured stress, as a measure of stress-loss due to relaxation, increased quickly and remained at a constant

level after about 12 h. However, this took about 3 d for blastfurnace concretes (Figure 10). This different behaviour is also due to the very high degree of load of OPC concretes at early ages. Therefore a direct comparison is not possible.

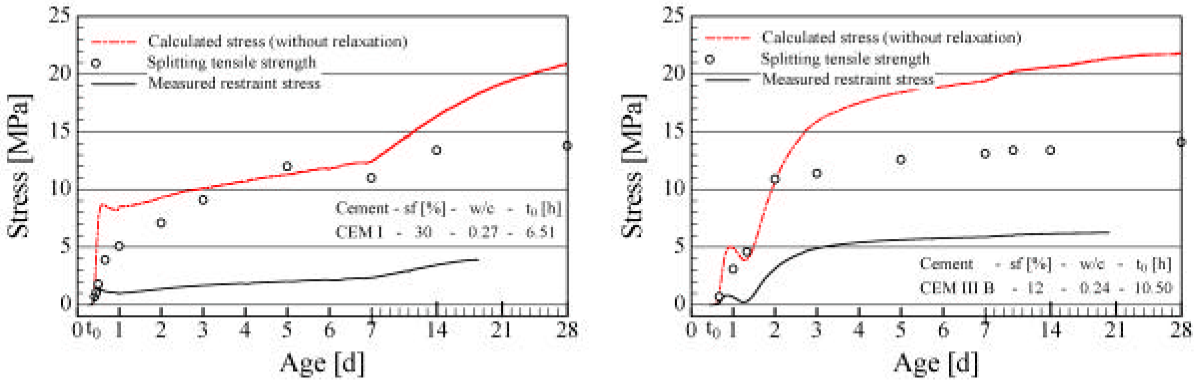

Figure 10: Development of restraint stresses, splitting tensile strength and calculated restraint stresses

For these specific conditions (degree of restraint in Figure 6, isothermal conditions 20 °C) the results permit a specification of the relaxed restrained stresses at a particular time. For example, the restrained stress for the OPC reference concrete relaxed by 88.5 or 78.9 % after 1 or 14 d, respectively.

The relaxation of concrete at early ages (up to 3 d) made from both types of cement tended to increases at lower silica fume contents. At high ages (14 days or more) the relaxation of the blastfurnace concrete was around 70 % irrespective of the silica fume content. Opposed to this, OPC concrete with a lower silica fume content (18 compared with 30 wt.%) showed a higher relaxation even after 14 d (87.0 and 78.9 %, respectively).

Only in the case of blastfurnace cement concretes did a decrease in w/c-ratio result in lower relaxation rates over the whole period of measurement (up to 14 or 28 d).

6 Conclusions

During the first two days of hydration, the splitting tensile strength increased continuously up to 10 MPa. At an age of two days, the restrained tensile stress reached as much as 3 MPa. The stress development calculated from the elastic modulus and autogenous shrinkage was larger than the splitting tensile strength. However, this stress was reduced due to early age relaxation.

The risk of cracking was defined by the degree of load as given by the ratio of restraint stress to tensile splitting strength. For Portland cement concrete at early ages between 12 and 15 h the risk was with a degree of load greater than 70 % very high. Following 14 to 28 days hardening under restrained conditions at 80 % or more restraint the degree of load was roughly 40 %, independent of the type of cement. In this case, later crack formation and failure due additional stress at discontinuities (air voids, corners, notches etc.) can not be excluded.

The rate of relaxation tends to increase for both Portland blastfurnace and Portland cement concrete with low silica fume content at ages up to 3 d. After 14 d, the relaxation of the concretes made with blastfurnace cement was roughly 70 % for all silica fume contents. At ages above 14 d, the Portland cement concrete with a lower silica fume content of 18 wt.% (with respect to cement content) exhibited a higher degree of relaxation than the concrete containing 30 wt.% silica fume (87.0 and 78.9 %, respectively). Only in the case of concrete made with blastfurnace cement did a reduction in w/c-ratio lower the rate of relaxation throughout the complete duration of measurement.

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