Mitigating autogenous shrinkage of hardening concrete

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ABSTRACT: The probability of early age cracking in hardening concrete can be affected by using additives that reduce the total shrinkage of a mixture with emphasis on the reduction of autogenous shrinkage. In order to become more insight in the effectiveness of shrinkage reducing additives, an experimental programme is currently running at TU Delft. Experiments are performed for water/cement ratios varying from 0.3 to 0.5, for Portland cement as well as Blast Furnace Slag cement. All mixtures are tested isothermally at 20ºC. The early-age shrinkage deformations are measured over a testing period of 90 days. The development of compressive strength, tensile splitting strength and elastic modulus will be determined from respectively cubes and prisms that harden under similar conditions. Results obtained from this experimental programme provide the effectiveness of shrinkage reducing additives and their influence on development of the mechanical properties. The autogenous shrinkage, being a single contribution of total shrinkage, will be addressed explicitly.

1 GENERAL

Autogenous shrinkage is one of the causes of cracking of hardening concrete elements. Autogenous shrinkage occurs if less water is present in the mixture than required to hydrate all binder material and that, as a result of this, capillary forces develop. During the hardening process of a so called low-water-binder ratio concretes, the internal demand for water is higher than the amount of water available. This is called 'internal' drying and causes the concrete to shrink ('autogenous shrinkage'). Mitigating autogenous shrinkage will reduce the probability of cracking of the hardening concrete elements.

Super Absorbent Polymers can be used to mitigate autogenous shrinkage by internal curing. To become more insight in the effectiveness of those Super Absorbent Polymers, an experimental programme (figure 1) is currently running at TU Delft. First two mixtures are compared, one mixture without polymers and one mixture with polymers. Preliminary results of those tests are presented are presented in this paper.

2 MIX DESIGN

Two mixtures have been tested, as presented in table 1. Firstly, a C68/85 concrete without polymers and secondly, the same concrete with polymer addition. First mixture has also been used in previously research by Sule (2003), Lokhorst (2001), and Koenders (1997). The polymer dosage was 2 kg/m3. The water-cement ratio was increased from 0.28 to 0.31 to compensate for the influence of the polymer on the workability.

Table 1. Mix proportions (kg/1000 l)

Mixture	32REF	32A133
water	125.4	144.9
CEM III/B 42.5 LH HS	237	232.6
CEM I 52.5 R	238	233.6
sand 0-4mm	755	740.7
aggregate 4-16 mm	1001	981.9
Addiment BV1	1	1
Addiment FM951	9.5	9.3
Silica fume slurry	50	49.1
Polymer Powder	0	2

3 SUPER ABSORBEND POLYMERS

Super absorbent polymers (figure 2) and extra water are added to the concrete mixture separately, in order to mitigate autogenous deformations. The polymers are considered to absorb all the extra added mixing water which will release during cement hydration. The release of the extra water during hardening will affect the internal drying and, as a result of this, the autogenous deformations as well.

Mixing procedure:
- prepare mixer;
- mix sand and gravel for 1 minute;
- add dry polymers and mix for 2 minutes;
- add cement and mix for 1 minute;
- add water and additives and mix for 1.5 min.

In order to achieve a homogenous distribution of the polymers and avoid clusters of polymers in the mixture, the polymers are added to the sand-gravel mixture in a dry configuration.

4 TESTING PROGRAM AND METHODS

The early-age shrinkage tests were carried out using three ADTM (Autogenous Deformation Testing Machine) apparatus. It measures the deformation of a specimen that is free to deform. Figure 5a gives an overview of its functioning. Three insulated moulds are used (figure 5b); two of 1000 mm long and one of 850mm long. All three are 150 mm wide and 100 mm high. The walls of the mould contain plastic tubes that are connected to cryostats units. The temperature of the specimen is measured by means of three thermocouples, one in the middle and two in the ends of the specimen. The cryostats control the water flow through the tubes to maintain the required temperature regime in the specimen. All tests are performed under isothermal conditions, at 20ºC. Directly after casting, all moulds are covered with plastic foil and covered with an insulated plate.

Two small steel bars were embedded in the three specimens, 750 mm apart from each other. These bars protrude through the two holes in the long side faces of the mould, while not making contact with the mould itself. Thus, the ends of the steel bars could move freely over a certain deformation range. As soon as the fresh concrete starts to develop some strength and stiffness, the LVDT's (linear voltage displacement transducers) positioned along the long side faces of the mould were activated and attached to the small steel bars that protrude through the mould (figure 5c). From that moment on (t-zero [8]), the deformation of the specimen over a 750 mm measuring length was registered, both at the front and rear of the specimen.

5 TEST RESULTS

5.1 *Adiabatic temperature development*

With respect to the adiabatic temperature development of the two tested mixtures (figure 7), slight differences are expected in terms of the degrees of hydration. It is likely that a prolonged hydration process will be observed due to the addition of the release of extra water from the SAP.

5.2 *Short term shrinkage – ADTM-tests*

Autogenous deformations are measured from three sealed specimens. During testing, similar conditions were applied, i.e. temperature of 20°C and a relative humidity of 50%. The measured autogenous deformations are presented in figure 6 and represent the mean values of the three specimens. Variation of the results, which turned out to be 2% for the concrete without SAP and 23% for the mixture with SAP, is calculated by dividing the standard deviation by the mean value. This high variation of the concrete with SAP is due to the mean value fluctuates around zero.

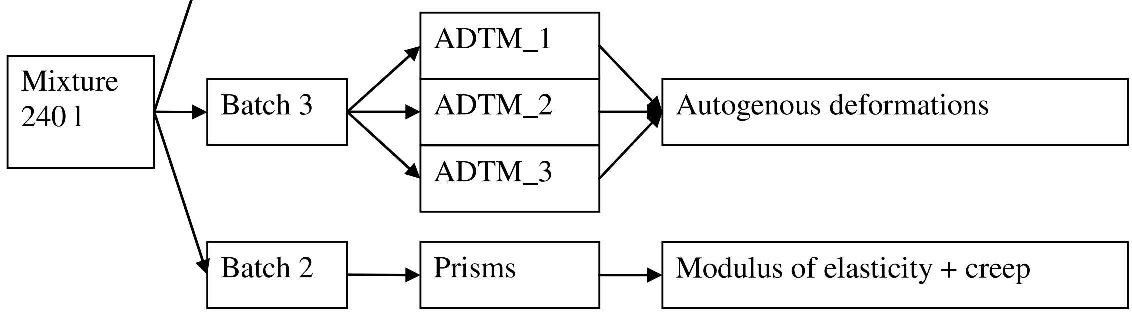

Figure 1. Testing program

Figure 2. From left to right two polymers, one unsaturated and one saturated [4], 25 grams of unsaturated polymers and 630grams of water absorbed by 25 gram polymers

Figure 3. Prisms Cubes

Figure 4. Long term shrinkage measurements

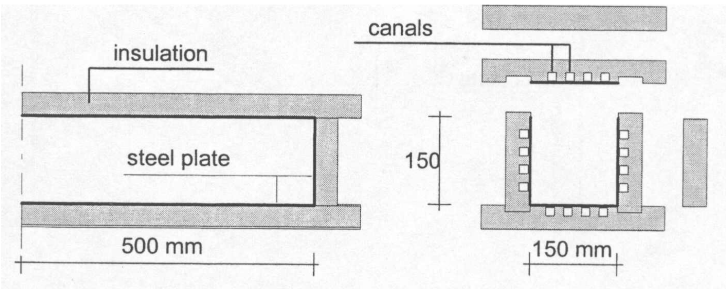

Figure 5b. Schematically drawing of ADTM-setup Lokhorst (2001)

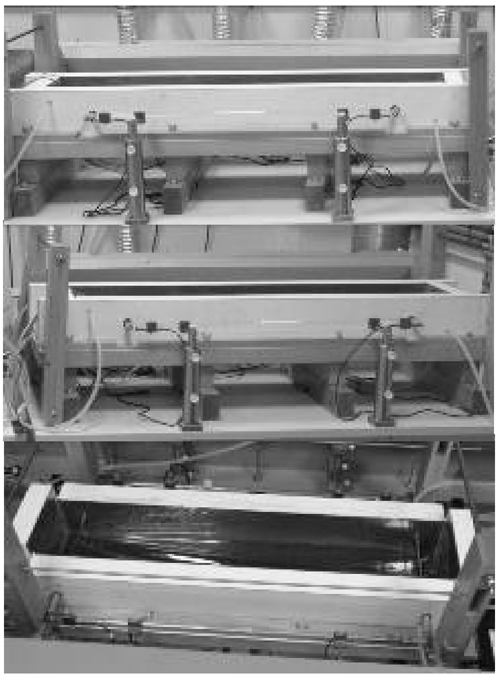

Figure 5a. ADTM1, 2 and 3

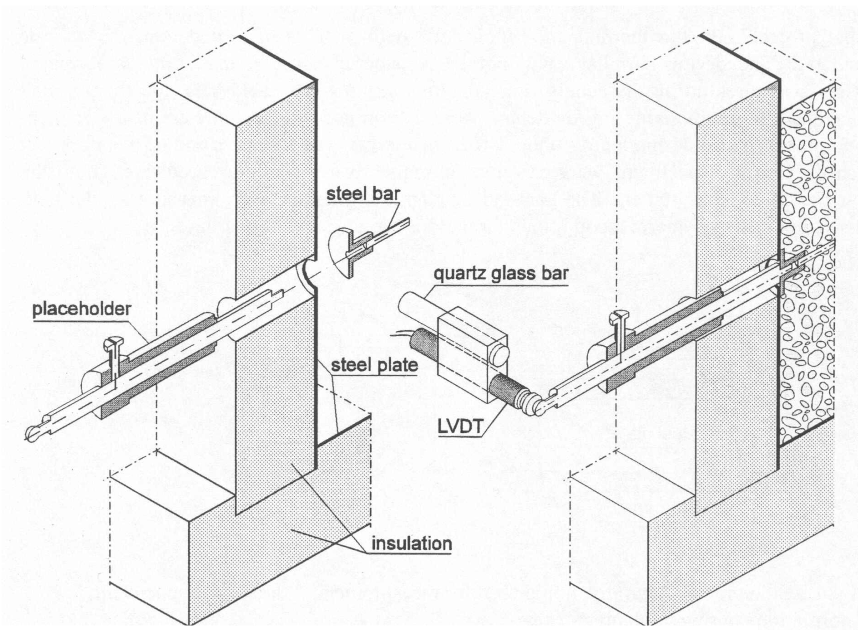

Figure 5c. Schematically drawing of LVDT placement Lokhorst (2001)

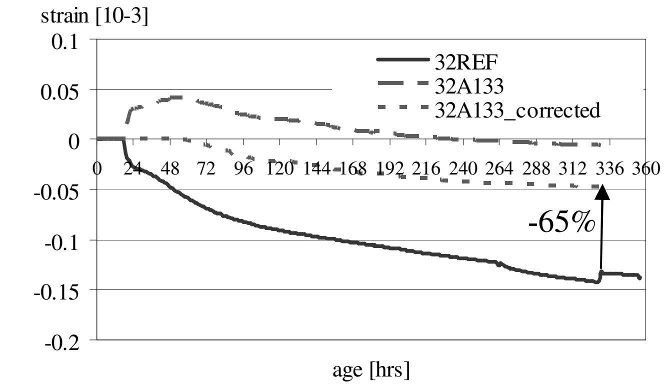

Figure 6. Measured autogenous deformations

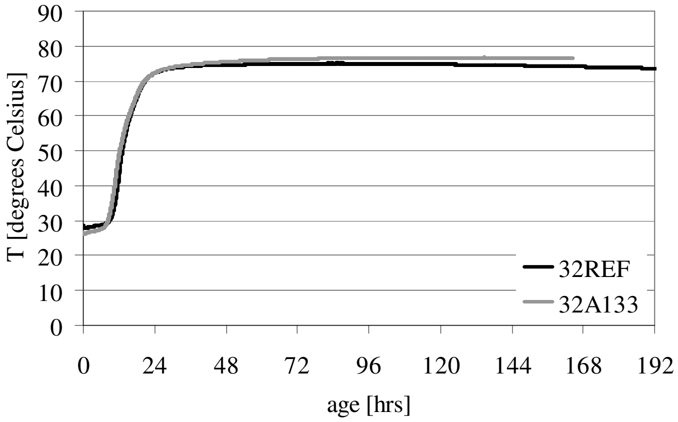

Figure 7. Adiabatic temperature development

The deformations of the 32A133 mixture are corrected for the expansion in the first 20 hrs (figure 6) because this will lead to relative small compressive stresses which will relax, compared to the tensile stresses due to the shrinkage after the expansion. The reduction of shrinkage between the reference concrete and the corrected deformations of the 32A133 mixture turned out to be about 65% (figure 6).

Note that this will not result in 65% lower stresses due to autogenous shrinkage. In order to determine the efficiency of the polymers in terms of mechanical properties, information is needed about the development of these properties of the concrete, like development of compressive strength, tensile strength, modulus of elasticity and relaxation.

5.3 *Long term shrinkage – ADTM-tests*

Because the extra water added to the mix to obtain a similar workability as the reference concrete it is to be expected that the hydration process will proceed for a longer period. This might result in an ongoing refinement of the pore structure and, hence, a possible higher shrinkage. It is therefore that the shrinkage of the 32A133 mixture is measured for a longer period of at least 90 days (figure 4). The results up to now are presented in figure 8. After correcting the expansion in the first 20 hours, the difference is still 50%.

5.4 *Tensile strength*

For the tensile strength, even bigger reductions (-14%) are observed (measured from cubes, figure 3) due to the addition of SAP, with a maximum reduction of almost 20% after 14 days of hardening (figure 9 middle).

5.5 *Modulus of elasticity*

Reductions in measured modulus of elasticity (measured from prisms, figure 3) are less (-6%) compared to differences in compressive strength and tensile strength. The results of the measurements are provided in figure 9 (right).

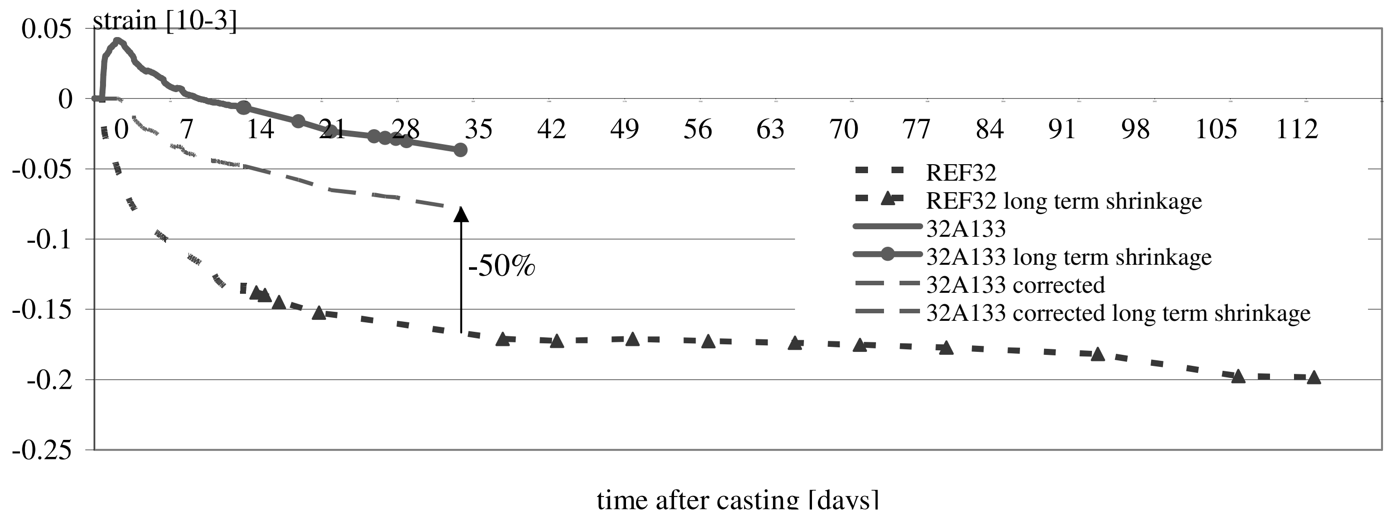

Figure 8. Measured and corrected long term shrinkage

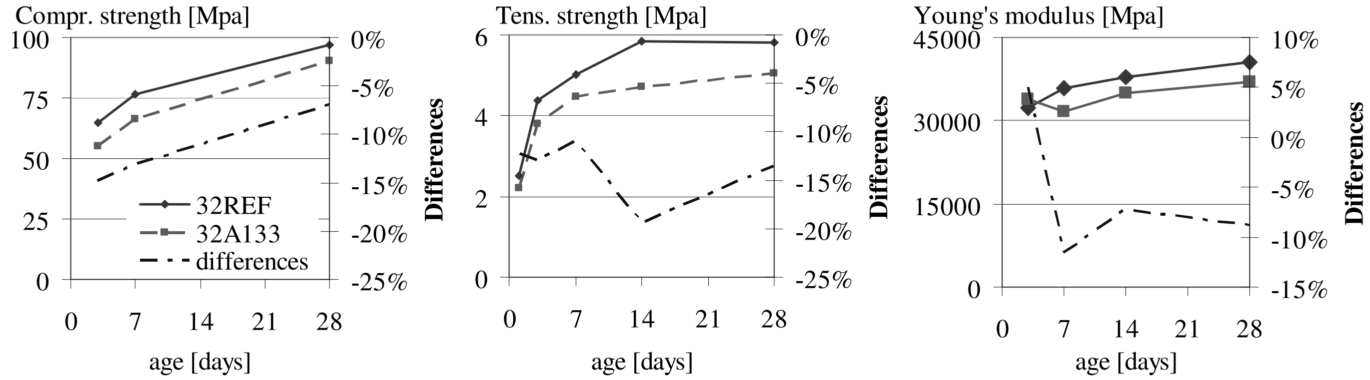

Figure 9. Development concrete properties and influence of SAP

6 CALCULATED STRESSES DUE TO MEASURED AUTOGENOUS DEFORMATIONS

From the experiments, substantial differences are observed in the development of the visco-elastic properties of the hardening concrete (figure 9) containing SAP compared to the ref. concrete (table 2).

Table 2. Average effect SAP on properties and probability of failure P_f

32A133 compared to reference mixture		effect on P_f
short term shrinkage (2 weeks)	- 65%	positive
long term shrinkage (5 weeks)	- 50%	positive
compressive strength	- 12%	negative
tensile strength	- 14%	negative
modulus of elasticity	- 6%	positive

To calculate the actual stresses due to the autogenous deformations, a trend line is fitted into the test results of the modulus of elasticity, both for the mixture with and without polymers. The development of the modulus of elasticity can be described by:

$$E = 3592 \cdot \mathrm{Ln}(t) + 17075 \quad (1)$$

for the mixture without polymers (32REF), and

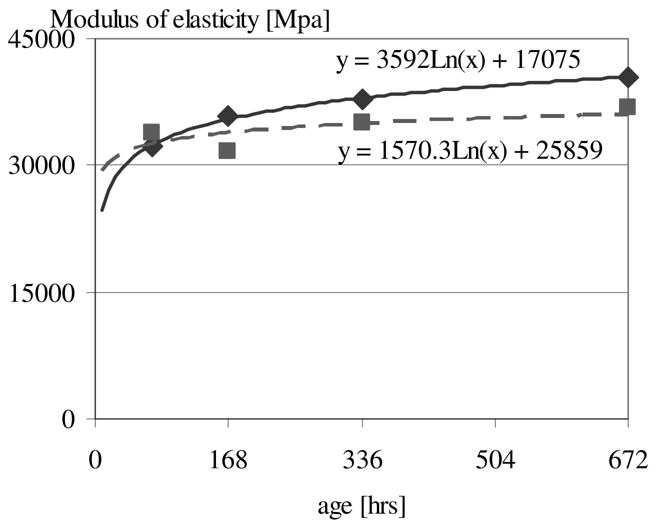

Figure 10. Measured and modelled modulus of elasticity

$$E = 1570{,}3 \cdot \mathrm{Ln}(t) + 25859 \quad (2)$$

for the mixture with polymers (32A133) in which t is the time after casting in hrs (figure 10).

Measured autogenous deformations of both mixtures are modeled by polynomial formulations, as presented in figure 11. To correct for the starting time of the measurements (17 hours after casting, see figure 6), the polynomial formulations are shifted for 17 hours.

The adiabatic degree of hydration is calculated from the adiabatic temperature development by:

$$\alpha_h(t) = \frac{(T_a(t) - T_a(0)) \cdot \frac{\rho \cdot c_c}{C}}{Q_{max}} \quad (3)$$

in which:

T_a = adiabatic temperature [K]
ρ = volumetric density of concrete [kg/m^3]
c_c = specific heat of concrete [kJ/kg/K]
C = amount of cement [kg]
Q_{max} = maximum heat production [kJ/kg]

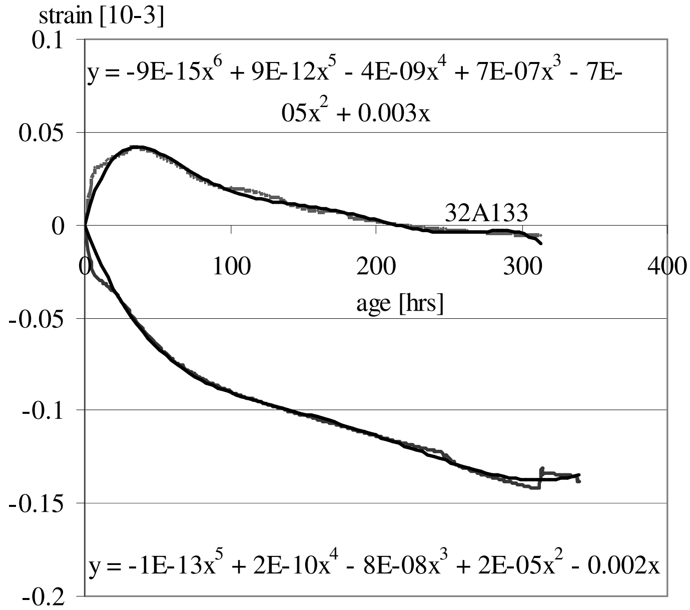

Figure 11. Measured and modelled autogenous deformations of both mixtures

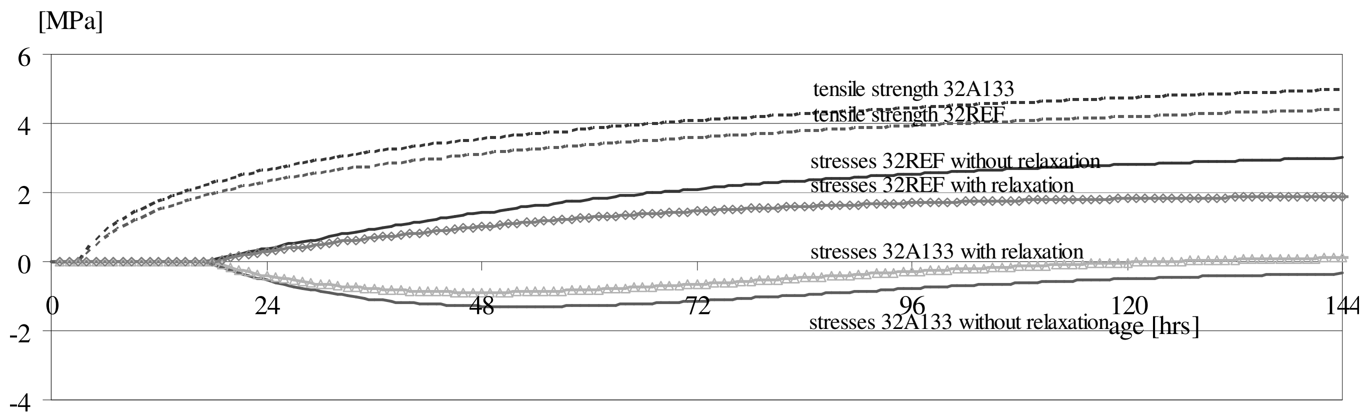

Figure 12. Calculated stress development due to measured autogenous deformations

Because the experiments are performed at isothermal conditions of 20 °C, the degree of hydration in the specimen will be lower compared to the adiabatic degree of hydration. To calculate the process degree of hydration, the heat production in the specimen can be calculated by:

$$\Delta Q_{p;j+1} = \Delta Q_{a;j+1} \cdot e^{-\frac{E_A(T_{p;j})}{R}\cdot\frac{T_{a;j}-T_{p;j}}{T_{a;j}\cdot T_{p;j}}} \quad (4)$$

In which:
E_a = apparently activation energy [kJ/mol]
R = universal gas constant [R=8,31J/mol/K]
$T_{a;j}$ and $T_{p;j}$ are the temperatures [K]
$\Delta Q_{p;j+1}$ = produced process heat in timestep j
$\Delta Q_{p;j+1}$ = produced adiabatic heat in timestep j

The calculation of the stress development is based on elastic and time-dependent deformational behavior of concrete. The elastic stress increments are calculated according to:

$$\Delta\sigma_e(\tau) = \Delta\varepsilon_a(\tau)\cdot E(\tau) \quad (5)$$

Where:
$\Delta\sigma$ = elastic stress increment [MPa]
τ = age at loading [hrs]
$\Delta\varepsilon_a$ = increment of autogenous def. [-]
E = modulus of elasticity [MPa]

The superposition principle is used to take into account the stress history [5]:

$$\sigma(t) = \sum_{i=0}^{j}\psi(t,\tau)\cdot\Delta\sigma_e(\tau) \quad (6)$$

With for the relaxation factor:

$$\Psi(\tau_i, t, \alpha_{\tau,i},) = \exp\left(-\left[\frac{\alpha_h(t)}{\alpha_h(\tau_i)} - 1 + 1.34 * \omega^{1.65} * \\ * \tau_i^{-d} * (t-\tau_i)^n * \frac{\alpha_h(t)}{\alpha_h(\tau_i)}\right]\right) \quad (7)$$

And
α_h = degree of hydration [-]
τ = age at loading [hrs]
ω = water/cement ratio [-]
d = 0.3 (slow) and 0.4 (rapid cement) [-]
n = 0.3 [-]

The results of the calculations with and without relaxation are shown in figure 12. The reference concrete without Super Absorbent Polymers will reach a tensile stress of about 2 MPa, while the concrete with Super Absorbent Polymers develops almost no

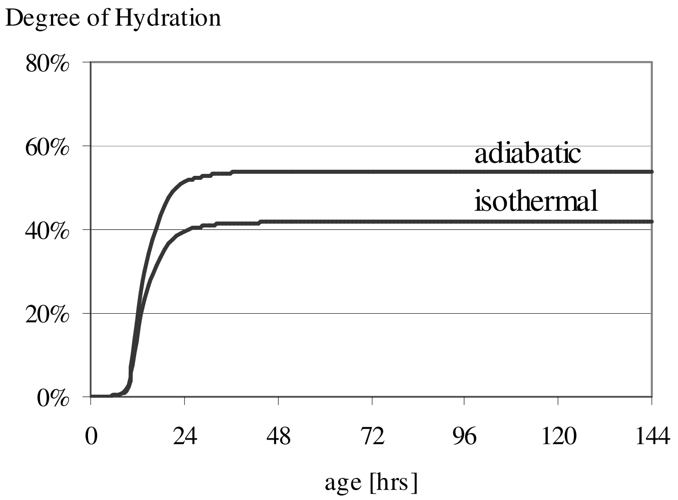

Figure 13. Adiabatic and isothermal degree of hydration

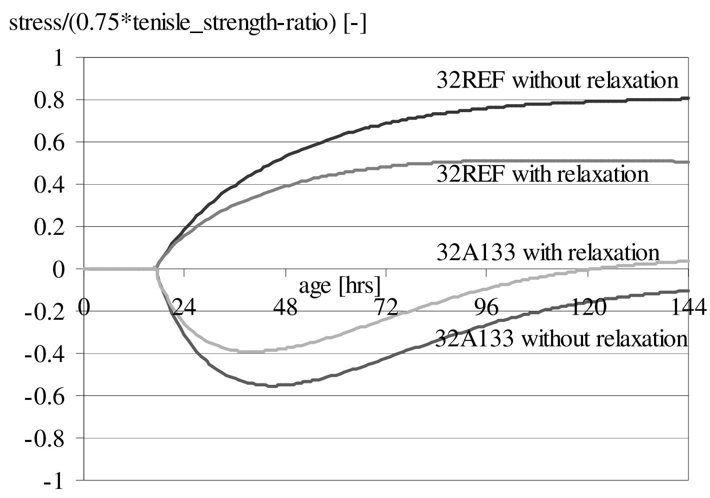

Figure 14. Calculated stress/(0.75*strength)-ratio

tensile stresses during the first 144 hours. After 144 hours, no extra tensile stresses will develop due to more autogenous shrinkage because those extra stresses will relax immediately.

For the calculations with relaxation, both calculations are performed using equal relaxation. For the concrete containing Super Absorbent Polymers, bigger relaxation is expected compared to the reference concrete, because of the bigger pores in the microstructure. The total pore volume will not change, but the amount of small pores will decrease Mőnnig (2005). To determine the influence of Super Absorbent Polymers on creep and relaxation of hardening concrete, creep experiments under a constant compressive load will be performed soon. This effect is not taken into account yet.

Stress/strength-ratios are calculated for both mixtures for the first 144 hours after casting. From experiments, a cracking criterion is proposed by Lokhorst (2001) to be stress > 0.75*tensile strength. If relaxation is taken into account, a maximum stress/strength-ratio due to only autogenous shrinkage is observed to be almost 0.5 for the reference concrete without Super Absorbent Polymers. For the concrete which contains Super Absorbent Polymers, The maximum stress/strength-ratio in the first 144 hours is almost 0. This positive effect of the SAP might be less at higher ages, due to faster shrinkage of the specimen what contains SAP, compared to the specimen without SAP (compare figure 6 and 8).

7 CONCLUSIONS

- Adding 2 kg/1000l Super Absorbent Polymers to the tested mixture results in a reduction of autogenous shrinkage after 336 hours of 65%. After 800 hours, this is reduced to 50%.
- Adding 2 kg/1000l Super Absorbent Polymers to the tested mixture results in an average reduction of the compressive strength of 12%, the tensile strength of 14% and the modulus of elasticity of 6%.
- Adding 2 kg/1000l Super Absorbent Polymers to the tested mixture, more relaxation is expected.
- Adding 2 kg/1000l Super Absorbent Polymers results to lower stresses in the hardening concrete (2 MPa after 144 hours), which results in a lower stress/strength-ratio due to only autogenous deformations from 0.5 to 0.04 after 144 hours. At higher ages, the effect of SAP might be less, due to a faster shrinkage after 144 hours of the mixture containing SAP compared to the mixture without SAP.

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