PARAMETER STUDY OF THERMAL CRACKING IN HPC AND NPC STRUCTURES

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ABSTRACT

This paper presents a study of HPC (High Performance Concrete) and NPC (Normal Performance Concrete) structures with regard to cracking due to thermal and autogenous deformations. Comparison of two reference walls is made by means of computations. Special attention is paid to parameters dominating cracking at early ages: the difference between placing temperature and adjoining concrete temperature, cement type, ambient temperature variation and the presence of reinforcement.

It is concluded that the HPC wall is more sensitive to early age cracking and needs more differentiated crack control criteria than the NPC structure. The most effective crack control criterion is the temperature difference between placing temperature and adjoining concrete. Halving the temperature difference leads to a crack risk reduction of about 35%. The effect of autogenous shrinkage can be reduced by more than 50% by using low heat cement in combination with low difference between placing temperature and adjoining concrete temperature.

Key words: HPC (High Performance Concrete), NPC (Normal Performance Concrete), thermal cracking, autogenous shrinkage, ambient temperature variation, reinforcement.

1. INTRODUCTION

A few years have now passed since the Swedish National Project on High Performance Concrete ended. With several subprojects, among others one dedicated to thermal stresses and early age cracking, this project was a unique investment in research focused on HPC. The results of the project are now concluded in practical handbooks on design rules [1], design examples [2] and on material properties and production [3, 4]. This paper relates to the subproject on thermal stresses and early age cracking carried out by researchers at Luleå Technical University, at the

Dept. of Structural Engineering. The main purpose of the paper is to extend the findings of one of the design examples by a parametric study of HPC in comparison to NPC structures.

HPC may be defined as concrete with water/binder ratio (w/b) below 0.4. Due to the low w/b ratio and consequently increased heat of hydration, HPC structures show an accentuated tendency for cracking at early ages. The presence of silica fume as a binder aggravates this tendency. Another characteristic of HPC is the self-desiccation causing deformations termed autogenous shrinkage. As autogenous shrinkage is explained as the decreased volume of reaction products when the water reacts with cement it also leads to increased tensile stresses and risks for cracking at early ages.

Many parameters in the process of crack control are well documented in NPC structures due to the intensive research during the last years, [5]. Traditionally, in thin NPC structures (<0.5 m) early age crack control is based on so-called temperature criterion limiting the temperature differences between the new concrete and the adjoining structure. This criterion, however, may be insufficient in HPC structures. HPC structures are in most of the cases slender (<0.5 m) with a considerable bearing capacity and therefore also show increased sensitivity to the external restraint acting on the structure. This becomes more important in the view of higher E-modulus values and more brittle behaviour at fracture of HPC compared to NPC. All in all this could lead to an accentuated tendency for through cracks in HPC structures.

Two reference walls (HPC and NPC) with approximately the same bearing capacity are investigated, see *Fig.1*. For computations the FEM-based 2D program Hacon$^{3.0}$ [6] is used. In Hacon$^{3.0}$ simulation of temperature and stress can be made in hardening concrete with possibility to model autogenous shrinkage. Symmetry of the structure is considered in both longitudinal (plane stress analysis) and transversal direction (plane strain analysis). The temperature development is studied in the transversal direction, while stresses are checked both in transversal and longitudinal direction for development of surface and through cracks.

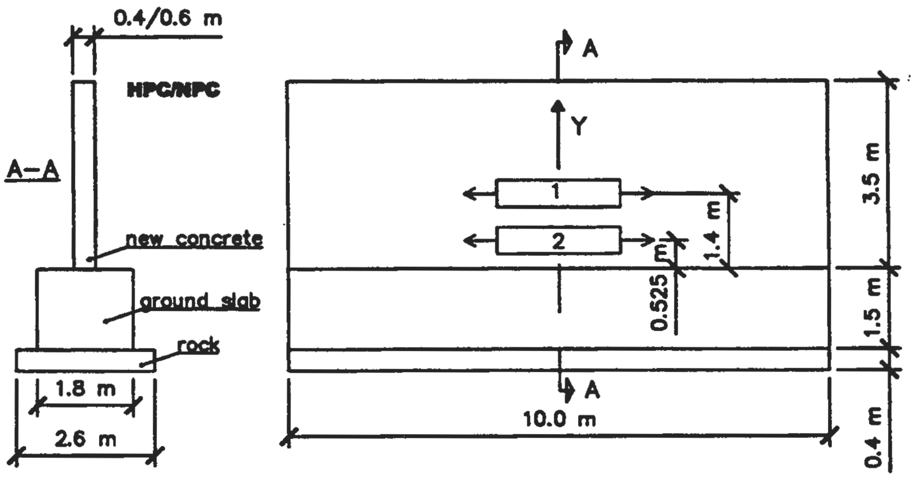

Figure 1 - Reference structure for HPC and NPC.

2. PARAMETRIC INVESTIGATION

General computation assumptions: the walls are 10 m long, the casting forms are not removed during the 10 days long studying period, forms of 22 mm wood are used, wind velocity is 1 m/s. The concrete recipes are corresponding to HPC K95 (cement Type I, Slite 450 kg/m^3, silica fume 22.5 kg/m^3, w/b ratio 0.31, reference autogenous shrinkage strain 1.5E-4) and NPC K45 (cement Type I, Slite 300 kg/m^3, w/c ratio 0.49).
In Hacon$^{3.0}$ autogenous shrinkage is modelled as proposed by Auperin [7]. Parameters included in the model are the maturity at start of autogenous shrinkage taken to t_a=50 h in this case, the development parameters t_2=75 h and κ_2=1.01 and the reference autogenous shrinkage strain taken as ε_{a0}= 1.5E-4. Values of these parameters originate from curve adjustment to test data [8]. Note that the reference autogenous shrinkage value is measured at sealed conditions and when used in outdoor climate leads to uncertainties in calculation results.

The wall is newly cast and assumed to become totally restrained by the ground slab (old concrete), while between the ground slab and underground (rock) only movements in the vertical direction are restrained. The risk for cracking is defined as the ratio between the tensile stress and the tensile strength of the concrete at a certain time. A maximum value between 0.6-0.7 is regarded as giving a reasonable safety against thermal cracking. The influence of several parameters is investigated with regard to maximum mean temperature during hardening and risks for both surface and through cracks at reference point 1 and 2 on the wall, see *Fig.1*.

The two reference points where chosen in accordance with findings in [2] showing that through cracking is likely to occur at y=1.4 m above the cast joint for the case with large temperature difference between placing and adjoining concrete and at y=0.525 m for the case with low temperature difference. The recommendation is based on the manual method for prediction of crack risk due to early age volume change by Emborg&Bernander [9] and it gave good agreement with the maximum stress location during the course of the computer simulations.

In this paper the term surface crack is used for cracks occurring in the heating phase of concrete hydration, generally of horizontal orientation and with tendency to close during cooling. Note though that not every crack in the heating phase of the concrete is surface crack. As surface cracks appear due to a temperature gradient through a concrete section the surface crack risk is assessed in the transversal direction of the wall while through crack having been caused by the external restraint acting on the wall are consequently assessed in the longitudinal direction.

2.1 The influence of the difference between placing temperature and adjoining concrete temperature

This is the most common crack control criterion at early ages in thin concrete structures. Two cases are studied: placing temperature 20°C and adjoining concrete temperature 8°C, respectively 10°C and 5°C. It is assumed that the air temperature is constant and is equal to the adjoining concrete temperature.

It is seen in *Tab.1* that in HPC simulations the maximum mean temperature occurs earlier and at higher values compared to NPC. The zero-stress temperature also occurs earlier and as the cooling processes more rapidly in a thin structure the span to the final temperature becomes larger. This leads to high values of tensile stress and even if the tensile strength develops more rapidly, the stresses develop faster and HPC shows higher crack risk. The decrease of crack risk from Case 1 to Case 2 is of the same order for NPC (34%) and HPC (33%), i.e. 60% reduction of the temperature difference at casting leads to almost 35% reduction of the crack risk.

Table 1 - Influence of temperature difference on crack risk

Structure	Maximum Mean Temperature, Age	Surface crack risk Transversal direction	Through crack risk at y=1.4 m Longitudinal direction	Through crack risk at y=0.525 m Longitudinal direction
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C				
NPC	34.4°C at 26 hours	0.15	0.96	0.74
HPC	42.6°C at 22 hours	0.27	1.26	0.95
HPC excl. autogenous shrinkage	42.6°C at 22 hours	0.27	1.17	0.90
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C				
NPC	24.4°C at 38 hours	0.15	0.63	0.47
HPC	31.9°C at 32 hours	0.26	0.84	0.62
HPC excl. autogenous shrinkage	31.9°C at 32 hours	0.26	0.81	0.61

The presence of autogenous shrinkage contributes to an increase in the crack risk with 3.5-7.1 % depending on the difference between placing temperature and old concrete temperature (at y=1.4 m). It seems that the reduction of $T_{placing}$-$T_{old\ concrete}$ from 12°C, (Case 1) to 5°C (Case 2) leads to an almost proportional reduction of the effect of autogenous shrinkage on crack risk. This means that by decreasing the differences between placing temperature and old concrete temperature a decrease of the effect of autogenous shrinkage on crack risk is possible. The explanation for this may lie in the autogenous shrinkage connected to the temperature circumstances at placing and in the old concrete through the maturity.

Regarding surface cracks: there is no risk for cracking in neither of the cases at the end of the studied period. During the heating process the principal tensile stresses on the surface of the concrete are of vertical orientation and keep a very low level and during cooling turn into compression. This can explain the fact that many of the horizontal surface cracks starting during hydration close up after cooling.

2.2 The influence of wall length

This is a crack control criterion often used for reduction of external restraint acting on the structure. Changing the cast length of a structure has not only the effect of changing the length of the restraining joint but also the spatial distribution of restraint in the wall if the height remains unchanged. The longer a structure is the more restrained it is over its height. By reducing the ratio length/height the structure becomes less restrained in the higher parts [10]. In this study the length of 5 m is compared with the reference length of 10 m for Case 1 and Case 2.

The computation results in *Tab.2* show that a halving of the structure length leads to about 10% reduction of the crack risk for both NPC and HPC independent of temperature differences at y=1.4 m. At y=0.525 m the crack risk reduction is only 4%, cf. *Tab.1*. By reducing the length/height to half the restraint at reference point 0.525 m decreases from 0.83 to 0.7 and at point 1.4 m from 0.6 to 0.3 [10, 11]. The practical benefit with shortening the wall is that for Case 2 even the HPC structure lands in the neighbourhood of reasonable safety against cracking.

Table 2 - Influence of wall length on crack risk

Structure	Maximum Mean Temperature, Age	Surface crack risk Transversal direction	Through crack risk at y=1.4 m Longitudinal direction	Through crack risk at y=0.525 m Longitudinal direction
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; L=5 m				
NPC	34.4°C at 26 hours	0.15	0.84	0.71
HPC	42.6°C at 22 hours	0.27	1.11	0.91
HPC excl. autogenous shrinkage	42.6°C at 22 hours	0.27	1.03	0.86
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; L=5 m				
NPC	24.4°C at 38 hours	0.15	0.55	0.45
HPC	31.9°C at 32 hours	0.26	0.73	0.59
HPC excl. autogenous shrinkage	31.9°C at 32 hours	0.26	0.71	0.58

An investigation of the case when bending of the wall is possible due to asymmetric temperatures (by release of vertical movements between the ground slab and underground) shows that it has no effect on the risk for cracking. This means that the self-weight of the wall with this size placed on the inflexible rocky sub-base counteracts the bending effect.
The increase in crack risk in a short wall due to autogenous shrinkage is of the same order as for the reference structure length, L=10 m, (cf. *Tab.1* and *Tab.2*). This means that by shortening the wall the relative effect of autogenous shrinkage compared to thermal effects remains unchanged.

2.3 The influence of cement type

The use of cement type with reduced heat of hydration is a crack control measure usually applied to massive concrete structures where the temperature increase is considerable. Using a low heat cement leads to reduced temperature development in the section and lower stress levels during hydration, but then even the strength of the concrete develops slower having influence on the time of form removal. In this study two cement types are investigated: the reference cement Type I, Slite (quantity of heat developed at complete hydration 500 kJ/kg according to the Bougue calculation) and low heat cement Type II, Degerhamn (465 kJ/kg).

Comparison of the crack risk values in *Tab.1* and *Tab.3* leads to the general conclusion that the temperature maximum is lower and occur somewhat later for Type II cement and that crack risks decrease as expected. It is seen that the largest decrease in crack risk occurs for HPC (17.4% decrease for Case 1, respectively 27.3% for Case 2 compared to NPC's 13.5% for Case 1 and 23.8% for Case 2). Studying NPC in the same manner it is seen that the largest decrease of crack risk occurs for changes in temperature differences from Case 1 to Case 2 (34% decrease for cement Type I and 42% for cement Type II compared to HPC's 33%, respectively 41%). This leads to the conclusion that HPC seems to be more sensitive to change in cement type, while NPC is more sensitive to changes in temperature between placing and adjoining structure.

Table 3 - Influence of cement type on crack risk

Structure	Maximum Mean Temperature, Age	Surface crack risk Transversal direction	Through crack risk at y=1.4 m Longitudinal direction	Through crack risk at y=0.525 m Longitudinal direction
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type II, Degerhamn				
NPC	30.2°C at 26 hours	0.11	0.83	0.63
HPC	36.2°C at 24 hours	0.19	1.04	0.78
HPC excl. autogenous shrinkage	36.2°C at 24 hours	0.19	0.98	0.75
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type II, Degerhamn				
NPC	19.9°C at 46 hours	0.10	0.48	0.35
HPC	25.1°C at 38 hours	0.17	0.61	0.45
HPC excl. autogenous shrinkage	25.1°C at 38 hours	0.17	0.60	0.45

Autogenous shrinkage is causing an increase in crack risk of the order 1.6-5.7% at reference point y=1.4 m. This is an almost 20% reduction of the effect of autogenous shrinkage for Case 1 and more than 50% for Case 2 compared to values in *Tab.1*. The least effect of autogenous shrinkage is occurring for low heat cement in combination with low temperature difference as in Case 2.

2.4 The influence of ambient temperature variation

For a more realistic simulation of the wall the ambient temperature variation is taken into account. The temperature differences for Case 1 and Case 2 are unchanged. The ambient temperature variation is provided by the Swedish Meteorological and Hydrological Institute for Lund, July 1996 and for Sundsvall, January 1996, see *Fig.2*.

The results in *Tab.4* show that the crack risk reduction is most accentuated in NPC particularly for Case 2 independent of cement type. The maximum mean temperature values are throughout higher yet the crack risk levels are lower (cf. *Tab.1* and *Tab.3*). This is due to the low differences between zero stress temperature and final temperature governed now by the ambient temperature variation with a daily average of 14.1°C, instead of the temperature of adjoining structure of 8°C respectively 5°C. This means that during summertime the cooling process to the ambient temperature is smoother leading to lower crack risk levels compared to those in *Tab.1* and *Tab.3,* where the air temperature is simply equal to the temperature of adjoining concrete.
The effect of autogenous shrinkage is more than 10%, with the strongest influence on cement Type II, Case 2.

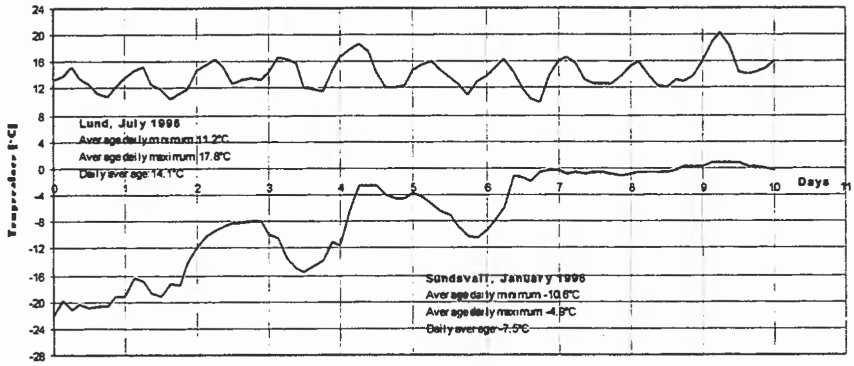

Figure 2 - Ambient temperature variation

Table 4 - Influence of ambient temperature on crack risk, summer

Structure	Maximum Mean Temperature, Age	Surface crack risk Transv. dir.	Through crack risk at y=1.4 m Longitudinal dir.	Through crack risk at y=0.525 m Longitudinal dir.
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type I, Slite; Lund, July 1996				
NPC	36.8°C at 28 hours	0.20	0.79	0.59
HPC	45.5°C at 22 hours	0.33	1.15	0.84
HPC excl. autog.shrink.	45.5°C at 22 hours	0.33	0.99	0.75
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type I, Slite; Lund, July 1996				
NPC	29.5°C at 38 hours	0.21	0.40	0.27
HPC	38.6°C at 32 hours	0.31	0.72	0.48
HPC excl. autog.shrink.	38.6°C at 32 hours	0.31	0.61	0.43
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type II, Degerhamn; Lund, July 1996				
NPC	32.9°C at 30 hours	0.16	0.66	0.48
HPC	39.4°C at 24 hours	0.24	0.93	0.67
HPC excl. autog.shrink.	39.4°C at 24 hours	0.24	0.80	0.60

CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type II, Degerhamn; Lund, July 1996				
NPC	25.8°C at 54 hours	0.18	0.26	0.19
HPC	32.6°C at 36 hours	0.26	0.50	0.31
HPC excl. autog.shrink.	32.6°C at 36 hours	0.26	0.41	0.30

For simulation of winter season insulated formworks are used. A 10 mm thick mineral wool insulation is placed both on the wood formwork and on the exposed surfaces after casting.

Table 5 - Influence of ambient temperature on crack risk, winter

Structure	Maximum Mean Temperature, Age	Surface crack risk Transversal direction	Through crack risk at y=1.4 m Longitudinal direction	Through crack risk at y=0.525 m Longitudinal direction
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type I, Slite; Sundsvall, January 1996				
NPC	29.4°C at 24 hours	0.10	1.10	0.84
HPC	36.8°C at 24 hours	0.17	1.45	1.10
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type I, Slite; Sundsvall, January 1996				
NPC	15.8°C at 40 hours	0.06	0.55	0.40
HPC	20.6°C at 40 hours	0.13	0.73	0.54
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type II, Degerhamn; Sundsvall, January 1996				
NPC	24.4°C at 24 hours	0.09	0.99	0.76
HPC	28.8°C at 24 hours	0.07	1.28	0.98
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type II, Degerhamn; Sundsvall, January 1996				
NPC	8.5°C at 34 hours	-	0.37	0.26
HPC	7.4°C at 34 hours	-	0.44	0.30

It is seen in *Tab.5* that the maximum mean temperature has throughout lower values than in *Tab. 1* and *Tab.3* with crack risk varying between increased levels for Case 1 and decreased levels for Case 2 independently of cement type. In both cases the varying crack risk level is coupled to the varying difference between zero stress temperature and final temperature. An increased crack risk level matches an increased difference between zero stress temperature and final temperature and vice versa. A realistic simulation of the ambient temperature during wintertime shows that the cooling process is more abrupt than in the simplistic simulation. For Case 2 the cold overcomes the hydration heat in the beginning making the heating process less accentuated, with lower temperature values and also with a much smoother cooling process.

Note that the use of concrete with higher strength is one of the measures in cold weather construction to mitigate freezing. By using HPC instead of NPC it is seen that this measure may successfully protect the structure from freezing but leads to higher early age crack risk levels. The increased crack risk levels are due to the ambient circumstances as the effect of autogenous shrinkage is insignificant in this case.

2.5 The influence of form removal and wind action

In most of the cases the form removal at building sites happens earlier than the 10 days period in the reference case. Therefore an early form removal is also investigated in accordance to the Swedish Standard BBK, [12]. It is assumed that form removal occurs at the time when 70% of the compressive strength in the concrete is achieved and when even the wind velocity increases from 1 m/s to 5 m/s. The foremost effect of a high wind velocity is that the transfer coefficient at the surface of the structure increases leading to a faster and more distinct cooling process. Thus the variations in the ambient temperature become more effective in combination with high wind velocities. The ambient temperature corresponds Lund, July month.

Table 6 - Influence of form removal and wind velocity on crack risk, summer

Structure	Maximum Mean Temperature, Age	Surface crack risk Transversal direction	Through crack risk at y=1.4 m Longitudinal direction	Through crack risk at y=0.525 m Longitudinal direction
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type I, Slite; Lund, July 1996				
NPC	36.8°C at 28 hours	0.39	0.92	0.70
HPC	45.5°C at 22 hours	0.69	1.14	0.85
HPC excl. autogenous shrinkage	45.5°C at 22 hours	0.69	1.10	0.83
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type I, Slite; Lund, July 1996				
NPC	29.5°C at 38 hours	0.38	0.49	0.33
HPC	38.6°C at 32 hours	0.43	0.72	0.48
HPC excl. autogenous shrinkage	38.6°C at 32 hours	0.43	0.68	0.47
CASE 1: $T_{placing}$=20°C, $T_{old\ concrete}$=8°C; Type II, Degerhamn; Lund, July 1996				
NPC	32.9°C at 30 hours	0.29	0.78	0.58
HPC	39.4°C at 24 hours	0.45	0.95	0.70
HPC excl. autogenous shrinkage	39.4°C at 24 hours	0.45	0.91	0.69
CASE 2: $T_{placing}$=10°C, $T_{old\ concrete}$=5°C; Type II, Degerhamn; Lund, July 1996				
NPC	25.8°C at 54 hours	0.37	0.36	0.21
HPC	32.6°C at 36 hours	0.40	0.51	0.31
HPC excl. autogenous shrinkage	32.6°C at 36 hours	0.40	0.49	0.31

Computation results in *Tab.6* show that after form removal the daily variations of temperature are more distinct and the crack risk levels increase with 20% in NPC, while in HPC the changes are insignificant (cf. *Tab. 4*). The presence of the form is comparable to a membrane and an early removal leads to a sudden cooling and to a slower development of strength at the same time as the tensile stresses develop faster. Additionally, in HPC the stresses oscillate with rather high amplitudes corresponding the to the daily variations in temperature and with values near the critical crack risk level. This would lead to a less uniform stress state in the section and explain the unchanged crack risk level in HPC. A somewhat slower cooling and less oscillation in the stress amplitude leads to a more uniform stress state in the section and to an increased crack risk in NPC. The more uniform the distribution of the imposed strains in the section is the more stress accumulates and the higher the crack risk level gets. The above reasoning is valid for cases where high temperature gradients act in the section corresponding sudden cooling independently of the magnitude of external restraint acting on the structure, as described in [13].

In direct connection to form removal the surface crack levels increase considerably and reach the critical value for thermal cracking, cracks which probably close when the stresses convert to compression. Autogenous shrinkage has an effect on crack risk level of about 3.5-5.5%.

2.6 The influence of reinforcement

Theories modelling early age cracking often disregard the presence of reinforcement. It is known from hardened concrete that the presence of reinforcement is of less importance prior cracking but the more effective after cracking by redistributing the stresses so that several narrow cracks arise instead of a few wide-opened. To achieve this the amount of reinforcement should be large enough to create new cracks without exceeding yield, [14]. It is however more difficult to model the presence of reinforcement in concrete at early ages when both the properties of concrete and the bond characteristics between the concrete and reinforcement are in development. Consequently most of commercial FEM programs for concrete at early ages have no built in modules for simulation of reinforcement.

A simple one-dimensional model of the reinforced concrete shows that the most important parameters for a totally restrained bar is the E-modulus of the concrete and the temperature development. It is seen that especially the timing between stiffness growth and temperature rise is of outmost importance with regard to crack risk, [15].

Other findings on the matter of reinforced concrete are those of early age modelling in Diana, a non-linear FEM-based program system dedicated to comprehensive analysis of concrete, [16]. The effect of reinforcement may be included here by modification of strain softening curves to also include the tension stiffening effect.

In [17] a simplified practical method is presented for cracking and bond slip at early ages following the JCI recommendations. The reinforcement is modelled with simple bar elements with a rectangular distribution of rebar strain for bond and the cracking is initiated at a point with a discrete crack approach. Thus modelling is done with elements commonly found in finite element programs though, without considering fracture mechanics modelling for crack localisation. Different values of bond zone length are investigated and the effect of reinforcement is investigated on crack width.

From findings in hardened reinforced concrete, [13], it can be stated that temperature variations in outdoor climate are generally of the type slow cooling (if no formwork removal happens meantime) leading to more uniform stress distribution and higher stress levels. This is valid for reinforced concrete elements of structural size irrespective of the ratio softening modulus/elastic modulus in concrete, and thus even for HPC structures. The influence of reinforcement on crack width is studied with a simple model, fully restrained with uniformly distributed bond stresses and temperature drop. It is found that the reinforcement is most effective in crack width reduction in long structures, long bond zone leads to large crack width and with increased reinforcement amount the crack width is decreasing in consensus with [17]. Note though that for partially restrained cases the crack width reduction of the reinforcement is not so effective, especially in long structures.

Recent findings regarding 2D modelling of hardened reinforced concrete, show that the effective crack width is almost doubled in HSC compared to NPC for low values of reinforcement ratios, [18]. This is explained by the high temperature at cracking and by yield in reinforcement, often observed in HPC. The studied case is a wall fully restrained at the base exposed to temperature drop up to 40°C. It remains though to be proved with a constitutive model for reinforced concrete that this is also valid at early ages.

3. CONCLUSIONS

A comparative study of two concrete walls (NPC and HPC) is made by means of FEM-computations. Special attention is paid to parameters governing the thermal cracking process at early ages. The crack risk is investigated in two reference points, affected by different restraint depending on their distance from the restraining joint. The thermal cracking process and autogenous shrinkage are modelled with the tools provided by computer program Hacon$^{3.0}$. Input material parameters for the NPC/HPC concrete are taken from test data [2, 8]. Note though that material parameter like autogenous shrinkage is measured at sealed conditions leading to some uncertainty in calculations at real conditions. No sensitivity studies were made regarding the input material parameters but it is likely to believe that simulation results are highly dependent on how well the input data relates to the real in-situ construction. Due to the complexity of thermal cracking process it is difficult to recommend general rules, therefore any simulation of crack risk should be based on tested input data for each specific construction.

Throughout this study it can be seen that HPC structures have higher maximum mean temperature values occurring earlier and thus the crack risk levels are higher compared to NPC structures. Generally, the use of low heat cement is advantageous and low temperature criterion is preferable in both types of concrete. Taking each parameter separately the following conclusions apply:

-a 60% reduction of the difference between placing temperature and adjoining structure temperature leads to ca 35% lower crack risk in both concretes but more studies are needed to establish quantifying relations between these factors; it reduces to half the effect of autogenous shrinkage on crack risk

-reducing to half the structure length leads to a 10% reduction of the crack risk for both HPC and NPC

-changing reference cement to low heat cement has most effect on HPC with more than 20% crack risk reduction and less than 20% for NPC; the effect of autogenous shrinkage is reduced with 20% for Case 1 and 50% for Case 2; reductive effect even on surface crack risk

-taking the ambient temperature into consideration during summertime leads throughout to lower crack risk levels; the practical benefit with a more realistic simulation of the ambient temperature is a general reduction of crack risk level

-taking the ambient temperature into consideration during winter leads to increased crack risk for Case 1 and decreased crack risk for Case 2; low temperature differences at low absolute values have the most benefit of this measure

-early form removal and wind action appears to increase crack risk with 20% in NPC, but HPC seems to be unaffected provided no drying shrinkage; increased surface crack risk in connection to form removal especially in HPC

-the presence of the reinforcement is investigated in the literature; it is seen that the reinforcement is most effective in crack width reduction in long structures and with increased reinforcement amount the crack width is decreasing; more studies are needed on modelling reinforced concrete at all ages with special attention to the effect of reinforcement on the post-crack behaviour; the model should enable analysis of different crack control measures and their effect on crack width or rather to suggest a suitable combination of measures in order to fulfil crack width requirements in a structure.

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