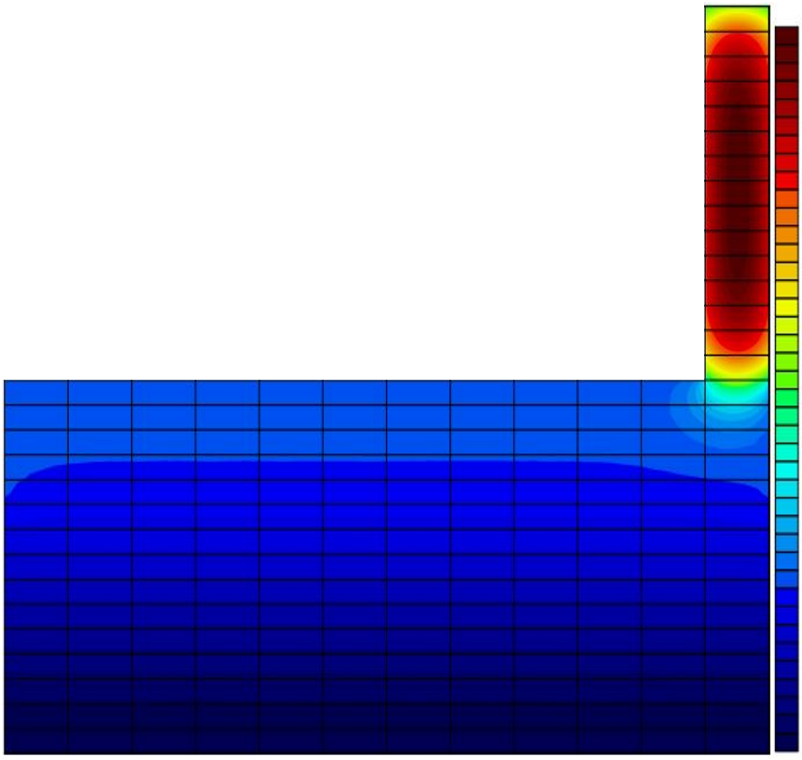

The risk of early-age thermal cracking using concrete with high GGBS content

A parametric study of two concrete mixes for a wall-to-slab section

Master's thesis in Structural Engineering and Building Technology

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Gothenburg, Sweden 2022
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Master's thesis ACEX30

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Cover: Temperature contour plot of a "Wall-to slab" section from FE software ConTeSt.

Department of Architecture and Civil Engineering
Gothenburg, Sweden 2022

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Abstract

Carbon reduced concrete, with highest possible cement reduction and incorporation of supplementary cementitious materials (SCM), is one necessary measure to reduce the carbon footprint of the built environment. In Sweden, one of the most used SCMs is slag, a by-product from steel production. Although the availability of slag is limited, it is a temporary solution for reduction of carbon emissions while research of alternative SCMs is being conducted. However, incorporation of slag provoke different hydration reactions, resulting in physical and chemical changes in early-age properties. As current production methods are developed for concrete with ordinary Portland cement (OPC), the different early-age behaviour is of concern.

The aim of this thesis is to compare the early performance of two concrete mixes on a principal case of wall-to-slab, one traditional with OPC and one with 50 % cement replacement by slag, in this thesis named S50. By FE analysis, thermal stresses were calculated and the risk of early-age thermal cracking of the two concrete mixes evaluated. A parametric study was conducted to study differences in the material behaviour, and the response to changed geometrical and environmental conditions. Thereafter, a study of risk reducing casting and curing measures was performed where the effect individual as well as combined measures were studied.

It was shown that the lower heat generation and early-age strength of slag concrete caused problems of reaching adequate strength levels in a studied cold case. Changes in heat and strength development in combination with a changed restraint, both due to increased dimensions, complicated the prediction of the risk of cracking. Furthermore, the slag concrete required different measures compared to the OPC concrete. Due to the slower strength development, hydration accelerating measures are needed for the S50 concrete. However, there is a fine balance between accelerating the strength gain while also maintaining a low crack risk. Casting with stricter deadlines appears to be more difficult for slag concretes in cold climates. Compromises with strict time plans in winter castings or adjusted production plans might be needed to minimize the cement amount and meet the environmental demands.

Keywords: Early-age thermal cracking, Crack risk analysis, Finite element analysis, GGBS, Wall-to-slab, Crack reducing measures.

Risk för temperatursprickor i ung betong med hög andel slagg
En parametrisk studie av två betongtyper för typfallet 'vägg på platta'
Examensarbete inom masterprogrammet konstruktion och byggnadsteknologi
PAULINA SUNDELIUS
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Sammanfattning

Klimatförbättrad betong, med högsta möjliga cementreduktion genom inblandning av cementersättningsprodukter är en nödvändig åtgärd för att minska klimatpåverkan av den byggda miljön. En av de mest använda cementersättningsprodukterna i Sverige är slagg, en restprodukt från stålindustrin. Trots att tillgången till slagg är begränsad är det en tillfällig lösning för att reducera koldioxidutsläppen medan forskning på alternativa cementersättningsprodukter fortgår. Inblandning av slagg ger upphov till förändrade hydratiseringsreaktioner vilket resulterar i förändrade fysikaliska och kemiska egenskaper hos den unga betongen. Eftersom dagens produktionsmetoder har utvecklats för traditionell betong, med Portland cement (OPC) som bindemedel, kan förändrade tidiga egenskaper ses som en osäkerhet.

Syftet med uppsatsen är att jämföra det tidiga beteendet hos två betongtyper för ett typfall av 'vägg på platta', en traditionell betong och en klimatförbättrad betong med bindemedel innehållande 50% slagg. Med hjälp av FE-analys beräknades termiska spänningar och sprickrisken för de två studerade betongerna. En parametrisk studie genomfördes för att studera skillnader i materialbeteende och respons till förändringar i geometriska och temperaturmässiga förutsättningar. Därefter genomfördes en analytisk studie av sprickreducerande gjutning- och härdningsåtgärder där effekten av enskilda och kombinerade åtgärder studerades.

Studien visade att den lägre värmeutvecklingen och tidiga hållfastheten hos slaggbetong orsakade problem att nå tillräcklig hållfasthetsnivå i ett studerat kallt fallet. Förändringar i värme- och hållfasthetsutveckling i kombination med förändrat tvång, båda till följd av ökade dimensioner, gjorde det svårt att förutse sprickrisken. Vidare behövdes andra åtgärder för slaggbetongen än för OPC-betongen. Till följd av långsammare hållfasthetsutveckling krävdes åtgärder för en accelerad hydratation för slaggbetong. Emellertid så är det en fin balans mellan att tillsätta accelererande åtgärder för att öka hållfasthetstillväxten och samtidigt bibehålla en låg sprickrisk. Resultaten tyder på det är en svårare uppgift att gjuta i kalla temperaturer med en kort tidsplan med slaggbetong än med traditionell betong. Följaktligen kan kompromisser med strikta tidplaner vid vintergjutningar eller anpassade produktionsplaner krävas för att minimera cementmängden och möta miljökraven.

Nyckelord: Temperatursprickor, Sprickriskanalys, Finita elementanalys, Slagg, Vägg på platta, Sprickreducerande åtgärder.

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Preface

This master's thesis is the final module of the master's programme Structural Engineering and Building Technology at Chalmers University of Technology, and was carried out between January and June 2022. The work is made in in a collaboration with the Division of Building technology at Chalmers University of Technology, Skanska Teknik AB, Göteborg and the Port and Marine structures department at Ramboll. There are several people we would like to thank for their valuable advice and support along the way.

We would like to express our deepest gratitude to our supervisor and examiner, Arezou Baba Ahmadi for your encouragement, for being an inspiration to our initial interest in this area of research and for supplying us with valuable knowledge. Great thanks to Hadi Mazaheripour and Stefan Svensson who have been our supervisors of this thesis for helpful comments and guidance throughout the project.

Additionally, we would like to thank several people from the industry for their valuable input. Thanks to Hans Hedlund for sharing your expertise and guiding us towards finding an interesting scope of the thesis. Special thanks to Nils Rasmark for your generosity with your time answering our many questions during the modelling. Thanks also to Mats Karlsson for providing background and context to the topic, and the enthusiasm for finding new solutions. We would also like to thank Jan Leinonen for your suggestions on sustainable implementation in the construction stage. Finally, thank you to Mattias Liewendahl for showing us around at Hamnbanan and taking time to answer our questions on the practicalities of casting.

Paulina Sundelius & Emy Wahlqvist, Gothenburg, June 2022

Nomenclature

Abbreviation

Al_2O_3	Aluminium oxide
C-A-S-H	Calcium aluminate silicate hydrate
C-S-H	Calcium silicate hydrate
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicte
C_4AF	Tetracalcium aluminoferrite
CaO	Calcium oxide, burnt lime
CCS	Carbon capture and storage
CH	Portlandite
Cl^-	Chloride
CO_2	Carbon dioxide
CSF	Condensed silica fume
EPE	Expanded polyethylen
FE	Finite element
Fe_2O_3	Ferric oxide
GGBS	Ground granulated blast-furnace slag
H	H_2O, Water
K_2O	Potassium oxide
LL	Linear line analysis
MgO	Magnesium oxide
Mn_2O_3	Manganese(III) oxide
$Na_{2O,eq.}$	Sodium oxide equivalent
Na_2O	Sodium oxide
Na_2OH	Natrium hydroxid

PLS	Plane surface analysis
RHA	Risk husk ash
S	Si, Silica
S^{2-}	Sulfide
OPC	Ordinary Portland cement
SCM	Supplementary Cementitious Material
SiO_2	Silion dioxide, silica
SO_3	Sulfur trioxide
TSA	Traditional semi-adiabat calorimetry
TSTM	Thermal Stress Test Method
XC2	Corrosion caused by carbonation, wet rarely dry
XC4	Corrosion caused by carbonation, cyclic wet and dry

Notations

α_c	Average thermal contraction coefficient
η_{max}	Maximum allowable stress strengh ratio
ρc	Specific heat of the material per volume [J/m^3K]
ρ	Density of the material [kg/m^3]
σ	Stress
σ_z	Stress in z-direction
σ_{max}	Maximum stress
c	Specific heat of the material per mass [J/m^3K]
E_c	Average modulus of elasticity during cooling [GPa]
$f_{cc,28}$	The compressive strength at 28 days curing in 20 ºC, cube
$f_{ck,28}$	The compressive strength at 28 days curing in 20 ºC, cylinder
f_{ck}	Compressive strength
$f_{ctk0,05}$	5 % fractile tensile strength
$f_{ctk0,95}$	95 % fractile tensile strength
f_{ctm}	Mean tensile strength
f_{ct}	Tensile strength
h_{free}	Heat transfer coefficient for a free surface surrounded by air [W/m^2K]

h_{surf}	Heat transfer coefficient for the external boundary [W/m^{2}K]
I	Heat radiation to the boundary from the surroundings [W/m^{2}K]
k_i	Heat conductivity of the i:th material [W/mK]
k_x	Heat conductivity for the heat flow in x-direction [W/mK]
k_y	Heat conductivity for the heat flow in y-direction [W/mK]
k_z	Heat conductivity for the heat in the z-direction, [W/mK]
l_i	Thickness of the i:th boundary material [m]
Q_H	Generated heat inside the body [W/m^{3}K]
q_n	Heat flow from the body to the boundary along the perpendicular to the boundary [W/m^{2}K]
q_z	Heat flow in the z-direction [W/m^2]
S	Safety crack risk factor [-]
T	Temperature in the studied structure, [°C or K]
T_{air}	Air temperature [°C]
$T_{casting}$	Casting temperature [°C]
T_{env}	Environmental temperature [°C or K]
T_{mean}	Mean temperature [°C]
T_{surf}	Temperature on the surface [°C or K]
v	Air velocity [m/s]

Material parameters

α_{cool}	Thermal contraction coefficient [1/K]
α_{CT}	Limit for the linear part of the σ - ϵ curve [-]
α_{heat}	Thermal expansion coefficient [1/K]
β_1	Fitting parameter/exponent [-]
β_D	Rate factor used for possible adjustments =1 [-]
ϵ_1	Strain associated with the tensile strength for a linear σ-ϵ curve [-]
ϵ_2	Fitting parameter [-]
η_{SH}	Fitting parameter autogenous shrinkage
κ_1	Fitting parameter [-]
κ_3	Fitting parameter [-]
κ_{Temp}	Fitting parameter [-]

ν	Poisson's ratio [-]
ρ_ϕ	Fitting parameter for non linear stress-strain curve
ρ_T	Fitting parameter for non-linear stress-strain curve [-]
θ_S	Fitting parameter [-]
θ_T	Fitting parameter [K]
θ_{ref}	Activation temperature at 20 °C [K]
C	Binder content [kg/m^3]
$D_{max,drop,28}$	Fitting parameter [-]
f_A	Calculated for t_A= t_e[MPa]
$F_{c,ref}$	Reference compressive strength [MPa]
$F_{t,ref}$	Reference tensile strength [MPa]
K_{Fi}	Fitting parameter [-]
N	Number of ages [-]
n_A	Fitting parameter[-]
n_{CC28d}	Fitting parameter [-]
s	Fitting parameter [-]
t_1	Fitting parameter [h]
t_A	Fitting parameter [h]
t_s	Fitting parameter [h]
t_{e0}	Formal equivalent maturity time at casting of the concrete,0 h [-]
t_{S1}	Fitting parameter [-]
t_{S2}	Fitting parameter [-]
$Temp_D$	Temperature [°C]
W_c	Heat generated from concrete [J/kg]

1
Introduction

1.1 Background

Considering the cement sector being the third-largest energy consumer among industries and the cement production being responsible of 7 % of the worlds CO_2 emissions (World Business Council for Sustainable Development 2018), there is a great interest in making environmental improvements in the building industry, where low-carbon concrete is one of the focus areas. Along with carbon capture and storage (CCS), reducing the clinker-to-cement ratio is one of the most efficient measures for a direct reduction of carbon emissions according to International Energy Agency (2021). One way to accomplish this is to replace part of the cement content by incorporation of supplementary cementitious materials (SCMs). A reduced amount of cement is also of interest due to the current cement crisis in Sweden.

Application of SCMs, provoking new types of hydration reactions in the cementitious system, is followed by possible micro and macro structural changes in physical and chemical properties of concrete. Early-age cracking, which is one of the key obstacles in concrete design, is one of the parameters which is found to be affected by incorporation of SCMs in concrete (Bamforth, 2007). This appears to be a mutual concern and hesitation for contractor and client to use carbon reduced concrete as unforeseen costs could arise in order to repair the potential damage. Furthermore, there is a need for adapted concrete proportioning and choice of SCM in different geographical regions due to local accessibility, climate, and exposure conditions. Apart from ground granulated blast-furnace slag (GGBS)[1], silica fume, fly ash, volcanic ash and calcinated clay represent other SCMs that are already used today or is expected to be used in a larger scale in the future. Considering that GGBS is one of the most used SCMs in the western part of Sweden, and has a great potential to perform well when substituting large portions of cement, the main focus in this thesis is concrete containing GGBS.

A thermal cracking analysis of slag concrete could give information about the expected behaviour, and provide guidance for a suitable production method to decrease the risk of thermal cracking, and in turn motivate a scaled up use of low-carbon concrete. In addition to the technical challenges with new mixes, the design approach is often conservative much due to the interpretation of norms and guidelines being strict requirements. In order to meet the stricter environmental demands, new methods which are not explicitly defined in the norms, will be required and could be allowed with the use of functional demands.

[1]Henceforth in this thesis, both 'slag' and 'GGBS' are used to refer to this material.

1.2 Problem description

There are ambitions of using more efficient materials to minimize the carbon footprint in the building industry. However, concrete mixes with a high level of cement replacement appears not to be used to the extent it could and the reason for this is not always clear. It is expressed that there are certain concerns using concrete of high slag content in cold climates, but only a few well-experienced individuals and experts within the area of carbon reduced concrete seems to be able to explain the complexity of the issue. Although the changed early-age properties due to incorporation of GGBS has been a research subject for several years, see for example Hwang and Shen (1991), it is not well-known to the majority of the constructions workers and structural engineers. Moreover, to accurately model the thermal and structural behaviour of a material, comprehensive experimental testing and verification of behaviour is required, which is not yet the case for GGBS concrete in Sweden. This, in combination with test methods and material models being based on the behaviour of OPC concrete, is one of the challenges arising with the development of the material. Insufficiency of widespread knowledge and experience of using slag-blended concrete creates concerns in predicting the early-age behaviour and hence, prescribing the most efficient crack mitigation measures. An understanding of the structural changes are needed to better assess the possible solutions.

1.3 Aim & Objectives

The aim is to analyse the risk of early-age thermal cracking of concrete, with minimized cement content using GGBS, for a wall-to-slab section. This is performed by studying the different behaviour of two different concrete mixes, one traditional concrete with ordinary Portland cement and one with 50 % cement replacement by GGBS. The concrete mixes are compared with regard to early-age performance, including early-age thermal cracking, curing, and early freezing for a variation of cross-sectional dimensions, casting lengths and environmental conditions. Focus is to investigate how differences in behaviour affect casting and curing measures, with an aim to provide recommendation for proper design and usage.

1.4 Scope and limitations

The thesis is limited to analysis of concrete with GGBS as replacement material. Other SCMs will be discussed but not analysed. The analyses are limited to two concrete mixes developed by Skanska Teknik, thereby the conclusions drawn from the study will be mix specific and cannot be applicable directly for mixes with a different composition or degree of replacement by slag. Further, the focus is early-age thermal cracks and does not include analysis of thermal cracks that could develop later during the service life of a structure due to climate variation. While thermal dilation and autogenous shrinkage is included in the analyses, the FE software used to compare the behaviour does not consider drying shrinkage, thus it is not considered in this study.

1.5 Methodology

Preparatory work included participation in the seminar 'Klimatförbättrad betong i Hamnbanan', which was held by the Swedish Transport Administration, Skanska and the Structural Engineering Centre at Chalmers, and a study visit at one of Skanska's concrete factories. In the initial phase of the thesis work, a literature review was carried out to deepen the knowledge within the topic and comprehend the theory behind the early-age chemical processes and heat generation by hydration as well as early-age thermal cracking. Keywords used when gathering relevant reports, articles and doctoral dissertations were thermal cracking, early-age, hydration, heat of hydration, slag, ggbs, low carbon concrete, etc.

Further on, interviews were carried out with key persons in the industry to identify the specific challenges and issues to be investigated. Respondents of interest for the interview study were material specialists, clients forming contracts, structural engineers, and production and project managers. Additionally, a field visit was made at a construction site during casting of concrete with slag to discuss potential differences compared to OPC concrete. Observations and discussions gave insight in construction conditions and was useful to make reasonable assumptions in the modelling.

Finally, a finite element (FE) analysis was performed in the software program ConTeST 5.1, to calculate thermal stresses and evaluate the risk of early-age thermal cracking of two different concrete mixes, OPC concrete and concrete with 50% cement replacement by GGBS. A parametric study was conducted in order to study the effect of chemical composition of binder for the two concrete mixes, and their response to variation in cross-sectional dimensions, casting lengths and environmental conditions. Thereafter, a study of risk reducing measures with respect to casting and curing was performed to study the effect of each individual measure for the two concrete mixes. Ultimately, risk reducing measures were combined to achieve feasible solutions for set deadlines of formwork removal, to assess the performance of the two concrete mixes.

1.6 Outline

This thesis is composed of six chapters, which are shortly described as follows:

2 Theory
The second chapter presents findings from the literature review and provides context for the subject.

3 Expert opinion
Experiences and opinions with respect to possibilities and challenges of cement replacement by slag are gathered from the interviews and summarised in the third chapter.

4 FE modelling
In the forth chapter, settings and assumptions made in the model are presented together with a description of the FE modelling approach.

5 Results and discussion
The fifth chapter presents and discusses the results from the parametric study and the effect of individual as well as combined measures.

6 Conclusion
Conclusions drawn based on the study are summarised in chapter 6, together with suggestions for further studies.

2
Theory

A review of the available literature and an understanding of the dominant factors and phenomena are necessary to analyse the issue of thermal cracking in concrete with high GGBS content. Concrete as a building material has been used for centuries and its essential characteristics and advantages are well-known. But with development of new concrete mix compositions and types of binders there is a continuous need for further research. In this section, an overview of cementitious materials, chemical compositions, hydration processes, prerequisites and limitations are presented, starting from ordinary Portland cement and progressing to modern approaches using SCMs. Experimental tests performed in order to develop mix specific material parameters are described, and the underlying factors of early-age cracking are presented. Finally, an introduction is made to the heat and stress computation used in the analysis.

2.1 Cementitious materials

The basic constituents of concrete include a binder, which typically is cement, water, and fine and coarse aggregates. Although cement constitutes the smallest proportion by volume in concrete, it is a central component and the series of chemical reactions of its hydration process govern the characteristic properties of both young and hardened concrete (Soutsos and Domone 2018). Key reactions and the influence of SCMs are reviewed to deepen the knowledge of fundamental processes.

2.1.1 Portland cement clinker production

Cement is produced by grinding limestone and clay into a fine mixture which later is heated to high temperatures whereupon a series of reactions takes place and form the main components of Portland cement. Limestone is decomposed in a reaction called calcination to remove carbon and yield calcium oxide, an essential ingredient. The calcination reaction requires a high temperature and the chemical process which follows emits carbon dioxides (CO_2), thus contribute tremendously to the negative environmental effects of cement production. Silicon dioxide, originating from the clay, form together with calcium oxide the main compounds of Portland cement, namely calcium silicates. Other compounds formed in the heating include calcium aluminates and calcium aluminoferrites, as a result of added aluminum oxide and iron oxide (Soutsos and Domone 2018).

Abbreviations are typically used to describe the principal oxides and the cement compounds and are defined as follows and as in Table 2.1.

$$CaO \text{ (lime)}=C,\ SiO_2 \text{ (silica)}=S,\ Al_2O_3 \text{ (alumnia)}=A,\ Fe_2O_3 \text{ (iron oxide)}=F$$

Table 2.1: Abbreviations for the main cement compounds

Chemical name	Chemical compositions	Abbreviation
Tricalcium silicate (Belite)	$3CaO \cdot SiO_2$	C_3S
Dicalcium silicate (Alite)	$2CaO \cdot SiO_2$	C_2S
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

A graphic illustration of the cement manufacturing process with respect to raw materials transformation to cement clinker compound is presented in Figure 2.1.

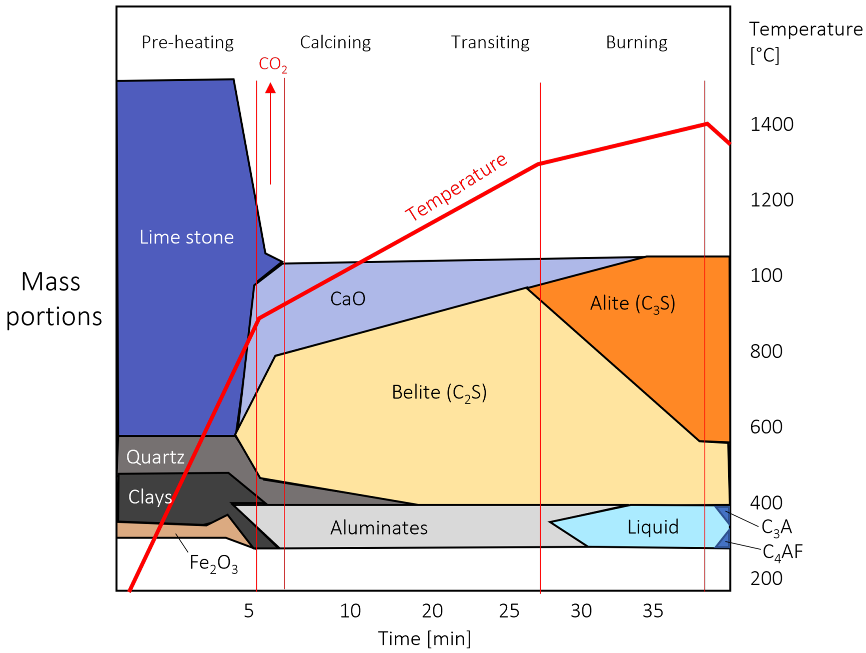


Figure 2.1: Phases for chemical compounds during manufacturing, modified from KHD Humbolt Wedag (n.d.)

A summary of the cement clinker production and the four main clinker components is illustrated in Figure 2.2.

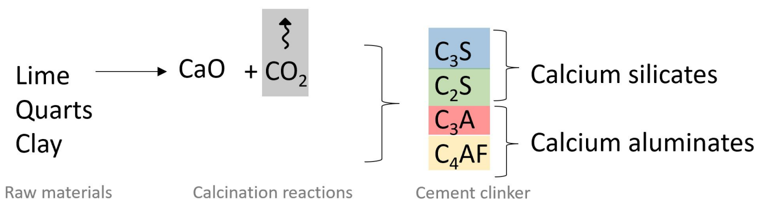


Figure 2.2: Cement clinker production summarized

2.1.2 Supplementary cementitious materials

Considering manufacture of cement being the most dominant factor with respect to environmental footprint of concrete production, materials with corresponding properties need to be incorporated to reduce the amount of cement clinker in concrete mixes. However, the degree of cement replacement is generally limited in order for required early material properties to develop. Thereby, these materials are most often used as supplement to cement. The limitation is partly dependent on the lime content of the SCM where high lime content allow a higher degree of cement replacement (up to 90%) and low lime content yields a lower replacement degree (up to 40%) (Soutsos and Domone 2018). Exceeding these limitations, underrating the needed cement amount, could cause an insufficient production of calcium hydroxide in order for the secondary reactions be fully feasible. The calcium hydroxide content is governing for the interaction between Portland cement and pozzolanic material (Ge et al. 2006).

When finding suitable SCMs, one must consider the available elements of the earth's crust, where the ten most abundant are oxygen, silicon, aluminum, iron, calcium, sodium, magnesium, potassium, titanium and hydrogen. Scrivener K, Vanderley J, and Gartner E (2018) raise several criteria that elements must fulfil in order to work as cementitious material. Firstly, only a few of the essential elements are available in a sufficient quantity to cover a global need for cement and not compromise with any other essential industry. Secondly, the element needs to possess the potential to form hydrates. The authors also define three main criteria considering the chemical properties of the element:

- The hydrates must have a higher volume than the dissolving cement.
- The ions forming the hydrates must be able to migrate from original particles into the previously water-filled space.
- The hydrates themselves must have a low solubility of hydrates to remain stable over long time periods.

(Scrivener K, Vanderley J, and Gartner E 2018)

Some of the most frequently used SCMs worldwide, according to Soutsos and Domone (2018), are fly ash (FA, previously called pulverised fuel ash, pfa), ground granulated blast-furnace slag (GGBS), condensed silica fume (csf) also called microsilica, calcinated clay or shale, rice husk ash (RHA) and natural pozzolans. What these materials have in common is that the main elements are silicon, aluminium or calcium, which all fulfil the criteria for creating an active ingredient in the binder mix. These elements will take part in the hydration process of Portland cement and create additional hydration reactions which are further explained in Section 2.1.3. The composition of main chemical compounds in the most frequently used SCMs are visualised in a ternary diagram, see Figure 2.3.

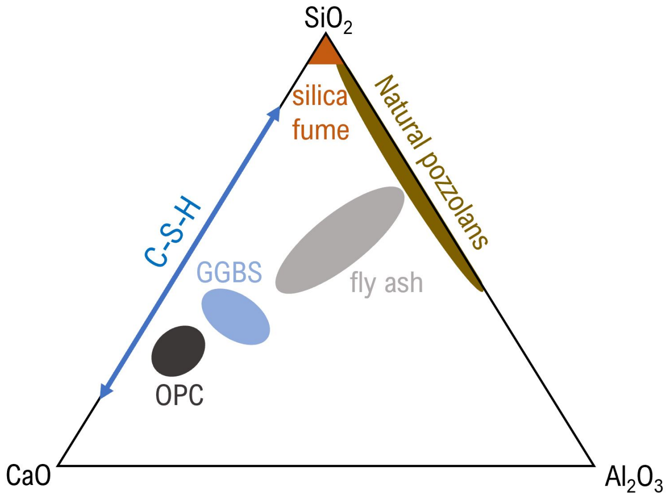


Figure 2.3: Ternary diagram showing compounds of different SCMs, modified from Kocaba (2009).

Slag is a by-product from blast furnace iron production and has been used as a supplementary cementitious material since before 1900 (Scrivener K, Vanderley J, and Gartner E 2018). When cooled rapidly, slag forms a glassy material with latent hydraulic properties which is then grounded to a fraction similar that of cement clinker. The result is ground granulated blast-furnace slag, in short GGBS. Due to slag being an established SCM, Swedish standards and references allow for a slag replacement level up to as high as 70 % by binder mass, dependent on prevailing exposure class. The equivalent maximum replacement level for fly ash is 35 %, resulting in a lower potential in terms of replacement and thereby also smaller reductions of CO_2 (Swedish Standards Institute 2021).

2.1.3 Pozzolanic behaviour enabling cement replacement

One prerequisite for cementitious materials is the pozzolanic or latent hydraulic characteristics. Some materials are natural pozzolans, for example certain types of volcanic ashes, while others become alkali-activated when pH is increased by the hydration of cement. The pozzolanic behaviour is dependent on the structure of silica within the material which has to be of glossy or amorphous form (Soutsos and Domone 2018).

When used in cement, the active silica and alumina will be involved in the chemical reactions of a secondary cement hydration, i.e. after portlandite is produced. The active silica and alumina reacts with the portlandite (calcium hydrates) and produces calcium silicates and calcium aluminates, forming C-S-H gel or C-A-S-H gel which provides the concrete with its strength. The pozzolanic reaction, when active silica is involved, is given as

$$\text{S} + \text{CH} + \text{H} \rightarrow \text{C-S-H}$$

where S is the abbreviation for silica, CH for portlandite, and H is short for H_2O.

The hydration product of Portland cement, calcium hydroxide (also called portlandite), comprise the necessary element to active SCMs. The portlandite in itself is not accelerating any reaction and the calcium could as well be exchanged for another chemical compound, for example sodium hydroxide or magnesium hydroxide. This is utilized in alkali-activated binders where the pozzolanic reaction is activated by Na_2OH. As portlandite is consumed during the reaction, the amount of portlandite produced by the cement hydration is decisive for the interaction between SCM and cement (Ge et al. 2006).

2.1.4 Chemical composition of Portland cement and GGBS

The exact chemical composition of Portland cement and GGBS can vary slightly depending on the origin of the material. However, this variation is expected to have a minor impact on the generated heat of hydration. In Table 2.2 typical compositions of Portland cement and slag are presented. The Portland cement composition is extracted from Table 13.1 in Soutsos and Domone (2018). The chemical composition of GGBS was retrieved February 10^{th} 2022 from 'GGBS Technical Datasheet' by Ecocem (n.d.). It can be noted that the main compounds of GGBS are calcium, silicon and aluminium oxides. The impact of additional silicon and aluminium in the binder mix, how hydration reactions and material properties are affected are further explained in the upcoming sections.

Table 2.2: Typical chemical composition of Portland cement (Soutsos and Domone 2018) and GGBS (Ecocem n.d.)

Oxides	Portland cement (w.%)	GGBS (w.%)
CaO	66	39.32
SiO_2	21	35.32
Al_2O_3	7	12.24
Fe_2O_3	3	0.31
MgO		9.13
Mn_2O_3		0.27
Cl^-		0.01
S^{2-}		0.64
SO_3	2	0.09
Na_2O		0.5
K_2O		0.56
Na_2O equivalent		0.72
Free CaO	1	

2.2 Hydration process

The hydration process is initiated when the cement is mixed with water and governs the physical, chemical and mechanical properties of concrete through its service life.

The majority of reactions happening during hydration occur at an early stage. However, the reactions are continuous yet decreasing in intensity which is why concrete is not a static material. The reactions during the hydration are exothermic and generate different amount of heat, which can be measured by calorimetry (Schick 2012). The calorimetry curve can in turn be used as an indicator of the rate of reaction and level of hydration which will be seen in the subsequent sections.

2.2.1 Stages of hydration of Portland cement

The hydration process is typically categorised both based on the hydration phases and hydration products, but also by stages of heat development. Figure 2.4 illustrates a typical heat evolution curve where both of these hydration categorise are combined and can be summarized in the following manner:

Stage I:	Rapid heat evolution stage (Ettringite formation)
Stage II:	Dormant period
Stage III:	Acceleration stage (Hydration of Alite C_3S)
Stage IV:	Deceleration stage (Hydration of remaining C_3A)
Stage V:	Diffusion control stage

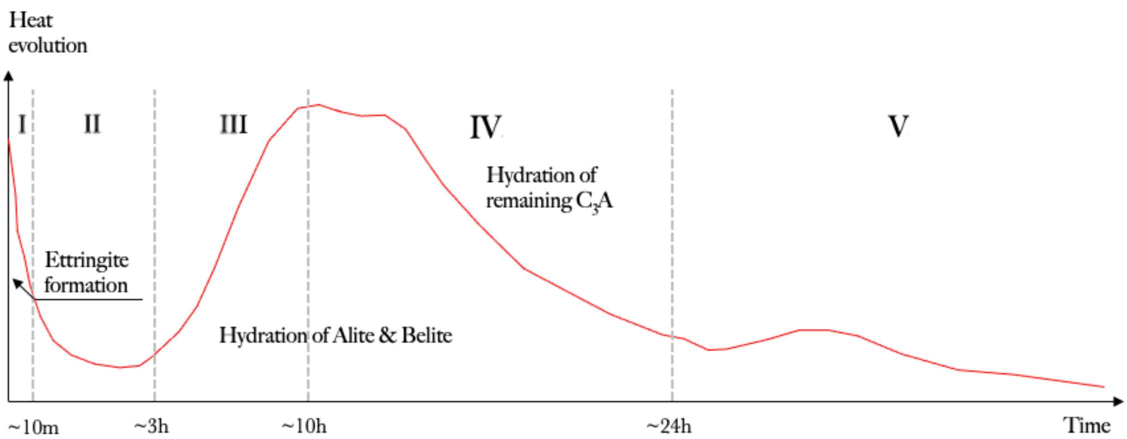


Figure 2.4: Typical heat evolution during early stages of the hydration process, modified from Kocaba (2009).

Remark that hydration of all four main components, C_3A, C_3S, C_2S, C_4AF, act simultaneously, but with different intensities. The following description is simplified according to the most intense phase during the early age.

Stage I: Prior to mixing with water, a small portion of gypsum is added to the cement to prevent the tricalcium aluminate C_3A to cause an instant flash set. In stage I, the reaction of tricalcium aluminate, C_3A, gypsum and water takes place. The hydration product ettringite is formed and a large amount of heat is also generated.

Stage II: The early production of ettringite slows down the hydration process as it forms a protective barrier around the C_3A (Ge et al. 2006). Consequently, a dormant period follows where the reaction rate, and therefore also the heat generation, is low and the workability of the concrete is good.

Stage III: When the permeability of the ettringite increases, the reactions are accelerated. In stage III, the calcium silicates alite, C_3S, and belite C_2S produces the principal hydration products portlandite and C-S-H gel in the presence of water and also large amount of heat. This corresponds to the peak at approximately ten hours in Figure 2.4. Portlandite contributes to the high alkalinity of concrete and the C-S-H gel contributes to the strength. The two calcium silicates differ as alite hydrates and hardens rather rapidly thus contributing to early-age strength, while belite does the opposite and instead contributes to the strength at later stages.

Stage IV: Remaining tricalcium aluminate, C_3A, and also ferrite, C_4AF, reacts and produces more ettringite but also aluminite and ferrite hydrates. This phase is delayed much due to the quick hydration in stage I, consuming most of the gypsum (Liu 2014). The concrete temperature gradually decreases and eventually meets the temperature of the surroundings. The hydration products grow and protect the yet unreacted cement, the layer acts as a diffusion area which slows down the reaction rate, and thereby also the heat generation.

Stage V: In the diffusion control phase, the hydration process continues in a controlled manner by diffusion through the hydration product layer (Kocaba 2009).

Remark that the hydration rate is dependent on temperature, as higher temperatures increase the hydration rate which in turn results in additional hydration heat, and so the hydration process accelerates (Engström 2007). As long as the heat generated by the hydration process exceeds the heat loss to the surroundings, the temperature in the concrete will proceed to increase until the amount of available unreacted cement decreases. The transformation from cement clinker compounds to hydration products is summarised in Figure 2.5.

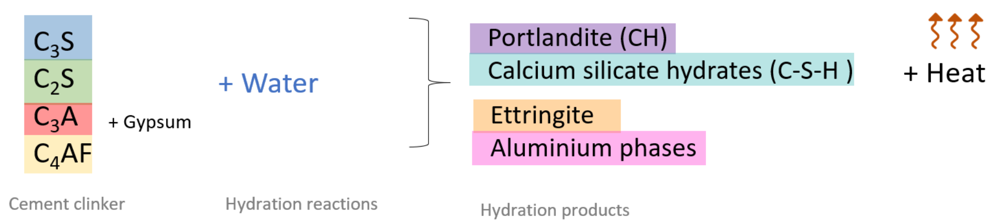


Figure 2.5: Hydration process of Portland cement summarised

The secondary hydration reaction, called pozzolanic reaction, which occurs if a SCM is incorporated in the mix was explained in Section 2.1.3. Figure 2.6 illustrates the pozzolanic reaction and how it is dependent on the primary hydration reaction of cement.

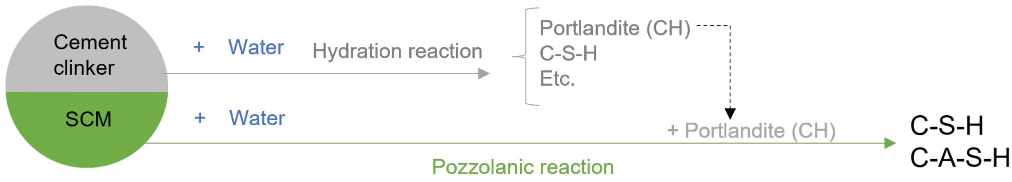
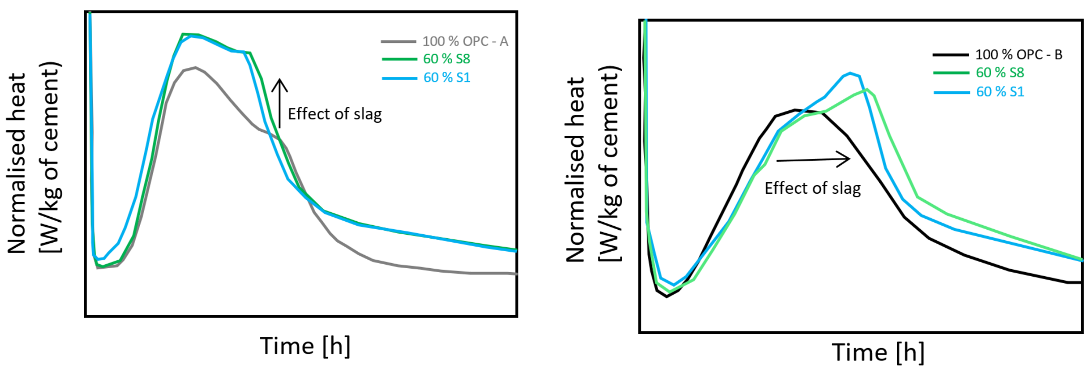


Figure 2.6: Hydration process of Portland cement and pozzolanic reaction summarised

2.2.2 Influence of slag

Partial replacement of cement by GGBS, slag, influences the hydration process in multiple aspects and ultimately the properties of both early-age and hardened cement. The slag hydration is slightly delayed compared to the hydration of the Portland cement as hydration products such as portlandite act as reactants for the pozzolanic slag (Gruyaert 2011). In broad terms, the slab-blended binder share most of the hydration products previously described, ettringite, portlandite and especially C-S-H. The largest differences compared to hydration of OPC are in which phases/ratios of composition dominates and at what time. Incorporation of slag delays the overall degree of hydration thereby also generates lower rates of heat, initially (Kocaba 2009). Finally, multiple factors affect the hydration of slag cement, such as cement type, particle size distribution, water-binder ratio and curing temperature (Ge et al. 2006). It is the total composition of cement and slag that ultimately determines the concrete behaviour. This is demonstrated by Figure 2.7 where the normalised heat from two different cement types are presented. Cement type A represent mixes with high C_3S, low C_3A and low alkali content and cement type B mixes with low C_3S, medium C_3A and high alkali content. The slag denoted S1 has a typical composition while S8 has a high alumina content and is part of crystalline phase. In Figure 2.7a, the effect of slag increases the normalised heat, while in Figure 2.7b it also delays the peak of heat generation.



(a) Cement type A

(b) Cement type B

Figure 2.7: Different effect of slag on the generated heat for two different cement types, modified from Kocaba (2009)

Differences in the hydration process due to incorporation of slag are further described as follows:

1. Acceleration and deceleration of phases

The larger ratio of water to cement, as a result of slag replacing part of the cement, causes an enhancement of the cement reaction. This is known as the filler effect. Substitution of cement by slag accelerates the hydration of tricalcium aluminate (C_3A), ferrite (C_4AF) and alite (C_3S), but delays the hydration of belite C_2S, prolonging the setting (Kocaba 2009). Slag itself forms a protective film when in contact with water, which inhibits further reaction and delays the reaction rate (Gruyaert 2011).

2. Consumption of portlandite

The liberated portlandite (CH) from the hydration of alite (C_2S) and belite (C_3S) reacts with the slag to form C-S-H, and if rich in aluminium, C-A-S-H (Gruyaert 2011). Due to the partial replacement of cement in combination with consumption of portlandite to form C-S-H, slag concrete contains less, or even sometimes not any, portlandite. A lower amount of portlandite reduces the alkalinity of the concrete, making it less resistant to carbonation.

3. Rate and cumulative heat production

Compared to hydration of pure Portland cement, a decrease in the total heat production is noticed for cement with slag which can be explained both by the dilution effect with lesser amount of cement that normally produces the heat, and also due to the latent-hydraulic effect that slag has (Mueller et al. 2017). The rate of heat production for slag concrete can be significantly reduced at early ages, and is more pronounced when the slag replacement level is increased (Ge et al. 2006). The graphs in Figure 2.8 demonstrate the generated thermal power of a concrete with only cement (C) in the binder and concrete with varying level of cement replacement by slag (S=16%, S1=30% and S2=50%). Generally, the slag concretes have a lower thermal power and the peak is delayed.

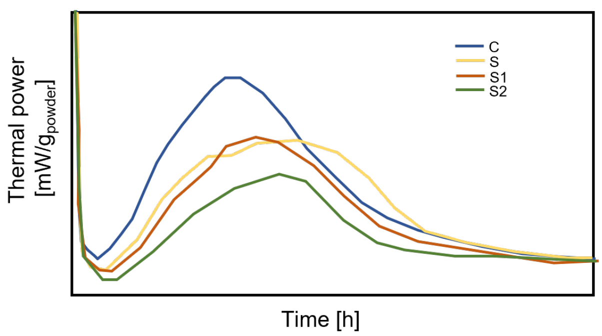


Figure 2.8: Thermal power for an OPC concrete (C) compared to three different slag concretes (S, S1 and S2), modified from Mueller et al. (2017)

2.3 Limitations and challenges of slag as a SCM

There is a limitation in amount of replaceable cement in the binder mix in relation to the desired strength development. As explained previously, slag requires hydroxide supplied by hydration products of Portland cement to become activated and with a limited amount of cement, part of the slag content will remain unreacted and the amount of formed C-S-H gel will be lower. Apart from the cement replacement level, the thermal conditions during curing are also greatly influencing the strength development. In a colder environment, insufficient hydration might become critical as the heat development for slag-blended cements are also lower.

An important note that is discussed by Scrivener K, Vanderley J, and Gartner E (2018) is the decreasing amount of produced GGBS in relation to production of cement. The international availability of GGBS is limited and a decreasing trend has been seen in recent years. Scrivener et al. describes how the availability of GGBS is expected to be further reduced partly due to an increased potential for recycling scrap steel and new technologies which will decrease the production of GGBS from steel. In the long-term, the availability of slag is, according to the authors, expected to be less than 8 % of cement production which support the argument that limiting the CO_2-emissions by only adapting GGBS as a SCM is not a long-term solution. However, this should not be an excuse to not utilize the resources available today to achieve environmental savings.

As the industrial production process of GGBS comes with economical investments it typically has a higher cost than Portland cement (Scrivener K, Vanderley J, and Gartner E 2018), also partly due to the relatively low cost of production of ordinary cement. The higher production cost of of slag-blended concrete creates a requirement of large environmental savings, in terms of lowered CO_2 emissions, to motivate the choice of the low-carbon concrete.

2.4 Slag effect on concrete properties

The altered hydration process due to incorporation of slag affects the micro structural development of the concrete, which affects both early-age properties and hardened properties. While it has a slower early-age strength, the ultimate strength will be higher. This is a result of the delayed hydration process of the slag. The improved long term strength is a result of the more efficient micro structure formed because of slower hydration rates, according to (Soutsos and Domone 2018).

Another effect of the slag is the development of a finer pore structure, which is beneficial as it becomes less prone to environmental impact (Mueller et al. 2017). The different distribution of hydration products, with slag producing more aluminium phases, also contributes to a better durability as the chemical binding capacity of chlorides increases with an increased amount of aluminum phases (Mueller et al.

2017). However, slag concrete has an increased vulnerability towards carbonation due to the consumption of hydroxide in the pozzolanic reaction (Gruyaert 2011). Nonetheless, the finer pore structure of slag concrete limit the transport within the pore system, which aids the resistance towards environmental impact, including carbonation (Mueller et al. 2017). Additionally, the slower hydration process with less heat generated makes the slag concrete sensitive to curing conditions, where cold temperatures strongly effect the hydration rate even further.

2.5 Early-age thermal cracking

In order to design structures of high durability, preventing early formation of cracks is essential, especially if the structure is exposed to water pressure, cyclic freezing-thawing or chlorides. Early-age cracking, arising in the beginning of the service life, should therefore be avoided. If the thermal movements, due to the exothermic hydration reaction, are restrained by an adjacent structure, there is a risk that the stresses induced become greater than the early-age strength of the concrete. This could potentially cause early-age cracks. There are multiple influential factors which affect the risk of early age cracking, which in turn have a complex interactive relationship, see Figure 2.9.

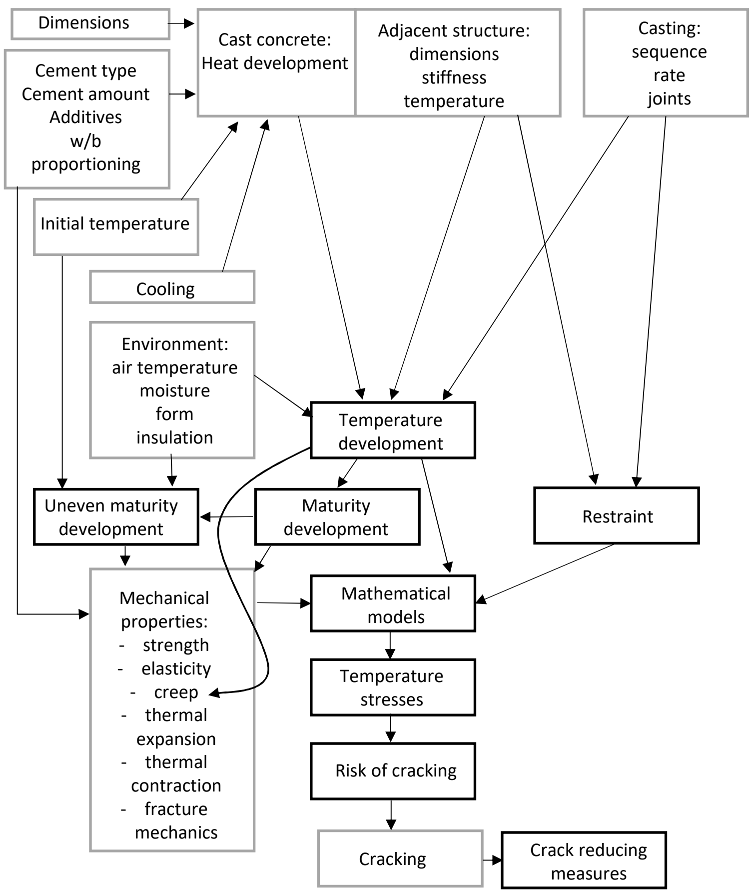


Figure 2.9: Block diagram showing the relation and interaction between influencing factors for early-age thermal analysis, modified from Martin Nilsson et al. (2015)

The most governing factors of early-age thermal cracking can be summarised as temperature, moisture and restraint conditions, early-age mechanical properties of the concrete, and the effect of an adjacent structure (Martin Nilsson et al. 2015). After the analysis, the governing stress-strength ratio, presenting the ratio between induced stresses and current tensile strength, is compared to limiting ratios. Limiting ratios are based on assessment of the potential damage of the early age cracking, which could depend on the exposure class and whether or not the structure is exposed to one or two-sided water pressure. If the stress-strength ratio exceeds the prescribed limit, measures are taken and the analysis is repeated. In the following subsections, first the general cracking process is described, followed by the influence of the main factors.

2.5.1 The cracking process

Heat is generated by the newly cast concrete as an effect of the exothermic hydration reaction. The temperature of the concrete increases if the generated heat is larger than the heat loss to the surroundings. Over time, the hydration process decelerates and the temperature of the concrete decreases to an equilibrium with the surrounding. Simultaneously, the strength and stiffness of the concrete increase. The temperature changes cause the concrete initially to expand, and later to contract. Prevention of these volumetric movements by the foundation or adjacent structure not experiencing the same thermal movements, causes restraint stresses. During the expansion, the restraint causes compressive stresses while tensile stresses occur during the contraction. Formation of early-age thermal cracks occur when the tensile stresses by contraction exceed the tensile strength of the concrete. Figure 2.10 illustrates the temperature, stress and strength development for an element under hardening with risk of early age cracking.

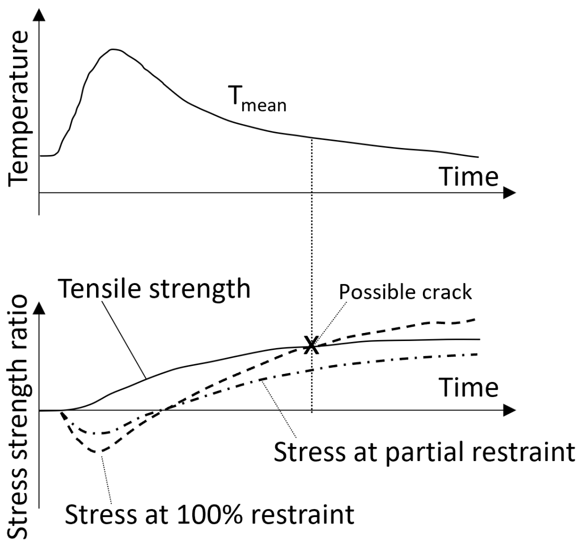


Figure 2.10: Development of a) mean temperature and b) stress and strength in an element with partial and full restraint, respectively, modified from Martin. Nilsson (2003)

Early-age thermal cracking can be further divided into cracks appearing during either the expansion phase, or during the contraction phase (Martin. Nilsson 2003). The expansion phase starts at the time of casting and continues until the maximum temperature of the concrete has been reached. Because of heat exchange with the surroundings, temperature differentials arise in the concrete element as the heat loss at the surface is generally higher than the heat loss in the core, causing a larger heat development in the core. In turn, this generates a non-uniform volumetric change within the element which induce internal restraint in the concrete. As the expansion is larger in the core than at the surface, tensile stresses will arise at the surface which could lead to surface cracking. Temperature differentials creating internal restraint are more critical for thick sections compared to thin sections since the heat exchange with the surrounding is more efficient for the thin section and therefore temperature differentials become smaller. Because of the low modulus of elasticity during the first days after casting, the deformations are mainly plastic and the effect of creep is high (Engström 2007).

As the concrete is cooling and contracting, the deformations are becoming more elastic and less plastic as the stiffness of the material is increasing with time. Consequently, the restraint, and thereby the tensile stresses, also increase with time when restrained by an adjacent structure. If the tensile stresses increase faster than and exceed the tensile strength in the contraction phase, through cracks might form. Even though the contraction can partly or fully close surface cracks from the expansion phase, through cracks from the contraction phase could cause permanent damage to the structure.

2.5.2 Temperature development

The temperature development in the concrete element has a significant impact on the risk of cracking. Small temperature differentials and a slow cooling is beneficial in this context. The maximum temperature can be decreased in multiple ways. First, the cement type and cement content should be chosen to limit the heat generation during hydration. A second alternative is to use a low casting temperature. The casting temperature can be specified in the order of the concrete, however, there are limits to what temperatures are possible to deliver to the construction site and depend on the environmental temperature and the distance between the factory and the site. A third option to decrease the peak temperature is to use cooling, where cold water cools the concrete through embedded water pipes.

The design of the structure and the surrounding temperatures are two additional factors which affect the temperature development in the concrete. The effect of wall thickness on the temperature development is illustrated in Figure 2.11, where the increased thickness generates a higher maximum temperature and decelerated cooling. To avoid temperature differentials, an even cross-section can be preferred prior to a varying one. The surrounding temperature has a great influence when casting in an outdoor environment, however it cannot be controlled. Careful consideration of the surrounding temperature is needed to avoid thermal chocks at formwork removal.

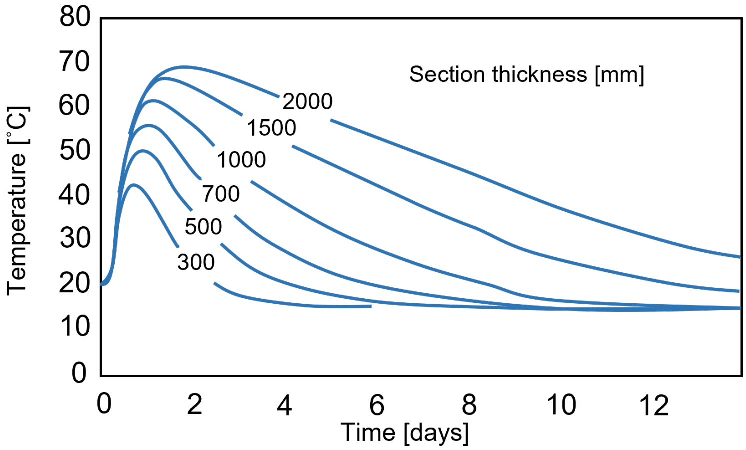


Figure 2.11: Temperature development based on predictive model for a concrete with 350 kg/m^3 CEM I and 18 millimeter formwork removed after seven days, effect of wall thickness (modified from Bamforth (2017))

2.5.3 Mechanical properties

There are multiple mechanical properties which affect the risk of cracking. These include the strength development, elasticity and creep, thermal dilation, nonlinear behaviour for high stress levels and plastic properties (Martin Nilsson et al. 2015). The hydration process is dependent on the chemical composition of the concrete mix that affects at which rate concrete properties are developed. Concretes with a slower early strength leading to undesirably long curing period could be accelerated by improving the thermal conditions, for example by either insulating the form or by casting with a higher temperature.

2.5.4 Restraint

In a theoretical situation without any external restraints and where the temperature distribution is uniform across the section, the concrete would expand and contract freely without any formation of stresses due to temperature (Engström 2007). However, in practise, restraining conditions are to some extent always present and must be considered as it is one of the most fundamental parameters influencing the risk of cracking (Martin Nilsson et al. 2015). The restraint is normally defined with respect to a maximum restraint. The external restraint is a result of the overall structural arrangement. This includes the relation between the dimension and stiffness of the new and old concrete, the adhesion of the adjacent surface and foundation type. Additional factors include the casting sequence and potential casting joints. An adjacent structure with an overall larger stiffness will provide a higher restraint, with a proportionally larger stress-strength ratio. The external restraint could be decreased by preheating the adjacent structure, thus minimizing the difference in thermal dilation between the new and adjacent structure. It could be avoided all together by casting the two elements at the same time. However, this is not always feasible in construction, resulting in the need of early-age crack assessments.

The wall studied in the coming analysis is assumed to be free at all edges except the bottom edge connecting to the slab which provides close to a fully fixed support as the concrete of the slab is assumed to be fully hardened. Hence the restraint degree in the longitudinal direction will be maximal, R=1, at the casting joint and gradually decreasing with the height of the wall. At a certain distance from the casting joint, there will be no restraint, R=0. The distribution of longitudinal restraint is illustrated in Figure 2.12.

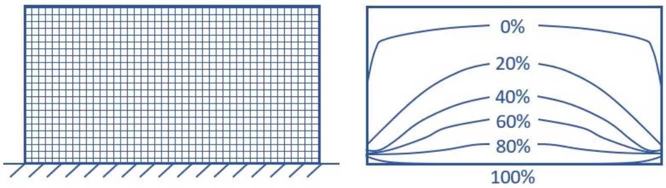


Figure 2.12: Principle of restraint distribution for a non-reinforced wall with free edges, cast on an already existing slab, modified from Engström (2007)

2.5.5 Regulation and guidelines related to early-age thermal cracking in Sweden

Regulations on risk of early-age thermal cracking can be found in several areas of publications both by authorities and as well as industry-wide informational companies. Whether or not regulations are binding is primarily dependent on if it is demanded by authorities or stated in contract. For civil works, there are generally more requirements regarding risk of early-age thermal cracking than for buildings. However, demands applied for civil works are often used as a reference and are therefore also used for comparison of results in this study. In addition to requirement of early-age thermal cracking, there are also requirements related to early strength and risk of early freezing which need to be fulfilled.

In SS-EN 13670:2009 Execution of concrete structures (Swedish Standards Institute 2009), recommendations regarding curing and protection are given. The curing period is related to different curing classes based on development of concrete properties at the surface and aims to minimise the risk of surface damage by, for example, weather conditions, freezing, vibrations or abrasion. The curing classes are presented in Table 2.3. SS-EN 13670:2009 is referred to by Boverket through EKS and by the Swedish Transport Administration through TRVK.

Table 2.3: Curing class requirements according to SS-EN 13670:2009 (Swedish Standards Institute 2009).

	Curing class 1	Curing class 2	Curing class 3	Curing class 4
Period [hours]	12	Not applicable	Not applicable	Not applicable
Percent of specified characteristic compressive strength after 28 days	Not applicable	35%	50%	70%

In addition, the standard for national application, SS-EN 137006:2015 Concrete construction - Execution - Application of SS-EN 136370:2009 in Sweden (Swedish Standards Institute 2015), is regulating which curing class is to be adapted. The choice of curing class is based on exposure classes, concrete composition, concrete cover to reinforcement, climate conditions and dimensions.

SS-EN 137003:2021 Concrete - Application of SS-EN 206:2013+A2:2021 in Sweden (Swedish Standards Institute 2021) includes requirements of fresh and hardened concrete and methods of validation. In Tables 7-10 in SS-EN 137003:2021, the maximum w/b ratio and accepted composition of binder for each exposure class are presented. The maximum allowed percentage of GGBS in the binder varies between 35 and 65% (70% for X0). However, the GGBS concrete mix used for this study has been quality tested and thus the replacement level is allowed to exceed the stated limits of w/b ratio and share of GGBS in binder. Remark that the analysed GGBS concrete mix was developed for a railway environment, thus demands for exposure classes with regard to chlorides are not included.

Besides the governing regulations by Swedish Standards Institute, the Swedish reference for general material- and execution description called AMA (Svensk Byggtjänst 2020) have set requirements of material and execution related to early-age thermal cracking. In the publication AMA Anläggning 20, safety factors for crack risk, which are used to assure there will not be any durability concerns, are stated. The safety factors for crack risk together with associated exposure class are presented in Table 2.4. The inverse of the safety factor represents the risk of cracking which is to be compared to the calculated stress-strength ratio. Notice that the safety factors for crack risk are lower for mix specific materials parameters in comparison to general material parameters. The general material parameters can be used for approved concretes according to EBE.1 alternative 1 or 2 (Svensk Byggtjänst 2020)

Table 2.4: Safety factors for crack risk, S, according to AMA Anläggning 20 table EBE.11/1 (Svensk Byggtjänst 2020)

Exposure class	Mix specific material parameters	General material parameters	
		$360 \leq C \leq 430\ kg/m^3$	$430 < \mathrm{C} \leq 460\ kg/m^3$
XC2	1,05	1,18	1,33
XC4	1,11	1,25	1,42
XD1, XS2	1,18	1,33	1,54
XD3, XS3	1,25	1,42	1,67

The regulations by AMA are presented in AMA Anläggning 20 section EBE.11 where three types of calculation methods for risk of cracking are introduced. The regulations and methods in AMA Anläggning 20 originate from 'the Swedish model of cracking' which was initiated in BRO 94, published by the Swedish Road Administration (1999). Method 1 differentiate between risk of surface cracks and risk of through cracks and list a number of conditions to be fulfilled in order to prevent each type of cracking. Common for both is that the cement amount should not be exceeding 430 kg/m^3 and that the w/b ratio should be higher than or equal to 0.4. The conditions in Method 1 are limiting the cement content, w/c ratio, dimensions, casting temperature, temperature of the air and temperature of adjacent structural elements. For prevention of through cracks, it is also limited to foundation type as it states that the structural element considered cannot be founded on solid rock for these regulations to apply. Method 2 are referring to Teknisk rapport 1997:02 Emborg et al. (1997) which presents calculation methods for four typical structural design cases. If non of these reference cases can be used, AMA Anläggning 20 are referring to Method 3 which includes performing an analyses by a verified calculation software program with documented calculation method and input and output data.

2.6 Experimental tests for development of material parameters

To find suitable parameters that provide an accurate representation of the material behaviour in the modelling software program, experimental tests are performed. Material parameters used in this study were developed by testing performed by Luleå Univeristy of Technology and is shortly described below to give an insight of the underlying work. The testing process itself is not part of this study. Test data is gathered in order for material models to be fitted to the test results by regression analysis. Material parameters can be extracted by finding suitable material models and adjusting the numerical values to the experimental data by fitting parameters. This set of mix specific material parameters can then be used to calculate thermal stress-strength with a better safety level. A summary of the tests that are performed in order to derive the material parameters are given below.

2.6.1 Hydration rate

To determine the heat development during hydration of a specific concrete mix, a semi-adiabatic testing method called TSA (traditional semi-adiabat calorimetry) is often used. A concrete sample is cast, with temperature monitors in the centre and at the surface, and placed in a semi-adiabatic box soon after casting. First, temperature is recorded during the hydration process, until the sample has reached the ambient air temperature. Thereafter, the sample is heated to a level just above the maximum measured hydration temperature. The temperature of the sample as well as the ambient air temperature are logged continuously. When using the semi-adiabatic method some heat loss must be accounted for and the correction factor for heat loss should therefore be determined (Fjellström 2013). The heat developed is approximately proportional to the degree of hydration and a time-temperature graph can be created. To verify that the sample has not dried out, the mass of the specimen is documented before and after the test. An example of time-temperature graphs obtained by adiabatic and semi-adiabatic testing is presented in Figure 2.13

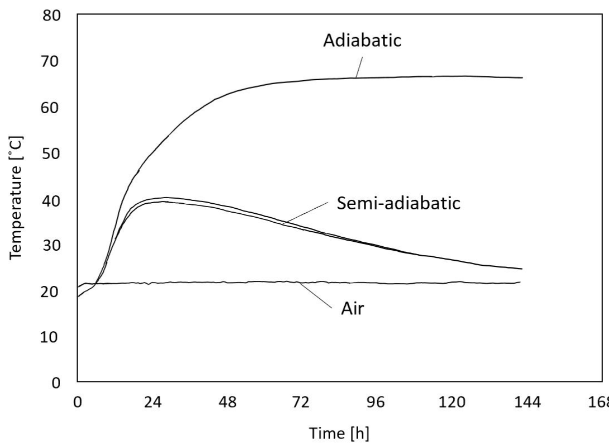


Figure 2.13: Example of test results showing the registered temperature of two TSA tests and one test with adiabatic equipment, modified from Hedlund and Utsi (2002)

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2.6.2 Strength development

The strength development can be determined by casting a large number of test specimens which are then stored in different curing temperatures of 5, 20, 35 and 50°C. The specimens are tested in a compressive test at different ages. Having tested specimens both at different temperatures and different ages enables one to create a maturity function, a tendency curve, for that specific concrete mix. Knowing the heat generation of a test, it can then be related to the tendency curve to know the current strength capacity. More accurate results can be obtained if individual equations are used for three time periods, which can be combined into a complete sequence (Fjällström, 2013).

2.6.3 Autogenous shrinkage and thermal dilation

Small volume changes such as autogenous shrinkage and thermal dilation can be determined by regulating the temperature of a specimen during curing and measuring the movements. Since autogenous shrinkage and thermal dilation are due to chemical reactions that happen simultaneously, they cannot be separated in the test. Therefore, two specimens are needed to separate the cause of volume change.

Besides the main specimen, a reference specimen is cast at the same time and with the same concrete mix but without thermal loads. In this way, the fundamental autogenous shrinkage can be measured. Methods for this kind of testing are designed for Portland cement concrete but could need further development to specifically fit a slag blended concrete mix (H. Hedlund, personal communication, February 8 2022). When the autogenous shrinkage is known, the thermal dilation can be calculated from the results of the main specimen.

2.6.4 Creep

To capture the creep behaviour during early age, multiple deformation tests are performed at different ages. The creep is found by comparing the deformation of one sample under constant loading, at a magnitude of 20 % of the measured compressive strength at that age, to the deformation of a non-loaded sample. By subtracting the deformation of the non-loaded sample from that of the loaded sample, the resulting strain can be obtained. The results are later evaluated based on current creep models and fitted by regression analysis (least square method). The creep function can be converted into relaxation which is used in the thermal stress calculations (Westman 1999).

2.6.5 Thermal stress

The set of material parameters can be verified by a special test, "Thermal Stress Test Method" also known as TSTM. Unfortunately, it requires a special built equipment which is very expensive. The selected concrete mix is cast inside the machine directly, and the temperature is controlled to simulate the temperature curve of the previous heat generation test. The specimen will aim to expand during heating but is held back by a loading cell which keeps the specimen at a constant length. Therefore, initially compressive stresses are developed, but as the specimen cools down the stresses convert into tensile stresses instead. The test method is described by Westman (1999). If the results in the TSTM can be represented by the set of material parameters, a better safety level can be obtained during design.

2.7 FE modelling in ConTeSt

The FE modelling program ConTeSt is an approved software to use for method 3, mentioned in Section 2.5.5. The program was developed by JEJMS concrete AB with the aim to design a software which calculates the temperature, the strength and the cracking risk for young concrete. This to predict the early behaviour prior to the casting and discover and avoid potential problems (JEJMS concrete 2008).

2.7.1 Heat computation

The heat computations performed in ConTeSt are analysing a two-dimensional plane in the xy-space, as in Figure 2.14. Thus the studied structure must be long enough, in z-direction, for any heat flow out of plane to be negligible.

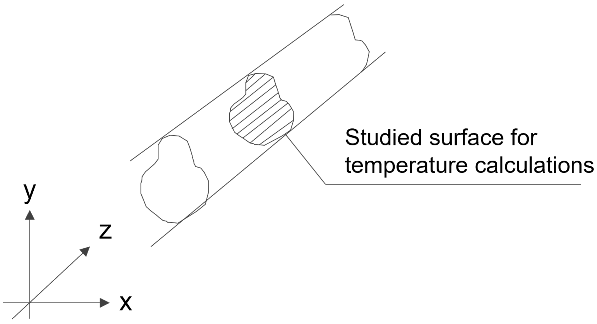


Figure 2.14: Illustration of the studied section for heat computation, modified from JEJMS concrete (2008)

The heat flow out of plane can then be described by the following expression in 2.1 according to JEJMS concrete (2008):

$$q_z = -k_z \frac{\partial T}{\partial z} \approx 0 \tag{2.1}$$

where: q_{z} = heat flow in the z-direction, W/m^2
k_{z} = heat conductivity for the heat flow in the z-direction, W/mK
T = Temperature in the studied structure, °C or K

The heat conduction equation for inner parts of the studied structure can then be described by Equation 2.2:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x} + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + Q_H \tag{2.2}$$

where: ρ = density of the material, kg/m^3
c = specific heat the material per mass, J/kgK
ρc = specific heat the material per volume, J/m^{3}K
k_{x} = heat conductivity for the heat flow in x-direction, W/mK
k_{y} = heat conductivity for the heat flow in y-direction, W/mK
Q_{H} = generated heat inside the body, W/m^3

The heat conduction in a material is assumed to be isotropic, resulting in $k_x = k_y = k$. Moreover, the heat flow along the external boundary of the studied structure is described by Equation 2.3

.

$$q_n = h_{surf}(T_{surf} - T_{env}) - I \tag{2.3}$$

where : q_{n} = heat flow from the body to the boundary along the perpendicular to the boundary surface in the xy-plane, $\mathrm{W/m^2}$
h_{surf} = heat transfer coefficient for the external boundary, $\mathrm{W/m^2K}$
T_{surf} = temperature on the surface,°C or K
T_{env} = environmental temperature,°C or K, most often denotes the air temperature
I = heat radiation to the boundary from the surroundings, $\mathrm{W/m^2}$

For external boundaries with air as the surrounding medium, the heat transfer coefficient is described by Equation 2.4:

$$h_{free} = \begin{cases} 5.6 + 3.95v & \text{for } v < 5 \text{ m/s} \\ 7.8v^{0.78} & \text{for } v > 5 \text{ m/s} \end{cases} \tag{2.4}$$

where: h_{free} = heat transfer coefficient for a free surface surrounded by air, $\mathrm{W/m^2K}$
v = air velocity, m/s

For external boundaries with several layers of different boundary materials, the combined heat transfer coefficient can be described according to Equation 2.5 for stationary conditions.

$$h_{surf} = (\frac{1}{h_{free}} + \sum_i \frac{l_i}{k_i})^{-1} \tag{2.5}$$

where: l_{i} = thickness of the i:th boundary material, m
k_{i} = heat conductivity of the i:th material, W/mK
$\frac{1}{h_{\mathrm{free}}} = \text{alt.} \begin{cases} \text{with } h_{\mathrm{free}} & \text{for cases in contact with air, according to Equation 2.4} \\ 0 & \text{for cases in contact with something else than air} \end{cases}$

2.7.2 Stress computation

The stress computation in ConTeSt are analysing out of plane stresses for a two-dimensional plane, where the heat computation have been performed. Figure 2.15 demonstrate stresses in the z-direction for a two-dimensional surface in the xy-space, with potential cracks formed by σ_z are perpendicular to the z-direction.

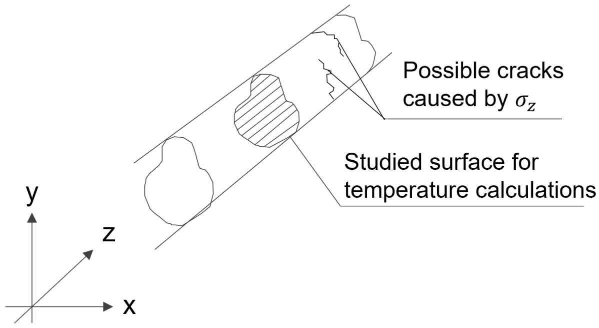


Figure 2.15: Illustration of the studied section for stress computation, modified from JEJMS concrete (2008)

There are two possible ways of calculating the stress variation in ConTeSt, consisting of either a 'Linear line analysis', LL, or a 'Plane surface analysis, PLS. The LL model can be regarded as an advanced beam analysis. The stress σ_z can be varied in one direction, either x or y, and the stresses in the other direction will then be averaged. For the PLS model, the stresses can vary in the xy-plane according to set boundary conditions chosen by the user. Further calculations details can be found in the user manual for ConTeSt Pro - *Program for temperature and stress calculations in concrete* (JEJMS concrete 2008).

3 Experts opinion

An interview study with key persons from the industry was conducted in order to better understand the subject, its context and to identify specific challenges to investigate. Experiences and opinions regarding the possibilities and challenges of cement replacement by slag are gathered in this chapter. Common challenges on all levels include the conservative and traditional way of working.

3.1 National and geographical conditions setting the basis of concrete design

Although concrete is used as a construction material globally and collaborations are conducted by international associations, there exist differences in how different nations work with concrete. Mats Karlsson, Professor of Practice at Chalmers and Head of Department at the Swedish Transport Administration described the background of how concrete is used in Sweden today. Each nation has its own history with research that has formed the general perception. One contributing factor to the differences are established industries in the nation which are a prerequisite for what by-products, such as slag, fly ash and silica, are available to use as SCMs. The alumina industry in Norway supplies silica, while the coal power plants in the Netherlands and Germany can take advantage of fly ash (M. Karlsson, personal communication, March 18, 2022).

In Sweden, a decision to work with high content of pure Portland cement was made in the 1980's as a solution to carbonation induced corrosion as the pure Portland cement has a high alkalinity. The Swedish way has been deviant and in Sweden a larger amount of cement in the concrete is generally used. Consequently, a bigger focus on early-age thermal cracks is required (M. Karlsson, personal communication, March 18, 2022). However, due to uncertainties of the cement clinker production in Sweden in the near future and an aim to limit the carbon-emissions of the building industry, the Swedish way needs to change. This by drastically decreasing the amount of cement used while still being able to design durable structures in a Swedish climate. To reduce the cement amount, incorporation of fly ash, a waste product from the coal power industry, has been applied in cement production. In the project Brf Viva, residential buildings built in Gothenburg during 2016-2019, a cement replacement level up to 30 % was used which resulted in 30 % lower environmental impact (Cementa AB n.d.). But due to coal fired electricity production being the largest emitter of anthropogenic CO_2 it is now being phased out together with other fossil fuels (Scrivener K, Vanderley J, and Gartner E 2018). In turn, this motivates the discussion of other available SCMs, such as slag.

3.2 Current use of slag-blended cements in Sweden and potential improvements

To understand the context of the issue of early-age cracking, an overview is given of the current use of slag-blended cements in Sweden. In a quest for more sustainable solutions, current issues and approaches are discussed including conservative perception in the industry, cement as an accelerator, delegated risk calculations, and the industrial logistics in Sweden.

3.2.1 Recent experiences dismantle aged perceptions of the performance of low-carbon concrete

Given the fact that slag concrete has not been used in Sweden to the same extent as in for example, the Netherlands, the behaviour of new concrete mixes involving slag has been questioned by people in the industry. Today, as concrete with slag content is getting more commonly used in both building projects and civil works, the perception might be changed. In construction of buildings, there are several different concrete types with a cement replacement level varying between 20-65 % adjusted to fit different structural parts. A study visit to Hamnbanan, an extensive civil construction project including tunnels and trough for a double-track railway where concrete with 10 % slag has been used during the winter castings, gave insight in the experience of working with GGBS concrete. The experience has been that there is little difference in the material behaviour compared to ordinary construction concrete and no special preparations or measures have been required for this level of replacement. However, there is still a common belief that slag concrete is not appropriate in for example key structures or underwater structures. Jan Leinonen, project manager at Skanska working with civil works, propose that more testing could be needed to further extend the use of slag concrete and that the performance in terms of freezing and chloride ingress needs to be proved (personal communication, March 7, 2022). As previously seen in Section 2.4, research has implied that the incorporation of a SCM with higher alumina content might be beneficial for the resistance towards of chloride ingress (Mueller et al. 2017).

3.2.2 Possibility to decrease the amount of cement

A high cement content is sometimes used to accelerate the hydration process enabling earlier formwork removal. The dimension of concrete walls in residential buildings are typically governed by other functions than its structural capacity, for example by acoustical regulations. There is a potential to decrease the cement amount significantly to utilize the material more efficiently. Mats Karlsson at the Swedish Transport Administration questions this as follows:

> How reasonable is it to use a large amount of cement that does not really have a function during the 50-100 year service life of a building in order to save one day in the concrete element factory? (M. Karlsson, personal communication, March 18, 2022, authors' translation)

The cement use can be decreased in a number of ways. Prescribing a lower concrete class while allowing longer curing times in formwork is one. Another one is to use SCMs which was previously mentioned in sub section 2.1.2. However, it is a big challenge as existing and verified SCMs are limited and the research of calcinated clays are at a relatively early stage. In addition to further research, logistical solutions are needed as the cement factories in Sweden typically are located near limestone quarries on Gotland and in Skövde, while large clay resources are located in Skåne, in the south of Sweden (M. Karlsson, personal communication, March 18, 2022).

Due to the traditional Swedish way of using pure Portland cement, incorporation of SCMs is relatively new. Building projects typically have milder exposure classes and thus a better basis for slag replacing cement. Therefore slag concrete has been used at a larger extent in buildings compared to civil work. The stricter exposure classes, such as XF4, which are more frequent in civil work projects have limited the use of SCMs up to 20 % until the release of the revised version of SS 137003:2021 (Swedish Standards Institute 2021). The allowed replacement level by slag for civil work according to the standard was increased from 20 to 35% for XF4 under certain conditions, enabling usage in a larger variety of projects.

3.2.3 Holistic perspective to be gained from in-house expertise

Due to the complexity of early-age thermal cracking, there are currently few companies performing risk controls with even fewer experts specialised on the topic. These experts can then use their experience in design, for example by avoiding large cross-section variations in through bridges to avoid the need of cooling measures. However, since most companies delegate the early-age crack risk control and get a solution with measures in return, there is a missed opportunity for knowledge feedback. By having the expertise in-house, a holistic perspective can be gained where one as a structural engineer learn with time the connection between design and measures to control early-age thermal cracking.

A first step could be to make the calculation process more user friendly and provide good guidance for less experienced structural engineers. Structural engineer Nils Rasmark focuses on early-age thermal analysis and explains limitations of some of the suggested methods. For example, the conditions for securing prevention of through cracks according to Method 1 in AMA Anläggning is seldom applicable for typical cases in Gothenburg. This as the combination of the weather conditions and casting temperatures rarely coincide (personal communication, February 28, 2022). The casting temperature is often higher than the stated limit when combined with the given air temperature. Another method available is the early-age thermal cracking tool "Crax1", where the user can specify the geometry of a centrally placed wall-to-slab structure together with the concrete type, amount of cement, formwork type, and get a good first indication of the crack risk. However, it relies on a large number of simulations with an older concrete type, which could make the results less accurate as concrete mixes have been developed during the last 20 years. In addition, Crax1 was developed based on pure Portland cement and thus cannot account for the influence of slag. Consequently, its usage is limited.

3.3 Implementing sustainable solutions

Early discussion of sustainable methods in the planning phase is the most efficient way of decreasing the carbon footprint of a project. However, this does not exclude the possibility of improvements later in the process. In the following sections, the role of contracts, functional demands, time plan, and climate demands are discussed.

3.3.1 Standards not always binding

The design of structures is based on the regulations of the client. They can in turn use references such as AMA that in turn can call on the Eurocode standards. There are some standards that are included in the government regulations, however most are not. Instead, they are typically invoked in contracts which ultimately makes them binding to follow. Although references like AMA and standards are typically used, they are not always binding and there could exists solution outside the standard practise.

Certain contracts are less restricted by standards and instead the regulations are formulated in term of functional demands to utilise the expertise of the contractor and create a possibility of new solutions. The contractor is then responsible to prove that the design will meet the functional demands, which could require significant amount of work. The special demand-specification, which is included in regulations by the Swedish Transport Administration, enables and creates an opportunity for moderns solutions not yet covered by the infrequently updated standards. It is also important to remember that it is impossible to cover all cases in the regulation in an industry with such diverse projects (M. Karlsson, personal communication, March 18, 2022).

Due to the transparency in the building and construction sector, in terms of visible construction sites and, in some situations, public documents, there are not as large incentives to promote innovation compared to other industries. Once a project is finished, other companies could more easily adapt a solution which the first company put a lot of money and effort in. Mats Karlsson explains how the investment of trying new methods might not be a direct financial gain, although it could generate an advantage in knowledge, a sustainable image and trust of current and future clients. Going forward, an alternative could be that big clients with an interest of a specific solution could invite companies to perform different parts in a demonstrating project, decreasing the investment cost of one single company and disseminate the knowledge (M. Karlsson, personal communication, March 18, 2022).

3.3.2 Taking green initiatives during construction process

The type of contract is decisive for possibilities of implementing sustainable solutions. In an execution contract, the construction work is usually executed according to the construction documents as the consultant hired by the client has already completed the project planning. This means that if the client and consultants delivering the construction documents have not considered alternative solutions in terms of more sustainable materials or production methods, it might be hard to implement the idea later on in the project. One example of this is, discussed by Nils Rasmark, is due to the lack of freeze tested slag-blended concrete mixes. Freeze tests are required for exposure class XF4 to verify the concrete performance. According to both the previous version SS-EN 137003:2015 and the current version SS-EN 137003:2021, a concrete mix with a binder content containing $\leq$ 20 % slag requires the ordinary freeze test, which takes approximately three months to perform. However, in the current standard, SS-EN 137003:2021, a freeze test on carbonated surface was introduced as a requirement for concrete mixes with a binder content of 20-35 % slag. The lead time for this type of test is typically 7-8 months, why the decision of concrete type in these situations needs to be made in an early stage. As slag-blended concrete mixes are becoming more frequently used, the concrete factory might establish an assembly of qualified freeze tested mixes (personal communication, February 28, 2022).

If the client is valuing soft parameters instead of economical from the beginning, the ambition of creating sustainable solutions could be infused throughout the project, from the tendering process to the design phase and final execution. An example of this is the climate bonus which has been used by the Swedish Transport Administration in certain projects to encourage the contractor to make more sustainable choices. The implementation of environmentally sustainable solutions is usually simplified by a turnkey contract where the contractor is part of all stages of the project. In a project where low environmental impact is not a benchmark stated in the procuring, there are still possibilities for the contractor to encourage green solutions. However, it will be a challenge of motivating potentially higher economical costs.

To avoid that initiatives of single individuals are decisive for the level of environmental savings in each project, the climate demands set by the Swedish Transport Administration and other clients could be more strict. This is done in certain areas of construction, for example railways (M. Karlsson, personal communication, March 18, 2022). To set stricter demands on climate accomplishments could encourage people in the industry to take more climate-positive initiatives and according to M. Karlsson, the level of environmental savings would be less dependent on one single project manager or specialist within the area (personal communication, March 18, 2022).

3.4 Challenges in design and analysis of slag concrete

Early-age thermal cracking is a complex topic with multiple material models based on large numbers of empirical data. Since slag concrete has been used in a much smaller scale compared to traditional OPC concrete, the amount of data available is less and thus existing material models are not as well calibrated. There is less experience of working with FE analysis with the material and as a result, there is additional calculation work.

3.4.1 Material models based on pure Portland cement

One of main issues when considering the design aspect is the fact that today's material models for analysis of early-age thermal cracking in concrete, are based on the behaviour of pure Portland cement with some adjustments for approximation of the effects of additional binder materials. Hans Hedlund, Doctor of Technology and concrete expert, provides an insight in the limitations of current material models with regard to slag concrete. These material models were mainly created during the 80' and 90's and were designed to correspond to the early-age material properties and heat development as a result of hydration reactions of Portland cement (H. Hedlund, personal communication, February 8, 2022). When involving any SCM there are additional chemical reactions happening simultaneously, which were explained in Section 2.2.2, yielding different heat and strength development. The additional reactions are partly accounted for by 'fitting parameters' combined with the material models applied in calculation and modelling software programs today.

The simple explanation of why material models and conventional calculations methods are becoming outdated is that verified material data of modern concrete mixes are not available to a desired extent. The lack of proven data cause difficulties for the majority of the industry to make accurate estimations of risk of early-age thermal cracking and in turn, determining appropriate safety measures during casting and curing, and pricing (H. Hedlund, personal communication, February 8, 2022). To describe a different early-age behaviour, new parameters might be needed that are not in today's material models. The experimental test methods today are designed to determine the parameters for these material models, meaning that for new material models, new testing methods may be required.

3.4.2 Adjustments for concrete with GGBS

The different early-age behaviour of concrete containing slag causes iterative calculation work as the outcome is not always intuitive. Thin sections are vulnerable to low environmental temperatures as the section is cooled down and the hydration reactions providing heat are in turn also slowed down. Concrete with high replacement levels of slag already generating less heat is then extra susceptible to the hydration reaction slowing down which could in an extreme case stop. To manage slag concrete cast in cold temperatures there is a fine balance between prescribing a higher initial casting temperature to ensure hydration development, while momentarily wanting a low temperature to achieve a lower stress-strength ratio to avoid a higher risk of cracking. Finding this balance appears more complex for slag concrete (N. Rasmark, personal communication, February 28, 2022). As there are multiple parameters affecting both the hydration development and stress-strength ratio, small adjustment could be sufficient to find the optimal solution. The non-intuitive influence of multiple factors is a difficulty when working with early-age thermal cracks even for concrete with pure Portland cement, and is further amplified for concretes including high amounts of slag.

3.4.3 Detailed idealised calculations versus the reality of production

Conclusions of calculations should not be too dependent of exact conditions as the reality of casting cannot be as precise. It is essential that material parameters used in the FE modelling are carefully calibrated and verified against experimental testing, to ensure the FE modelling does not provide a false security (H. Hedlund, personal communication, February 8, 2022). Additionally, knowledge of the underlying assumptions and approximation in the calculation process is needed when assessing results. Good knowledge of production methods and realistic timelines for formwork removal and insulating coverage is beneficial to find a solution that will result in a successful casting. Initial calculations might also need to be altered due to the planning of construction occurring at a later stage. Communication and compromises are key factors to find a feasible production method that also result in low risk of cracking.

Different projects have various conditions which determine if it is known during which season of the year the casting will be carried out, or if it is determined later on in the planning process. If a shorter interval for the planned casting can be set, fewer alternatives needs to be considered and potential measures can be better specified. Railway construction is one example where scheduled traffic breaks are planned far ahead and the day of the casting is set. Nils Rasmark explains that if the time of the casting is known and the risk of freezing is to be investigated, the minimum temperature can be used instead of the typically used monthly average temperature to better represent the environmental conditions during the first critical hours after casting. Statistical data, which are often used in design by assuming monthly average, might differ notably from the actual weather conditions. If this is the case and the casting is to be performed within the nearby future, weather forecasts may be considered. However, it is more common that the time of casting is not specified, which is managed by performing calculations for the two most extremes of a warm case and a cold case of either a set season, or in even more uncertain plannings, for the entire year. According to Nils Rasmark, one measure which is often effective to reduce the risk of thermal cracking, is to increase the time with formwork. Unfortunately, formwork is an expensive measure which could also delay the construction process and thus other alternatives are common to limit the number of days with formwork (personal communication, February 28, 2022).

4

FE modelling

The modelling and analysis are performed in several steps in the FE software ConTeSt. To evaluate the effect of cross-sectional dimensions and casting length, nine different geometries are studied. First, the early-age behaviour is simulated for each geometry without any mitigation measures to reduce the risk of cracking whereon results are evaluated. In the next step, suitable casting and curing measures are applied to limit the stress-strength ratio with respect to risk of early-age cracking, to meet requirements of strength development, and to avoid the risk of early freezing. Measures are initially applied separately to study the effect of each and then combined to fulfil the requirements while meeting a deadline of number of days before formwork removal.

4.1 Prerequisites

There are multiple factors which influence the early-age behavior of concrete. Small differences in casting and curing conditions can make a significant difference in the final result. The influencing factors can be described as thermal or structural. The thermal conditions are broadly decided by the outdoor conditions, heat transfer capacity of the formwork, casting temperature, temperature of adjacent surface and cross-sectional dimensions. The structural conditions, directly affecting the restraint, are mainly dependent on the casting order, temperature of adjacent surface (rate of contraction) and the casting length. Changes in the thermal conditions are affecting the temperature differentials governing the tensile stresses after contraction and in turn the resulting stress-strength ratio. All structural and thermal conditions regarding the real casting process must therefore be carefully considered when making choices in the modelling process. In the subsequent sections, the assumptions of casting and curing conditions applied in this study are presented.

4.1.1 Geometry and restraint

The studied structural section chosen for the FE modelling is a wall-to-slab section. The wall-to-slab can represent different structural parts in any division of construction, for example building walls, tunnels, slab bridges, retaining walls etc. Thereby it is considered to be applicable in many different situations even though the dimensions might vary.

The study involves three different cross-sectional geometries for three different casting lengths each resulting in nine combinations. The wall height and slab width is set to 3 and 6 meters, respectively, and will not be varied throughout the analysis. Figure 4.1 is presenting the studied cross-sections. The wall height has a negligible influence on the restraint compared to the wall thickness and can therefore be set constant. The thickness of the slab is always twice the thickness of the wall as a thicker slab is more common and as it provides a larger restraint for the wall, thus a more critical case. Moreover, a slab-on-ground foundation is assumed and the wall is cast on an already existing slab.

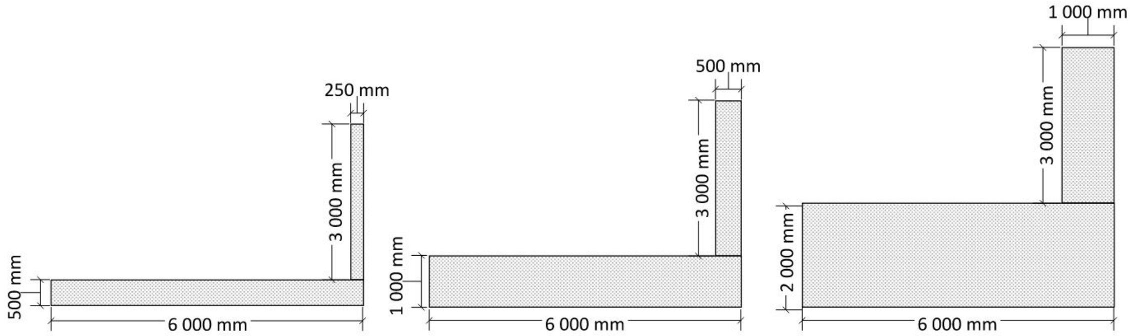


Figure 4.1: Cross-sectional dimensions analysed in the parametric study

4.1.2 Wind

Given that the wind affect the cooling of the formwork, and in turn the early-age material behaviour, it is an important parameter to include in the model. The normal wind for structures close to the ground is set to 5 m/s according to the technical report which AMA Anläggning is based on (Emborg et al. 1997).

4.1.3 Material

The different concrete mixes applied for the wall consists of one traditional concrete with ordinary Portland cement (OPC) and one concrete with 50 % slag in the binder (S50). The early-age properties of these two concrete mixes have been tested at Luleå University of Technology, and were later translated into a set of material parameters. Early access to preliminary material parameters of the S50 concrete as well as parameters of the OPC concrete were provided by Skanska Teknik via Hans Hedlund (personal communication, ongoing project, SBUF 13872). Moreover, a mature concrete is applied for the slab as it is assumed to be cast prior to the wall. Specifications regarding the studied concrete mixes applied to the wall are presented in Table 4.1.

Table 4.1: Specifications for studied concrete mixes

Concrete mixes	OPC	S50
Strength class	C32/40*	C32/40
Cement type	Brevik CEM I 42.5 N	Brevik CEM I 42.5 N
Cement amount [kg/m^3]	365	200
w/b ratio	0.5	0.5

*Adjusted compressive strength

The concrete class of the S50 concrete is C32/40. When choosing an OPC concrete for comparison, a tested concrete of the same w/b ratio was chosen even though it obtain a somewhat lower concrete class, C30/37. To optimise the study, the compressive strength of the OPC concrete is adjusted in the modelling software to be equivalent to one of C32/40.

4.1.4 Temperature

The casting temperature of the fresh concrete, the air temperature and the temperature of the adjacent surfaces all affect the stress-strength ratio of the structure. Calculations regarding early-age thermal cracking are typically done for a cold case, and a warm case for the planned casting period. However, sometimes decisions of concrete mixes are taken without knowledge about the planned casting period of the year. Therefore, in this study the casting period is assumed to be the entire year. Table 4.2 is presenting the monthly average air temperature in Gothenburg and casting temperature, provided by Skanska Teknik. The air temperatures used for calculations are based on statistical data for average day temperatures in Gothenburg during the last 30 years. The initial temperature of the fresh concrete is based on statistical data from concrete factories.

Table 4.2: Monthly average air temperature for Gothenburg, casting temperature and chosen cases for analysis.

Month	T_{air} [°C]	$T_{casting}$ [°C]	Analysis
January	-1	13	Cold case
February	-1	13	
March	1	13	
April	6	16	
May	11	20	
June	15	22	
July	17	24	Warm case
August	17	24	
September	13	21	
October	9	18	
November	4	15	
December	2	13	

The temperature of the adjacent surfaces are assumed to be in equilibrium with the air temperature, but 5°C at minimum to prevent the newly cast concrete from the risk of early freezing. The temperature of the ground is assumed to vary linearly with the top surface equal to the air temperature, and at a depth of 2 meters equal to the yearly average temperature of Gothenburg, 8.9°C (SMHI the Swedish Meteorological and Hydrological Institute 2021). The yearly average temperature is retrieved from SMHI and is the based on data collected between 1991-2020.

4.1.5 Exposure class and maximum stress-strength ratio

The S50 concrete was designed for railway environment, excluding exposure classes related to chlorides. The relevant exposure classes for an early-age thermal cracking analysis for the S50 concrete are XC2 and XC4. Each exposure class is associated with a specific safety factor for the risk of cracking. If the structure is exposed to one-sided water pressure, this needs to be considered as well, and has its own safety factor. The material parameters used in this analysis are mix-specific, and therefore a lower safety factor is used. The safety factors can be converted to an allowable utilization ratio by calculating the inverse of the value, $1/S$. The allowable utilization ratios set the requirement to be fulfilled by the calculated stress-strength ratios. Table 4.3 presents the relevant exposure classes (together with one-sided water pressure) from tables AMA EBE.11/2 and EBE.11/2 (Svensk Byggtjänst 2020), corresponding safety factors and the maximum stress-strength ratios which should not be exceeded.

Exposure class	Safety factors for crack risk, S	Max. allowed stress-strength ratio, $1/S = \eta_{\max} = (\sigma/\mathrm{f_{ct}})_{\max}$
XC2	1.05	0.952
XC4	1.11	0.900
One-sided water pressure	1.42	0.704

Table 4.3: Exposure classes with associated safety factors for crack risk and maximum allowable stress-strength ratio (Svensk Byggtjänst 2020)

4.1.6 Formwork and curing measures

Depending on project, there exist multiple interests for the time of formwork removal. With respect to the risk of early-age thermal cracks, it is normally beneficial to keep the formwork as long as possible. However, formwork is a substantial economical cost of concrete casting and is typically reused for multiple repetitive parts in building construction, therefore it is also of interest to remove the formwork as early as possible after casting. Minimizing the number of days with formwork is also of interest for civil works to maintain a desirable rate of production.

Normally, the governing aspect of early formwork removal is to avoid a thermal shock where the temperature difference between the structure and the air temperature is too large, thus the risk for this is larger during the winter season. Another aspect is the compressive strength at 10 mm from the surface which needs to meet the requirement with respect to the curing class at formwork removal, as specified in SS-EN 13670 chapter F.8.5 (a) (Swedish Standards Institute 2009).

The average compressive strength in the wall is also considered in the decision of formwork removal and of special interest if the formwork is also acting as load-bearing system. Typically a compressive strength for formwork removal is prescribed for the specific structure. Otherwise, a minimum of 70% of the required design strength is recommended by BBK (Boverkets handbok om Betongkonstruktioner). For a non-load bearing, vertical form the minimum requirement of compressive strength according to the Swedish reference work 'Betonghandboken' is 6 MPa (Svensk Byggtjänst and Cementa 1992).

Besides considering the crack risk and surface endurance when removing the formwork, the risk of early freezing needs to also be considered. The minimum temperature in the newly cast structure is of interest as it must not be below 0°C before compressive strength has reached 5 MPa to be protected against early freezing, according to notation 8.5 (12) in SS-EN 13670 (Swedish Standards Institute 2009). However, it is common to apply the former Swedish concrete norm requirement by 'Betongnorm B7' where the minimum temperature was 5°C instead of 0°C as it is considered a good recommendation, which is followed in this study.

4.2 Parametric study

The prerequisites, environmental, material and structural conditions are implemented in the model. In this section, the modelling approach and specific input parameters for the parametric study are presented.

A matrix presenting the variation of input parameters and desired output is developed to formulate a modelling strategy, see Figure 4.2. In the first modelling stage, 36 different cases are studied where the cross-sectional dimensions, casting length, material and environmental temperature are varied. Each case will result in different stress-strength ratio corresponding to risk of cracking. However, the compressive strength and temperature development will be the same regardless of the restraint conditions meaning that varying the casting length will not affect the strength and temperature.

		S50																		OPC																	
		Cold									Warm									Cold									Warm								
Input	t_{wall} [mm]	250			500			1000			250			500			1000			250			500			1000			250			500			1000		
	L_{cast} [m]	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20
Output	Stress-strength ratio	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	aa	ab	ac	ad	ae	af	ag	ah	ai	aj
	Compressive strength	A			B			C			D			E			F			G			H			I			J			K			L		
	Temperature	A			B			C			D			E			F			G			H			I			J			K			L		

Figure 4.2: Schematic figure of parametric study

4.2.1 Geometry and time

The cross-sections of the geometries are visualised in Figure 4.1. For each cross-section, there are three different casting lengths of 5, 10 and 20 meters in total generating the nine studied geometries. An additional block, with a width equal to the slab and depth of two meters, is added in the model to represent the ground. The total run time for the simulation is set to 28 days in order to study the early-age behaviour. The formwork is removed after 4 days for both the warm case and the cold case as an assumed base setting, to be later varied in Section 4.3 where different measures are studied.

4.2.2 Material

The material parameters for the S50 and OPC concretes are presented below in Table 4.4 with the heat properties gathered to the left and the mechanical properties in to the right. Presented values are retrieved by a ConTeSt material file for each material and it should be understood that if input are changed the behaviour of the tested material would no longer be fully represented. Here, the exception of modifying the 28-day compressive strength of the OPC material is done for the sake of the study.

Table 4.4: Recipe specific material parameters concerning heat and mechanical properties (H. Hedlund, personal communication, ongoing project SBUF 13872, February 24, 2022)

Heat properties	**OPC**	**S50**
Density [kg/m3]	2336	2350
Heat capacitivity [J/kgK]	1020	1000
Heat conductivity [W/mK] for eq. maturity time [h]: 0 96 120 10000	 2.2 2.2 1.7 1.7	 2.1 2.1 1.7 1.7
Wc [J/kg]	356000	404000
C* [kg/m3]	365	400*
t_1 [h]	9.16	37.129
κ_1[-]	1.54	1.01
t_{e0} [h]	0	0
β_D[-]	1	1
θ_{Ref}[K]	3599	5307
κ_3[-]	0.2185	0.22
F_{cc28} [MPa]	40	48.3
s [-]	0.245424	0.317
t_S [h]	9.32353	3
t_A [h]	11.3235	5
n_A[-]	4	3
n_{CC28d}[-]	0.55992	0.749
f_A[MPa]	0.5	0.5
$Temp_D$[° C]	1	35
κ_{Temp} [-]	1	3.7
$Time_D$ [h]	1	92.4
κ_{Time} [-]	1	7.3
$D_{MaxDrop28}$ [-]	0	0.15

Mechanical properties	**OPC**	**S50**
Poisson's ratio [-]	0.18	0.18
α_{Heat} [1/K]	9.80E-06	1.30E-05
α_{Cool} [1/K]	9.80E-06	1.30E-05
θ_T [K]	5000	5000
Number of ages	10	10
Number of rel.units	8	8
RelTime2 [d]	0.005	0.005
t_0 [d]	0.47184	0.125
F_{cc28} [MPa]	40**	48.3
F_{tref} [MPa]	3.31377	3.46
F_{cref}[MPa]	40	48.3
β_1[-]	0.58	0.667
α_{CT}[-]	0.9	0.771
ρ_T[-]	0	0.472
ρ_ϕ[-]	0	0.365
K_{fi}[-]	2	2
ϵ_1[-]	0	0
t_{S1}[h]	2	2
ϵ_2[-]	-8.00E-05	-2.6633e-4
t_{S2}[h]	11.3235	4
θ_S [h]	12.1337	60
η_{SH}[-]	0.563519	0.379

* Total binder content
** Modified according to Section 4.1.3

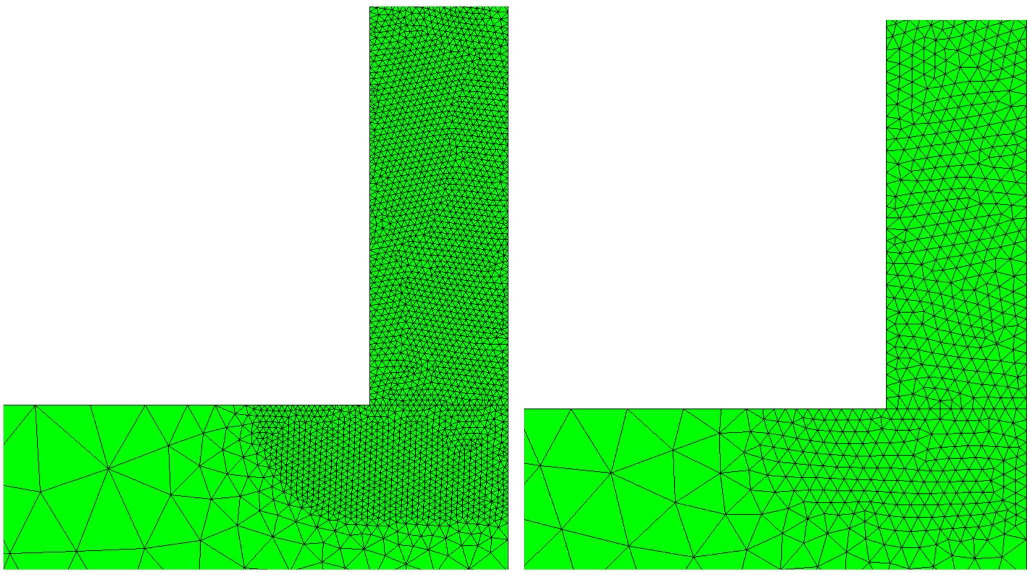
4.2.3 Element size

Mesh size sensitivity analyses are performed to decide an appropriate element size in relation to the width and height for each model. Results used to determine the element size are presented in Appendix A. Two separate mesh size sensitivity analyses are performed, one for each material. The slag concrete proved to need a finer mesh compared to the ordinary concrete. If there are large behavioural differences between the nodes in an element, the interpolation for the element is not a good representation for the behaviour. A reliable result requires a fine enough mesh where property changes are captured in all equilibrium calculations in the network. However, since a finer mesh also requires more computational time, the finest mesh is only used for the slag concrete. The mesh size sensitivity analyses are performed for the wall thickness of 250 millimeters. As the wall thickness is doubled, so is the element size resulting in the same number of elements across the wall thickness. As only the wall is of interest, the other elements have a coarser mesh which is kept constant for the different geometries to limit the number of elements and computational time. The element sizes used for the wall, slab and ground are presented in Table 4.5.

Table 4.5: Element sizes in millimeters for different blocks and materials

	Wall			Slab	Ground
	t250	t500	t1000		
OPC	0.02	0.04	0.08	0.1	0.3
S50	0.01	0.02	0.04	0.1	0.3

Figure 4.3 is demonstrates the different element sizes for S50 and OPC for the wall thickness of 250 millimeter.



(a) S50 concrete, t=250 **(b)** OPC concrete, t=250

Figure 4.3: Detail figure of wall showing the chosen mesh for S50 and OPC, respectively

4.2.4 Heat properties

The settings of the outer boundaries are specified to correspond to the conditions during the first 28 days. For each boundary, the environmental temperature, the wind velocity and a potential insulation layer is set. The temperatures used in the analysis are presented in Table 4.6.

Table 4.6: Temperatures used in analysis

Category	Warm case	Cold case
Air temperature	17°C	-1°C
Casting temperature	24°C	13°C
Adjacent temperature	17°C	5°C
Ground temperature	8.9°C	8.9°C

All outer boundaries, except for the ground, are assigned "Free surface" which includes the surface heat resistance and the effect of the wind velocity. Additional layers, such as formwork, tarpaulin or insulation are added for the relevant boundary. The formwork used in the analyses is a typical wood form with a thickness of 22 mm and heat conductivity of 0.14 W/(K·m). Tarpaulin is represented by 2.5 mm of expanded polyethylene, EPE, with heat conductivity 0.036 W/(K·m). The insulation used typically comes in thicknesses of 10 mm of EPE. One layer is used for the walls, and two layers are used to insulated the preheated slab. The boundary settings are presented in Table 4.7 and Table 4.8 for the warm and cold case, respectively.

Table 4.7: Boundary settings for the warm case

		Time	
		0-96 h	*96-672 h*
Warm case	Wall sides	Wood 22 mm Free surface	Free surface
	Wall top	EPE 2.5 mm Free surface	Free surface
	Slab top and sides	Free surface	
	Ground bottom and sides	Adiabatic	

Table 4.8: Boundary settings for the cold case

		Time	
		0-96 h	*96-672 h*
Cold case	Wall sides	Wood 22 mm Free surface	Free surface
	Wall top	EPE 10 mm Free surface	Free surface
	Slab top and sides	EPE 20 mm Free surface	Free surface
	Ground bottom and sides	Adiabatic	

Remark that insulation is added to the slab boundaries in the cold as the slab is preheated to 5 °C. The top of the wall is also insulated in the cold case, to better maintain the heat in the wall and prevent early freezing. The insulated layers are kept for 4 days, equivalent to 96 hours, and from there on there is only free surface. The ground boundaries are assigned to be adiabatic, thus assuming there is no heat exchange with larger areas in the ground. Inner segments between blocks have full thermal contact.

Acknowledge that the base condition set are chosen to get comparable results, and are not always the realistic choice. In practice, it is uncommon to not have more measures for a winter casting.

4.2.5 Plane surface analysis

The stress-strength ratio is to be checked in a critical point with regard to early-age thermal cracking. The first crack is most likely to appear at a vertical distance between one to two wall thicknesses from the casting joint. A decision is made to consider the critical level at a vertical distance of 1.5 times the wall thickness from the casting joint, in agreement with senior advice based on empirical evidence. Since only this level is of interest, a constant restraint of the entire wall can be set in ConTeSt. However, one needs to be careful only to look at stress related results at this level.

The standard case of wall-to-slab is found as a section of larger structures. Depending on the relevant structure, a restraint analysis is needed to estimate the restraint degree for the calculations. For this thesis, estimations of the restraint have been calculated using the finite element software LUSAS Bridge 19.1 with linear elastic analysis. A fictitious thermal load of -10°C is applied to the wall, causing it to shrink while also being restrained by the slab. One point is fully fixed in translation to prevent rigid body movements. The distribution of the principal stress S1 is extracted for a slice along the longitudinal centre line of the wall. Thereafter a vertical path is placed at the middle of the casting lengths to extract the highest principal stress along the wall, as seen in Figure 4.4.

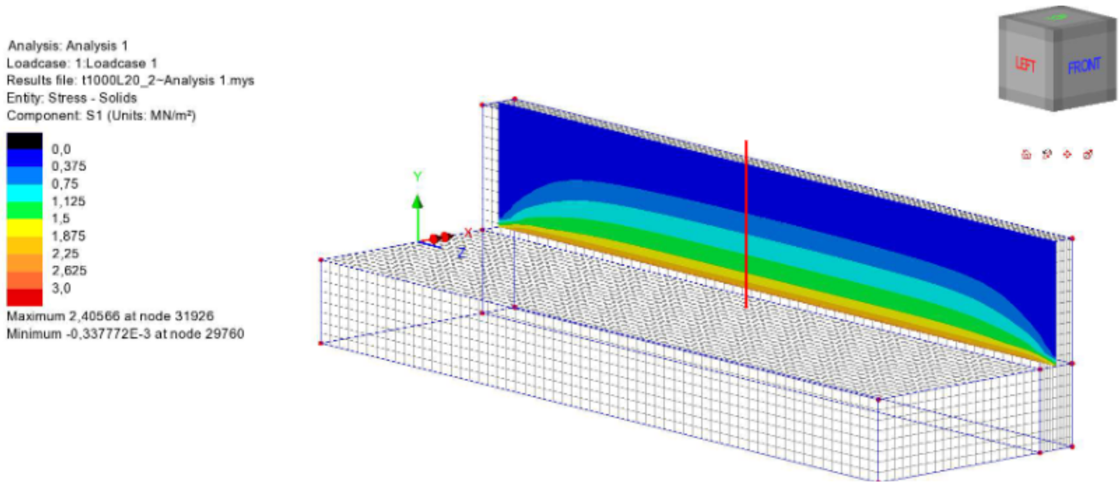


Figure 4.4: Main principle stress S1 for a slice along the centre line of the wall, vertical line (in y-direction) representing the path for extracted results

The results along the vertical line represent the variation of stress along the height of the wall induced by the temperature decrease, which can be seen in Figure 4.5.

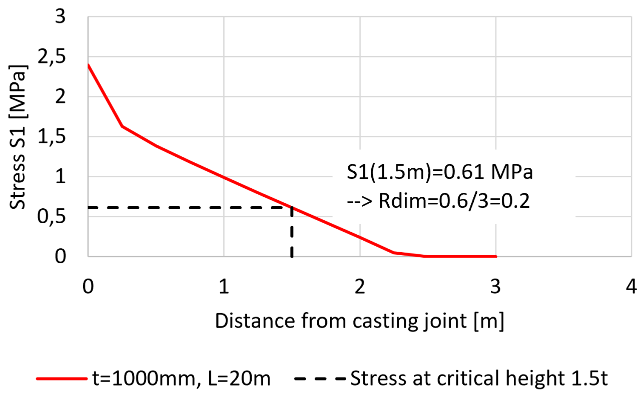


Figure 4.5: S1 stress along height of wall for the case of a wall thickness of 1 meter, with a casting length of 20 meter

The stress at the critical level can then be extracted from the graph and divided by the maximum theoretical stress at the casting joint, calculated by Equation 4.1 to 3 MPa.

$$\sigma_{max} = E_c \cdot \Delta T \cdot \alpha_c \qquad (4.1)$$

where σ_{max} is the maximum theoretical stress, E_c (30 GPa) the average modulus of elasticity during cooling for the newly cast concrete, ΔT (-10°C) the temperature differential and α_c($-1.0 \cdot 10^{-5}$ 1/°C) the average thermal contraction coefficient for the S50 and OPC concrete.

The ratio between the principal stress at the critical level and the maximum theoretical stress results in the restraint at the critical level. The restraint is a result of the entire structure with its dimensions, material properties and boundary conditions. The calculated restraints of the critical level, with respect to risk of cracking, for the different geometries are presented in Table 4.9.

Table 4.9: Calculated restraints from LUSAS for the nine different geometrical cases

Wall thickness [mm]	250			500			1000		
Casting length [m]	5	10	20	5	10	20	5	10	20
Restraint [-]	0.48	0.59	0.60	0.29	0.42	0.43	0.07	0.17	0.20

The restraints are visualised in Figure 4.6, where the variation of restraint in relation to thickness and casting length is demonstrated. Notice that there are large differences in restraint between the cross-section with wall thickness 1000 millimeters compared to wall thickness 500 millimeters.

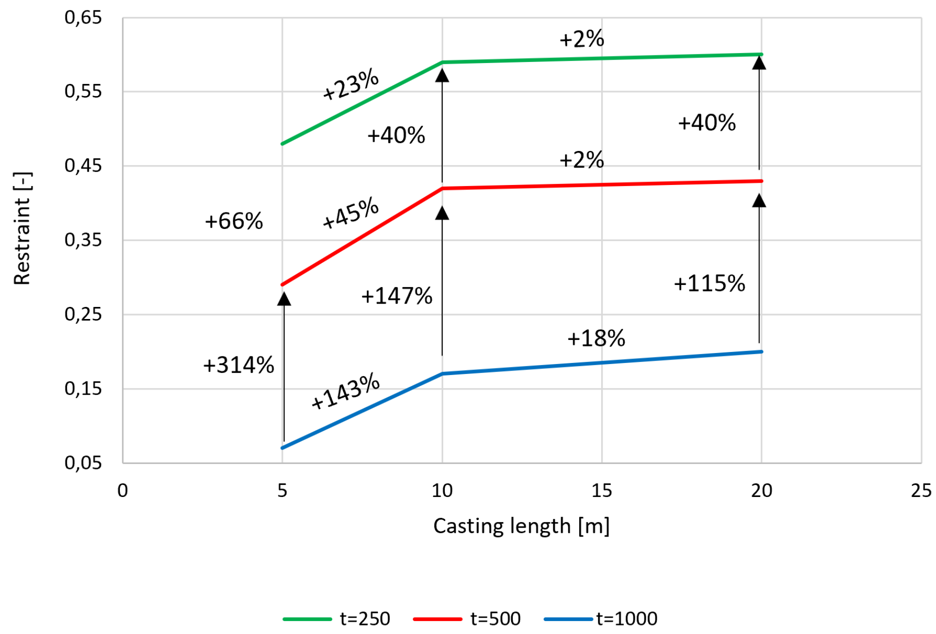


Figure 4.6: The restraint variation for different thicknesses and casting lengths

The calculated restraint from LUSAS is applied for the entire wall in the setting "Restraint translation", with full rotational restraint. The remaining blocks, representing the slab and ground, are left out of the plane surface analysis, but are included indirectly as they were included in the restraint setting used for the wall. Moreover, there are some limits to the chosen method of modelling the restraint to acknowledge:

- The stress-strength ratio is only fully valid at the middle point along the critical level. The restraint is extracted from the centre of the wall cross-section, however applied for the entire wall in ConTeSt. This means that evaluated points outside the centre along the critical level are affected by a different restraint than they should as the restraint varies across the wall due to the asymmetrical geometry, see Figure B.1 and B.2 in Appendix B. The surface critical point has a 6.5 % higher restraint than the middle critical point. However, the centre value is chosen as it represents an average for the critical level, in order to minimize the amount of simulations required.

- The constant restraint does not include the effects of an increasing restraint with time. This is because the calculated restraint in Lusas is based on the average modulus of elasticity during cooling for the newly cast concrete. It is an reasonable assumption as the cracking is likely to occur during the cooling, however it is important to remember it is still an approximation.

- The restraint is only valid under the assumption that the thermal cracking is the first cracking to occur, and it is why the restraint can be calculated using linear elastic analysis. Any cracking due to other reasons than temperature differentials are not included.

4.2.6 Analysis and extracting results

Heat simulations are run for the three different cross-sections. Plane stress analysis is needed for each geometry, as the different castings lengths are modelled with different restraints. After the simulations, results are extracted to examine the material behaviour and assess whether or not the set requirements have been fulfilled. The examined requirements both include maximum limits for stress-strength ratios, but also requirements linked to curing.

Examined requirements:

- A sufficiently low stress-strength ratio to meet safety factors of risk of cracking in Table 4.3
- To reach the required surface compressive strength corresponding to prescribed curing class at the end of the curing period. In the parametric study, this corresponds to the time of formwork removal
- To reach the required average compressive strength to remove formwork, 6 MPa for a vertical non-bearing formwork or 70% of $f_{ck,28}$
- To reach a minimum of 5 MPa in compressive strength before the minimum temperature falls below 5°C to prevent from early freezing
- For the maximum temperature to not exceed 70 °C

The following results are extracted from ConTeSt:

- Temperature in critical points
- Temperature in corner points, 5 mm from surface (horizontally and vertically)
- Tensile strength in critical points
- Stress-strength ratio in critical points

- Compressive strength 10 mm from surface
- Average compressive strength in wall
- Minimum compressive strength in wall
- Minimum temperature in the wall
- Maximum temperature in the wall

The requirements and extracted results needed to assess these are summarised in an illustration in Figure 4.7. Note that the critical points are located at a vertical distance of 1.5 times the wall thickness from the casting joint, thus varying depending on the geometry. One is placed in the centre of the wall thickness and the other 5 millimetres from the surface.

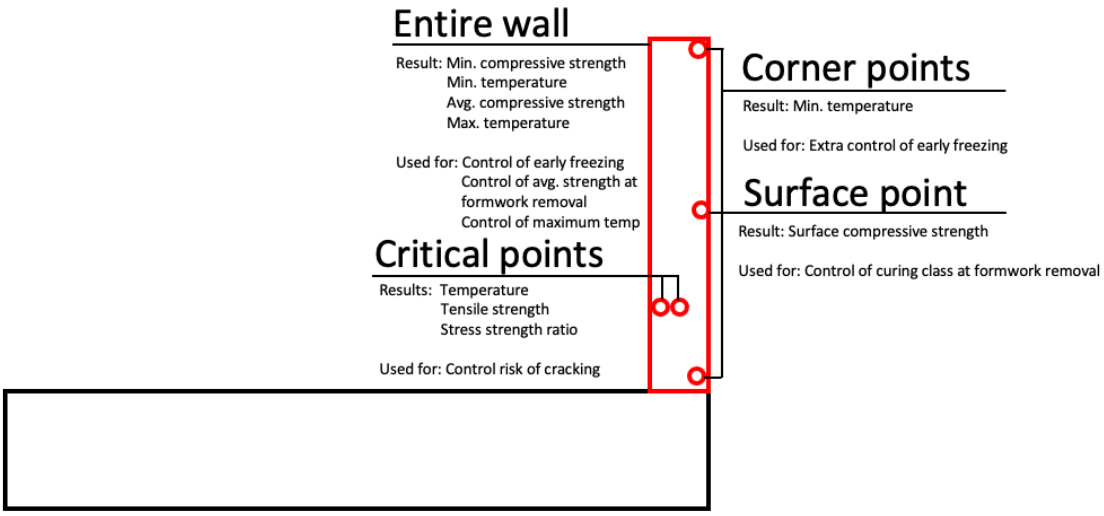


Figure 4.7: Illustration of extracted results at different points in the wall

4.3 Risk reducing measures

After the parametric study of geometry, material and environmental temperature, one geometry is chosen to be studied further in the study of risk reducing measures. The geometry of 500 millimeters wall thickness was chosen due to its performance in the parametric study, later to be presented in Section 5.1 Starting from the default settings for the cold case of the chosen geometry, different mitigation measures for reducing the risk of cracking or freezing or improving the strength development are applied one at a time and varied by intensity to study the impact of each measure individually. This is done for both the OPC concrete and the S50 concrete and differences in impact of measures are expected depending on which material is studied. Typical winter casting measures are chosen based on their suitability for the chosen dimensions. For example, heating of the adjacent structure is not an appropriate alternative due to the thickness of the slab being 1000 and 2000 millimeter for two of the studied cross sections. Table 4.10 is presenting the method of the study, which condition is to be changed or added in the model.

Table 4.10: Matrix for study of risk reducing measures, with original cold case settings and chosen measures with varied intensity

	Days before formwork removal	**Casting temperature**	**Insulated form**	**Replacement coverage**	**Heating /Cooling**
Original settings	4 days	13 °C	4 days non-insulated form	No replacement	No heating
Variation	8 days, 16 days	16 °C, 19 °C	2 days, 4 days	3 days, 6 days	2 days, 4 days

The requirements to be fulfilled are the same as in the parametric study, thus the same results are extracted in the study of risk reducing measures. The subsequent sections describe how each measure are modelled and varied by different settings.

4.3.1 Days before formwork removal

In addition to the parametric study with 4 days of formwork, two additional cases are studied where the formwork is removed after 8 days and 16 days. Changes are done for the outer boundaries of the wall, extending the time with formwork on the sides, tarpaulin/insulation on top, and the insulation covering the slab (for the cold case). Extending the time with formwork is beneficial for the strength development and for letting the concrete cool at a slower pace.

4.3.2 Casting temperature

An increased casting temperature could potentially result in the compressive strength developing at a faster rate and prevent the risk of early freezing, therefore two additional simulations are performed using casting temperatures of 16°C and 19°C are studied. The casting temperature can be adjusted by the temperatures of the aggregates and water, and is specified in the order to the concrete factory.

4.3.3 Insulated form

In order to decrease the heat loss resulting in both low early compressive strength and risk of early freezing, a layer of 10 millimeters insulation is added to the formwork, still removed after 4 days to evaluate the effect of the insulation, In addition, 2 days with insulated form is tested as well since early formwork removal is of interest.

4.3.4 Replacement coverage

An alternative to keeping the formwork, is to apply replacement coverage after formwork removal consisting of 10 millimeters EPE which slows down the cooling of the concrete and thus decreasing the risk of cracking. A realistic timeline requires 2 hours after the formwork removal until replacement coverage can be added.

4.3.5 Temperature regulating pipes

Water pipes with a diameter of 14 millimeters are distributed in the centre line of the wall thickness with a centre-to-centre distance 0.4 meters covering the full casting length of 20 meters. Figure 4.8 is showing the cross-sectional distribution of water pipes. Heating by pipes instead of cables are considered a more beneficial solution in this case as heating cables are more likely to break during the casting process of a wall. The water is supplied directly after casting the wall and will therefore initially increase the heat development. If the concrete temperature exceeds the water temperature, it will instead have a cooling effect. The average temperature of the heating water is chosen to 15°C, which is also set as the boundary temperature of each pipe in the modelling. The model does not consider the water temperature varying by the pipe length as the water is losing or gaining heat from the concrete.

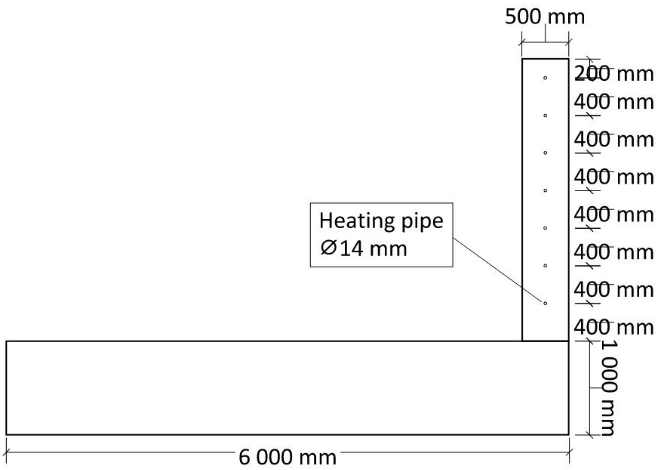


Figure 4.8: Distribution of heating pipes in the cross section

4.4 Combination of measures

Casting in a cold environment typically include a combination of measures to achieve the best result. In the final analysis, the needed combination of measures in order to meet a deadline of one and four days for the S50 and OPC concrete is analysed. The one-day deadline is representing a frequently used deadline for house projects, while the four-day deadline is more common in civil work projects. In this analysis, the geometry of 500 millimeters wall thickness and 20 meters casting length is once again used and the initial case of four days formwork before formwork removal and a casting temperature of 13°C is used as the basis for comparison of the effect of the combined measures. The findings from the study of risk reducing measures are used to set up an initial combination. However, the process is iterative as the combined effect of different measures is difficult to fully predict. The aim is to find the most feasible, with respect to construction, and economical solution.

In the study of combined measures, a distinction is made between hard demands and general requirements. The hard demands are

- not exceeding the stress-strength ratio for one-sided water pressure,
- reaching at least curing class 3,
- exceeding 6 MPa at formwork removal, and
- not having any risk of freezing

Additionally the days of formwork removal are strictly limited to one day and four days respectively, but keeping replacement coverage is accepted for a reasonable time, in this project chosen to approximately two weeks if needed.

5

Results & discussion

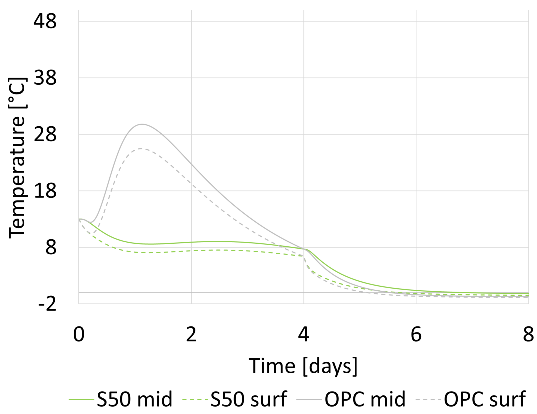
The result chapter is divided into three subchapters. The first describes the outcome of the parametric study, where the general performance of the S50 concrete and the OPC concrete is presented and compared. The second subchapter shows how the two concrete mixes respond to typical mitigation measures for prevention of early-age thermal cracking, slow curing and freezing. In the third subchapter suggestions of combination of measures to get a functional solution are given for the OPC concrete and S50 concrete, respectively.

5.1 Parametric study

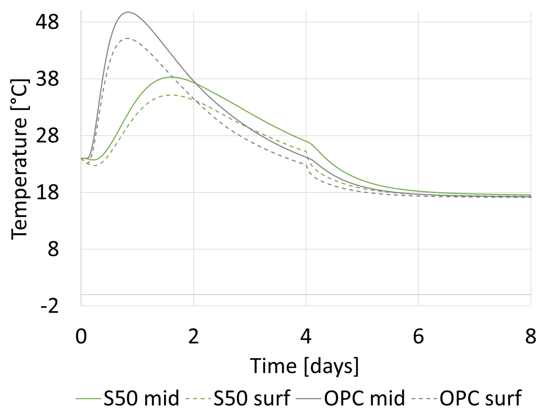
The following subsections present the different material behaviour regarding temperature, stress and strength development with respect to set requirements. The temperature in the critical points (see Figure 4.7) is presented first, followed by the tensile strength as the two both affect stress-strength ratio, which is presented next. The temperature development is also useful in order to understand the other behaviour results. Next the average and surface compressive strength is presented followed by the risk of early freezing to assess if curing demands are met. Finally, the maximum temperature is reviewed to control that it is below the limit. For each subsection, first the material behaviour is compared by presenting results of the geometry with a wall thickness of 500 millimeters and a casting length of 20 meters. Only one wall thickness is presented to demonstrate the general behaviour of the two materials in cold and warm case, respectively. Further results of geometries with wall thicknesses 250 and 1000 millimeters can be found in Appendix C. Second, the effect of wall thickness variation and casting length is presented.

5.1.1 Temperature in critical points

The temperature in the critical points is presented in Figure 5.1 with the cold case to the left, and the warm case to the right. The mid point, located in the centre of the wall thickness, is represented by a solid curve, and the surface point, 50 millimeters from the surface, is represented by a dashed curve. Both are located at the critical level with respect to cracking.



(a) Cold case

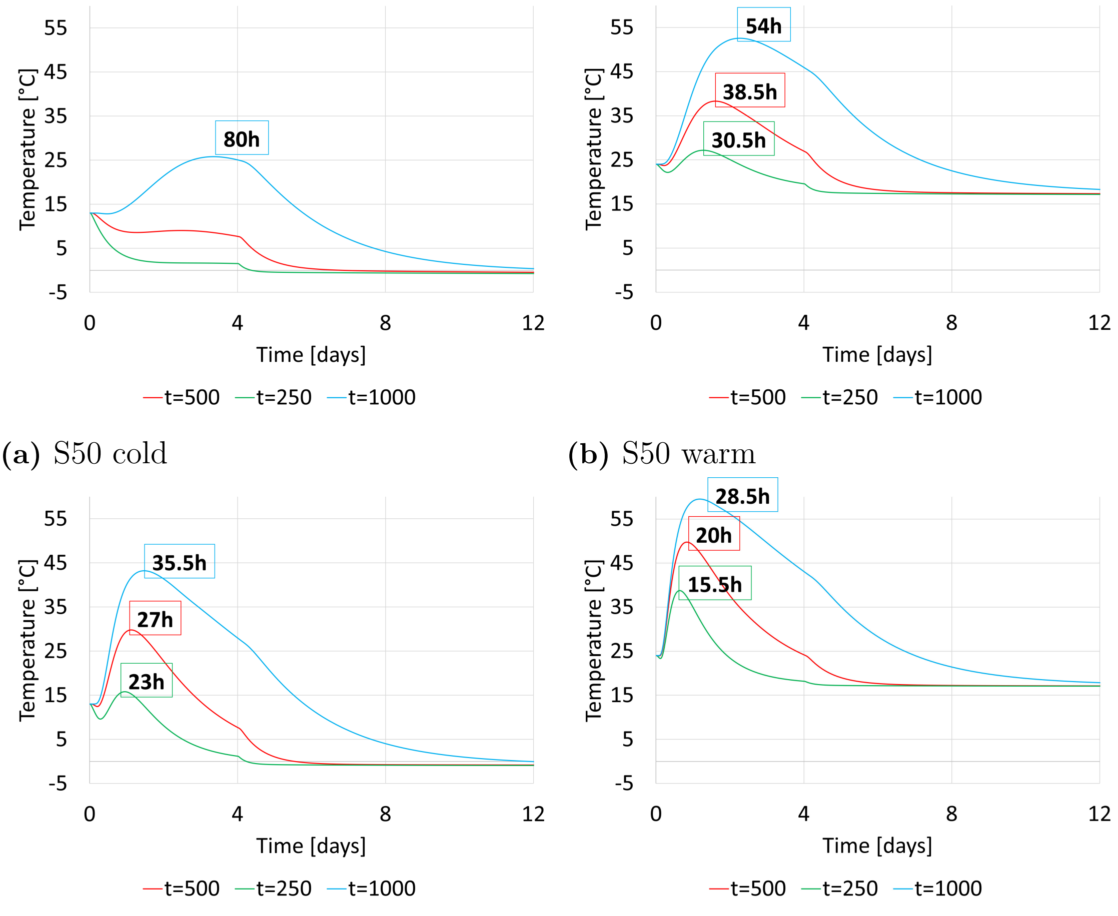


(b) Warm case

Figure 5.1: The temperature development in critical points for S50 and OPC, for wall thickness 500 mm

The initial temperature is the casting temperature, of 13°C in the cold case and 24°C in the warm case. The temperature decrease is instantaneously accelerated by the formwork removal at four days and then gradually approaching equilibrium with the air temperature of -1°C and 17°C for the cold and warm case, respectively. Observe that the S50 concrete in the cold case generates heat slower than it is being cooled down in the critical points, thus its initial casting temperature of 13°C is the maximum temperature. The OPC concrete succeed to generate enough heat early on in the cold case for the hydration reaction to get a more characteristic temperature curve also recognised in the figure to the right for the warm cases. The S50 concrete has a lower temperature development compared to the OPC concrete in the warm case too, and the peak temperature is delayed which corresponds well to Figure 2.8 in Section 2.2.2. Thus, the S50 has a higher temperature than OPC at the time of formwork removal at 4 days. The temperatures at formwork removal is almost identical for the cold case.

Figure 5.2 shows how the temperature in the mid critical point varies over time for the different wall thicknesses, t, and concrete mixes. The mid point is chosen as it was later proven to be governing for the stress-strength ratio in the parametric study.



(a) S50 cold

(b) S50 warm

(c) OPC cold

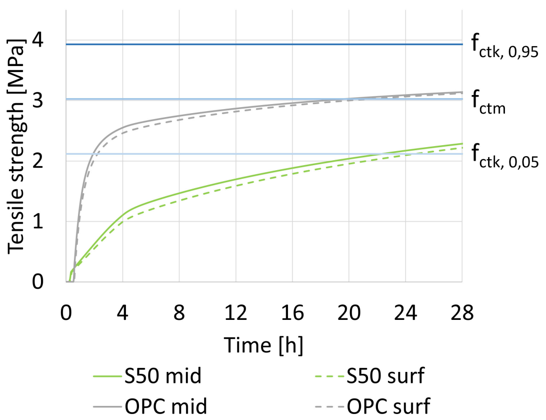
(d) OPC warm

Figure 5.2: Effect of thickness variation on temperature development for the mid critical point, with hours of peak temperature

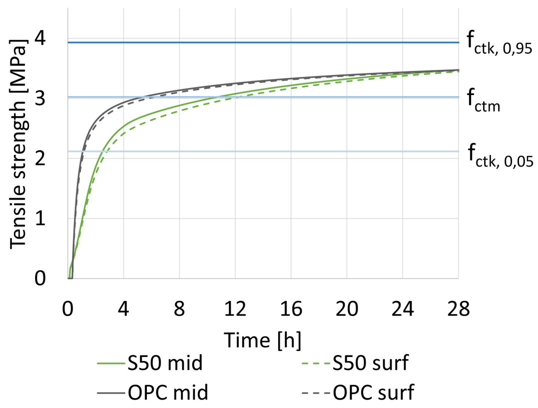
The increased thickness naturally result in increased temperature, and the peak is gradually delayed, which for the warm cases shows a similar trend to Figure 2.11 in Section 2.5.2. It can be noted that the temperature magnitude of the OPC concrete corresponds fairly well to the prediction for the same thickness since the conditions are similar. Remember that the height of the critical points alter for the different thicknesses and are consequently at different position in relation to the maximum temperature in the wall.

5.1.2 Tensile strength in critical points

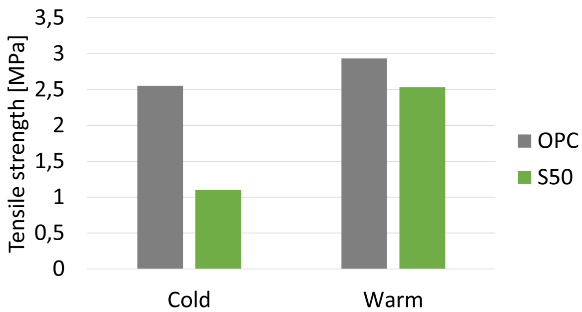
The development of tensile strength in the critical points is presented in Figure 5.3 for the cold case to the left, and the warm case to the right. The blue lines represent the 5 % fractile, mean, and 95 % fractile tensile strength.



(a) Cold case



(b) Warm case



(c) Tensile strength at the day of formwork removal (4 days), cold and warm case

Figure 5.3: Tensile strength development in critical points for S50 and OPC, for wall thickness 500 mm

There are a couple of observations to be made:

1. The tensile strength development is faster for the OPC than the S50 concrete, with the small exception of the first hours after casting.

2. The S50 and OPC concrete has the same tensile strength after 28 days in the warm case.

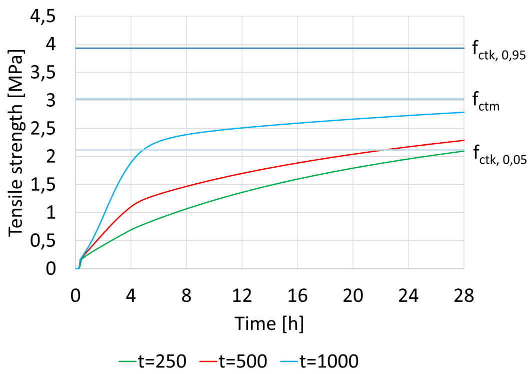
3. There is a significant deceleration in strength development at four days for S50, cold case. This correlates to the time of formwork removal.

4. The surface has a slightly slower tensile strength development than the middle point. This is due to the lower temperature at the surface.

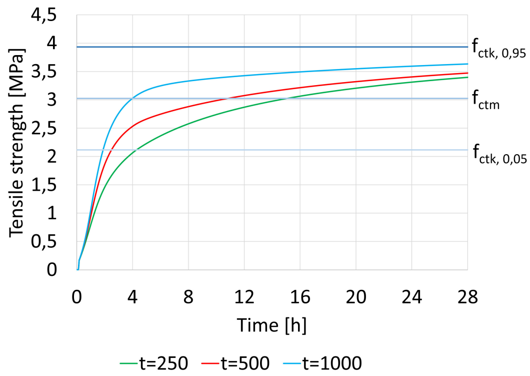
5. There is a much larger difference between tensile strength development of the OPC concrete and the S50 concrete when cured in a cold climate.

6. All four cases have reached the 5% fractile tensile strength after 28 days, while all but S50 cold has also reached the mean tensile strength after 28 days.

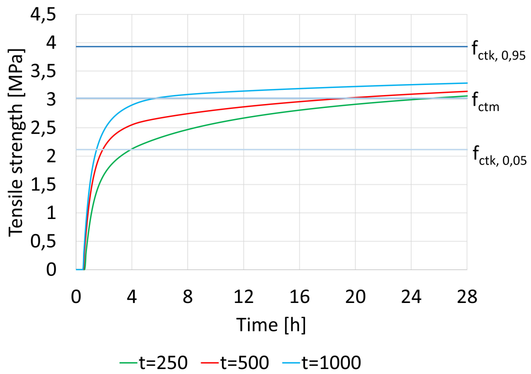
The tensile strength development for the different thicknesses and concrete mixes is shown in Figure 5.4. As the tensile strength is highly dependent on the temperature, the increase in thickness results in an increase in temperature, and in turn an increase of tensile strength.



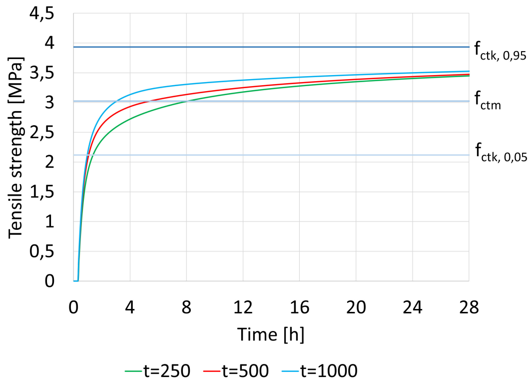
(a) S50 cold



(b) S50 warm



(c) OPC cold



(d) OPC warm

Figure 5.4: Effect of wall thickness variation on tensile strength development for the mid critical point

The tensile strength of the mid critical point at four days is presented in Table 5.1, for the different wall thicknesses and materials. It can be noted that the strength development of S50 in the warm case is very similar to that of OPC in the cold case.

Table 5.1: Tensile strength [MPa] in the critical mid point at the time of formwork removal (4 days) for OPC and S50, cold and warm case

	Cold		Warm	
	S50	OPC	S50	OPC
250 mm	0.69	2.13	2.06	2.72
500 mm	1.10	2.55	2.53	2.93
1000 mm	1.89	2.90	3.03	3.13

5.1.3 Stress-strength ratio in critical points

Figure 5.5 shows the stress-strength ratio in the mid critical point with a solid curve, and in the surface critical point with a dashed curve compared to the maximum stress-strength limits for XC2, XC4, and one-sided water pressure (WP). The mid critical point is ultimately the most critical one generating the highest stress-strength ratio, which is a behaviour that repeats itself for all cases in the parametric study. In order to better compare the S50 and OPC, only the mid critical point is kept in Figure 5.6.

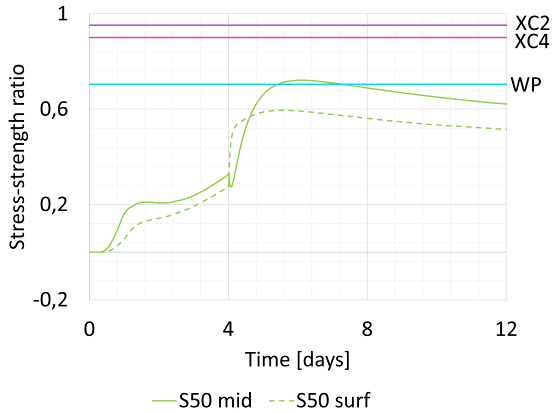
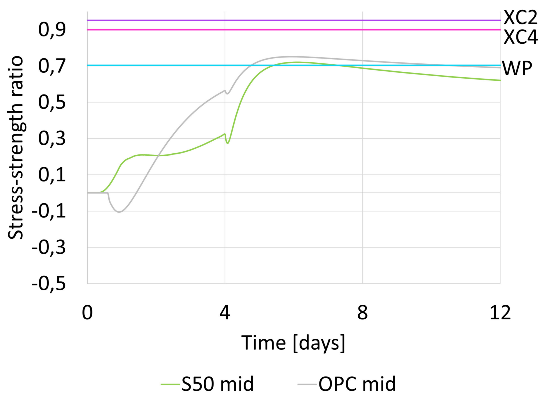
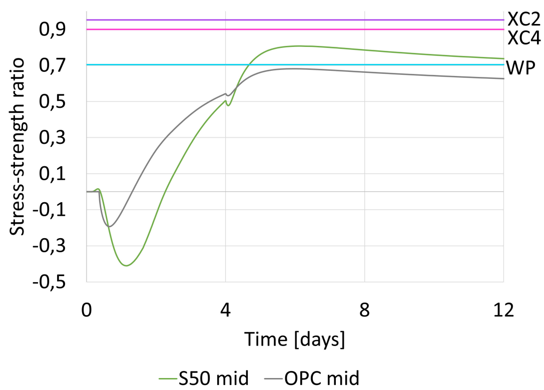


Figure 5.5: Stress-strength ratio in critical points for S50 cold case compared to requirements of relevant exposure classes



(a) Cold case

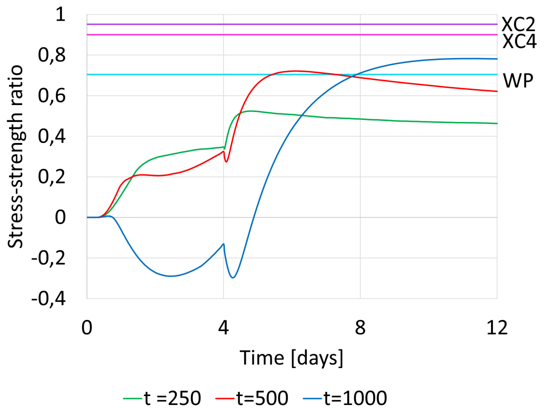


(b) Warm case

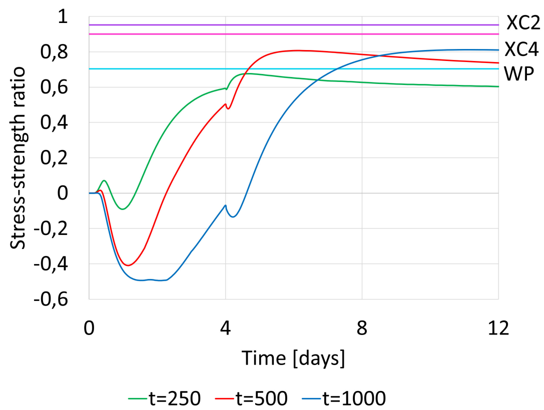
Figure 5.6: Stress-strength ratio in middle critical point for S50 and OPC

There is a rapid increase of stress-strength ratio when the formwork is removed, as the concrete is cooled down and quicker contracts thus accelerates the growth of tensile stresses. The increase is more pronounced for the cold case compared to the warm case, as the temperature drop is larger in the cold case. As the OPC concrete has reached a higher hydration level than the S50 concrete when the formwork is removed at four days, and thus a higher tensile strength, the increase in stress-strength ratio because of the formwork removal is smaller. Larger compressive stresses appear for the two warm cases, as the higher temperatures allow for a larger extension, before cooling down and contracting. Observe that the OPC concrete reaches a higher stress-strength ratio than the S50 concrete in the cold case. This could be explained by the faster cooling of the OPC compared to the S50 in the previous Figure 5.1, as a result of the different hydration rates. Notice also that the S50 concrete struggles in the warm case as well. Due to its delayed reactions, it reaches the peak of maximum temperature later and maintains a higher temperature at the time of formwork removal, resulting in a larger temperature drop than for the OPC, thus inducing larger tensile stresses and a higher stress strength ratio. Additionally, as seen in Figure 5.3 the tensile strength for the S50 concrete is lower as well, which further increases the stress-strength ratio.

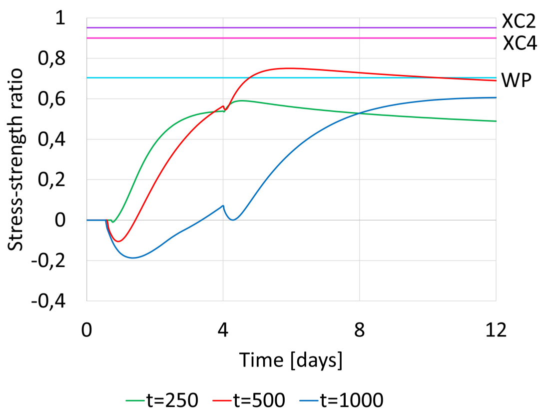
The effect of wall thickness variation on the stress-strength ratio is shown in Figure 5.7.



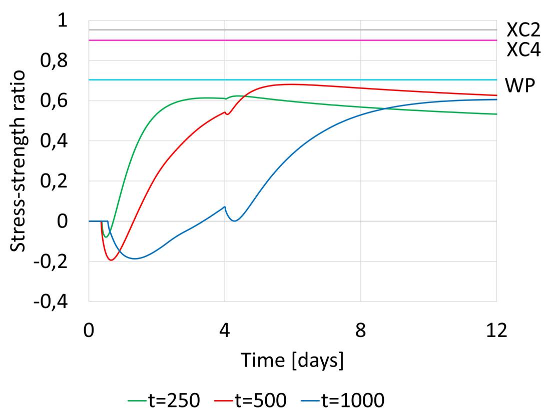
(a) S50 cold



(b) S50 warm



(c) OPC cold



(d) OPC warm

Figure 5.7: Effect of wall thickness variation on stress-strength ratio in the mid critical point

The results shows that an increased thickness delays the peak of the stress-strength ratio for the studied cases. As the graphs adopt negative y-values, it indicates compressive stresses at the studied point. In those situations where compressive stresses are formed, an increased wall thickness either result in larger compressive stresses or that the studied point is in compression for a longer period of time or a combination of both.

The maximum stress-strengths for casting length 20 meter for the different wall thicknesses and concrete mixes are gathered in Figure 5.8. The wall thickness of t=500 is the most critical in most cases, with the exception of S50 cold case where the t=1000 gives the highest peak of stress-strength ratio.

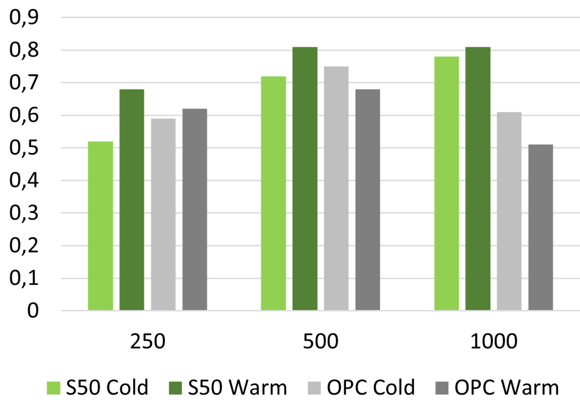
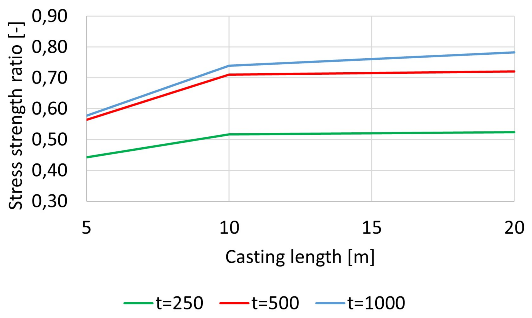


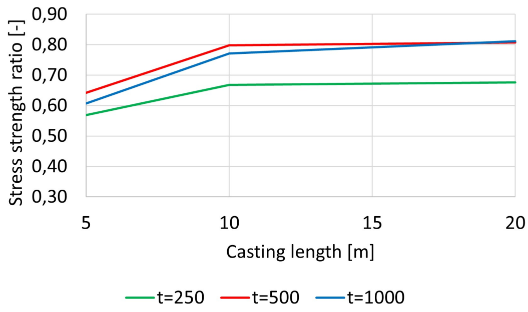
Figure 5.8: Maximum stress-strength ratio in wall for casting length 20 meters, for the different wall thicknesses and concrete mixes

The results shown in Figure 5.8 indicate that the stress due to restraint increases the most when doubling the wall thickness from 250 to 500 millimetres for the OPC concrete. Between 500 to 1000 millimetres the increase in temperature, thus also tensile strength development, instead decrease the risk of through cracks. For the S50 concrete the largest increase in stress-strength ratio is also seen between 250-500 millimetres wall thickness, although not with the same intensity as for OPC. However, between 500-1000 millimetres the stress-strength ratio is still increasing for the S50, indicating that the stress increase due to restraint is larger in proportion to the strength increase due to temperature.

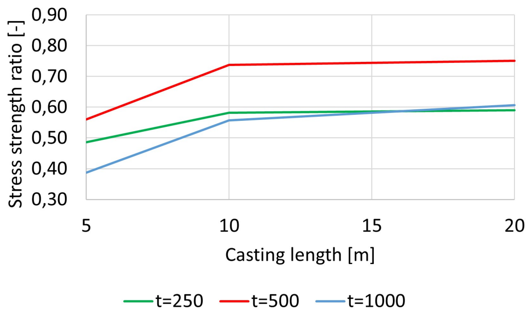
The variation in casting length results in different restraint which affects the stresses in the structure. Therefore, the maximum value of stress-strength ratio is compared for the different castings lengths and wall thicknesses for each concrete mix respectively in Figure 5.9.



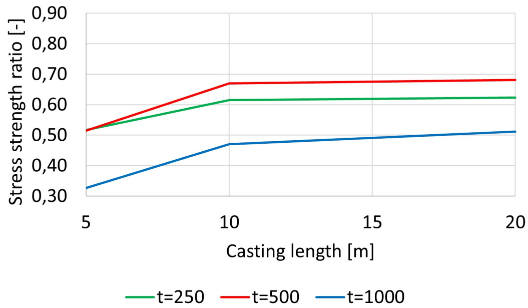
(a) S50 cold



(b) S50 warm



(c) OPC cold



(d) OPC warm

Figure 5.9: Effect of casting length variation on maximum stress-strength ratio

The maximum stress-strength ratio increases with the casting length, as it provides a larger restraint for the same cross-sectional properties such as heat and strength development. Remark that although the graphs follows a similar trend as the restraint did in Figure 4.6, the development is not proportional for the different wall thicknesses. The combination of restraint and hydration process for each thickness can result in rather unpredictable stress-strength ratios. For the S50 concrete, the thinnest wall results in the lowest stress-strength ratio, while for the OPC concrete, the thickest wall generally generates the lowest ratio. However, t=500, represented by red line, has an overall high stress-strength ratio.

5.1.4 Average compressive strength

The average compressive strength of the wall cross-section is studied to assess if it has developed enough strength to remove the formwork. In Figure 5.10, the average compressive strength is presented for a wall thickness of 500 millimeter during the first four days after casting and compared to requirements of strength at formwork removal. It can be noted that the higher air temperature in the warm cases generates a significantly faster strength development.

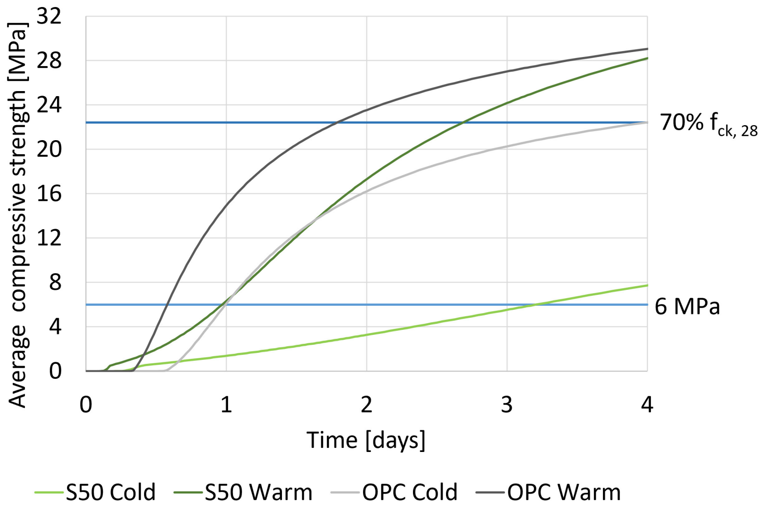


Figure 5.10: Average compressive strength in wall, for t=500 mm

Notice how the S50 concrete has a higher compressive strength the first hours after casting. This is likely due to the filler effect. Although the compressive strength of the OPC starts later, it also gains strength at a higher pace.

The effect of wall thickness on the average compressive strength at formwork removal is shown in Figure 5.11. It is clear that the larger thicknesses generate more heat, which ultimately leads to faster strength development. The OPC concrete in the warm case has a faster early strength development for the thicknesses 250 and 500. However, for the thickness of 1000 millimeters, the S50 concrete in the warm case reaches a higher average compressive strength at 4 days than OPC concrete.

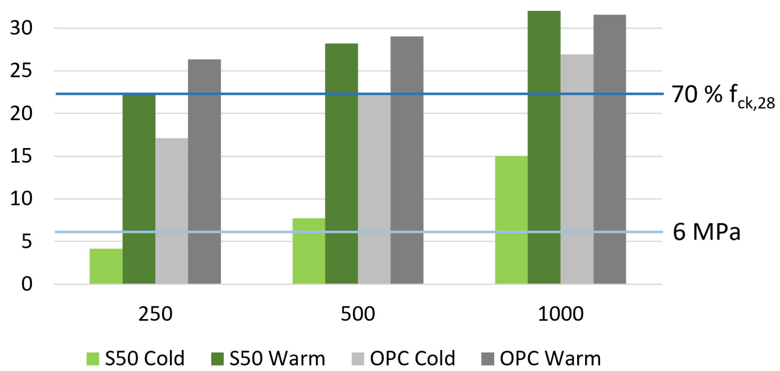


Figure 5.11: Average compressive strength in wall for different wall thicknesses and concrete mixes at time of formwork removal (4 days)

The average compressive strength at 28 days is presented in Figure 5.12. Although the 28-day compressive strength is not a specified requirement in this analysis, it is interesting to study as it can be directly compared to the design compressive strength. For structures that will be loaded with parts of, or the full design load relatively soon after the casting it is crucial to know when the concrete has developed sufficient strength.

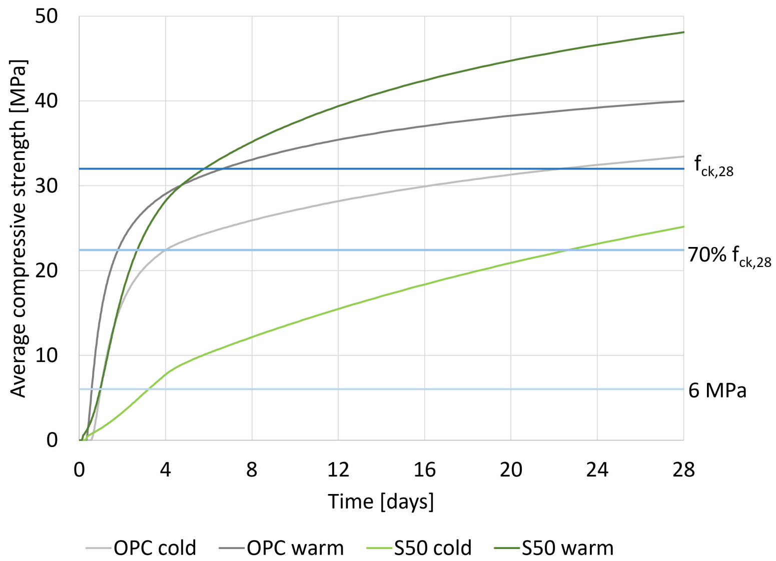


Figure 5.12: Average compressive strength in wall with thickness 500 millimeter during 28 days with formwork removal at four days

Remark:

1. There is a crossover effect between the fourth and fifth day, where the S50 concrete has a higher compressive strength than the OPC concrete for the warm case.
2. The effect of formwork removal is significant for the S50 concrete in the cold case, where the compressive strength looses its inclination at four days.
3. For the cold case, it takes 19 more days for the S50 concrete to reach above 70 % of $f_{ck,28}$ compared to the OPC concrete. Thus it is essential that in the cold case the slower strength development of the S50 concrete is taken into account in the time plan for when load can be applied, or measures are provided to accelerate the strength development.

5.1.5 Surface compressive strength

The magnitude of the surface compressive strength is similar to the average surface strength, but slightly lower. The surface compressive strength is as mentioned evaluated at the end of the curing period, which coincides with the formwork removal in the parametric study, and is seen in Figure 5.13. The surface compressive strength is compared to limits for the different curing classes previously described in Table 2.3.

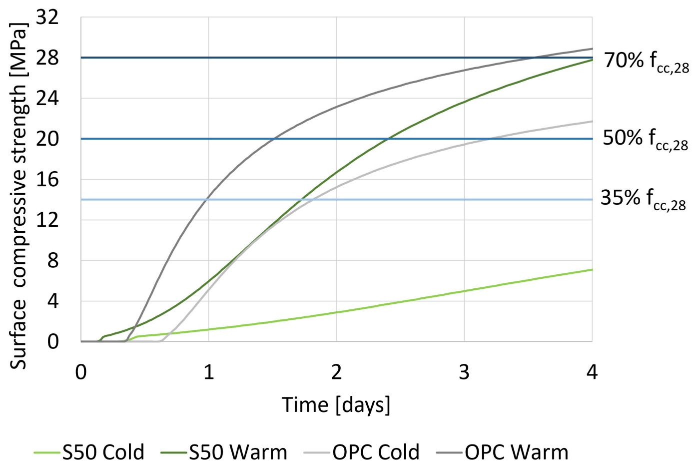


Figure 5.13: Surface compressive strength for the S50 and OPC concrete in cold and warm case

It is clear that the S50 concrete gains strength slowly in the cold case without measures, as it has not even reached 35% after 4 days. The effect of thickness on the surface compressive strength is presented in Figure 5.14

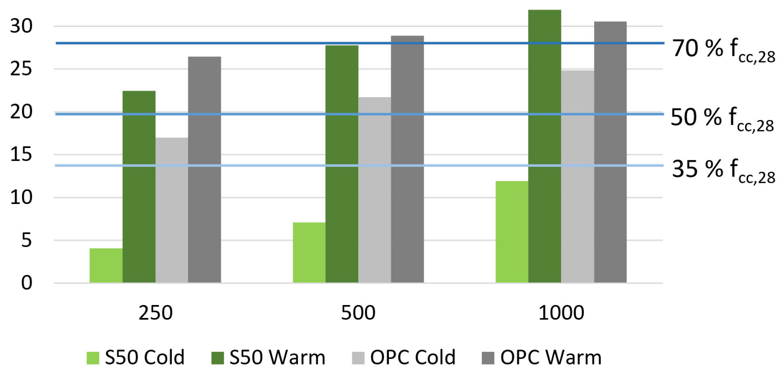
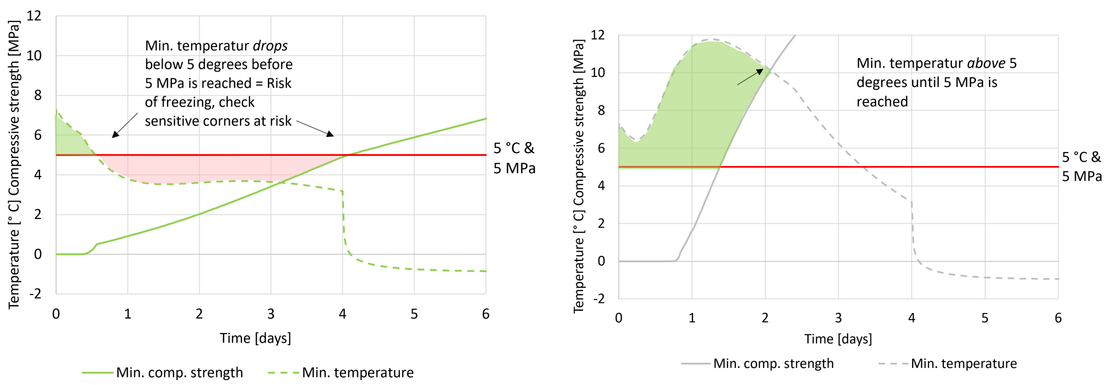


Figure 5.14: Surface compressive strength at formwork removal (4 days) for different thicknesses and concrete mixes with limits for different curing classes

5.1.6 Risk of early freezing

To make sure the concrete is not damaged by early freezing, a control is made. The minimum temperature in the wall is plotted together with the minimum compressive strength in the wall to make a first assessment, visualised in Figure 5.15. One axis is used for both the temperature and the compressive stress, the limit for the temperature of 5 °C coincides with the limit for the strength development of 5 MPa.



(a) S50 **(b)** OPC

Figure 5.15: Control of early freezing by minimum temperature and minimum compressive strength in the wall

In Figure 5.15a, showing the temperature development of S50 concrete, the minimum temperature drops below 5°C before reaching 5 MPa, thus is in risk of early freezing and will need to be evaluated closer. In Figure 5.15b, the OPC concrete passes the test as the dashed curve representing the minimum temperature does not drop below 5°C before it has reached a compressive strength of 5 MPa.

The temperature variation at 50 millimetres in from the top and bottom corners of the wall is studied for cases which do not pass the first freeze control to assess the risk more in detail. Figure 5.16 shows the temperatures in the top and bottom corner together with the minimum temperature and minimum compressive strength in the block for the S50.

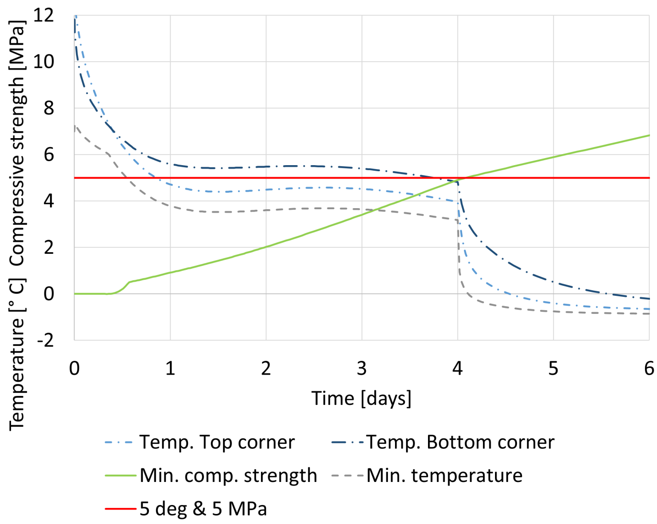
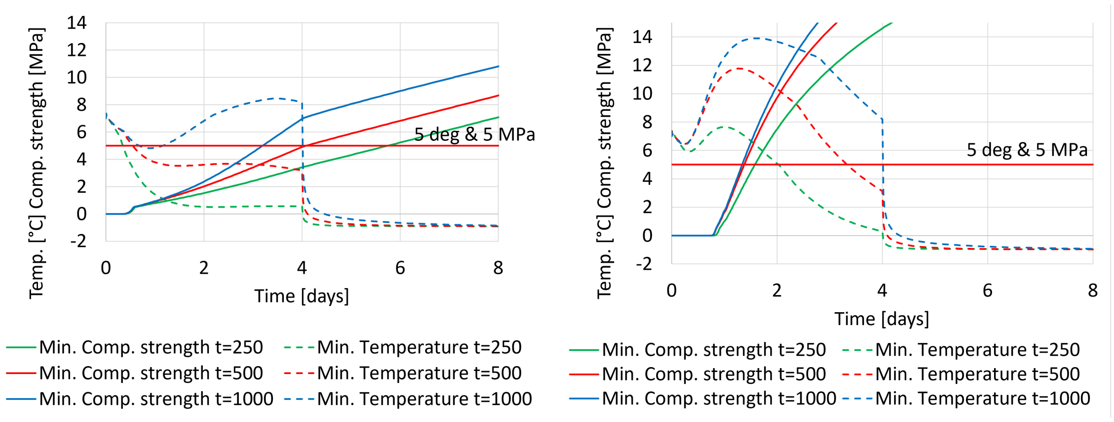


Figure 5.16: Detailed freezing control in sensitive corners for S50 cold case, 500 millimeter wall thickness

The top corner is the most sensitive, and also fails to meet the requirement for early freezing. Thus some measure is required in order to prevent the risk of early freezing.

Even though the minimum temperature is not representing a real point, it is still kept in mind for the assessment. A minimum temperature of 2-3°C at the surface of the structure might be accepted on the premise that the temperature 50 millimetres into the concrete is above 5°C. From here on, only the top corner is presented as it proved to be the most governing one for this structure.

The effect of thickness variation on the risk of early freezing is shown in Figure 5.17. The increased thickness has a dual effect on the risk of early freezing. It increases the minimum temperature in the wall by generating more heat and maintaining it better, and because of that it also develops a higher early compressive strength.



(a) S50 **(b)** OPC

Figure 5.17: Effect of thickness variation for the risk of early freezing

5.1.7 Maximum temperature

The maximum temperature in the wall for the warm cases reached 39°C for the S50 concrete and 50°C for the OPC concrete for the thickness of 500 millimeters. There is a large margin up to the maximum temperature limit of 70°C. The maximum temperature for the wall is shown for the different wall thicknesses in Figure 5.18 for the warm cases. As expected, the maximum temperature increases with wall thicknesses and the OPC concrete generates more heat than the S50 concrete.

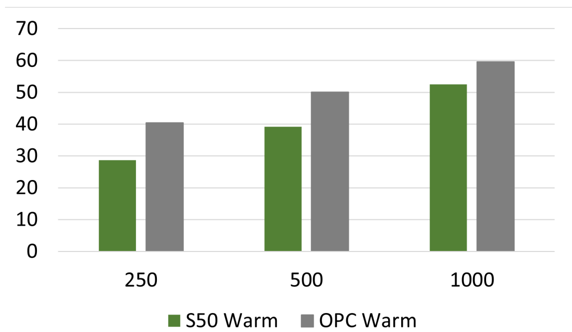


Figure 5.18: Maximum temperature in wall for the different wall thicknesses

5.1.8 Summary of parametric study

The parametric study gave a clear view of the different material behaviour of the S50 and OPC concretes. In Figure 5.19 the performance of the S50 concrete and OPC concrete with the set requirements stated in the FE modelling chapter is gathered in a summarising matrix. The cases, consisting of a geometry and concrete mix, are marked on a scale with green or red depending on their performance for that specific criteria, and the deviance from the requirement is presented in percent. Remark that stress-strength ratios are compared to a maximum limit, thus a negative means it is below that maximum stress-strength ratio. For strength related requirements, the opposite is true as the compressive strengths should exceed the minimum compressive strength. Figure 5.19 can be found in full size in Appendix D.

	S50 Cold									S50 Warm								
	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Freeze control	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Max temp [°C]
	XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa		XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa	70
t250L5	-54%	-51%	-37%							-40%	-37%	-19%						
t250L10	-46%	-43%	-27%	-30%	-81%	-71%	-80%	-85%	NOT OK	-30%	-26%	-5%	59%	12%	60%	12%	-20%	-59%
t250L20	-45%	-42%	-26%							-29%	-25%	-4%						
t500L5	-41%	-37%	-20%							-33%	-29%	-9%						
t500L10	-25%	-21%	1%	29%	-65%	-49%	-65%	-75%	NOT OK	-16%	-11%	13%	101%	41%	98%	39%	-1%	-44%
t500L20	-24%	-20%	2%							-15%	-10%	15%						
t1000L5	-39%	-36%	-18%							-36%	-33%	-14%						
t1000L10	-22%	-18%	5%	150%	-33%	-15%	-40%	-57%	OK	-19%	-14%	10%	146%	72%	128%	59%	14%	-25%
t1000L20	-18%	-13%	11%							-15%	-10%	15%						

	OPC Cold									OPC Warm								
	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Freeze control	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Max temp [°C]
	XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa		XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa	70
t250L5	-49%	-46%	-31%							-46%	-43%	-27%						
t250L10	-39%	-35%	-17%	186%	-23%	21%	-15%	-39%	OK	-35%	-32%	-13%	340%	18%	89%	32%	-6%	-42%
t250L20	-38%	-34%	-16%							-34%	-31%	-11%						
t500L5	-41%	-38%	-20%							-46%	-43%	-27%						
t500L10	-23%	-18%	5%	275%	0%	55%	9%	-22%	OK	-30%	-26%	-5%	385%	30%	106%	44%	3%	-28%
t500L20	-21%	-17%	7%							-28%	-24%	-3%						
t1000L5	-59%	-57%	-45%							-66%	-64%	-54%						
t1000L10	-41%	-38%	-21%	350%	21%	77%	24%	-11%	OK	-51%	-48%	-33%	427%	41%	118%	53%	9%	-15%
t1000L20	-36%	-33%	-14%							-46%	-43%	-27%						

Figure 5.19: Result matrix parametric study, percentage representing deviance from the requirement of maximum or minimum limit

For the S50 concrete in the cold case, the wall thickness of 500 millimeters did not meet multiple of the requirements, having both a high stress-strength ratio while developing strength at a slow pace and even being at risk of early freezing. The OPC also exceeds the maximum stress-strength ratio, but without risk of early freezing and with a reasonable compressive strength growth.

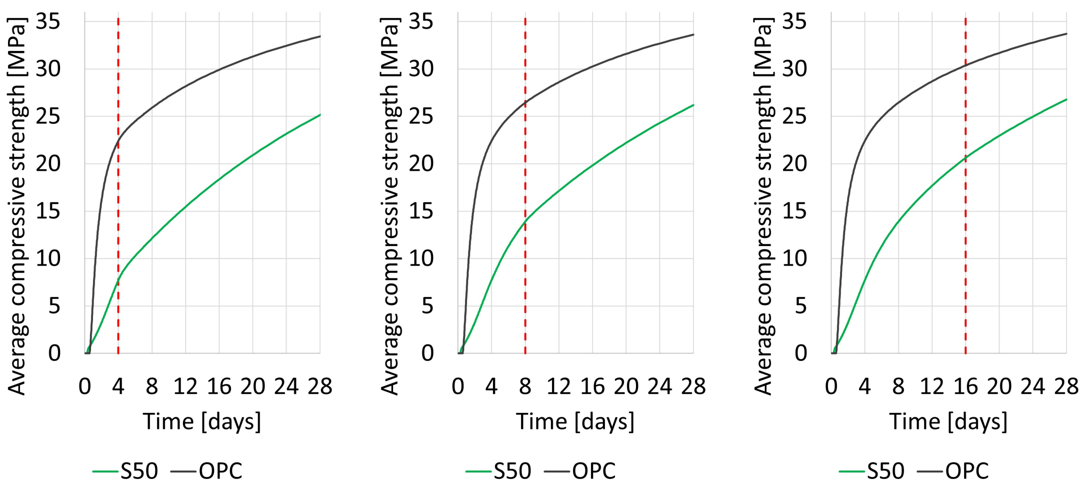
The S50 concrete did not meet the stress-strength ratio in the warm case either, while the OPC concrete did not have any issues. This could be due to the fact that a w/b ratio of 0.5 is studied in this analysis. For lower water-binder ratios it is likely that both concretes would struggle. It would be interesting to study the need for cooling for the different concretes. Since the S50 concrete generates less heat, and seems to be more sensitive to cooling, it could require less cooling and in the end be the better solution.

5.2 Risk reducing measures

After finishing the parametric study and analysis of different geometries, 't500 L20' is chosen as a basis for studying the effect of individual mitigation measures, as considered of special interest since it requires both an early increase in strength development and a decrease in stress-strength ratio.

5.2.1 Number of days with formwork

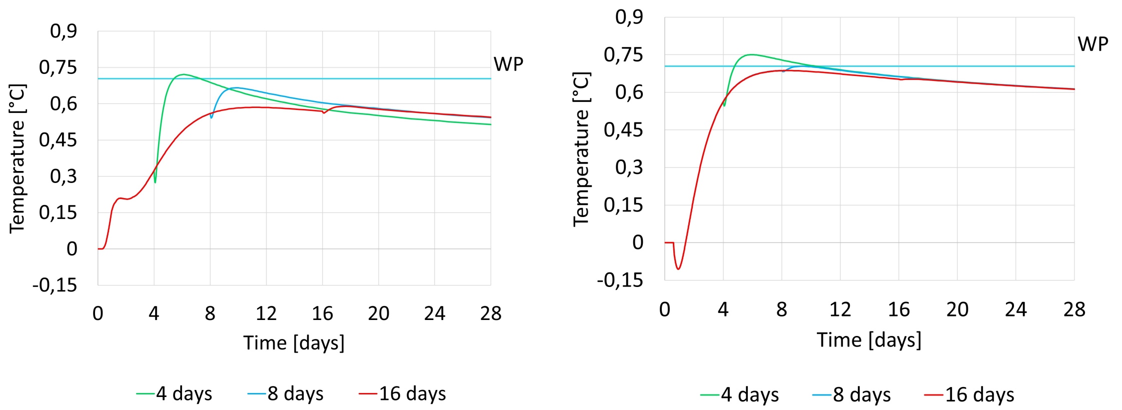
As the required compressive strength must be fulfilled by the end of the curing period, in this case time of formwork removal, keeping the formwork for longer time will result in a higher chance of exceeding the required strength as there is a large increase in strength during the first few days after casting. The effect is studied by increasing the days before formwork removal from 4 days in the original case, to 8 and 16 days. Thereby the requirements of compressive strength for formwork removal and curing class are also checked at 4, 8 and 16 days, respectively. As seen in Figure 5.20, increasing the days has a minor impact on the strength development of S50 while the effect on OPC is negligible. The high early of compressive strength of the OPC appears to be one argument to why it is not affected by the increase in formwork days to the same extent as the S50. However, the postponed time of control of compressive strength appears to be more beneficial than the actual effect of the formwork.



(a) 4 days **(b)** 8 days **(c)** 16 days

Figure 5.20: Average compressive strength for S50 and OPC with different number of days with formwork

Figure 5.21 is illustrating the impact of formwork days on the stress-strength ratio. It can be concluded that removing the formwork earlier in the curing process increase the stress-strength ratio more drastically and that extending the time with formwork from 4 to 8 days results in fulfillment of the stress-strength ratio requirement. This as the insulating effect of the formwork slows down the cooling and the temperature drop at formwork removal becomes smaller.



(a) S50 **(b)** OPC

Figure 5.21: Stress-strength ratio for S50 and OPC with 4, 8, and 16 days of formwork

Increasing the number of days with formwork is improving both the stress-strength ratio and final compressive strength with respect to the requirements, for both the S50 and OPC concrete. However, examining the results of the S50 concrete shows that increasing days of formwork is not a measure which is on its own enough to fulfill the demands without applying an unreasonable large number of days and should therefore be combined with other measures. It is also found that the S50 concrete is not fulfilling the early freezing demand of reaching 5 MPa before the temperature drops below 5°C and because the extra days of formwork is neither improving the strength development, nor raising the temperature during the first days, the situation is not changed. For the OPC concrete, the demands of stress-strength ratio is just about fulfilled with 8 days of formwork reaching curing class 3. In Figure 5.22 the percentage increase for extending the number of days with formwork is presented for the two concrete mixes. It can be estimated that approximately 13 days are needed for curing class 4 to be fulfilled which is also, in most cases, too many days to be considered reasonable in a project time plan.

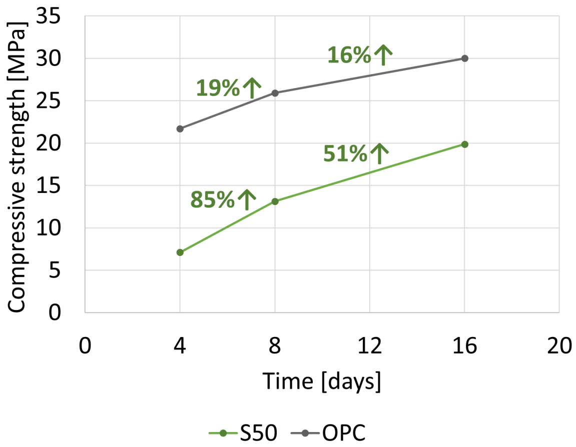
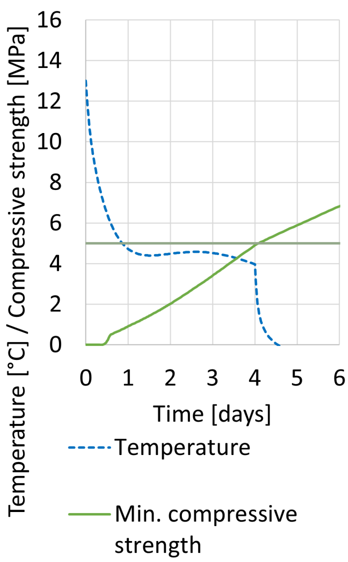


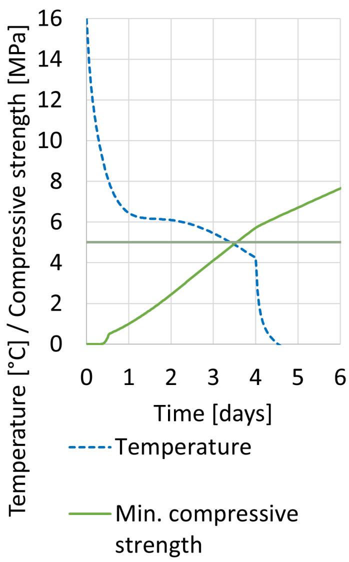
Figure 5.22: Effect on surface compressive strength at formwork removal for 4, 8, and 16 days of formwork, for S50 and OPC concrete

5.2.2 Casting temperature

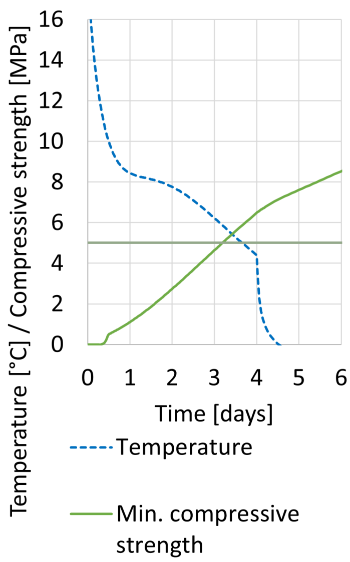
The effect of increasing the casting temperature, from 13°C to 16°C and 19°C, is decreasing the risk of freezing for the S50 concrete. In Figure 5.23 the risk of freezing is controlled by comparing the temperature at the top corner of the wall by the minimum compressive strength. It can be concluded that there is no risk of freezing when a casting temperature of 19°C is used, but with a casting temperature of 16°C the corner temperature is just below 5°C when reaching 5 MPa.



(a) T_{cast} 13°C



(b) T_{cast} 16°C



(c) T_{cast} 19°C

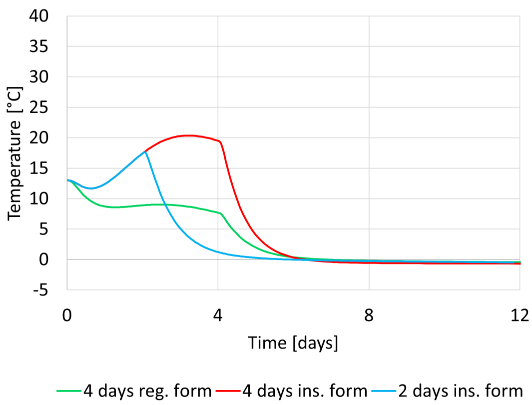
Figure 5.23: Risk of freezing by temperature in top right corner and minimum compressive strength in wall for S50

The increased casting temperature is however also increasing the stress-strength ratio, impairing the chance of fulfilling the demand. In addition, it only had a small effect on increasing the compressive strength compared to the effect of the additional formwork days. For the OPC which did not have a risk of early freezing to start with, the increased casting temperature was not an effective measure as it raised the stress-strength ratio while only slightly improving the compressive strength.

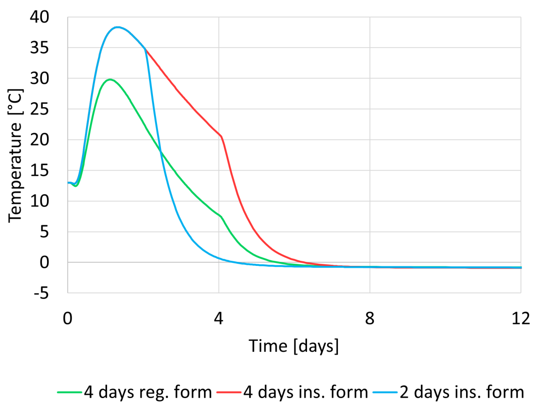
5.2.3 Formwork insulation

The original case is exemplifying the behaviour with 4 days of regular (non-insulated) form. In the following comparison, 2 days and 4 days of insulated form are applied instead of the regular form. The form is assumed to be insulated by 10 mm EPE.

Figure 5.24 presents the temperature development in the central critical point for original case, 2 days with insulated form, and 4 days with insulated form for the two concrete mixes.



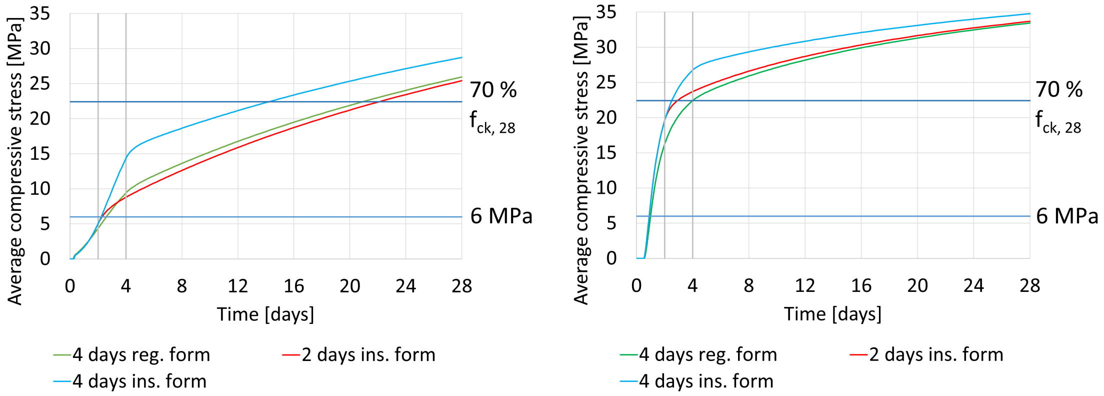
(a) S50



(b) OPC

Figure 5.24: Temperature development in mid critical point for regular and insulated form

The different hydration rates for the concrete mixes are clear. The OPC concrete reaches its peak early on, and the temperature has started to decrease when the formwork is removed for the 2-day insulation measure. Although the insulated form aids the S50 and accelerates the hydration process, it is still slower and reaches its peak somewhere between the 3rd and 4th day. Figure 5.25 shows effect of insulated formwork on the average compressive strength. The higher temperatures achieved by addition of formwork insulation increased the strength development significantly for both the S50 and OPC concrete. It also put the S50 concrete out of risk for early freezing. However, it is at the expense of an increased stress-strength ratio caused by a larger temperature decrease at formwork removal.

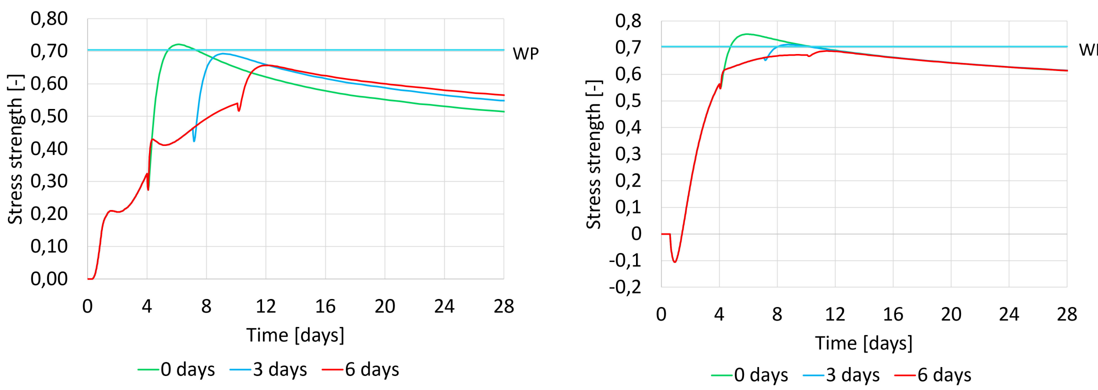


(a) S50 **(b)** OPC

Figure 5.25: Average compressive strength development for the measure insulated form

5.2.4 Replacement coverage

The replacement coverage is considered as part of the curing method. Thus, the curing class is dependent on the surface compressive strength when the replacement coverage is removed. The effects of applying replacement coverage has multiple similarities to extending the days with formwork, with the exception that there is a two-hour gap after the formwork removal until the replacement coverage is positioned. The gap, leaving the wall exposed to the surrounding temperature, causes the temperature to drop and the compressive strength rate is thereby decreased. Figure 5.26 shows the improved stress-strength ratio that decreases when replacement coverage is used for both S50 to the left, and OPC to the right.



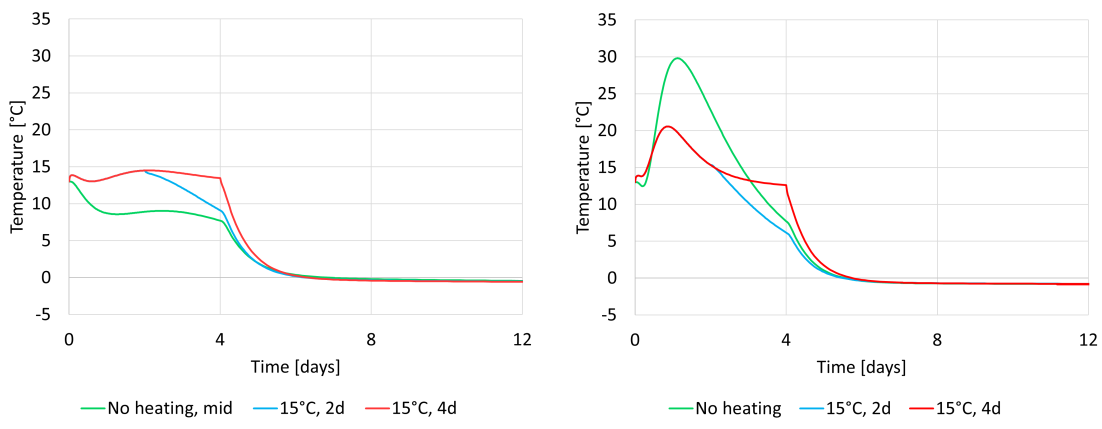
(a) S50 **(b)** OPC

Figure 5.26: Stress-strength ratio in middle critical point using the measure replacement coverage

5.2.5 Heating pipes

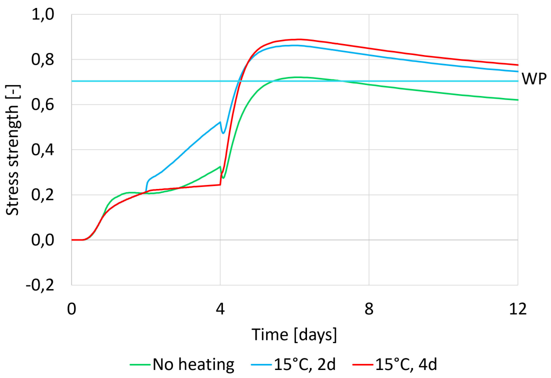
As seen previously, the S50 concrete develops low temperatures after it is cast with a temperature of 13°C in an environment of -1°C. Therefore, 15°C water is run through the water pipes in order to add heat and accelerate the hydration process. The measure is successful with respect to early freezing as it both rises the minimum temperature and in turn also accelerates the compressive strength growth. The accelerated compressive strength due to the heated water also improves the compressive strength. However, similar to increasing the casting temperature, the added heat increases the stress-strength ratio.

The same measure has the opposite effect depending on which material are used. The water will heat up the S50 but cool down the OPC. This as the OPC concrete generates enough heat by itself, and the water having a lower temperature decreases the temperature of the OPC concrete. This has a positive effect on the stress-strength ratio, as it get a smaller temperature drop at formwork removal. Depending on if the water is on for 2 or 4 days, the compressive strength behaves differently. For 2 days, the water only has a cooling effect, thus the compressive strength is reduced. If the water is on for 4 days, it starts to heat the concrete after it has cooled down to 15°C, as it counteracts the cooling from the surroundings. The compressive strength is still reduced, but just enough for it to still pass curing class 3. The temperature development for the concrete mixes using 15°C water is shown in Figure 5.27, and the resulting stress-strength ratio due to the measure is shown in Figure 5.28, both figures for 12 days.

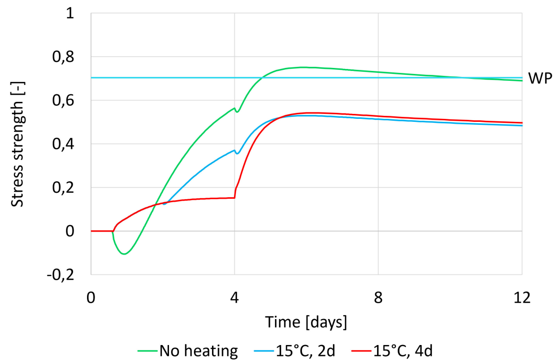


(a) S50 **(b)** OPC

Figure 5.27: Temperature development in mid critical point using water regulating pipes



(a) S50



(b) OPC

Figure 5.28: Stress-strength ratio in middle critical point using water regulating pipes

5.2.6 Summary measures

The measures had both similar and different effects on the two concrete mixes. A summarising matrix presenting the original performance from the parametric study, together with two intensities of the measure can be seen in Figure 5.29 for the two concrete mixes. The deviance from the requirement is presented in percent, similar to Figure 5.19. Each cell is given a color based on its performance, red if the requirement is not met, and green is it has been met. The full size matrix can be found in Appendix D.

		S50 Cold t500 L20									
		Cracking safety factors			Compressive strength at formwork removal		Curing class (10 mm from surface)			Freezing control	Max. temp. [°C]
		XC2 (0,952)	XC4 (0,9)	One-sided water pressure (0,704)	Non-bearing formwork (6 MPa)	Bearing formwork (70%f_{ck})	2 (14 MPa)	3 (20 MPa)	4 (28 MPa)		
Days of formwork	4 days	-24%	-20%	2%	29%	-65%	-49%	-65%	-75%	NOT OK	13,0
	8 days	-30%	-26%	-5%	132%	-38%	-6%	-34%	-53%	NOT OK	13,0
	16 days	-38%	-35%	-16%	244%	-8%	42%	-1%	-29%	NOT OK	13,0
Casting temperature	13°C	-24%	-20%	2%	29%	-65%	-49%	-65%	-75%	NOT OK	13,0
	16°C	-14%	-9%	16%	57%	-58%	-38%	-57%	-69%	NOT OK	16,0
	19°C	-7%	-2%	26%	87%	-50%	-26%	-48%	-63%	OK	19,0
Formwork insulation	None	-24%	-20%	2%	57%	-58%	-49%	-65%	-75%	NOT OK	13,0
	2 days	-7%	-2%	26%	-17%	-78%	-64%	-75%	-82%	NOT OK	17,6
	4 days	-3%	3%	31%	139%	-36%	7%	-25%	-47%	OK	20,4
Replacement coverage (after formwork removal)	0 days	-24%	-20%	2%	57%	-58%	-49%	-65%	-75%	NOT OK	13,0
	3 days	-27%	-23%	-2%	118%	-42%	-10%	-37%	-55%	NOT OK	13,0
	6 days	-31%	-27%	-7%	180%	-25%	17%	-18%	-42%	NOT OK	13,0
Heating/cooling	None	-24%	-20%	2%	57%	-58%	-49%	-65%	-75%	NOT OK	13,0
	2 days	-9%	-4%	22%	104%	-45%	-43%	-60%	-72%	OK	14,5
	4 days	-7%	-1%	26%	187%	-23%	-33%	-53%	-66%	OK	14,5

		OPC Cold t500 L20									
		Cracking safety factors			Compressive strength at formwork removal		Curing class (10 mm from surface)			Freezing control	Max. temp. [°C]
		XC2 (0,952)	XC4 (0,9)	One-sided water pressure (0,704)	Non-bearing formwork (6 MPa)	Bearing formwork (22.4 MPa)	2 (14 MPa)	3 (20 MPa)	4 (28 MPa)		
Days of formwork	4 days	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	8 days	-26%	-22%	0%	341%	18%	85%	30%	-7%	OK	29,8
	16 days	-28%	-24%	-2%	406%	36%	114%	50%	7%	OK	29,8
Casting temperature	13°C	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	16°C	-14%	-9%	16%	285%	3%	60%	12%	-20%	OK	32,8
	19°C	-7%	-1%	26%	296%	6%	65%	15%	-18%	OK	35,9
Formwork insulation	None	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	2 days	-4%	1%	29%	226%	-13%	40%	-2%	-30%	OK	38,3
	4 days	-8%	-3%	25%	346%	19%	93%	35%	-3%	OK	38,3
Replacement coverage (after formwork removal)	0 days	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	3 days	-25%	-21%	1%	331%	15%	81%	27%	-10%	OK	29,8
	6 days	-28%	-24%	-2%	364%	24%	96%	37%	-2%	OK	29,8
Heating/cooling	None	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	2 days	-44%	-41%	-25%	274%	0%	34%	-6%	-33%	OK	20,5
	4 days	-43%	-40%	-23%	348%	20%	44%	1%	-28%	OK	20,5

Figure 5.29: Result matrix of the study of risk reducing measures, percentage representing deviance from the requirement of maximum or minimum limit

Although the OPC concrete has a higher stress-strength ratio for the parametric study in the cold case, the fact that it is not sensitive to early freezing and develops compressive strength early on creates greater conditions for simple solutions. The slower hydration reaction and less generated heat makes the S50 sensitive to cold castings. Once one problem is fixed, another one might be created. For example, measures to avoiding early freezing increase the stress-strength ratio.

No measure is by itself sufficient to meet all demands efficiently. The measure which decreased the stress-strength ratio the most was adding days with formwork for the S50 concrete, and adding cooling for the OPC concrete. The most efficient measure in order to improve the strength development was the time-extending measures such as more days of formwork and adding replacement coverage, otherwise insulating the form was the best option. To minimise the risk of early freezing, which was higher for the S50 concrete, heating with water pipes was the most efficient. The advantages and disadvantages of the different measures are summarised in Table 5.2.

Table 5.2: Advantages and disadvantages of risk reducing measures

Measure	**Advantages**	**Disadvantage**
Days of formwork	+ Decreases stress-strength ratio + Improved strength at end of formwork removal	- Requires more time and formwork - No difference in risk of early freezing
Casting temperature	+ Decreased risk of early freezing + Small improvement of strength development	- Increased stress-strength ratio
Formwork insulation	+ Decreased risk of early freezing + Improved strength at end of formwork removal	- Increased stress-strength ratio
Replacement coverage	+ Decreased stress-strength ratio + Improved strength at end of formwork removal	- No difference in risk of early freezing
Heating/Cooling water pipes	S50: + Decreased risk of early freezing + Improved strength at end of formwork removal OPC: + Decreased stress-strength ratio + Longer time (4d) improved stress-strength development	S50: - Increased stress-strength ratio OPC: - Short time (2d) decreased strength development

The time aspect of adding more days with formwork or replacement coverage is interesting as its main advantage is delaying the time at which the requirement need to be fulfilled, which is at the end of the curing period. If there is no intention to perform further work on the wall shortly after casting and the formwork or replacement coverage is not kept as a cracking measure but for curing, air curing could be an option. For air curing, the surface needs to be kept saturated, for example covered by tarpaulin, and the period of curing is then extended further.

5.3 Combination of measures to meet a deadline

Combinations of measures are developed in an iterative process, each with the intention to improve the early-age performance. Measures which are typically more beneficial in terms of economy and time plan are evaluated in the first place and if needed, more complex or expensive measures are considered. For example, insulated form and replacement coverage is preferred over higher casting temperatures and embedded water pipes. The results of different measure combinations are compared by studying the stress-strength ratio, curing class, risk of freezing and compressive strength at formwork removal and comparing to the hard demands. The temperature at the critical points are often helpful in evaluating the effect and timing of applied measures and is often used when deciding the next combination. The prerequisites of each concrete type can be summarised based on findings from the previous chapter and are presented in Table 5.3.

Table 5.3: Challenges or advantages of the OPC and S50 concrete, respectively, with regard to hard demands

	OPC	S50
Cracking safety factors	Generally too high to meet demand for one-sided water pressure in the previous analysis	Similar to OPC but a bit lower
Avg. comp. strength at formwork removal	Generally fulfilling the required compressive strength for bearing and non-bearing form	Generally fulfilling the required compressive strength for non-bearing form but not for the bearing form
Curing class	Just meeting the demands for bearing formwork with four days of formwork	Lower than OPC, needs to be drastically increased to meet demand for curing class 3
Risk of early freezing	No risk of early freezing in the previous analysis	Generally high risk of early freezing in the previous analysis

5.3.1 Four-day deadline with OPC concrete

Initially the stress-strength ratio for OPC concrete cured with four days of formwork exceeded the one-sided water pressure limitation. To adjust this, replacement coverage is applied after formwork removal which is enough to meet the hard demands, see Figure 5.30. The OPC concrete is, with combination 1, reaching an average compressive strength of 22 MPa at formwork removal, corresponding to 69% of f_{ck}.

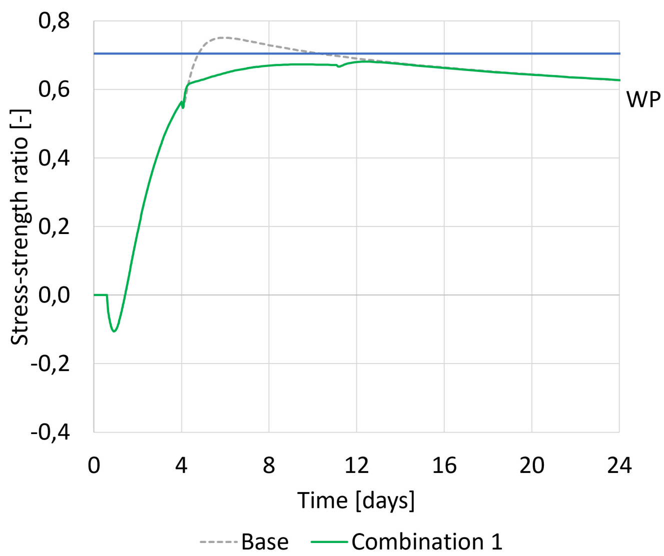
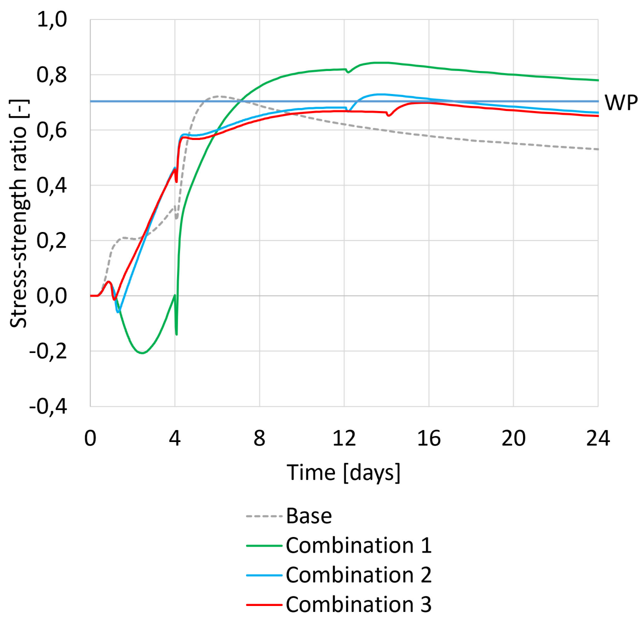


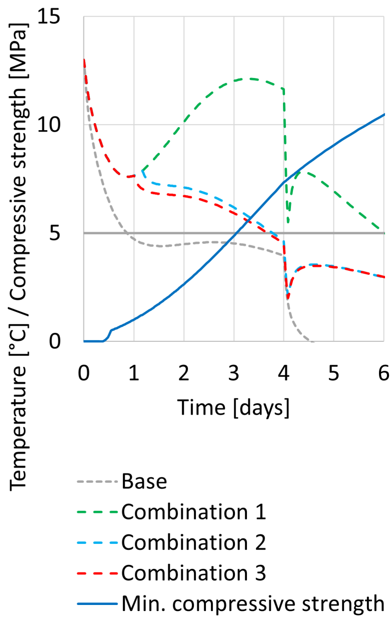
Figure 5.30: Stress-strength ratio of OPC concrete with different combination of measures

5.3.2 Four-day deadline with S50 concrete

For the S50 concrete, only applying replacement coverage is not enough to meet all demands as there is also a risk of freezing during the first four days. Therefore, four days of insulated formwork is applied in combination 1 to slow down the early cooling, together with eight days of replacement coverage after formwork removal. Combination 1 results in a too high stress-strength ratio, which can be seen in Figure 5.31. Combination 2 is adjusted by removing the insulation of the formwork after 28 hours and keeping the non-insulated form until four days are passed. It is found that this adjustment is not sufficient to meet the stress-strength ratio demand. In combination 3, one day of insulated form is followed by one day of non-insulated form, two days of insulated form and finally, ten days of replacement coverage. The idea is to insulate until there is no longer a risk of early freezing, then remove insulation to minimise the temperature peak, and then to add insulation once again to slow down the cooling. This might also be possible to accomplish through heating/-cooling pipes but the measure of embedded water pipes was in this case excluded as formwork insulation and replacement coverage are believed to be a cheaper solution.



(a) Stress-strength ratio

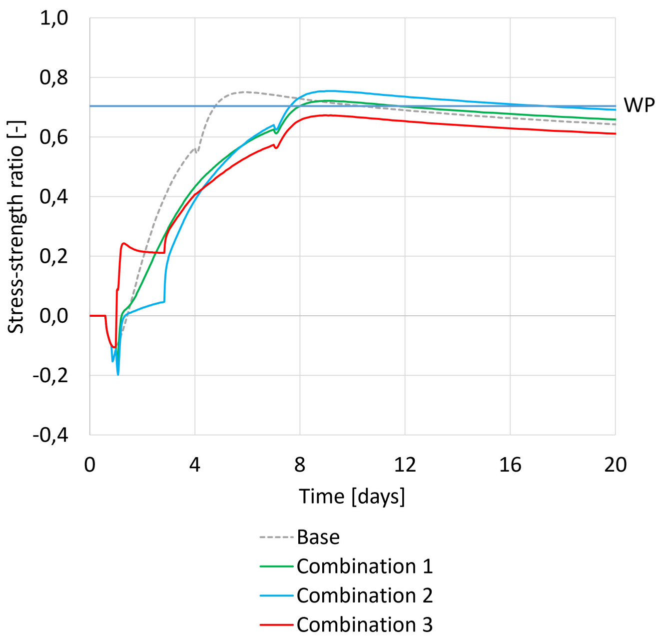


(b) Risk of freezing by temperature in top corner and minimum compressive strength in wall

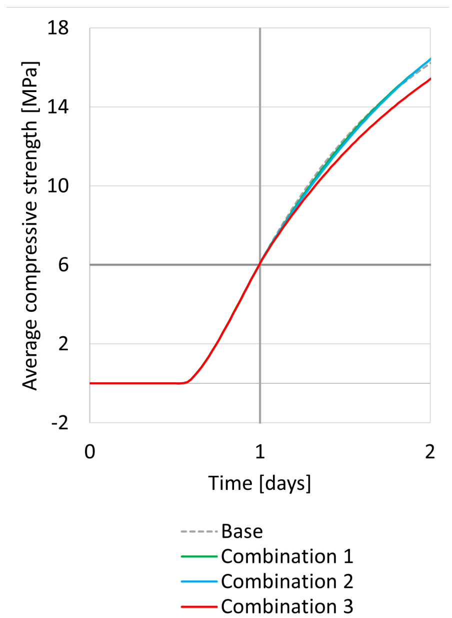
Figure 5.31: Risk of cracking (a) and freezing (b) for S50 concrete with different combinations of measures

5.3.3 One-day deadline with OPC concrete

As the original case with four days of non-insulated formwork did exceed the cracking safety factor for one-sided water pressure, a lowered stress-strength ratio is the main aim. Replacement coverage is thereby added here as well to decrease the stress-strength ratio after the formwork is removed. Combination 1 represents one day of non-insulated form followed by six days of replacement coverage, unsuccessfully resulting in a stress-strength ratio higher than the initial case. Since fulfilling the demand of cracking safety factor by only formwork and replacement coverage appears to be unattainable, more complex measures are considered. A lower casting temperature is not considered as the required compressive strength at formwork removal is just passed and cannot be decreased, see Figure 5.32b. In combination 2, water pipes distributing water with an average temperature of 30°C are added a few hours before the formwork removal and kept for two days to limit the stress increase after formwork removal. To slightly further reduce the stress-strength ratio, in combination 3 the water temperature is set to 20°C and the water is supplied during the hours 24-68. In Figure 5.32a the result in stress-strength ratio of each combination of measures can be seen.



(a) Stress-strength ratio



(b) Avg. compressive strength

Figure 5.32: Development of material properties of OPC concrete with different combinations of measures and formwork removal after one day

5.3.4 One-day deadline with S50 concrete

Finding solutions for meeting the one-day deadline with S50 concrete proves to be a complex assignment. As the strength development of the S50 concrete is much slower than that of the OPC concrete, keeping a high temperature during the first day is crucial for fulfilling the demand of average compressive strength at formwork removal.

Combination 1 includes one day of insulated formwork followed by six days of replacement coverage. In addition, water pipes supplying water with an average temperature of 25 °C are added during the hours 20-48. To further increase the early strength development, a casting temperature of 20 °C is chosen. As a result, the average compressive strength is, to some extent, raised compared to the base case, which can be seen in Figure 5.33. Unsuitably, the measures also result in an increased stress-strength ratio exceeding the limit further. Conclusively, the strength development during the first day must be improved while the stress-strength ratio after formwork removal must be decreased.

With the intention of accomplishing these aims, the adjustment for combination 2 is to keep an insulated form during 18 hours, non-insulated form during hours 18-24, applying replacement coverage during hours 26-168 and increasing the casting temperature to 27 °C. However, after running the model it is concluded that this results in a thermal shock causing undesired stress results.

In combination 3, replacement coverage is applied earlier to limit the temperature decrease after formwork removal. Instead of two hours, one hour is set between the formwork removal and application of replacement coverage. The replacement coverage is also kept until 10 days after casting. The average water temperature in the pipes is raised to 30°C and the casting temperature of 27°C is kept. Increasing the water temperature in the pipes seeks to counteract the temperature drop at formwork removal. Unfortunately, the changes are not sufficient to avoid a thermal shock and the results are once again that the model fails to handle the rapid shift of stresses.

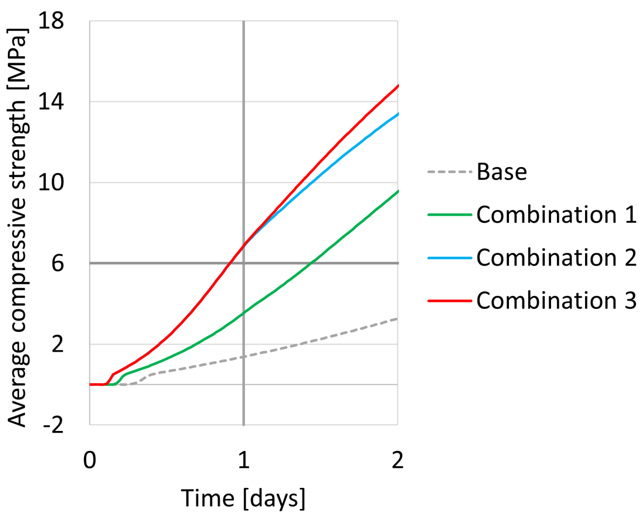
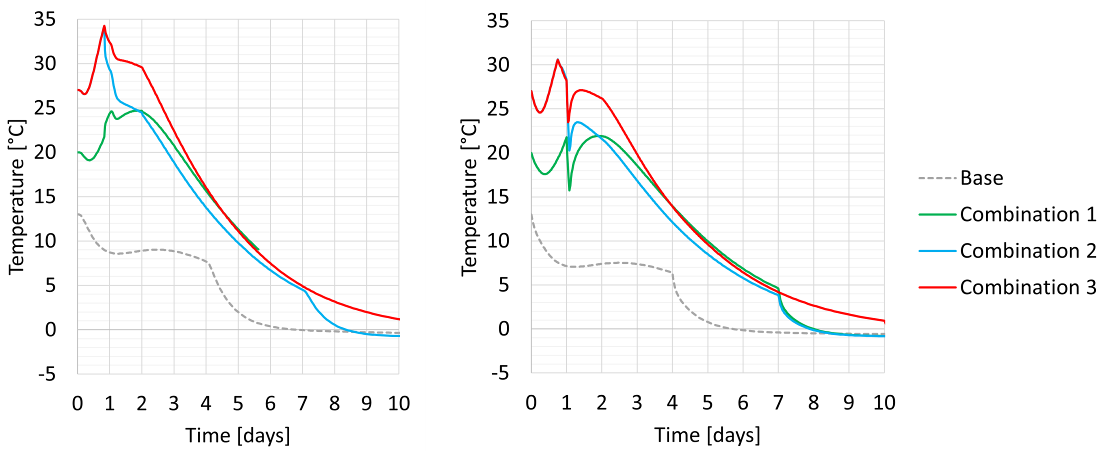


Figure 5.33: Average compressive strength of S50 concrete with formwork removal after one day, for different combinations of measures

Figure 5.34 is visualising the temperature development in the mid and surface critical points. It can be seen that the largest temperature drop occurs at the surface which is expected as the impact of boundary temperature is higher and the impact of heating water pipes is lower. Moreover, some of the applied measures might be considered as unreasonable from a practical perspective. For example, a casting temperature of 27°C would be hard to achieve when delivering the concrete mix from factory to construction site in an outdoor air temperature of -1°C. Therefore, it is concluded that fulfilling the hard demands by the previously mentioned measures with a one-day deadline while avoiding a thermal shock would be complex and yield a non-realistic solution for the S50 concrete. Others ways of potentially accomplishing the casting and curing are however available. When casting in cold climate one method for maintaining the heat development and avoiding a thermal shock at formwork removal is to perform the casting in a construction shelter with a heat supplier keeping the air temperature in the shelter at a preferred level. The air temperature inside the shelter can then be gradually decreased after the formwork is removed until the concrete properties are sufficient to handle the temperature differential. Moreover, it can be noted that the studied structure has a set casting length of 20 meters, which is often convenient when having strict time plans, but yields a higher restraint degree then if the casting was performed in shorter sections. Thus a shorter casting length would also be beneficial in terms of risk of cracking but the largest effect would be seen if decreasing the casting length below 10 meters as the restraint was not significantly changed between 10 and 20 meters, see Figure 5.9.



(a) Mid critical point **(b)** Surface critical point

Figure 5.34: Temperature development in critical points for S50 concrete with a formwork removal deadline of one day

5.3.5 Conclusion and discussion of combination of measures

The required measures to meet the set deadlines differed significantly for the two concrete mixes, as they had different issues to solve. Figure 5.35 is presenting the measure combinations for OPC and S50 with a one-day and four-day deadline, respectively.

	Regular formwork [hours]	Insulated formwork [hours]	Replacement coverage [hours]	Heating/ cooling water [hours]	Water temperature [°C]	Casting temperature [°C]
OPC						
Combination 1	0-96	-	98-266	-	-	13
S50						
Combination 1	-	0-96	98-290	-	-	13
Combination 2	28-96	0-28	98-290	-	-	13
Combination 3	24-48	0-24, 48-96	98-336	-	-	13

(a) Four-day deadline

	Regular formwork [hours]	Insulated formwork [hours]	Replacement coverage [hours]	Heating/ cooling water [hours]	Water temperature [°C]	Casting temperature [°C]
OPC						
Combination 1	0-24	-	26-168	-	-	13
Combination 2	0-24	-	26-168	20-68	30	13
Combination 3	0-24	-	26-168	24-68	20	13
S50						
Combination 1	-	0-24	26-168	20-48	25	20
Combination 2	18-24	0-18	26-168	20-48	25	27
Combination 3	18-24	0-18	25-240	20-48	30	27

(b) One-day deadline

Figure 5.35: Measure combinations and timing for S50 and OPC concrete

The OPC concrete has an advantage by its larger heat generation when cast in cold temperatures. Thereby, only measures to decrease the stress-strength ratio are needed. For the four-day deadline, adding replacement coverage was enough. When the formwork needed to removed after one-day, water regulating pipes were also needed to slow down the cooling thus decreasing the stress-strength ratio to acceptable levels.

Multiple measure was needed to meet the deadlines for the S50 concrete, which included measures both to accelerate the early strength, and to decrease the stress-strength ratio. For the four-day deadline, adding insulation to the formwork at a well chosen time was a successful measure in combination with keeping replacement coverage for a longer time. There was no solution with previously presented measures that worked for the S50 concrete with a deadline of one day. Abnormal casting temperatures of 27°C were tried in combination with insulation to boost the early strength development and to reach an acceptable compressive strength at the time of formwork removal. The accelerating measures increases the risk of exceeding stress-strength ratio limits, which no tested water regulation was able to handle before the replacement coverage was added. Adding a secondary row of water pipes was not enough efficient. It can be concluded that other measures are needed.

5.4 Extended discussion

It was previously noted that the studied materials obtain differences regarding development of strength properties. In particular, the 28-day compressive strength which was set as input in the modelling is differing, being 40 MPa for the OPC concrete and 48.3 MPa for the S50 concrete. This means that the mechanical properties are not directly equivalent and thus, should be kept in mind in the evaluation of the results. As the compressive strength of the S50 concrete exceeded the OPC concrete while the tensile strength did not, the matter is investigated further. The average values of the compressive and tensile strength of the wall are analysed in order to compare the strength development. The compressive strength of OPC is normalised by adjusting the value of $f_{cc,28}$ from 40 to 48.3 MPa. In the modelling software, the tensile strength is calculated based on the compressive strength, thus the tensile strength in also increased when normalising $f_{cc,28}$. The average compressive strength and related tensile strength are presented with and without normalisation of $f_{cc,28}$ in Appendix E. The tensile strength of the OPC concrete is higher in relation to its compressive strength, in difference to the S50 concrete. When comparing the OPC with normalised $f_{cc,28}$ to the S50 it is even more clear that the S50 concrete is more sensitive to tensile stresses.

Furthermore, the cement content of the OPC concrete mix is 365 kg/m^3 while it is 200 kg/m^3 for the S50. Thereby it should be noted that the S50 concrete does not contain half the amount of cement compared to the studied OPC concrete, but rather a reduction of 45.2 %.

In the modelling process the element size it set to 10, 20, 40, and 80 millimetres respectively for the different wall thicknesses and materials. It was concluded that the S50 concrete required half the element size compared to the OPC concrete to obtain results which was not too sensitive to element size. However, choosing this small values of element size might be problematic when also aiming for a realistic representation of the material. In the modelling, concrete is considered a homogeneous material while in reality, it consists of paste and aggregates. Thus, defining an element size that is smaller than the aggregate size does not make sense and one should be aware of the limitations of the model.

Another interesting aspect is that the different hydration rates of the materials generate different temperature development. In turn, it is expected that the cooling rates are also different. The restraint is calculated based on the average modulus of elasticity during cooling, E_c. In this study, E_c was assumed to be 30 MPa for both the S50 concrete and thereby the OPC concrete and the restraint was set equal for the S50 and and OPC concrete. Thereby, the restraint is only varied due to the cross-sectional dimensions and casting length. However, as the cooling profiles of the materials look different, it is probable that also E_c varies for the two materials which would have an effect on the resulting restraint. Nonetheless, the potential difference in restraint for the two materials is assumed to be negligible.

Moreover, the method of modelling heating or cooling by water pipes in the chosen modelling software is simplified as the water temperature is set at a constant values along the pipes and in time. In a realistic situation, the water temperature would either be heated or cooled by the concrete and obtain different inlet and outlet temperatures dependent on the temperature difference between the water and the concrete. The actual temperature difference in each position of the pipe is a complex relation as the heat of hydration must be known in order to calculate the difference but is in turn dependent on the temperature of the supplied water.

Finally, as previously mentioned the material parameters for the S50 were developed using material models based on pure Portland cement. Consequently they can be assumed to be less accurate than the parameters for the OPC concrete, thus the behaviour presented in this thesis could differ from reality. Nonetheless, analyses using these material parameters could give a good indication of expected behaviour which could be valuable to assess potential development of production methods and in turn result in better utilization of slag concrete. Furthermore, assessment of differences between the real behaviour and estimated behaviour using existing material models might be needed in order to develop material models adapted to slag concrete and methods of experimental testing of slag concrete.

6 Conclusion

The aim of the study was to analyse the risk of early-age thermal cracking for a concrete with a GGBS content of 50 % by binder mass and a traditional OPC concrete with similar properties for a wall-to-slab section. This by comparing the early-age performance including early-age thermal cracking, curing and early freezing for varying environmental and geometrical conditions and crack risk mitigation measures. Concluding remarks based on this study are presented below.

- The largest behavioural differences between the two concrete mixes were seen for the cold case with an environmental temperature of -1 °C. The S50 concrete proved to be sensitive to low environmental temperatures, which slowed down the hydration rate and resulted in lower temperatures and strength compared to the OPC concrete, and additionally a risk of early freezing. The S50 in the cold case did generate a lower stress-strength ratio compared to the OPC concrete, but at the cost of other properties. The warm cases were generally more similar, but the S50 concrete generated higher stress-strength ratios for all thicknesses compared to the OPC concrete, which can be partly attributed to the lower tensile strength of the S50 concrete.

- The stress-strength ratio increases with the casting length, as it provides a larger restraint for the the same cross-sectional properties such as heat and strength development. The largest effect was seen when doubling the casting length from 5 to 10 meters, while a significantly smaller effect was seen for the 10 to 20 meter length increase. The increased casting length had a different effect on the maximum stress-strength ratio of the S50 and OPC concrete, which did not increase proportionally as the increase was generally larger for the OPC. The casting length variation clearly showed the effect of solely changing the restraint conditions without any noticeable effect on the heat and strength development.

- While the variation in wall and slab thicknesses resulted in predictable results in terms of temperature and strength development, both increasing with the thickness, the effect on stress-strength ratio was more unpredictable. It was seen that the strength gain due to temperature increase when increasing the thickness was either larger or smaller in proportion to the stress gain due to increased restraint, dependent on the material and wall thickness. Stress-strength ratio increased when going from a thickness of 250 to 500 millimetres for both materials, but when doubling the casting length again the maximum stress-strength ratio decreased for the OPC, opposite of the S50 which continued to increase slightly. Conclusively, increased heat and strength development in combination with increased restraint, by cause of the larger dimensions, resulted in different geometries being the most critical with respect to stress-strength ratio, dependent on the material and thermal conditions. However, in general the wall thickness of 500 millimetres proved to be the most critical with the set configuration.

- For the wall thickness 500 millimeters in the cold case, no measure was by itself enough to fulfil the crack safety factor for one-sided water pressure while also meeting the requirements of curing class 3 and risk of freezing when using the S50 concrete. This was accomplished by three measures, individually, when using the OPC concrete. A higher casting temperature and formwork insulation improves the early strength development but generally leads to a higher stress-strength ratio which increases the crack risk. On the contrary, the largest reduction of stress-strength ratio, and thus the crack risk, was to extend the days with formwork for the S50 concrete and to apply cooling by water pipes for the OPC concrete.

- Multiple measures was required for the S50 concrete in order to meet the hard demands with the given days of formwork removal while measures where easier determined for the OPC concrete due to its advantage of gaining strength at a faster rate. Thus only stress-strength limiting measures where needed for the OPC while measures for increased early strength where also needed for the S50.

- The slower hydration process of the slag concrete makes it sensitive to low temperatures and is a challenge for strict deadlines of formwork removal. However, satisfactory results with slag concrete can be achieved by extending the time with formwork, alternatively the curing period. Moreover, considering the limited availability of GGBS it could be argued that future usage of GGBS as SCM should be applied where it performs the best.

6.1 Future studies

There are several aspects related to this study which could be of interest in future studies. A few examples are treated in the sections below.

- As the slag concrete in this study generated a higher stress-strength ratio than the OPC concrete for the warm case, it would be of interest to study the difference in need of cooling for the two mixes. In a situation where both concrete types obtained a higher stress-strength ratio, for example when using a lower water-binder ratio which is common in civil works or when casting in a warmer environment than that studied, the concrete might require cooling. Investigation of the cooling need for an OPC concrete in comparison to a slag concrete could help to clarify if and in what conditions the lower heat generation of a slag concrete could be beneficial.

- In order to consider the often decisive aspect of economy, an analysis including quantification of costs is highly relevant. There are multiple aspects to include. As seen in this thesis, the slag concrete required additional measures when casting in a cold climate, resulting in certain costs. Potential savings could be found when casting in a warm climate if the slag concrete requires less cooling. Another aspect is that initially new concrete mixes could need comprehensive testing to attain mix specific material parameters and expensive freeze tests. However, with time there will be multiple approved mixes that could be used directly and eventually also general material parameters for slag concrete. A cost analysis including the cost of experimental testing, raw materials, measures and potential economical bonuses for sustainable solutions could bring argument for when usage of slag concrete is economically affordable and not.

- This study is limited to calculations and results of a wall-to-slab section. An analysis of other structural elements, such as a ground slab, intermediate floor slab or deck, would be needed to investigate behavioural differences related to concrete type with other restraint conditions and structural requirements. It would also be interesting to investigate potential benefits of slag concrete in marine structures which often has stricter requirements linked to the relevant exposure classes.

- Lastly, it would be convenient to identify the relation between the level of cement replacement by GGBS and changes in early-age and long-term behaviour. Analyses of concrete with lower replacement levels, which are more commonly used for casting in cold climate, and comparison of concrete types with low, intermediate, and high level of replacement could be beneficial in determining the most suitable and efficient composition for a certain situation.

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List of Figures in Appendix

A

Mesh convergence study

The mesh convergence study is performed by studying the stress strength ratio over 28 days, for a cold case with formwork removal 7 days after casting. The thinnest wall, with a thickness of 250 mm, is the studied cross section. In Figure A.1 the mesh convergence for the OPC concrete is presented.

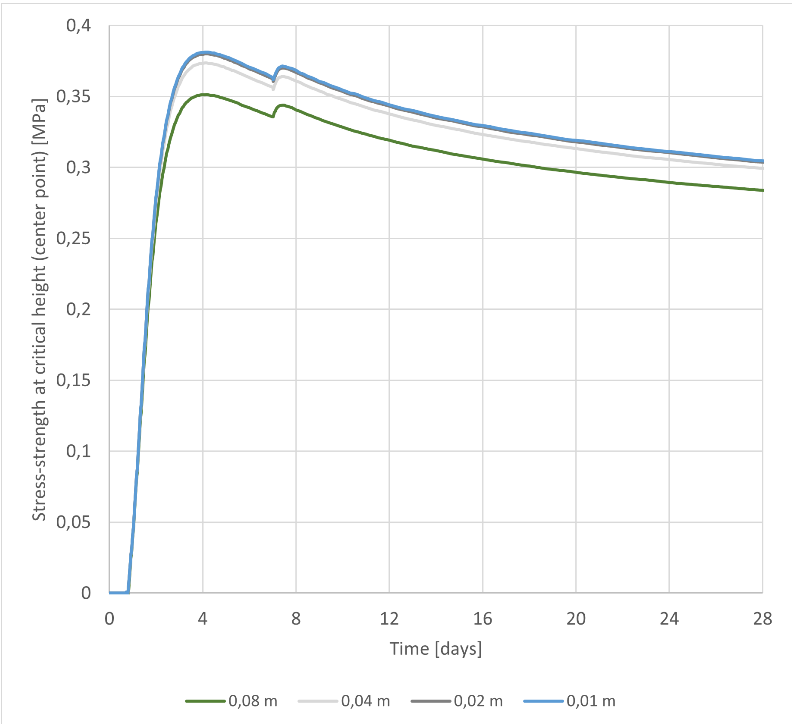


Figure A.1: OPC mesh convergence

The coarsest element size starts at 0.08 meters and is divided by a factor of 2 for each new element size. The difference between the element size 0.08 and 0.04 is relatively large, however, the difference between 0.04 and 0.02 is rather small. The stress strength ratio for element size 0.01 is almost identical with the result for element size 0.02, resulting in 0.02 being an almost hidden curve. The chosen element size is 0.02 meters for the wall thickness of 250 millimeter, resulting in approximately 12 or 13 elements across the wall.

Figure A.2 shows the stress strength ratio for a S50 concrete in the winter.

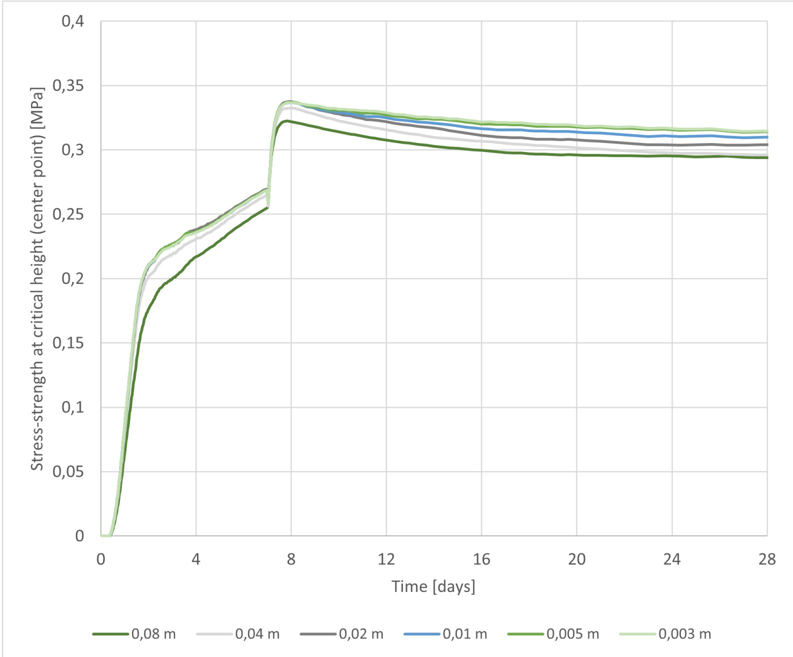


Figure A.2: S50 mesh convergence

The S50-concrete convergence differs from the OPC-concrete. In addition to the element sizes used for the OPC-concrete convergence study, two smaller element sizes are required to determine the appropriate element size. The chosen element size is 0.01 for the wall thickness of 250 millimeter, resulting in 25 elements across the wall.

B

Restraint across cross-section

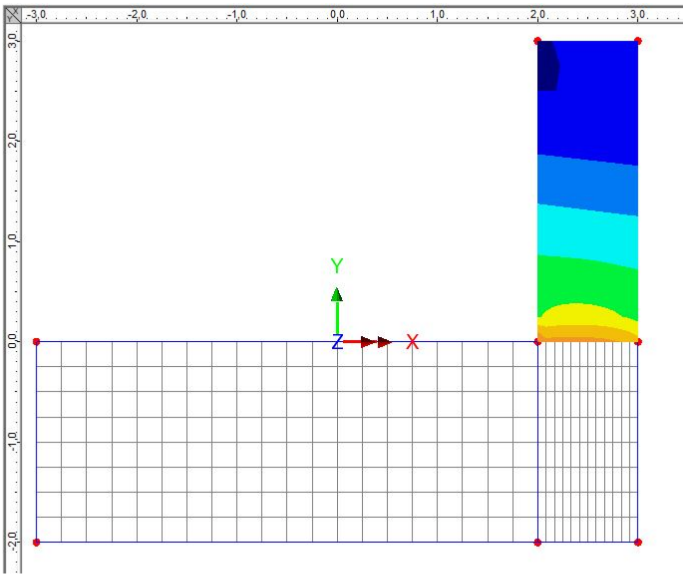


Figure B.1: Principal stress (S1) map of wall cross-section for thickness 1000 mm, casting length 20 m

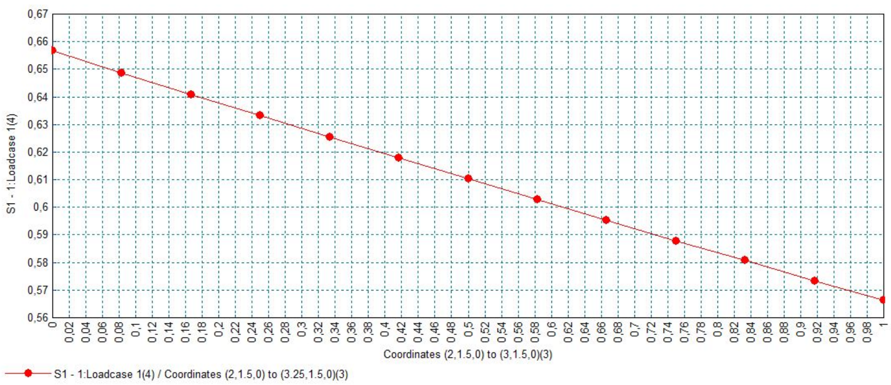
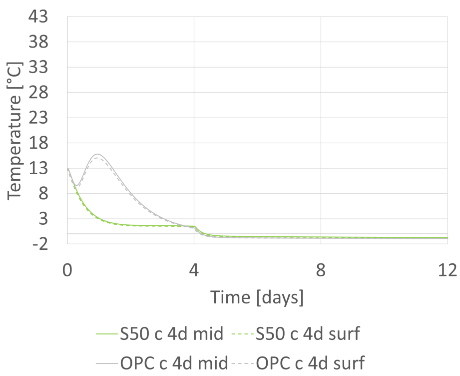


Figure B.2: Variation of principal stress (S1) on the critical level for thickness 1000 mm, casting length 20 m

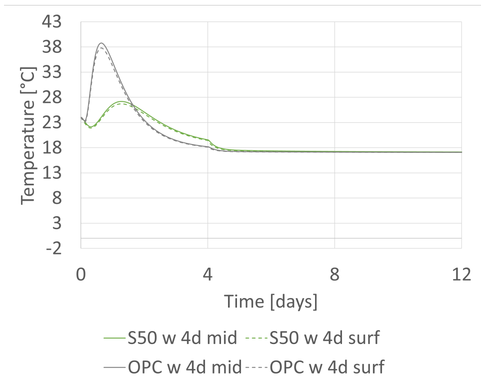
C

Results

C.1 Base variation

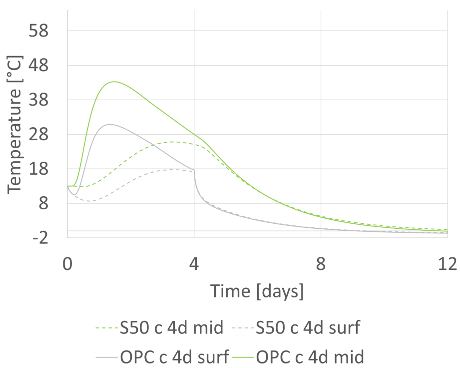


(a) Cold case

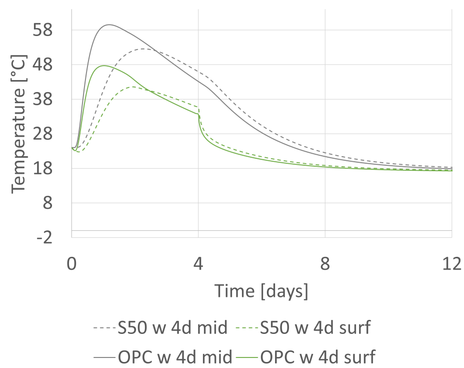


(b) Warm case

Figure C.1: The temperature development in critical points for S50 and OPC for wall thickness 250 mm

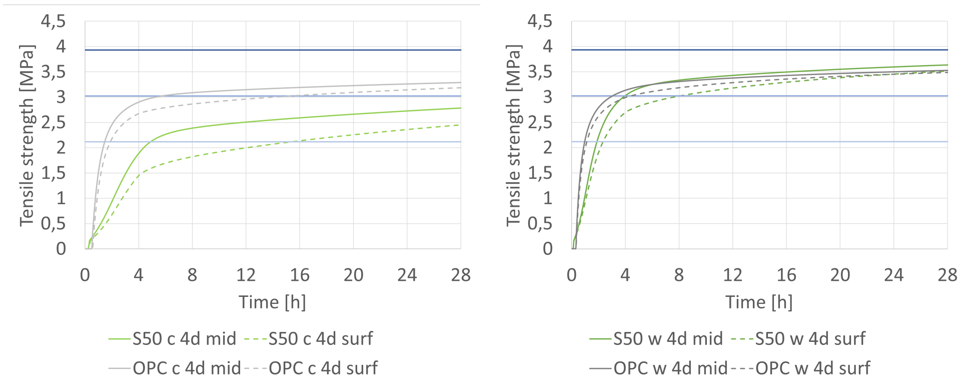


(a) Cold case



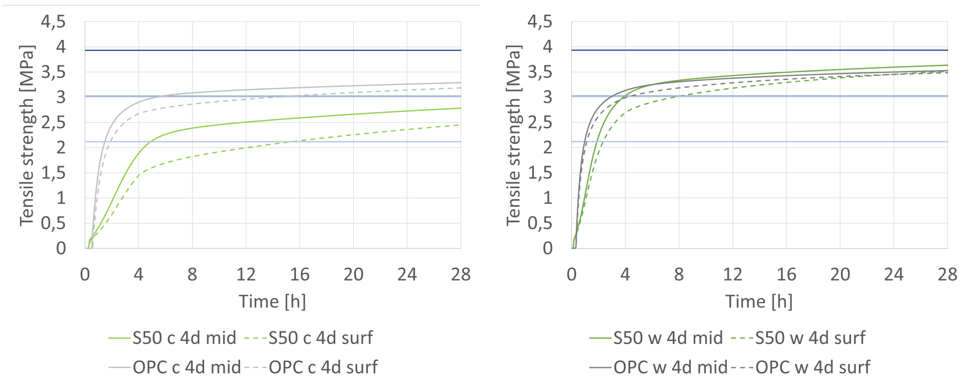
(b) Warm case

Figure C.2: The temperature development in critical points for S50 and OPC for wall thickness 1000 mm



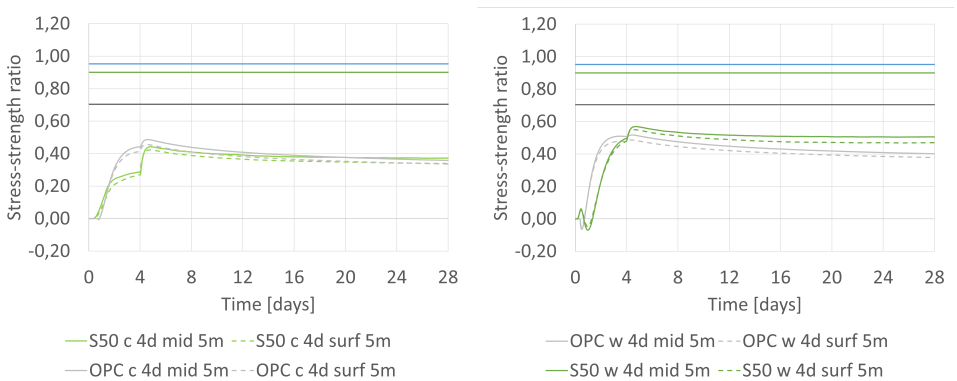
(a) Cold case **(b)** Warm case

Figure C.3: Tensile strength development in critical points for S50 and OPC for wall thickness 250 mm



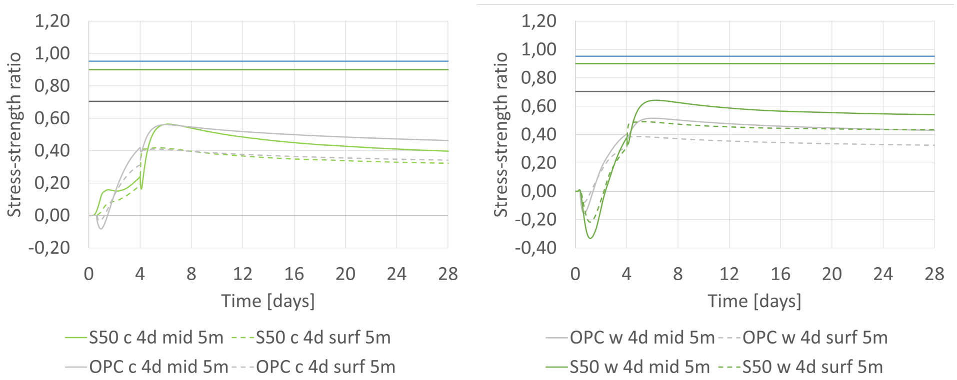
(a) Cold case **(b)** Warm case

Figure C.4: Tensile strength development in critical points for S50 and OPC for wall thickness 1000 mm



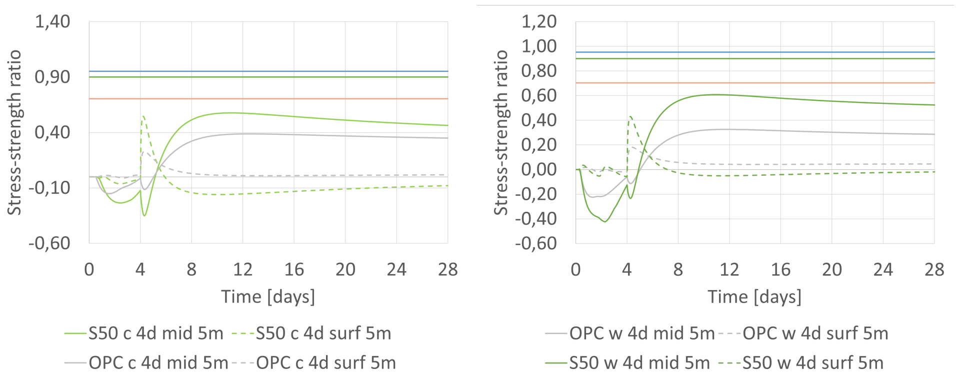
(a) Cold case **(b)** Warm case

Figure C.5: Stress strength development in critical points for S50 and OPC for wall thickness 250 mm, casting length 5



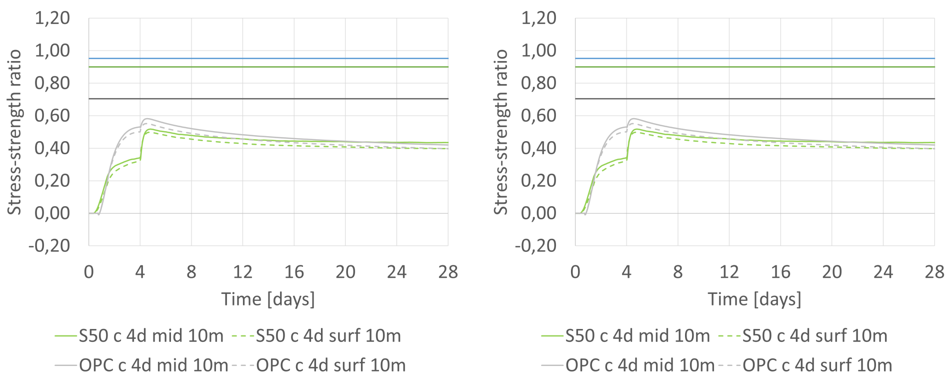
(a) Cold case **(b)** Warm case

Figure C.6: Stress strength development in critical points for S50 and OPC for wall thickness 500 mm, casting length 5



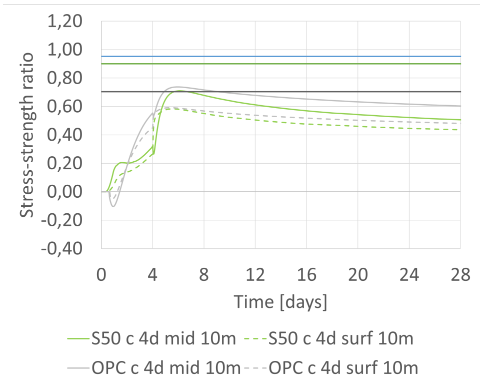
(a) Cold case **(b)** Warm case

Figure C.7: Stress strength development in critical points for S50 and OPC for wall thickness 1000 mm, casting length 5

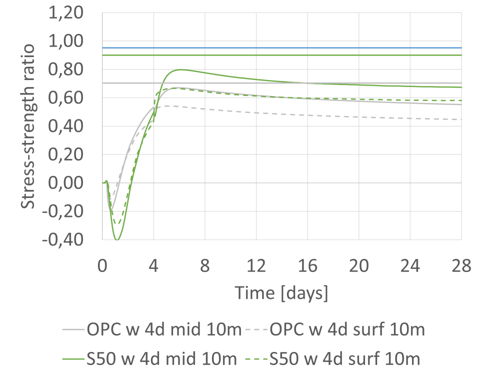


(a) Cold case **(b)** Warm case

Figure C.8: Stress strength development in critical points for S50 and OPC for wall thickness 250 mm, casting length 10

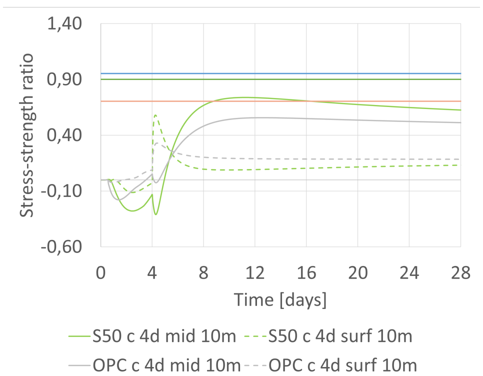


(a) Cold case

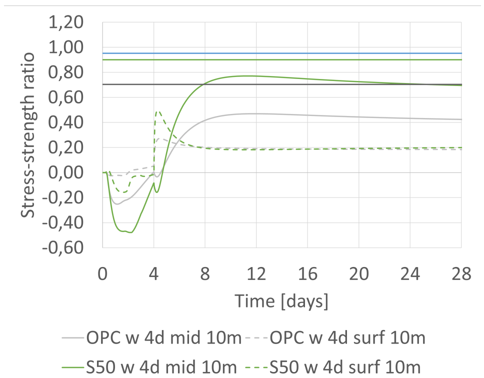


(b) Warm case

Figure C.9: Stress strength development in critical points for S50 and OPC for wall thickness 500 mm, casting length 10

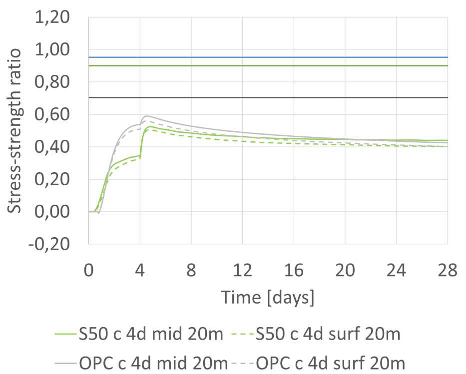


(a) Cold case

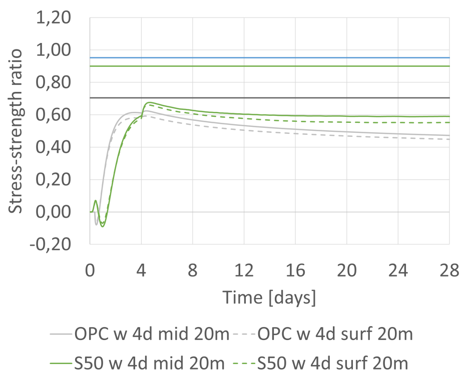


(b) Warm case

Figure C.10: Stress strength development in critical points for S50 and OPC for wall thickness 1000 mm, casting length 10



(a) Cold case



(b) Warm case

Figure C.11: Stress strength development in critical points for S50 and OPC for wall thickness 250 mm, casting length 20

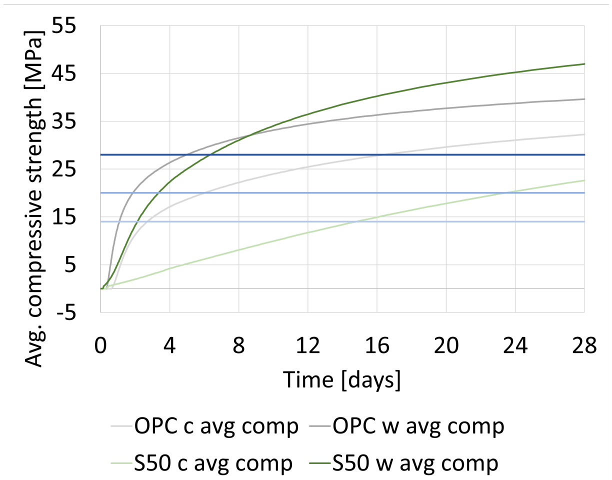


Figure C.13: Average compressive strength in wall for wall thickness 250

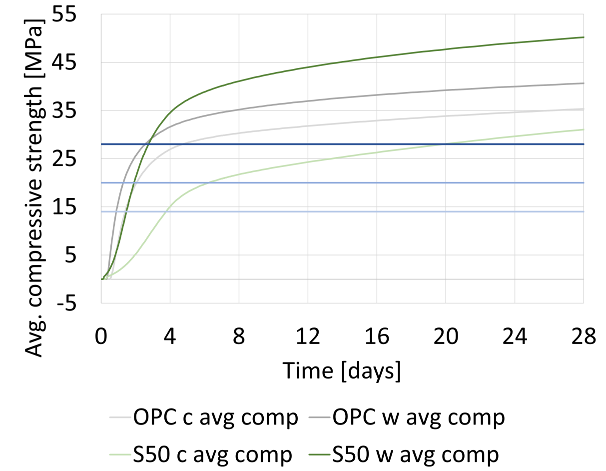
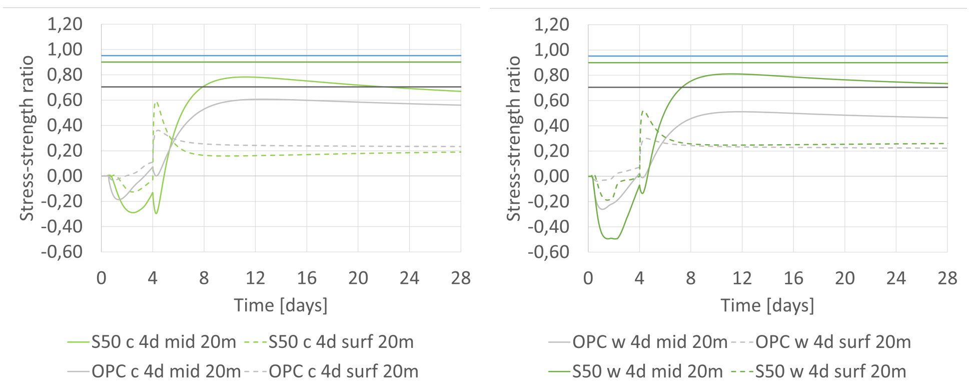


Figure C.14: Average compressive strength in wall for wall thickness 1000



(a) Cold case **(b)** Warm case

Figure C.12: Stress strength development in critical points for S50 and OPC for wall thickness 1000 mm, casting length 20

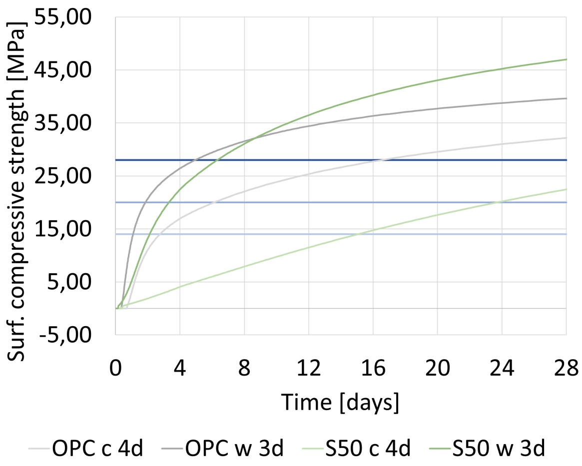


Figure C.15: Surface compressive strength in wall for wall thickness 250

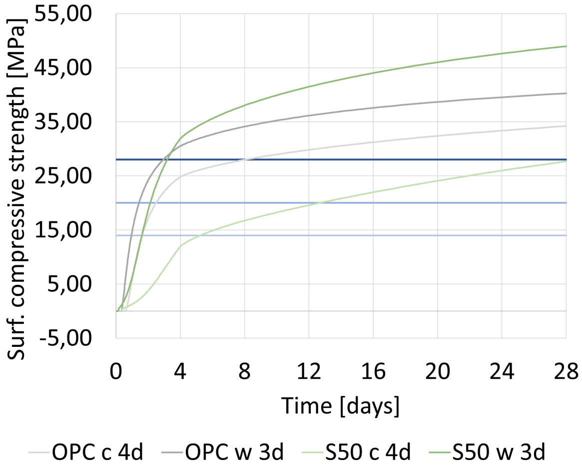


Figure C.16: Surface compressive strength in wall for wall thickness 1000

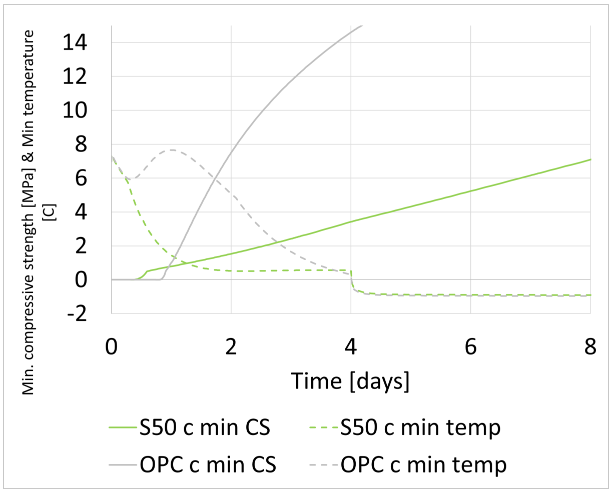


Figure C.17: Risk of early freezing in wall for wall thickness 250

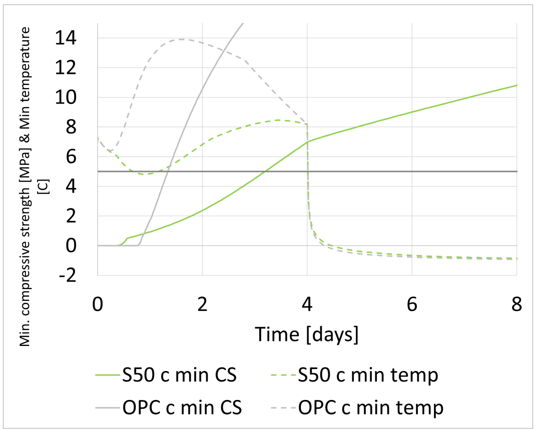
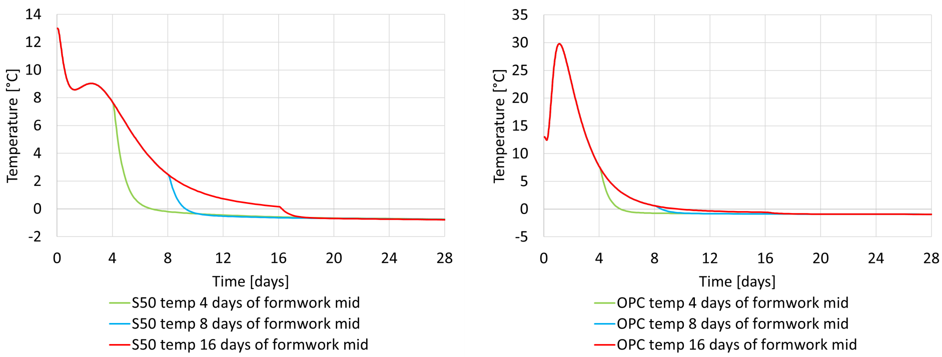


Figure C.18: Risk of early freezing in wall for wall thickness 1000

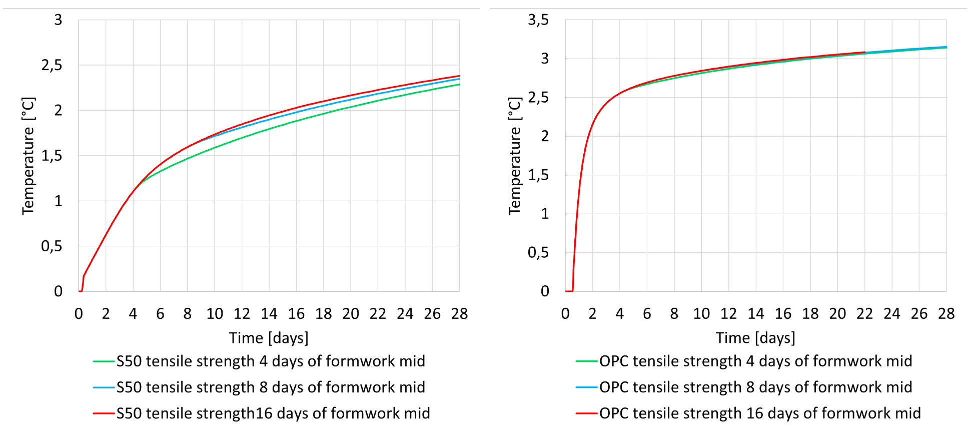
C.2 Study of risk reducing measures

C.2.1 Number of days with formwork



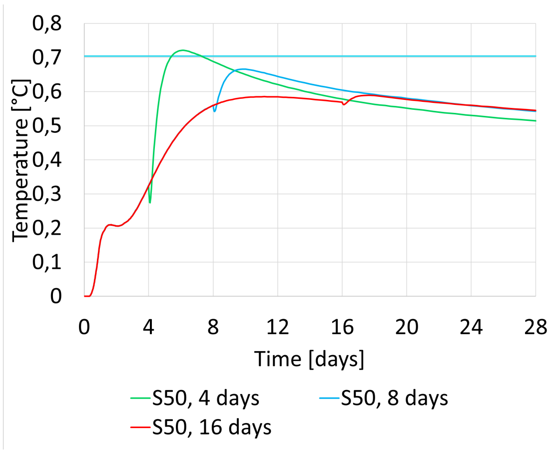
(a) S50 (b) OPC

Figure C.19: Temperature variation with 4, 8 and 16 days of formwork

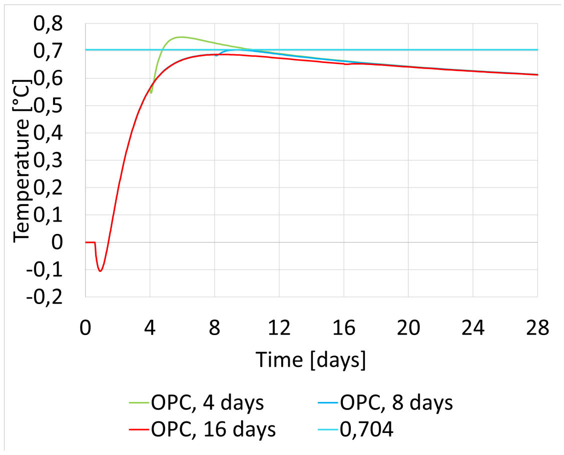


(a) S50 (b) OPC

Figure C.20: Tensile strength variation with 4, 8 and 16 days of formwork

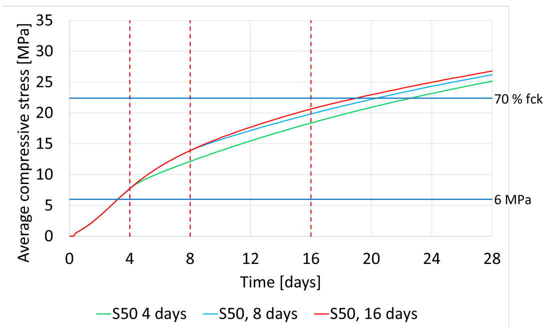


(a) S50

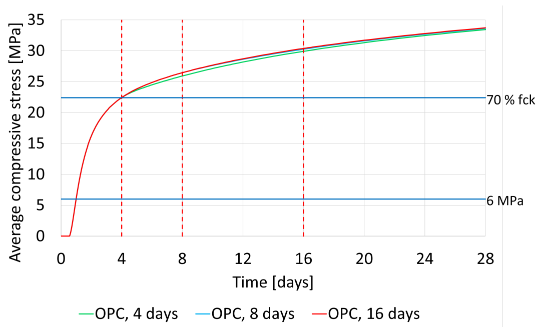


(b) OPC

Figure C.21: Stress strength ratio with 4, 8 and 16 days of formwork

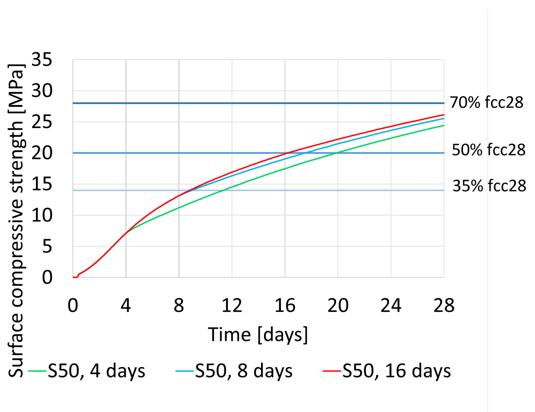


(a) S50

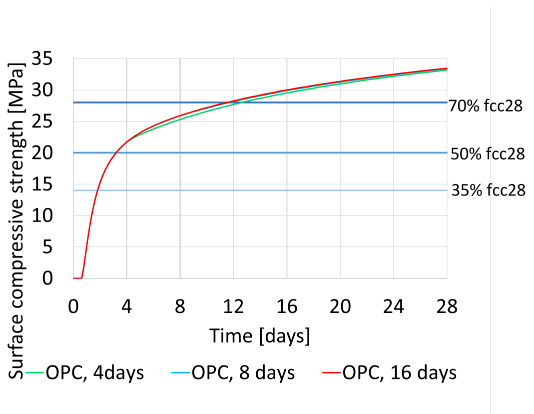


(b) OPC

Figure C.22: Average compressive strength with 4, 8 and 16 days of formwork

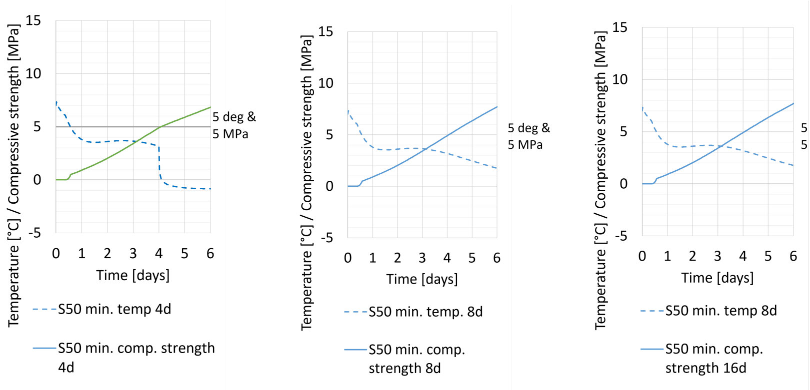


(a) S50



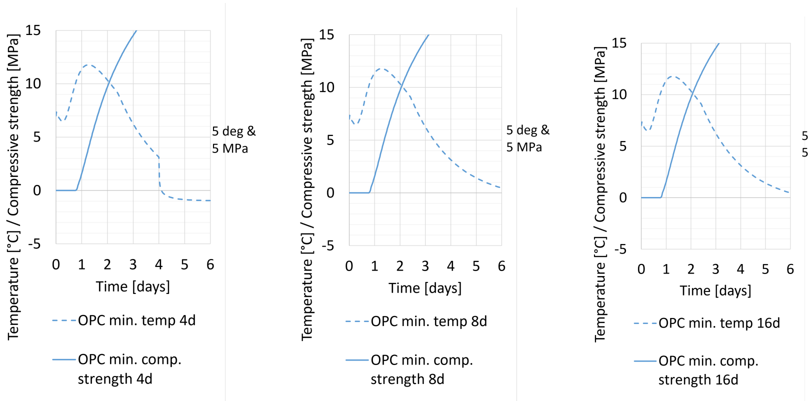
(b) OPC

Figure C.23: Surface compressive strength with 4, 8 and 16 days of formwork



(a) 4 days of formwork **(b)** 8 days of formwork **(c)** 16 days of formwork

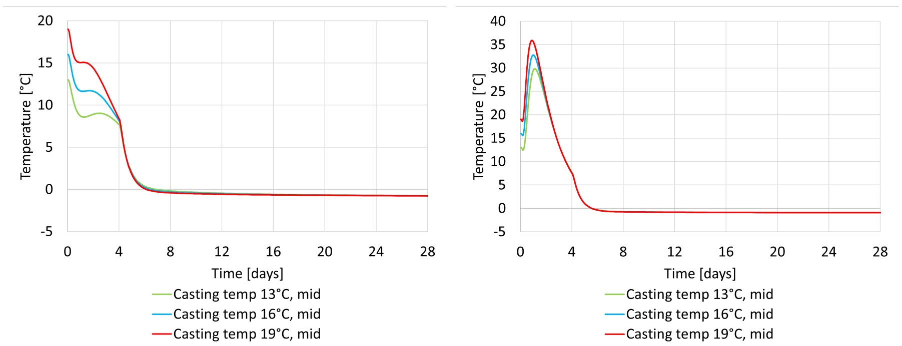
Figure C.24: Risk of freezing by min. temp. and min. compr. strength for S50



(a) 4 days of formwork **(b)** 8 days of formwork **(c)** 16 days of formwork

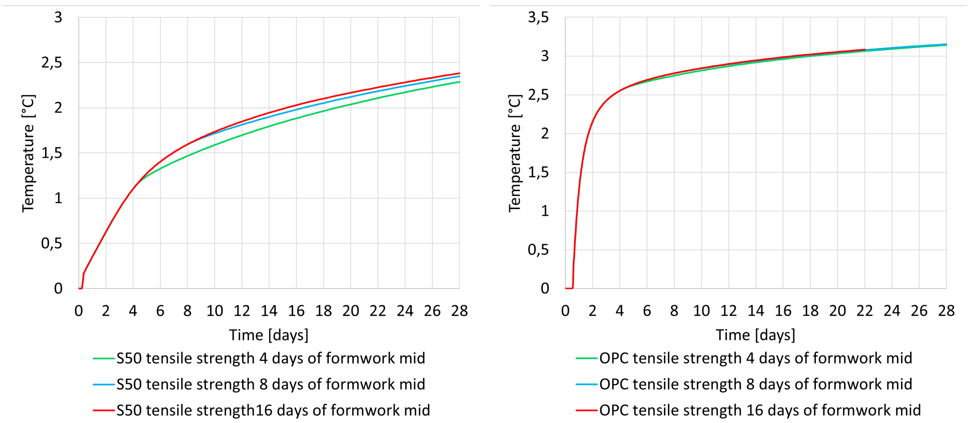
Figure C.25: Risk of freezing by min. temp. and min. compr. strength for OPC

C.2.2 Casting temperature



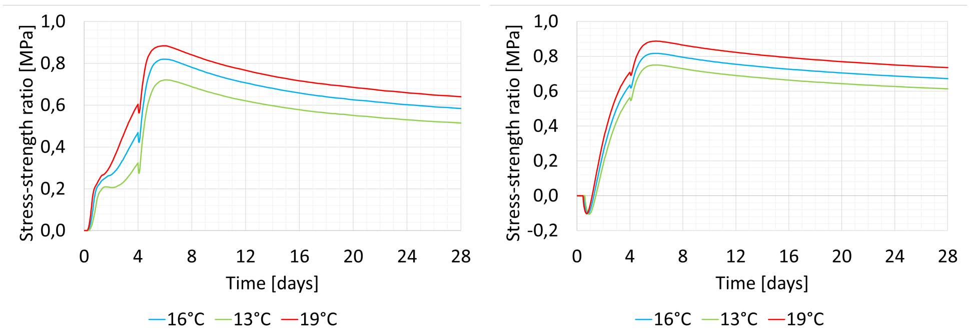
(a) S50 **(b)** OPC

Figure C.26: Temp. variation for with T_{cast} 13, 16 and 19 °C



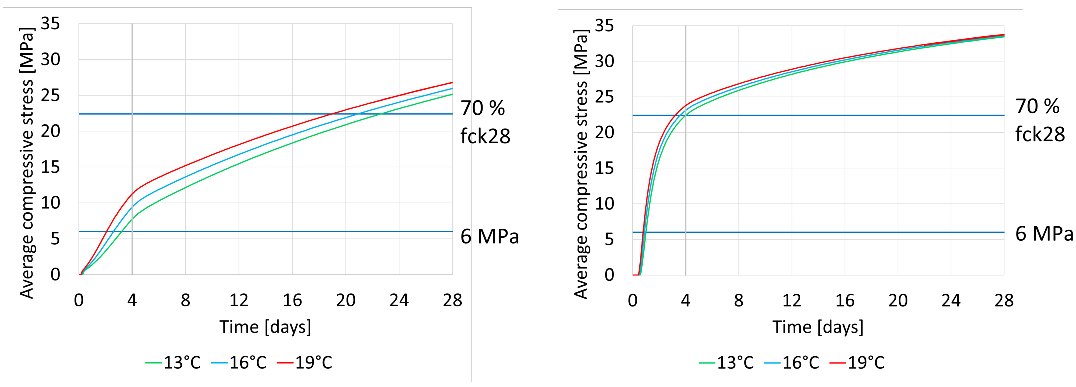
(a) S50 **(b)** OPC

Figure C.27: Tensile strength variation for with T_{cast} 13, 16 and 19 °C



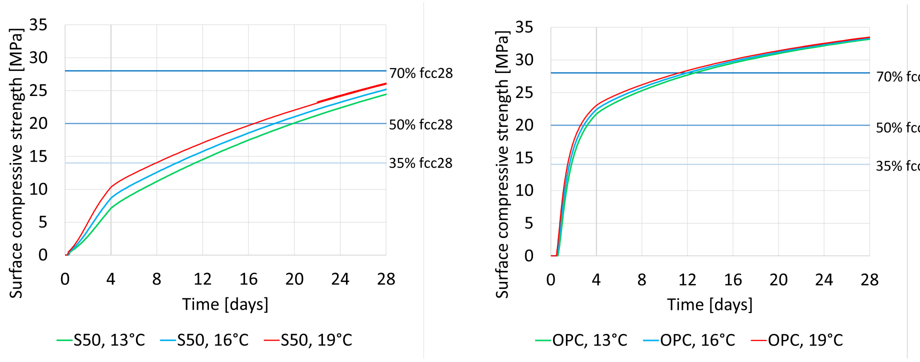
(a) S50 **(b)** OPC

Figure C.28: Stress strength ratio with T_{cast} 13, 16 and 19 °C



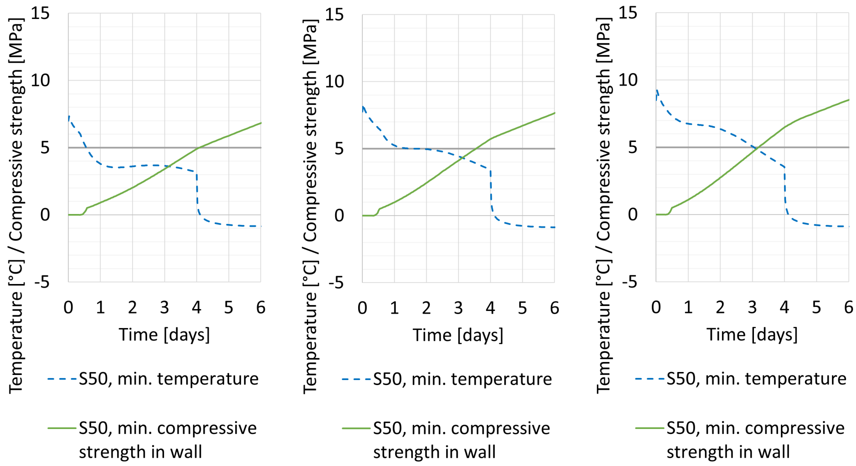
(a) S50 **(b)** OPC

Figure C.29: Average compressive strength for a) S50 and b) OPC with 13, 16 and 19 °C casting temperature



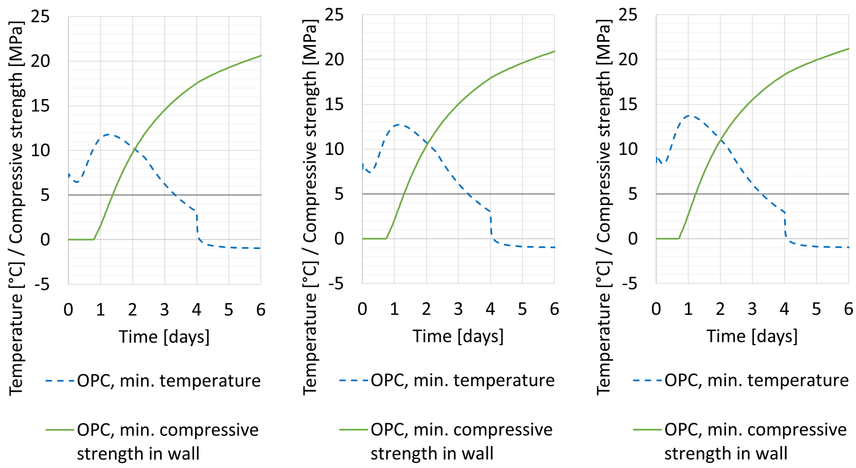
(a) S50 **(b)** OPC

Figure C.30: Surface compressive strength with T_{cast} 13, 16 and 19°C



(a) T_{cast} 13°C **(b)** T_{cast} 16°C **(c)** T_{cast} 19°C

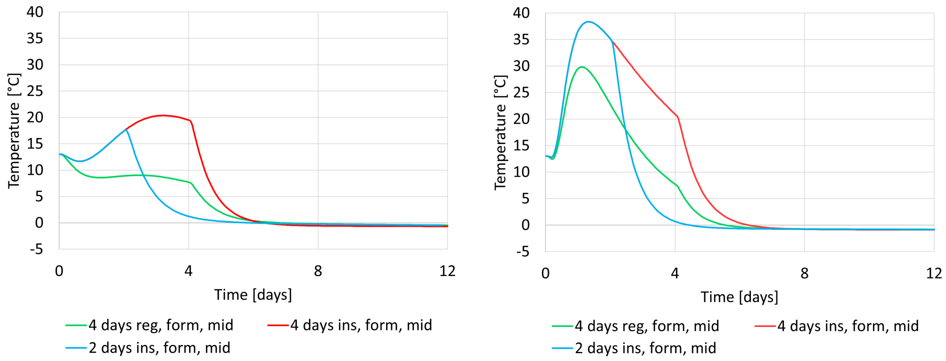
Figure C.31: Risk of freezing by min. temp. and min. compr. strength for S50



(a) T_{cast} 13°C **(b)** T_{cast} 16°C **(c)** T_{cast} 19°C

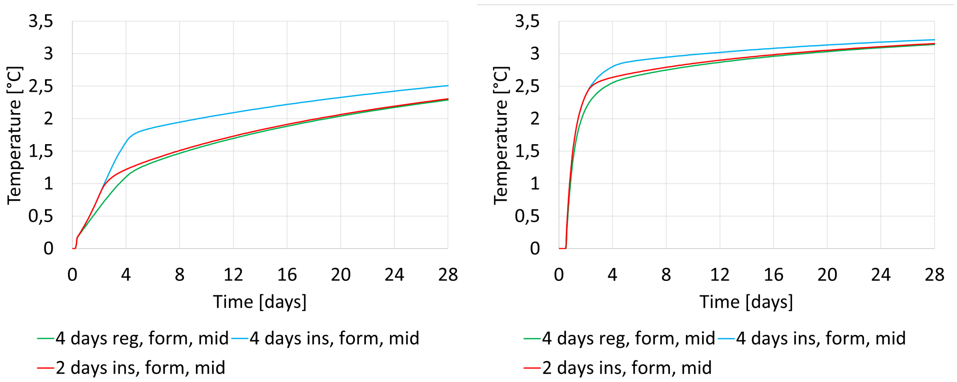
Figure C.32: Risk of freezing by min. temp. and min. compr. strength for OPC

C.2.3 Formwork insulation



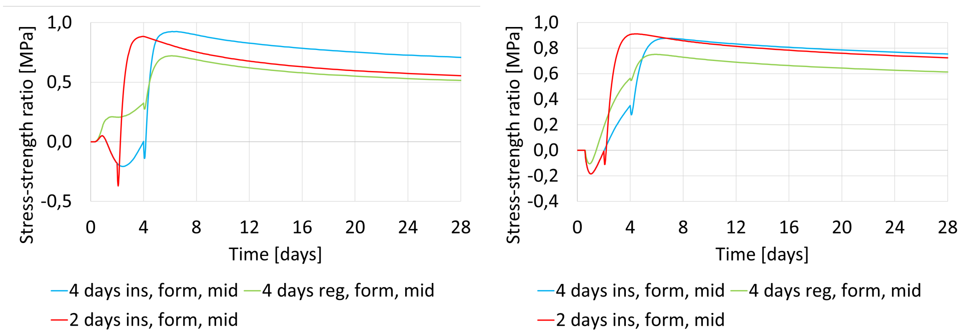
(a) (b)

Figure C.33: Temperature variation for a) S50 and b) OPC for 4 days with regular form, 2 days with insulated form and 4 days with insulated form



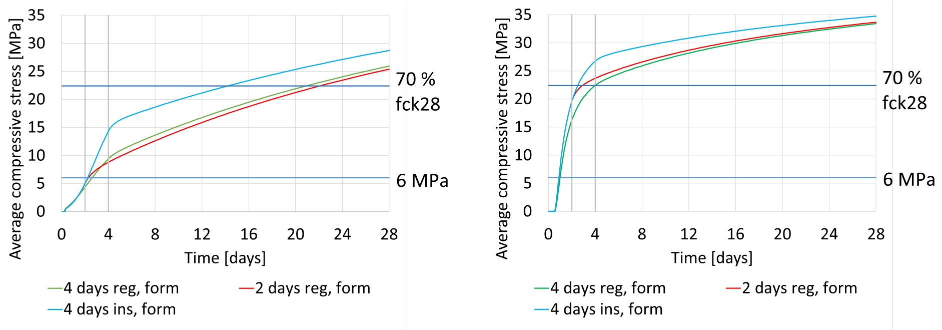
(a) (b)

Figure C.34: Tensile strength variation for a) S50 and b) OPC for 4 days with regular form, 2 days with insulated form and 4 days with insulated form



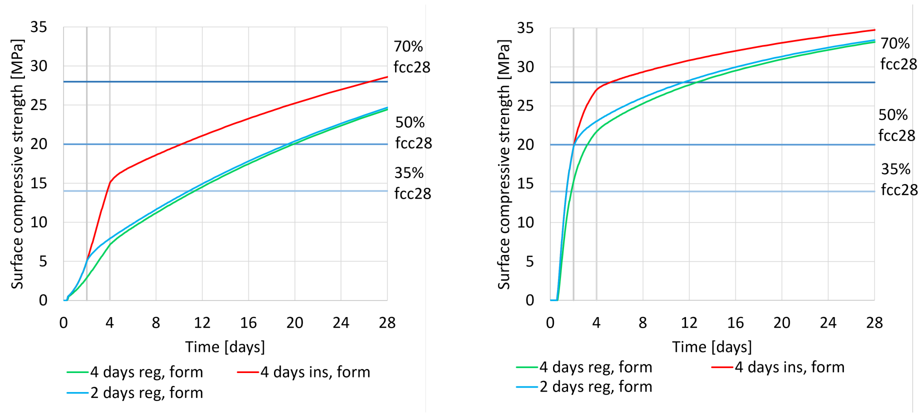
(a) (b)

Figure C.35: Stress strength ratio for a) S50 and b) OPC for 4 days with regular form, 2 days with insulated form and 4 days with insulated form



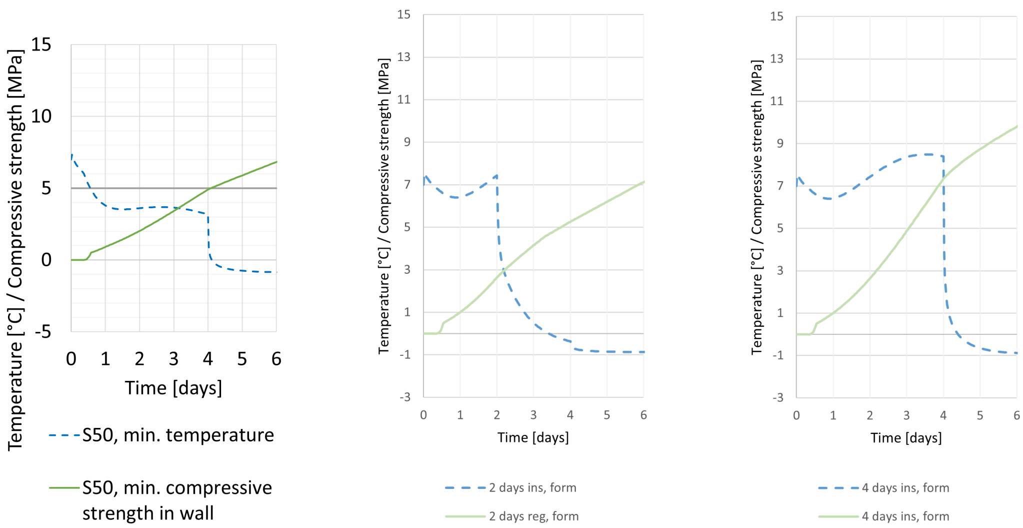
(a) S50 **(b)** OPC

Figure C.36: Average compressive strength for a) S50 and b) OPC for 4 days with regular form, 2 days with insulated form and 4 days with insulated form



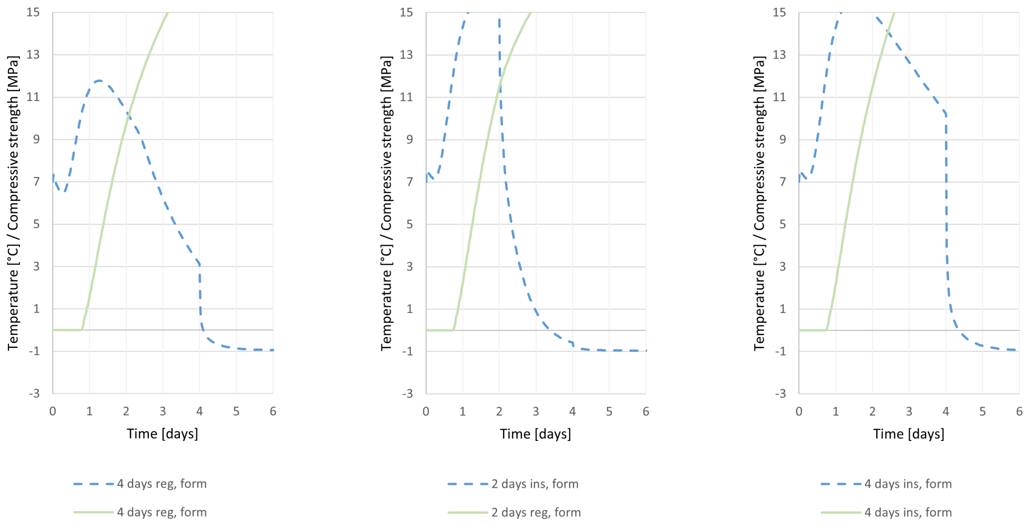
(a) S50 **(b)** OPC

Figure C.37: Surface compressive strength for a) S50 and b) OPC for 4 days with regular form, 2 days with insulated form and 4 days with insulated form



(a) 4 days, regular form **(b)** 2 days, insulated form **(c)** 4 days, insulated form

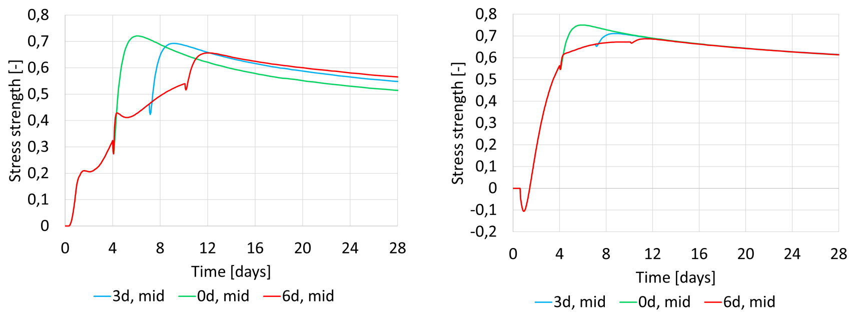
Figure C.38: Risk of freezing by min. temp. and min. compr. strength for S50



(a) 4 days regular form **(b)** 2 days insulated form **(c)** 4 days insulated form

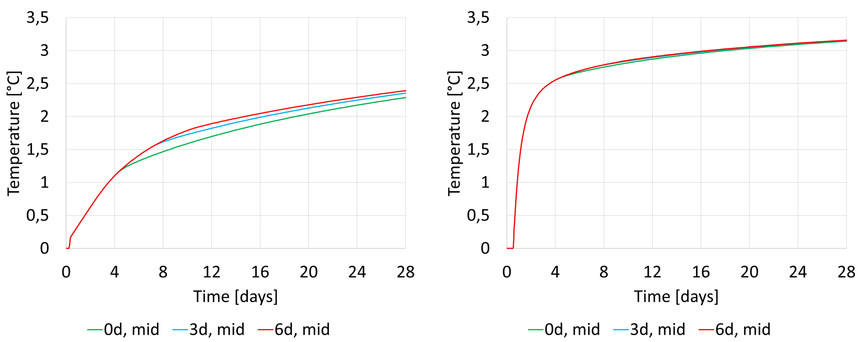
Figure C.39: Risk of freezing by min. temp. and min. compr. strength for OPC

C.2.4 Replacement coverage



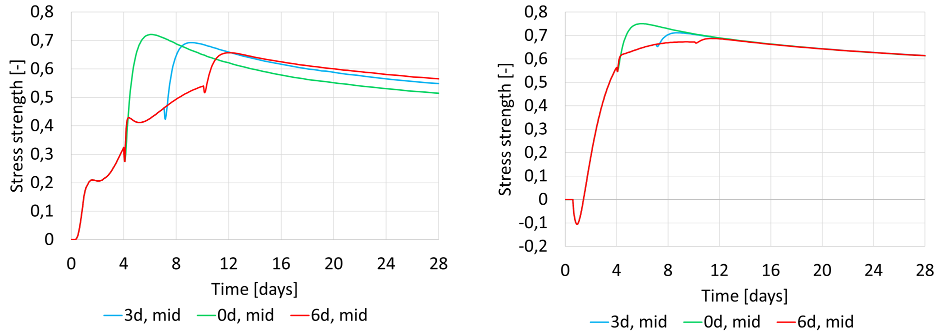
(a) S50 **(b)** OPC

Figure C.40: Temperature variation for no replacement coverage, 3 days and 6 days with replacement coverage



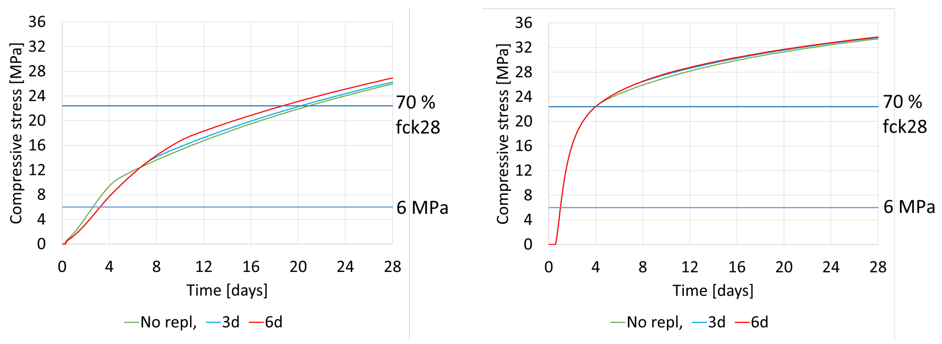
(a) S50 **(b)** OPC

Figure C.41: Tensile strength variation for no replacement coverage, 3 days and 6 days with replacement coverage



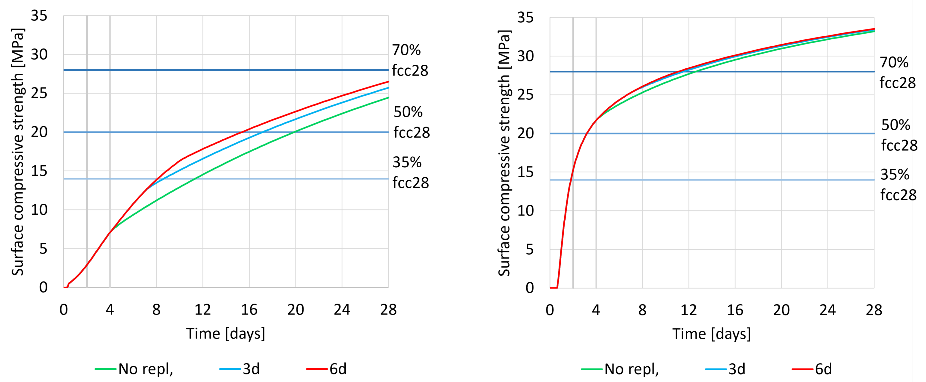
(a) S50 (b) OPC

Figure C.42: Stress strength ratio for no replacement coverage, 3 days and 6 days with replacement coverage



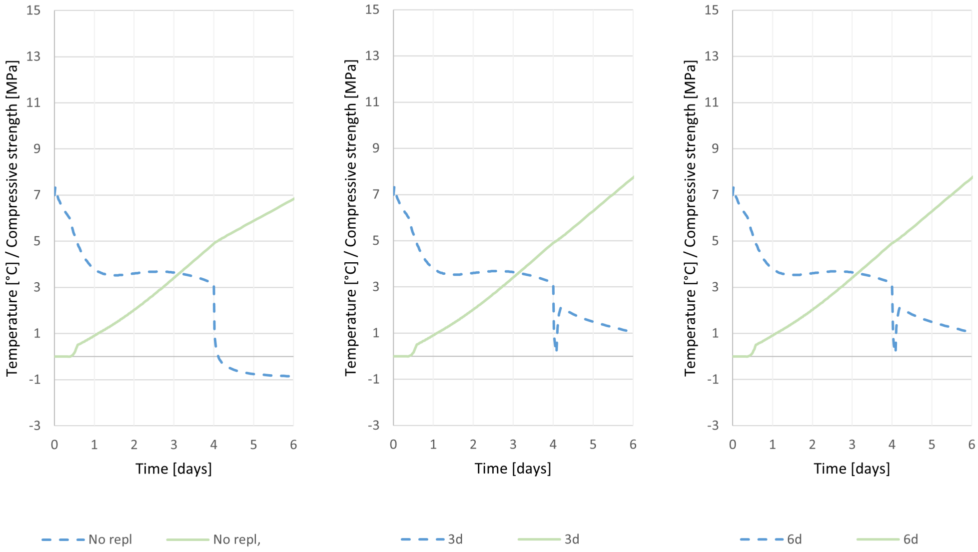
(a) S50 (b) OPC

Figure C.43: Average compressive strength for no replacement coverage, 3 days and 6 days with replacement coverage



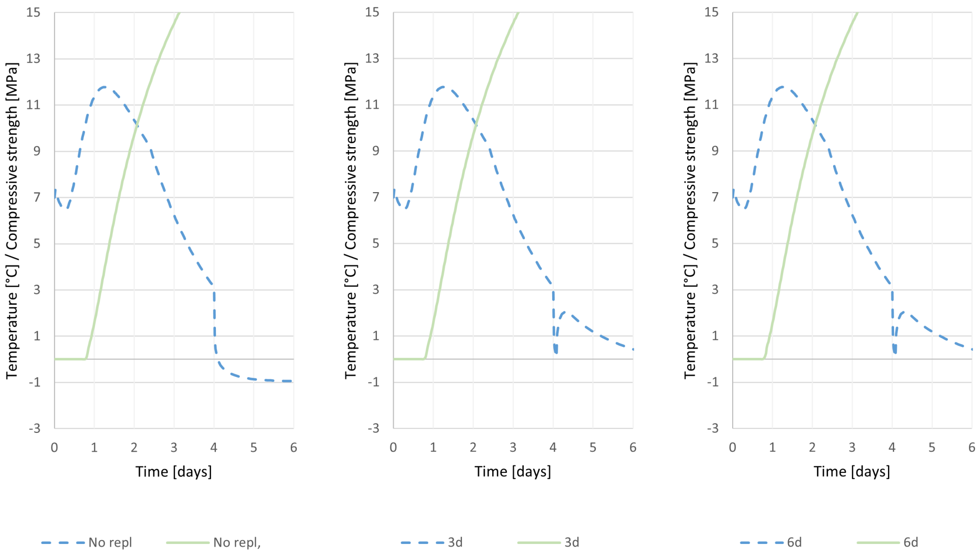
(a) S50 (b) OPC

Figure C.44: Surface compressive strength for no replacement coverage, 3 days and 6 days with replacement coverage



(a) No replacement coverage **(b)** 3 days replacement coverage **(c)** 6 days replacement coverage

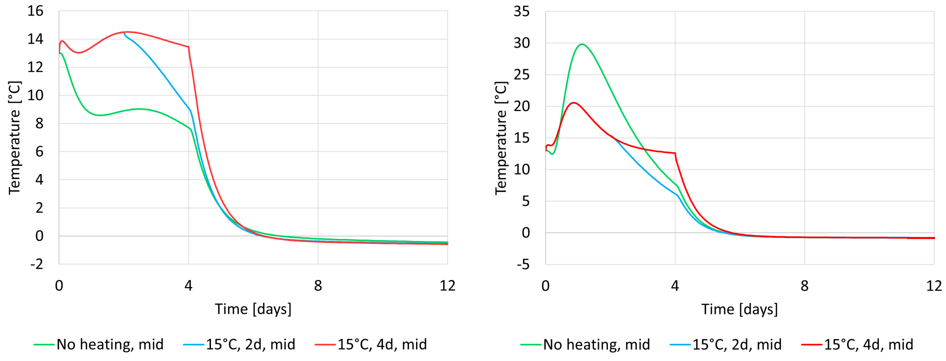
Figure C.45: Risk of freezing by min. temp. and min. compr. strength for S50



(a) No replacement coverage **(b)** 3 days replacement coverage **(c)** 6 days replacement coverage

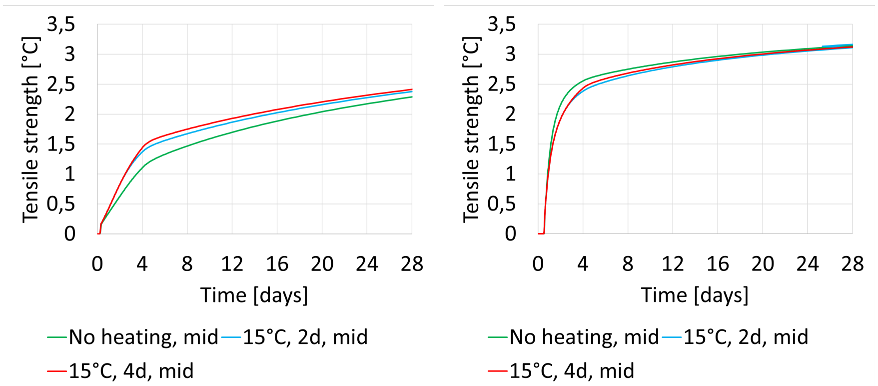
Figure C.46: Risk of freezing by min. temp. and min. compr. strength for OPC

C.2.5 Water regulating pipes



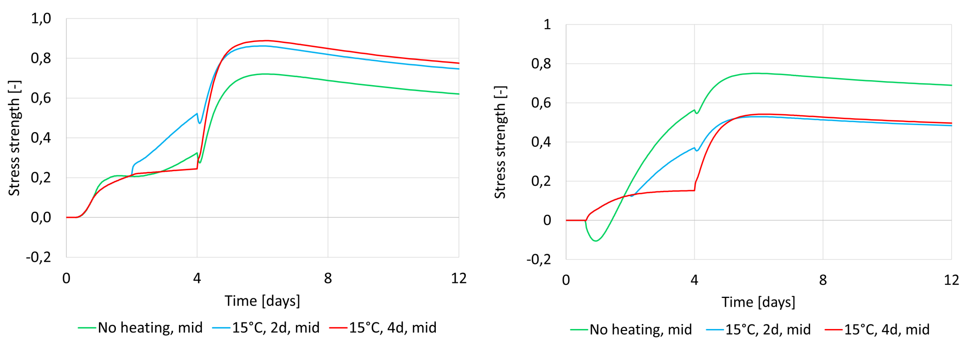
(a) (b)

Figure C.47: Temperature variation for a) S50 and b) OPC for no pipes, 2 days with 15°C and 4 days with 15°C



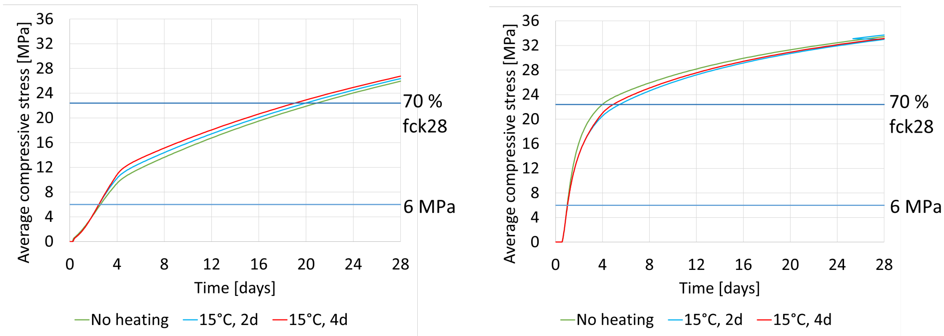
(a) (b)

Figure C.48: Tensile strength variation for a) S50 and b) OPC for for no pipes, 2 days with 15°C and 4 days with 15°C



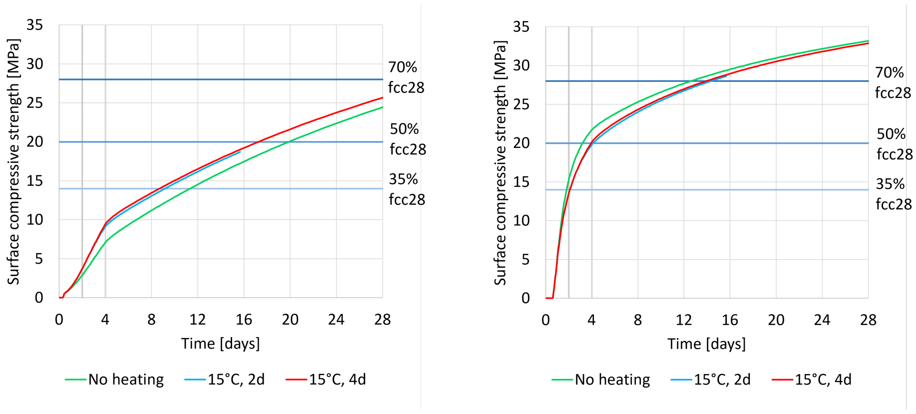
(a) (b)

Figure C.49: Stress strength ratio for a) S50 and b) OPC for no pipes, 2 days with 15°C and 4 days with 15°C



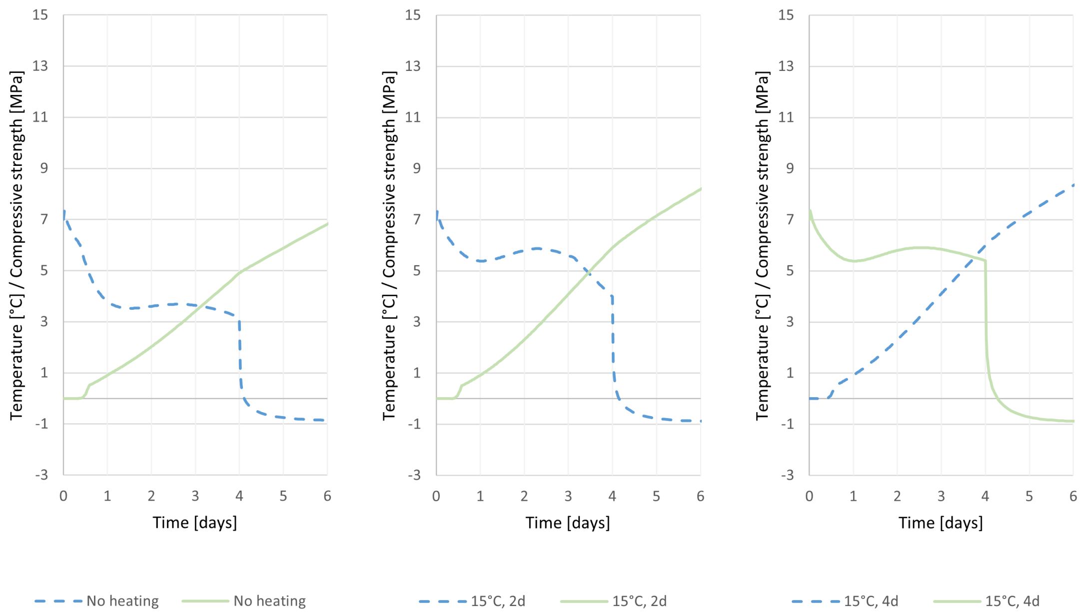
(a) S50 **(b)** OPC

Figure C.50: Average compressive strength for a) S50 and b) OPC for no pipes, 2 days with 15°C and 4 days with 15°C



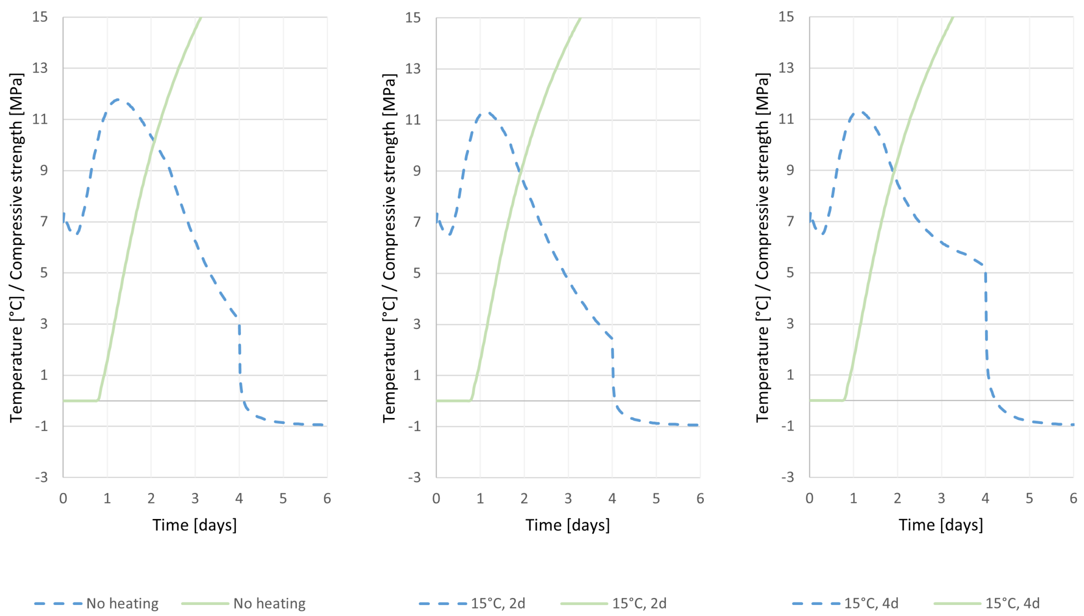
(a) S50 **(b)** OPC

Figure C.51: Surface compressive strength for a) S50 and b) OPC for no pipes, 2 days with 15°C and 4 days with 15°C



(a) No heating **(b)** 2 days with 15°C **(c)** 4 days with 15°C

Figure C.52: Risk of freezing by min. temperature and min. compressive strength in wall for S50

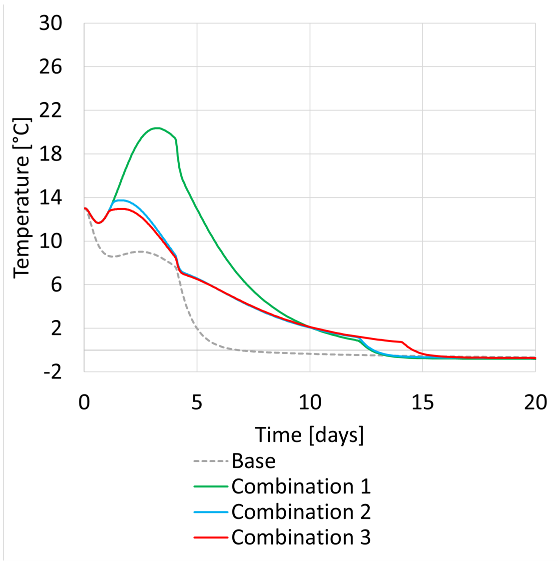


(a) No heating **(b)** 2 days with 15°C **(c)** 4 days with 15°C

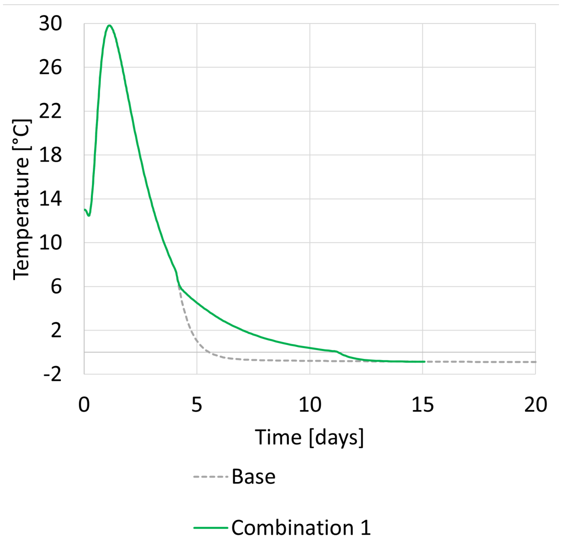
Figure C.53: Risk of freezing by min. temperature and min. compressive strength in wall for OPC

C.3 Combination of measures to meet a deadline

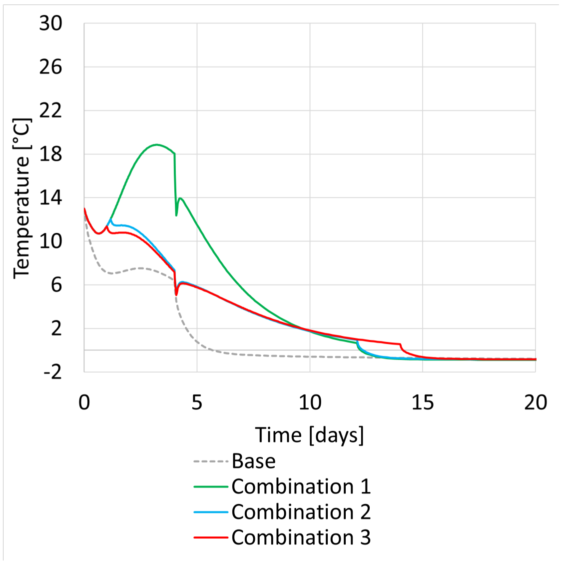
C.3.1 4 days



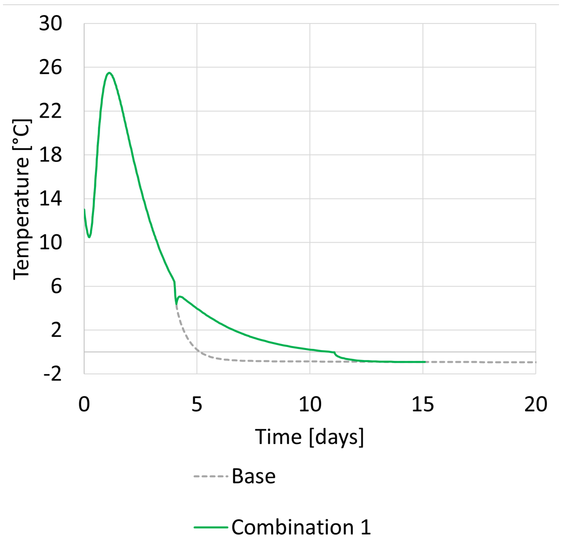
(a) S50



(b) OPC

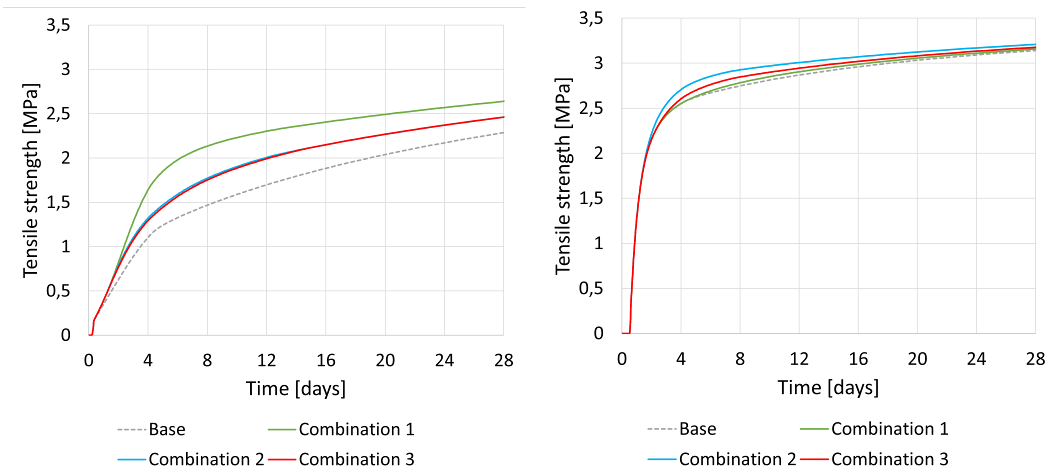


(c) OPC



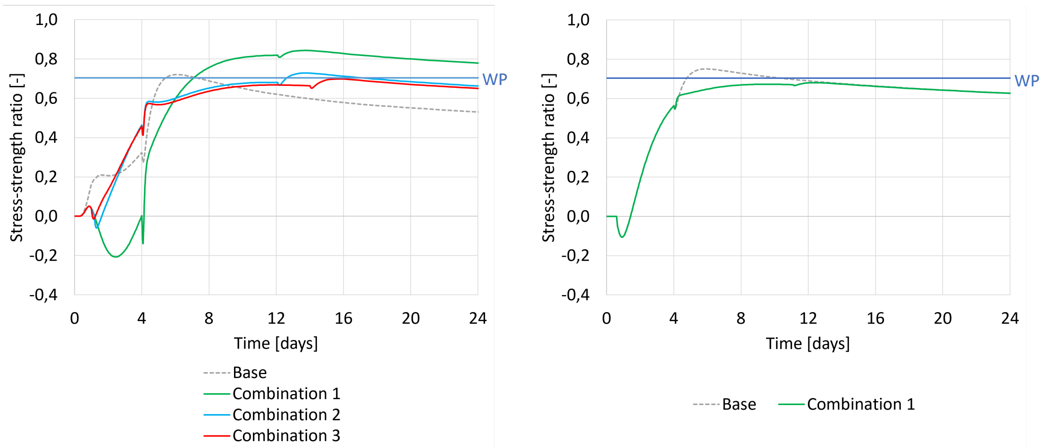
(d) OPC

Figure C.54: Temperature development for different combinations of measures, four-day deadline

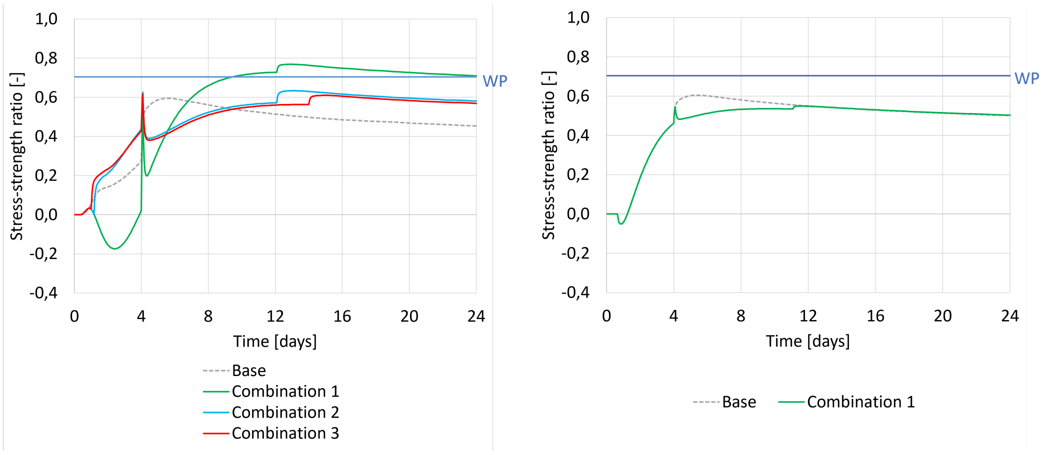


(a) S50 **(b)** OPC

Figure C.55: Tensile strength development for different combinations of measures, four-day deadline

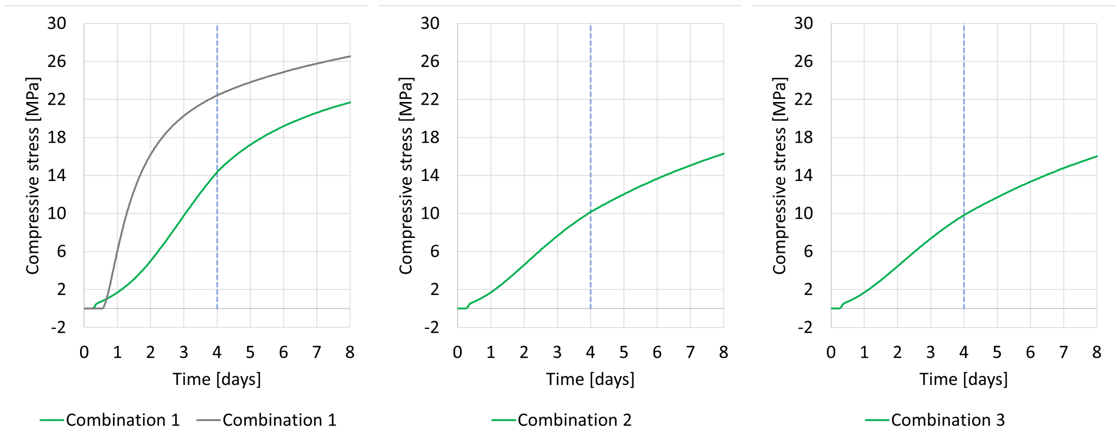


(a) S50 mid **(b)** OPC mid



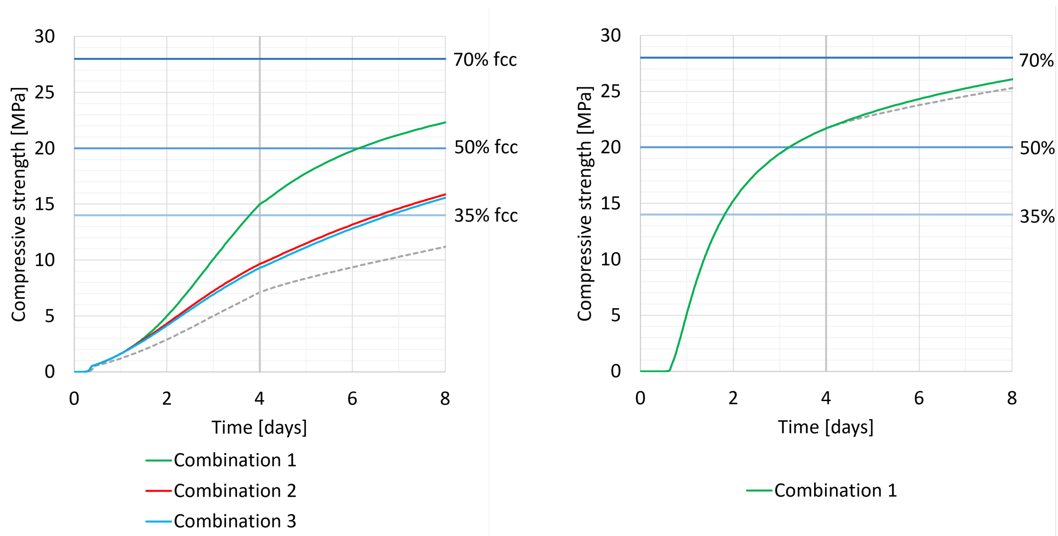
(c) S50 surf **(d)** OPC surf

Figure C.56: Stress strength ratio for different combinations of measures for the S50 and OPC concrete, four-day deadline



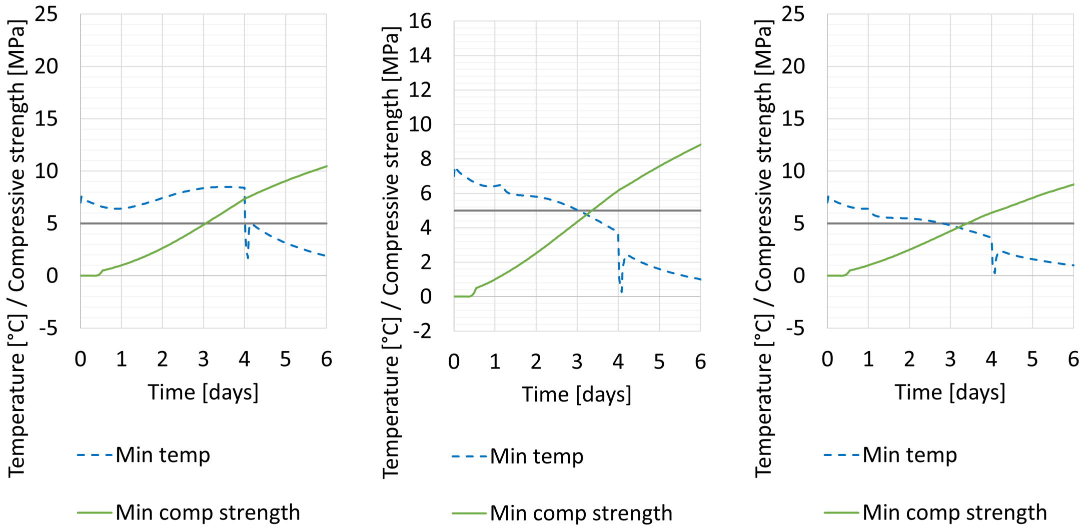
(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

Figure C.57: Average compressive strength development for different combinations of measures for the S50 and OPC concrete, four-day deadline



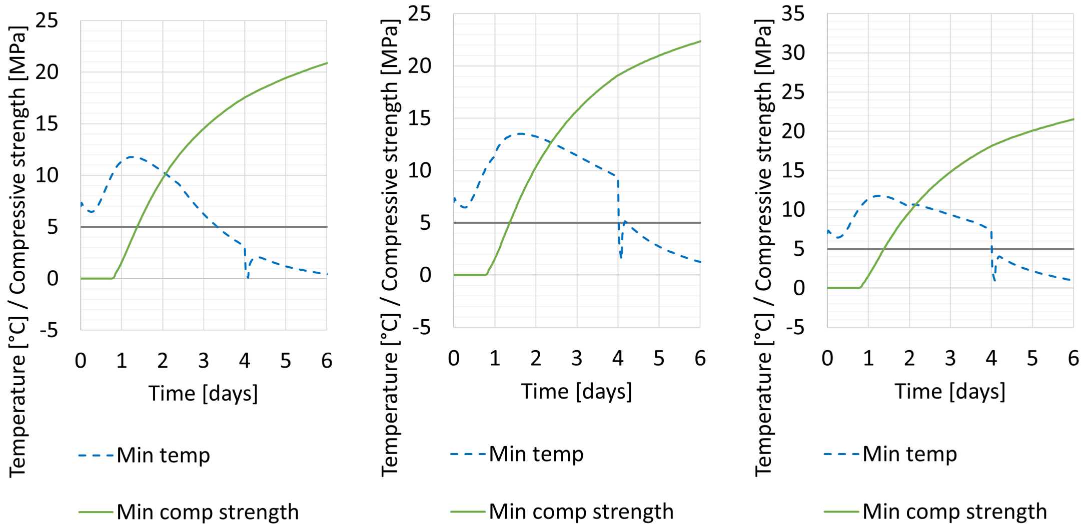
(a) S50 **(b)** OPC

Figure C.58: Surface compressive strength for different combinations of measures, four-day deadline



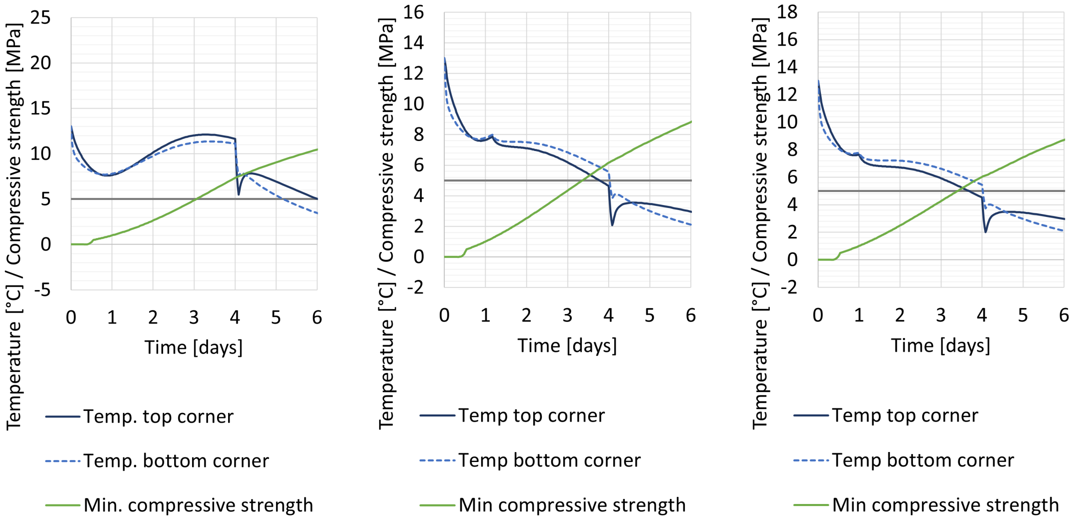
(a) Combination 1 (b) Combination 2 (c) Combination 3

Figure C.59: Risk of freezing by min temperature and min compressive strength for S50 concrete, four-day deadline



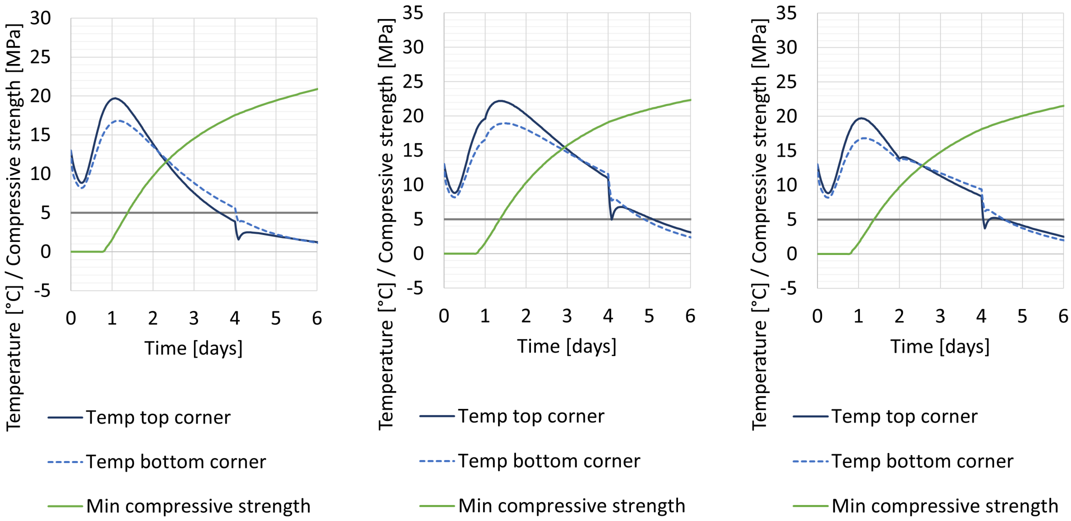
(a) Combination 1 (b) Combination 2 (c) Combination 3

Figure C.60: Risk of freezing by min temperature and min compressive strength for OPC concrete, four-day deadline



(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

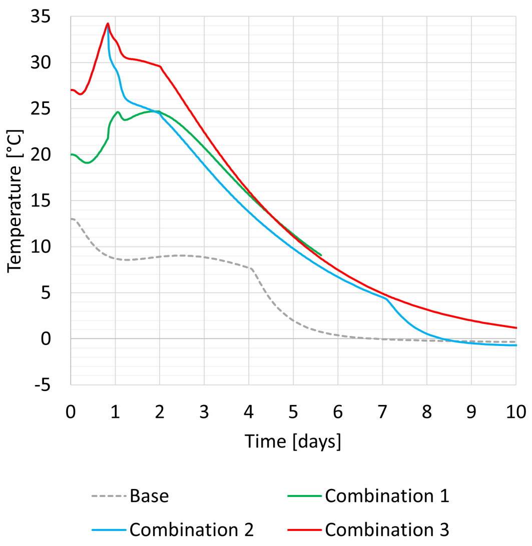
Figure C.61: Risk of freezing by temperature in top and bottom corner, and min compressive strength for S50 concrete, four-day deadline



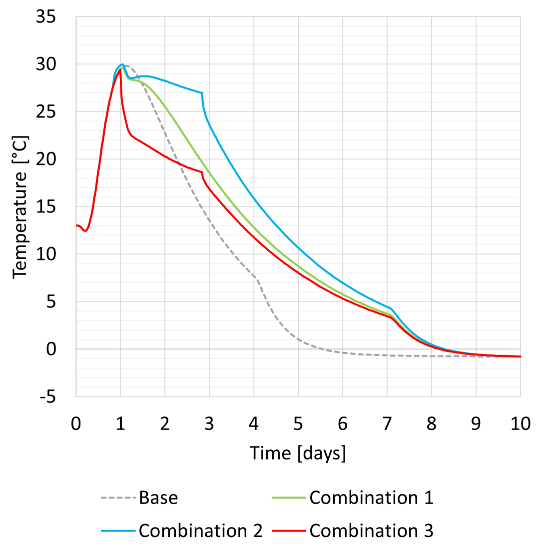
(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

Figure C.62: Risk of freezing by temperature in top and bottom corner, and min compressive strength for OPC concrete, four-day deadline

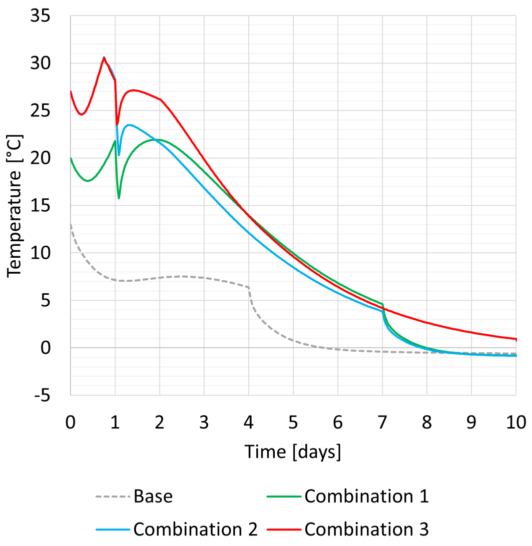
C.3.2 1 day



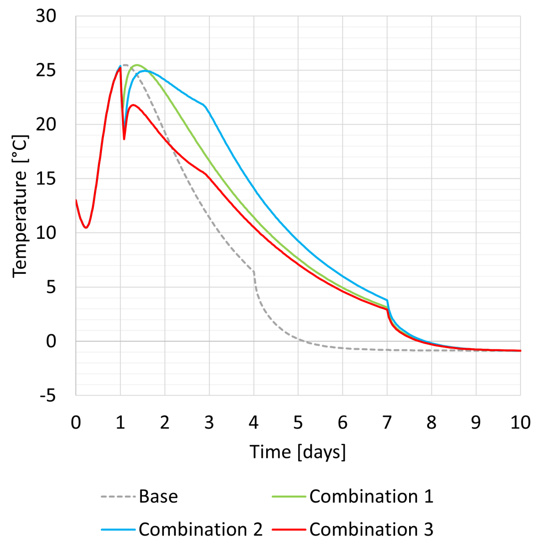
(a) S50 mid



(b) OPC mid

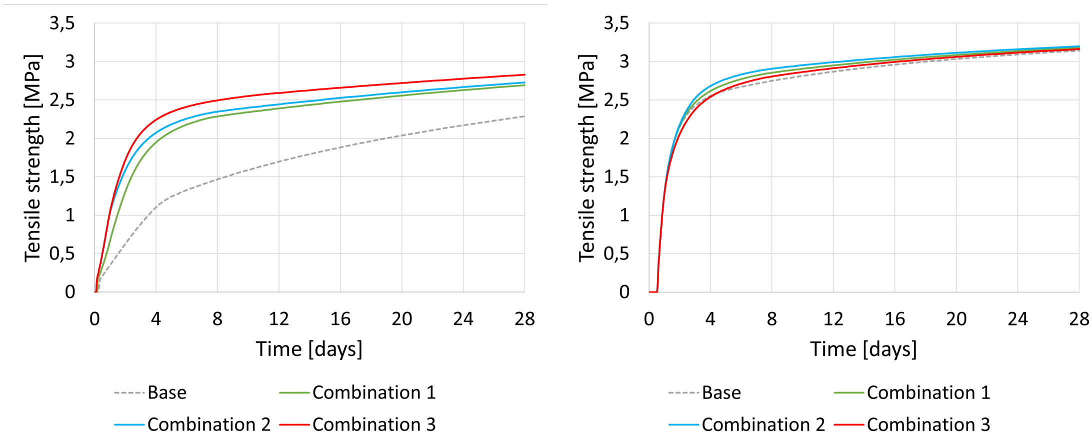


(c) S50 surf



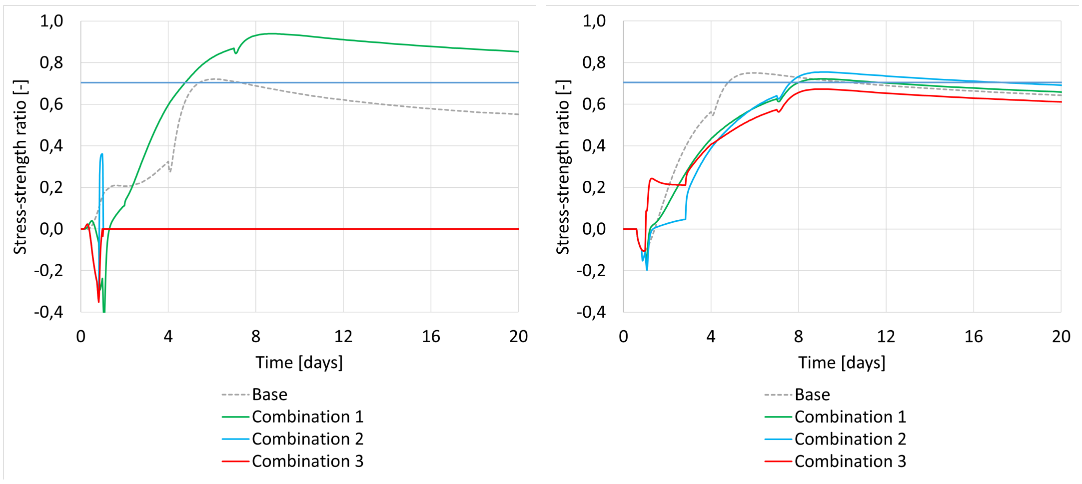
(d) OPC surf

Figure C.63: Temperature development for different combinations of measures, one-day deadline

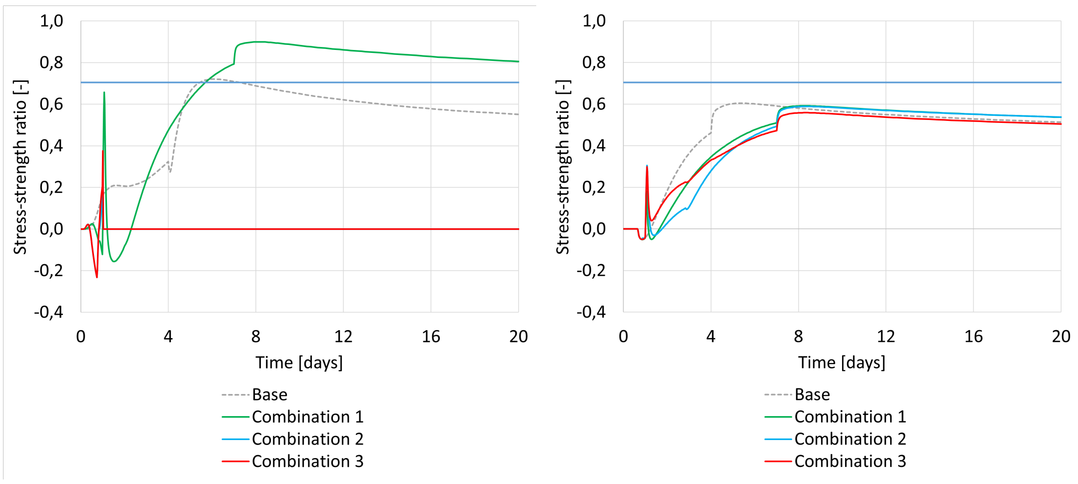


(a) S50 (b) OPC

Figure C.64: Tensile strength development for different combinations of measures for S50 and OPC concrete, one-day deadline

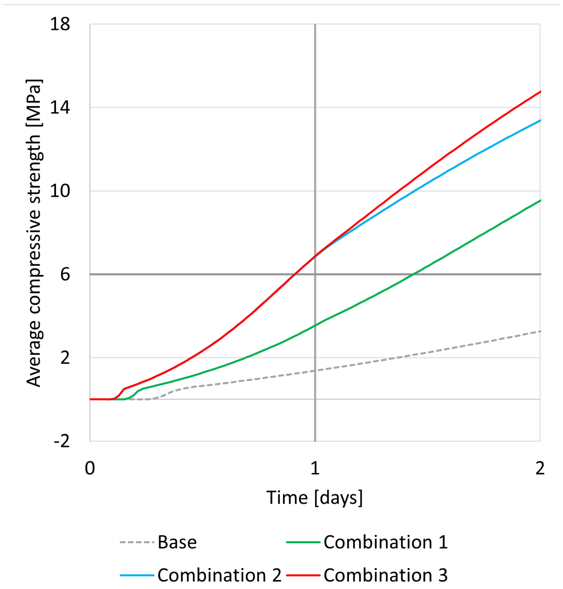


(a) S50 mid (b) OPC mid

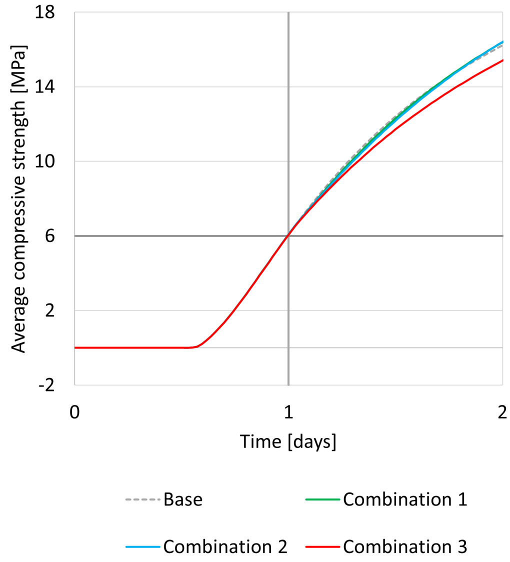


(c) S50 surf (d) OPC surf

Figure C.65: Stress strength ratio for different combinations of measures for the S50 and OPC concrete, one-day deadline

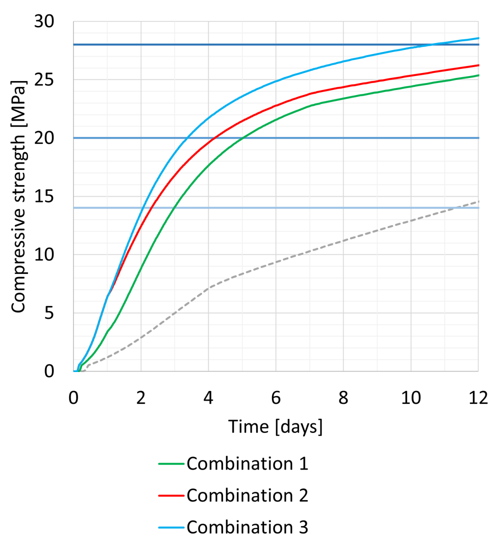


(a) S50

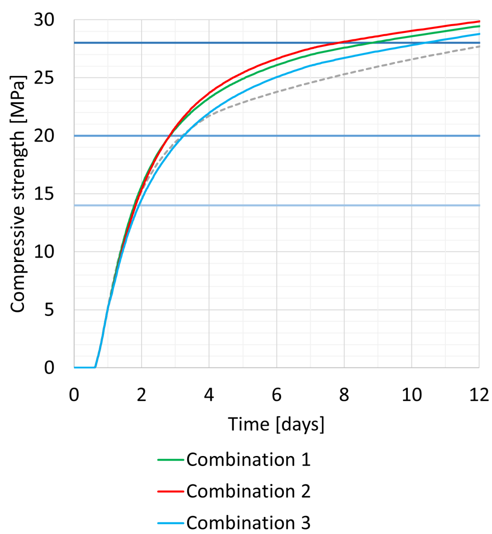


(b) Combination 2

Figure C.66: Average compressive strength development for different combinations of measures for the S50 and OPC concrete, one-day deadline

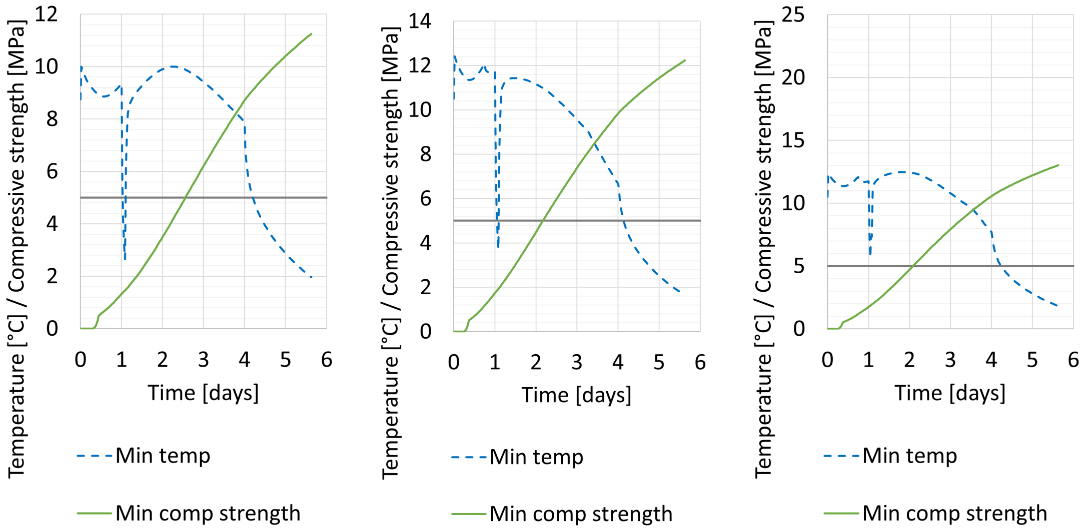


(a) S50



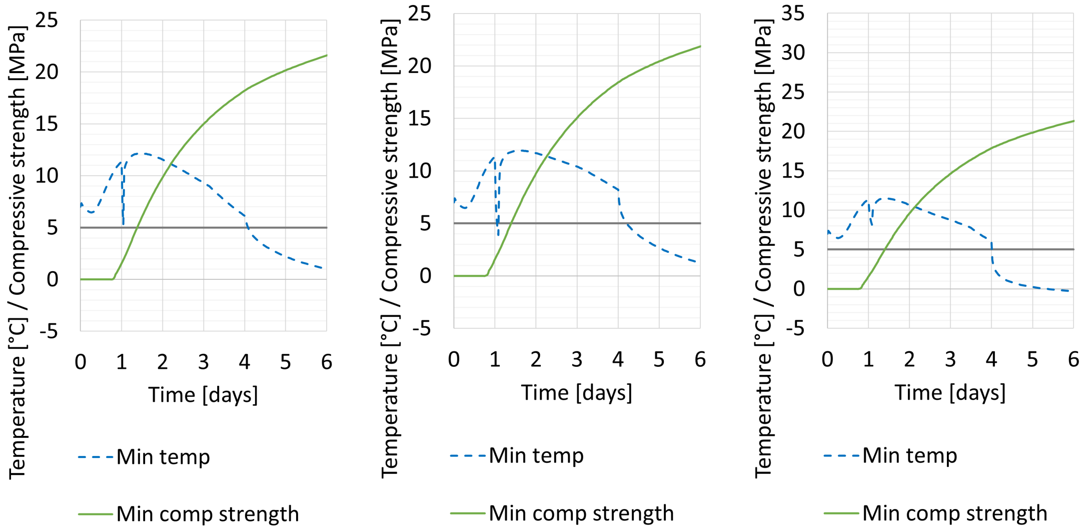
(b) OPC

Figure C.67: Surface compressive strength for different combinations of measures, one-day deadline



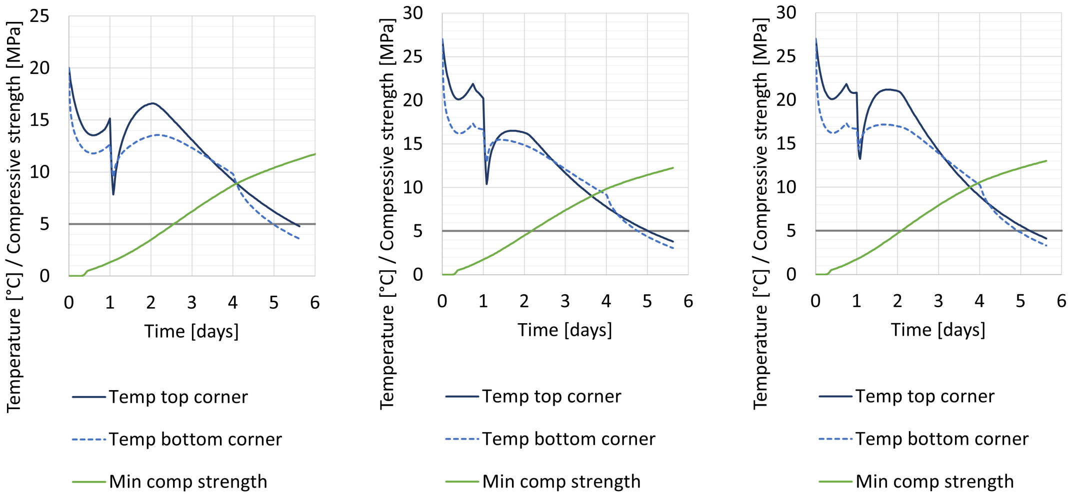
(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

Figure C.68: Risk of freezing by min temperature and min compressive strength for S50 concrete, one-day deadline



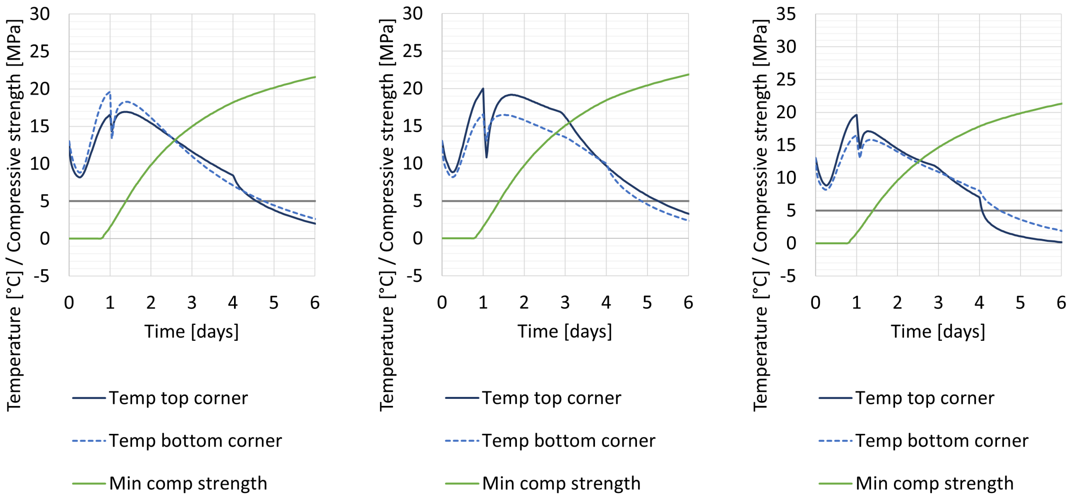
(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

Figure C.69: Risk of freezing by min temperature and min compressive strength for OPC concrete, four-day deadline



(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

Figure C.70: Risk of freezing by temperature in top and bottom corner, and min compressive strength for S50 concrete, four-day deadline



(a) Combination 1 **(b)** Combination 2 **(c)** Combination 3

Figure C.71: Risk of freezing by temperature in top and bottom corner, and min compressive strength for OPC concrete, four-day deadline

D

Result matrices

S50 Cold

	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Freeze control
	XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa	
t250L5	-54%	-51%	-37%	-30%	-81%	-71%	-80%	-85%	NOT OK
t250L10	-46%	-43%	-27%						
t250L20	-45%	-42%	-26%						
t500L5	-41%	-37%	-20%	29%	-65%	-49%	-65%	-75%	NOT OK
t500L10	-25%	-21%	1%						
t500L20	-24%	-20%	2%						
t1000L5	-39%	-36%	-18%	150%	-33%	-15%	-40%	-57%	OK
t1000L10	-22%	-18%	5%						
t1000L20	-18%	-13%	11%						

S50 Warm

	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Max temp [°C]
	XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa	70
t250L5	-40%	-37%	-19%	59%	12%	60%	12%	-20%	-59%
t250L10	-30%	-26%	-5%						
t250L20	-29%	-25%	-4%						
t500L5	-33%	-29%	-9%	101%	41%	98%	39%	-1%	-44%
t500L10	-16%	-11%	13%						
t500L20	-15%	-10%	15%						
t1000L5	-36%	-33%	-14%	146%	72%	128%	59%	14%	-25%
t1000L10	-19%	-14%	10%						
t1000L20	-15%	-10%	15%						

OPC Cold

	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Freeze control
	XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa	
t250L5	-49%	-46%	-31%	186%	-23%	21%	-15%	-39%	OK
t250L10	-39%	-35%	-17%						
t250L20	-38%	-34%	-16%						
t500L5	-41%	-38%	-20%	275%	0%	55%	9%	-22%	OK
t500L10	-23%	-18%	5%						
t500L20	-21%	-17%	7%						
t1000L5	-59%	-57%	-45%	350%	21%	77%	24%	-11%	OK
t1000L10	-41%	-38%	-21%						
t1000L20	-36%	-33%	-14%						

OPC Warm

	Cracking safety factors			Avg. comp. strength formwork removal		Curing class			Max temp [°C]
	XC2 0,952	XC4 0,9	1-sided water pressure 0,704	Non-bearing formwork 6 MPa	Bearing formwork 70%f_{ck}	2 14 MPa	3 20 MPa	4 28 MPa	70
t250L5	-46%	-43%	-27%	340%	18%	89%	32%	-6%	-42%
t250L10	-35%	-32%	-13%						
t250L20	-34%	-31%	-11%						
t500L5	-46%	-43%	-27%	385%	30%	106%	44%	3%	-28%
t500L10	-30%	-26%	-5%						
t500L20	-28%	-24%	-3%						
t1000L5	-66%	-64%	-54%	427%	41%	118%	53%	9%	-15%
t1000L10	-51%	-48%	-33%						
t1000L20	-46%	-43%	-27%						

Figure D.1: Results matrix of parametric study

		S50 Cold t500 L20									
		Cracking safety factors			Compressive strength at formwork removal		Curing class (10 mm from surface)			Freezing control	Max. temp. [°C]
		XC2 (0,952)	**XC4 (0,9)**	**One-sided water pressure (0,704)**	**Non-bearing formwork (6 MPa)**	**Bearing formwork (70%f_{ck})**	**2 (14 MPa)**	**3 (20 MPa)**	**4 (28 MPa)**		
Days of formwork	4 days	-24%	-20%	2%	29%	-65%	-49%	-65%	-75%	NOT OK	13,0
	8 days	-30%	-26%	-5%	132%	-38%	-6%	-34%	-53%	NOT OK	13,0
	16 days	-38%	-35%	-16%	244%	-8%	42%	-1%	-29%	NOT OK	13,0
Casting temperature	13°C	-24%	-20%	2%	29%	-65%	-49%	-65%	-75%	NOT OK	13,0
	16°C	-14%	-9%	16%	57%	-58%	-38%	-57%	-69%	NOT OK	16,0
	19°C	-7%	-2%	26%	87%	-50%	-26%	-48%	-63%	OK	19,0
Formwork insulation	None	-24%	-20%	2%	57%	-58%	-49%	-65%	-75%	NOT OK	13,0
	2 days	-7%	-2%	26%	-17%	-78%	-64%	-75%	-82%	NOT OK	17,6
	4 days	-3%	3%	31%	139%	-36%	7%	-25%	-47%	OK	20,4
Replacement coverage (after formwork removal)	0 days	-24%	-20%	2%	57%	-58%	-49%	-65%	-75%	NOT OK	13,0
	3 days	-27%	-23%	-2%	118%	-42%	-10%	-37%	-55%	NOT OK	13,0
	6 days	-31%	-27%	-7%	180%	-25%	17%	-18%	-42%	NOT OK	13,0
Heating/cooling	None	-24%	-20%	2%	57%	-58%	-49%	-65%	-75%	NOT OK	13,0
	2 days	-9%	-4%	22%	104%	-45%	-43%	-60%	-72%	OK	14,5
	4 days	-7%	-1%	26%	187%	-23%	-33%	-53%	-66%	OK	14,5

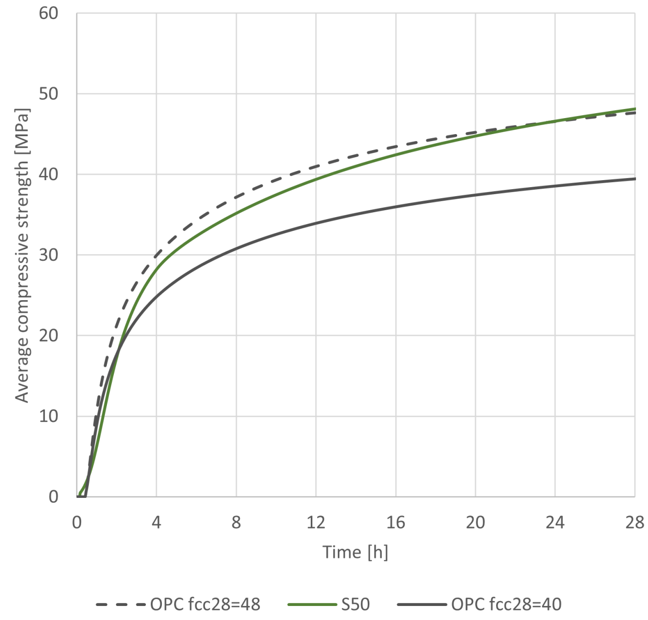
Figure D.2: Result matrix of risk reducing measure, S50

		OPC Cold t500 L20									
		Cracking safety factors			Compressive strength at formwork removal		Curing class (10 mm from surface)			Freezing control	Max. temp. [°C]
		XC2 (0,952)	**XC4 (0,9)**	**One-sided water pressure (0,704)**	**Non-bearing formwork (6 MPa)**	**Bearing formwork (22.4 MPa)**	**2 (14 MPa)**	**3 (20 MPa)**	**4 (28 MPa)**		
Days of formwork	4 days	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	8 days	-26%	-22%	0%	341%	18%	85%	30%	-7%	OK	29,8
	16 days	-28%	-24%	-2%	406%	36%	114%	50%	7%	OK	29,8
Casting temperature	13°C	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	16°C	-14%	-9%	16%	285%	3%	60%	12%	-20%	OK	32,8
	19°C	-7%	-1%	26%	296%	6%	65%	15%	-18%	OK	35,9
Formwork insulation	None	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	2 days	-4%	1%	29%	226%	-13%	40%	-2%	-30%	OK	38,3
	4 days	-8%	-3%	25%	346%	19%	93%	35%	-3%	OK	38,3
Replacement coverage (after formwork removal)	0 days	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	3 days	-25%	-21%	1%	331%	15%	81%	27%	-10%	OK	29,8
	6 days	-28%	-24%	-2%	364%	24%	96%	37%	-2%	OK	29,8
Heating/cooling	None	-21%	-17%	7%	274%	0%	55%	9%	-22%	OK	29,8
	2 days	-44%	-41%	-25%	274%	0%	34%	-6%	-33%	OK	20,5
	4 days	-43%	-40%	-23%	348%	20%	44%	1%	-28%	OK	20,5

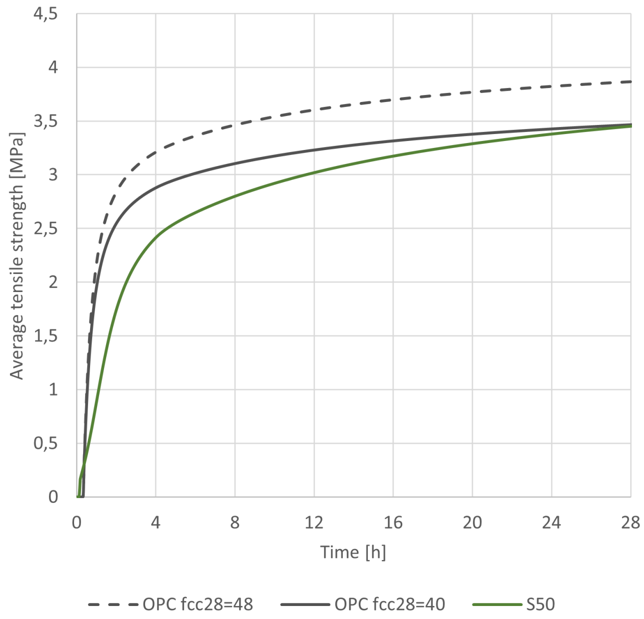
Figure D.3: Result matrix of risk reducing measure, OPC

E

Tensile and compressive strength development



(a) Average compressive strength



(b) Average tensile strength

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