OsloMet – Oslo Metropolitan University

Department of Civil Engineering & Energy Technology
Section of Civil Engineering

ACCESSIBILITY

Master Program in Structural Engineering & Building Technology

MASTER THESIS

TITLE Control of the curing process for hybrid concrete in post-tensioned slabs	DATE 25.05.2022 PAGES / ATTACHMENTS 100/44
AUTHOR(S) Petter Klock Wergeland	SUPERVISOR(S) Gro Markeset Sverre Smeplass

IN COLLABORATION WITH Skanska Norge AS	CONTACT PERSON Sverre Smeplass Frederic Aarnæs Hermansen

SUMMARY / SYNOPSIS

Through the computer-based curing technology program CrackTeSt COIN, the thesis has made measurements of two concrete compositions with high pozzolan dosage, respectively 50% and 65% of the total effective binder. The task is related to Skanska's project Gullhaug Torg 2A, designed with post-tensioned slabs, where the mentioned concrete will be used. Due to the tensioning of compressive forces and the project's progress, the slabs must achieve a compressive strength of 25 MPa within 3 days. This has led to the thesis dealing with the concrete's development of mechanical properties in the form of temperature and compressive strength. This study has shown that the environmental ambitions regarding concrete are possible but that it entails challenges due to the concrete's low heat development and relatively slow strength development. At minus degrees, it is imperative to control the curing process with the correct use of measures and possibly use the concrete with the lowest amount of pozzolans. The pozzolan reaction proceeds slowly at low temperatures and rapidly at high temperatures. The results have shown that progress can be accelerated at high temperatures as the required strength is well within the 3-day requirement.

KEYWORDS
Hybrid Concrete
Curing Technology
CrackTeSt COIN

Preface

This master's thesis is written in the spring of 2022 at OsloMet – Oslo Metropolitan University. The thesis covers 30 ECTS credits and is registered under the course *MABY5900 Master's Thesis* at the Faculty of Technology, Art and Design. The thesis has been prepared in collaboration with Skanska Norge AS.

The purpose of the master's thesis is to answer how concrete compositions with a high dosage of fly ash perform during curing. The intention is to control and optimise the curing process through the choice of curing measures. Skanska's ongoing project, Gullhaug Torg 2A, has set the framework for the content of the thesis. The project has high environmental ambitions, which is the motivation behind the thesis.

The thesis' connection to Skanska's project Gullhaug Torg 2A has provided valuable insight into the practical aspects of concrete work and the sustainable development that is constantly in focus. The interdisciplinary approach to the work has provided an exciting insight. Together with the knowledge and competence I have been supported with, this has been invaluable during the thesis.

Foremost, I would like to thank my external supervisor Sverre Smeplass, professor II and chief adviser at the concrete department at Skanska Teknikk, who has been of great support with his knowledge and involvement. It has been a significant contribution, and his commitment and encouragement have been a great motivation in the completion of the thesis.

I would like to continue to enunciate my gratitude to my internal supervisor Gro Markeset, professor at the Department of Civil Engineering and Energy Technology, for the great contribution to the design of the thesis and valuable feedback.

A big thank you to Frederic Aarnæs Hermansen, concrete technologist at Skanska Teknikk. He has been my contact person and has been involved throughout this endeavour, providing insight and help in CrackTeSt COIN, arranging inspection of the project, and including me in the fieldwork during casting. This has been crucial for the completion of the thesis.

Abstract

Curing technology has come a long way since the Danes Freiesleben-Hansen and Pedersen introduced it in the late 70s. Now that the cement and concrete industry is focusing heavily on the environment and opportunities to reduce the Greenhouse gas emissions, this has led to supplementary cementitious materials creating low-carbon concrete and, in extension, the term "hybrid concrete". Ordinary Portland cement production contributes to significant CO_2 emissions, where it is impossible to reduce the emissions from the calcination process itself. Still, we can reduce the amount of cement clinker in the finished cement by using supplementary cementitious material that has sufficient binder properties and, at the same time, a much smaller carbon footprint. Such materials can be pozzolans or hydraulic binders, typically fly ash, silica fume, and slag. All these replacement materials are residual products from industry, which are sources of significant CO_2 emissions. The carbon footprint is always associated with the primary production, and the residual effects are thus considered energy and carbon neutral. The different properties of the supplementary cementitious materials compared to cement will impact the curing process, a crucial and sensitive part of concrete production.

Through the computer-based curing technology program CrackTeSt COIN, this thesis has made measurements of two concrete compositions with high pozzolan dosage, respectively 50% and 65% of the total effective binder. The pozzolanic material consists mainly of fly ash and silica fume. The high proportion of pozzolanic material leads the thesis to the topic of low-carbon and “hybrid concrete”.

The thesis is related to Skanska's project Gullhaug Torg 2A, designed with post-tensioned slabs, where the mentioned concrete will be used. Due to the post-tensioning and the project's progress, the slabs are required to achieve a compressive strength of 25 MPa within 3 days. This requirement has led to the thesis dealing with the concrete's development of mechanical properties in temperature and compressive strength. Several simulations and accompanying analyses have been performed of the concrete's behaviour in different weather conditions and with the use of different curing measures alone and in combination. These new concrete compositions that have been developed for sustainability purposes lead to new challenges regarding property development, especially in winter casting.

This study has shown that the environmental ambitions of using supplementary cementitious material in the concrete are possible. However, it entails challenges due to the accompanying low heat development and relatively slow strength development. At minus degrees, it is imperative to control the curing process with the correct use of measures and possibly use the concrete with the lowest amount of pozzolans. The pozzolan reaction proceeds slowly at low temperatures and rapidly at high temperatures. The results have shown that progress can be accelerated at high temperatures as the required strength is well within the 3-day requirement.

Table of content

Table of figures

Table of tables

Key abbreviations and notations

Abbreviations

AAM	Alkali-activated material
EPD	Environmental product declaration
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
OPC	Ordinary Portland cement
SCM	Supplementary cementitious material

Notations

A	Activation energy parameter
B	Activation energy parameter
c	Specific heat capacity
C	Amount of binder
$E(\theta)$	Activation energy
f_{c28}	28-day compressive strength
H	Hydration rate function
$H(\theta)$	Rate of hydration
k	Efficiency factor
M	Maturity time
n_c	Model parameter compressive strength
R	Universal gas constant
s	Material model time-development parameter
t_0	Start time for stress development
v/c	Water/cement-ratio, or mass ratio

Greek letters

α	Curve fitting parameter
ρ	Density
τ	Curve fitting parameter
θ	Temperature

1. Introduction

The thesis's background, scope, research questions, and purpose are mapped in this chapter. The thesis' close connection to the climate and environmental aspects of the buildings and construction sector will be described. Furthermore, the content, clarifications, limitations, and the outline of the thesis, will be mentioned.

1.1. Background

1.1.1. Constructions and climate

The global climate is changing. Climate change is considered the most complex and severe environmental issue that human societies ever have faced [1]. Observing increases in GHG concentrations since around 1750 makes it unambiguous that human influence on the climate system has contributed to the increased average temperatures of global air and ocean. The last four decades have been warmer than the ones preceded since 1850. In 2015, a vision for a zero-carbon future was mapped out by world leaders, resulting in a collective response to climate change – the Paris Agreement. This is the first universal and legally binding climate agreement ever adopted when 195 countries accepted the agreement and the world entered into a pact to combat climate change. The historic breakthrough was a response to the objective made by the UN Framework Convention on Climate Change (UNFCCC) of preventing "dangerous anthropogenic interference with the climate system". The Paris Agreement established goals with trajectories limiting the increase in global average temperatures to well below 2°C above pre-industrial levels while pursuing efforts to limit the rise to 1.5°C above said levels [2].

On a global basis, the buildings and construction sector use approximately 40% of all resources, including materials and energy. In the construction and operation of buildings, the global energy-related CO_2 emissions accounted for 38% (13.1 gigatons) in 2015. Five years later, in 2020, the emissions saw a reduction of approximately 10% (11.7 gigatons), levels not seen since 2007. Although one must recognise the effects and adjust for the impact of the global pandemic that COVID-19 was, one should also acknowledge the continued efforts and work to decarbonise the sector. The energy consumption in 2020 reduced to 36% of global demand, or 149 exajoules (EJ), and the energy-related CO_2 emissions accounted for 37%, or approximately 8.7 gigatons CO_2. In 2015, 90 countries that signed the Paris Agreement addressed buildings-related emissions and actions to improve energy efficiency in their Nationally Determined Contributions (NDCs). Since then, the number of countries to include building emission reductions in their NDCs has increased to 136 in 2020 [3].

In order to achieve the goals set out in the Paris Agreement, the global buildings and construction sector needs to decarbonise by 2050. A triple strategy focusing on reducing the building emissions along their lifecycle is required. The process combines reducing energy demand, decarbonising the power supply, and addressing embodied carbon stored in building materials. The first two mentioned can almost eliminate carbon emissions from the building operations by 2050. The emissions stemming from building materials and construction processes must be dealt with urgently to ensure optimisation of the buildings being constructed today concerning low-carbon solutions for the whole life cycle. The optimisation includes maximising refurbishment, evaluating design choice through a lifecycle approach (such as lean construction, low-carbon materials and construction processes), and avoiding future embodied carbon [3].

In 2020, Norway announced its commitment to an intensified climate target under the Paris Agreement. The promise implies that Norway commits to reducing GHG emissions by at least 50%, and up to 55%, in 2030 compared to the levels in 1990. The government wants to fulfil the increased goal in collaboration with the EU. In the recommendation for the proposition on consent to ratification of the Paris Agreement, the Storting decided that the government should assume that Norway will be climate neutral from 2030 onwards [4]. In Norway, several sectors have prepared their road maps for green competitiveness, the buildings and construction sector being one of them. This initiative emphasises the potential for improvement and the willingness to solve the global climate and environmental challenges. Increased investment in expertise, serious companies, industrialisation, digitalisation, research and development (R&D), and innovation strengthens the basis for the sector to contribute to and be a part of the "green shift" [5]. The indication of willingness is further confirmed as several commercial initiatives and government measures have been implemented to create a greener construction industry. These initiatives include the Norwegian Green Building Council, FutureBuilt, the Powerhouse collaboration, and the Research Centre on Zero Emission Buildings (ZEB). The commercial initiatives have paved the way from passive houses to plus houses at a tremendous pace - Powerhouse and plus houses, and with Nydalen Vy, we have the first model project stripped of redundant technology.

As a key input into concrete, the world's most widely used material after water, cement is by far the most prominent contributor to climate change. The cement's contribution is approximately 90% of concrete's energy consumption and GHG emissions. The production of OPC stands for considerable portions of GHGs released into the atmosphere. Over 4 billion tonnes of cement are produced every year, representing 8% of the global CO_2 emissions, corresponding to 27% of the total industrial CO_2 emissions in 2015. As an energy consumer, the cement industry is the third-largest, with 7% of the global industrial use [6]. The majority of the emissions regarding cement derive from the inherent chemistry and the high-temperature process needed for its synthesis. To avoid these emissions, radical changes in the chemistry and synthesis pathways are required. On a positive note, there are significant potential and opportunities to reduce these emissions. It is a prerequisite for achieving the political goals set in the Paris Agreement.

The most important raw material in the production of cement is limestone. In clinker production, limestone is heated up to approximately 1400°C to split into calcium oxide (CaO) and CO_2, as presented in equation 1. This process amount to about 50% of emissions related to environmental gases in cement production. Approximately 40% derives from thermal energy emissions and around 10% from mechanical energy. Decomposition of limestone cannot be done.

$$\underset{\text{Calcium carbonate}}{\mathrm{CaCO_3}} \rightarrow \underset{\text{Calcium oxide}}{\mathrm{CaO}} + \underset{\text{Carbon dioxide}}{\mathrm{CO_2}} \tag{1}$$

Thermal energy emissions have been significantly reduced in recent decades by using alternative energy sources such as organic waste from households and industrial waste, which are not included in the energy accounts. Mechanical energy can be reduced somewhat by streamlining the production system. However, the most considerable contribution can be achieved by replacing a proportion of the clinker with SCMs [7]. This reduction of the concrete's carbon footprint is the basis of this thesis. The thesis considers the curing process of low-carbon post-tensioned concrete slabs, looking into how the concrete behaves and how compressive strength and temperature development properties affect each other over time.

1.1.2. Gullhaug Torg 2A

The thesis is based on Skanska's ongoing project at Gullhaug Torg 2A in Oslo. *Vertikal Nydalen* is a project created with the environment in mind and a future in line with the Paris Agreement. Gullhaug Torg takes place in the centre of Nydalen in Oslo, where an innovative environmental mixed-use building is being established. The project is part of the owner, Avantor's, further development of Nydalen, with a development plan towards 2030 called *Nydalen+*. Avantor is one of the biggest commercial developers in Norway, with a strong environmental focus and ambitions concretised in their environmental strategy where the UN's sustainability goals are central.

The parking lot at Gullhaug Torg is removed at the expense of an innovative energy building out of the ordinary. A shift that highlights and demonstrates future solutions within green mobility and measures to reduce greenhouse gas emissions from transport. Avantor proposes that all traffic in Nydalen in the future will consist of cycling, walking and public transport and has developed a separate master plan to make large parts of the city centre car-free. The structure will consist of two towers connected on the lower floors with an attractive combination of residents, offices, and retail units. The northern part is an 18-story high-rise building, and the southern part is a 7-story low-rise building. Both structures consist of commercial areas on the ground floor, and the low-rise has office spaces on the remaining floors. The high-rise building consists of office areas from the 2nd to the 5th floor and the residential regions above. Through integrated design, where architecture and technology complement each other, the building will demonstrate that environmental buildings can be made simpler and more robust than what is traditionally built today. Simultaneously, new architectural designs and solutions introduce new challenges, opening reduced carbon footprint opportunities. Skanska has been heavily involved in the project since 2015, from the initial phase to the ongoing construction phase.

Figure 1. Gullhaug Torg 2A [8]

Gullhaug Torg is a pilot building in the research project "Naturligvis" and a FutureBuilt-project. As a FutureBuilt-project, it is committed to meeting ambitious environmental and sustainability criteria. FutureBuilt is an innovative programme supporting climate-friendly urban development in the Oslo region, with a vision to show that the product of climate-neutral urban areas based on high-quality architecture is possible. The project's source of inspiration was obtained during a study trip to Austria that the CEO and project director of Avantor attended, together with the Green Building Alliance and FutureBuilt. The acknowledged, innovative low-energy *2226* building in Lustenau was presented, a concept Avantor wanted to construct in Nydalen [9]. Gullhaug Torg aims at no delivered energy for heating, cooling, and ventilation, known as "triple-zero". Instead, the project will take advantage of natural and hybrid ventilation. At the same time, the temperature management concept is based on geothermal and low-temperature heating and cooling in the walls and floors. As a mixed-use building, the contrasting functions require different solutions. The office spaces are planned with only natural ventilation, while the residents will operate with hybrid ventilation. The goal is to make Gullhaug Torg the first naturally ventilated zero-energy building in Norway. The environmental goals set for Gullhaug Torg include a 50% reduction in GHG emissions from materials, transport, and energy compared to a conventional reference building. The total energy use aims to be compensated by producing renewable energy to a "near-zero" standard, as defined by FutureBuilt in 2016. The office premises aims to be certified as BREEAM-NOR Excellent, while the residents aim at BREEAM-NOR Very Good [10, 11].

Gullhaug Torg is related to the second category of environmentalism, defined by many as the last of the four Rs: Rethink. Rethinking is defined as taking a step back, not being confused with going backwards, and seeing the best way to reach the desired goal [11]. Gullhaug Torg has significant environmental goals. Instead of incorporating energy-efficient but expensive and complex heating and cooling systems, buildings could be designed less dependent on such systems, if not completely independent. This independence is the case for Gullhaug Torg, convinced that simplified technical facilities and high-quality materials will provide greater robustness and flexibility over the life span of the building. Simultaneously, the implementation of technical solutions in prominent future projects is essential. When we change the question's wording, the chance of new answers emerges. Rethinking is a game-changer, a concept that can alleviate environmental concerns and improve lives.

The most relevant focus area of the project regarding this thesis is the sustainable use of material and the challenges associated with execution and performance. The construction principle with post-tensioned concrete slabs, concrete cores and steel columns that follow the façade life provides flexibility in programming the areas. In addition, complex ground conditions with several existing culverts require large spans. The load-bearing structure is based on in-situ concrete, which entails a large amount of concrete. The project focuses on materials and solutions with low GHG emissions from production and long service life. The collective goal regarding GHG emissions from the concrete should not exceed 180 kg CO_2-eq/m^3, ensuring sustainable use of materials. The materials are based on the most significant degree of proper recycling and reuse. Skanska has studied the use of hybrid concrete for the buildings, challenging the material-technical basis due to the high fly ash and silica fume content, which entails technical production challenges [12].

1.2. Scope and research question

Concrete has a significant impact on the progress of projects. To a greater or lesser extent, the implementation of curing measures can affect the curing process. Using concrete with a high fly ash dosage will significantly affect the curing process. A slow curing process generally characterises this concrete in terms of compressive strength and temperature development. These properties entail both advantages and disadvantages, depending on the construction design. For post-tensioned slabs, "low-heat concrete" will require curing measures to achieve the desired strength development and thus avoid impairing the progress.

The master's thesis collaborates with Skanska and addresses their concrete compositions to further reduce energy consumption and GHG emissions. The thesis' primary focus is to study the extent to which concrete compositions with high fly ash dosage affect the development of strength and temperature and how the curing process emerges when considering various curing measures and weather conditions. Skanska's project at Gullhaug Torg will be conducted with post-tensioned hybrid concrete slabs, and the master's thesis will be carried out in parallel with the construction project. The concrete in the post-tensioned slabs makes up a substantial proportion of the total concrete volume in the project, and emphasis has been placed on limiting the GHG emissions in this concrete. The aim is to satisfy the requirement for low-carbon class Plus following The Norwegian Concrete Association's publication number 37 (NB37). There is a goal of achieving a GHG emission of under 180 kg CO_2-eq. pr. m^3 concrete. This goal is realised by proportioning the concrete with a high proportion of pozzolans, 50% and 65%, respectively. Furthermore, the project aims to use hybrid concrete containing 65% pozzolans as much as possible.

The requirement regarding the curing process of the post-tensioned slabs is to reach a minimum compressive strength of 25 MPa in 3 days. Hybrid concrete cast in Norwegian winter conditions is very demanding; thus, curing measures must be implemented to maintain satisfactory progress. The thesis will use the computer-based curing technology program "CrackTeSt COIN" to study how hybrid concrete behaves during the curing process. Therefore, the objectives are primarily approached experimentally, providing a large amount of output data. Furthermore, fieldwork considering the first cast of post-tensioned slabs at the project has been conducted. The additional analytical approach consists of the evaluation of the experiments and fieldwork. The main scope of the thesis is to carry out simulations of selected curing strategies in different representative weather conditions. By analysing the compressive strength and temperature development, it is possible to control and optimise the curing measures in advance of casting and determine for which conditions and when the requirements are achievable. In this thesis, the scope was pursued by defining the framework and objectives:

- Development of separate and combined curing measures.
- Simulations of the compressive strength and temperature development.
- Examine the behaviour of the different concrete compositions.
- Examine the effect of curing measures under representative weather conditions.
- Optimisation of curing measures to achieve 25 MPa compressive strength prior to 3 days.

The hypothesis of the thesis is to assess the concretes' sufficiency regarding strength development when using SCMs (in the current work exemplified by pozzolanic material) with the means of experimental and analytical approaches.

1.3. Content and general clarifications

The thesis is a study that mainly considers compressive strength and temperature development in hybrid concrete and the curing technology that comes with it. The thesis is constructed using a curing technology program and the findings that have been made in the context. Furthermore, the thesis deals with the fieldwork of concrete casting at the construction site at Gullhaug Torg, where the choice of curing measures is based on the simulations carried out in advance. The study can be categorised under the field of concrete technology. Simultaneously, the term hybrid concrete deals with several chemical reactions regarding the development of mechanical properties, including the alkali-activated concrete (AAC) composition. Therefore, a small literature study has been carried out regarding various binder systems.

During the theoretical part of the thesis, an introduction will be given according to considered themes and subject areas before the methodology, and the subsequent results from the completed simulations and practical work will be explained. Regarding the given requirements for goal achievement, recommendations will be given on the curing measures that prove most suitable in different weather conditions.

An essential part of the work is to explain relevant background theory to give the reader a good basic understanding. Hybrid concrete is a new milestone and yet another climate step in the right direction. Simultaneously, the thesis assumes that the reader has sufficient knowledge of concrete as a building material. Fundamental insight into cement chemistry and knowledge of the properties of concrete in the various phases is deemed necessary.

The thesis contains several abbreviations and notations, of which the necessary clarifications are listed in advance of this chapter.

1.4. Limitations in the thesis

The thesis will primarily focus on the findings made through the simulation program and practical experiments, assessing the properties of the concrete. The current project at Gullhaug Torg deals with the compressive strength and temperature development in the hardening phase concerning the post-tensioned concrete slabs. Therefore, this thesis is limited to dealing with such structures.

The post-tensioned slabs dominate the total volume of concrete used at Gullhaug Torg. The project is considered built with two different concrete compositions with different amounts of pozzolanic material, 50% and 65%, respectively. The project primarily aims at using the concrete with the highest amount of pozzolanic material as an environmental contribution. The reason for developing two different concrete compositions is that when adding high amounts of fly ash and silica fume, the property development of the concrete changes, making it more temperature-sensitive and, therefore, more difficult to cure in winter conditions. Thus, the composition with 50% pozzolanic material will be used to substitute for the 65% in conditions where it does not reach sufficient strength development. Both compositions are placed in exposure class XC1, durability class M60 and strength class B55, an unusually high strength class for this type of construction. The choice is triggered by the need for increased shear capacity contribution from the concrete material in the columns. Another critical point is that the concrete slabs have a greater challenge in progress and early strength development. These are the concrete compositions that are assessed in this master's thesis.

1.5. Outline of the thesis

The thesis is organized into 7 chapters. Chapter 1 introduces the topic and defines the background, environmental aspects, and the objectives and scope of the work. Chapter 2 presents relevant background theory and a brief literature review regarding AAM.

Chapter 3 presents a description of the methods used throughout the thesis. Chapter 4 presents the test results and the fieldwork results regarding the casting of the post-tensioned slab at the project.

Chapter 5 presents the discussion related to the results achieved in the thesis with a comparison to an industry-standard used as a reference concrete. Chapter 6 gives the main conclusions, while chapter 7 presents future perspectives regarding the current topic.

2. Background theory

This chapter aims to present and summarise relevant theory, giving insight and knowledge deemed necessary for completing the thesis and introducing the practical work in chapter 3. Furthermore, the chapter consists of a small literature review regarding AAMs. The literature review is conducted through a structured search to provide a reliable overview of the topic that can serve as a mapping tool.

2.1. Post-tensioned slabs

The purpose of prestressed concrete is that the applied compressive stresses compensate for the tensile stresses that arise during bending due to the applied payload. The principle consists of utilising the strong sides of concrete, i.e., the compressive strength. The compressive strength is utilised optimally, simultaneously, as the lack of tensile strength is compensated. The advantages of using prestressed concrete are its large capacity, long spans, and slim constructions. The latter also provides an environmental benefit by reducing the amount of concrete.

There are two different types of prestressed concrete slabs, pre-tensioned and post-tensioned. The former are typically hollow-core slabs where the concrete encloses pre-tensioned reinforcement that is cut when the concrete is sufficiently hardened. For in-situ concrete, this is not applicable. The alternative to pre-tensioned is post-tensioned concrete. The method involves placing ducts in the concrete where tensile forces constructively occur. The prestressed reinforcement can be placed with the desired curved profile through the construction to adapt the prestressing to the moments from external loads. The curvature is, in practice, limited by the flexibility of the tensioning units. After casting and when the concrete has reached an intended strength during curing, the high-strength steel tendons are tensioned in the cast-in pipes, and the construction will then be able to take up larger loads. Architects, engineers, and contractors can take advantage of the opportunities and develop more flexibility in the building.

In contrast to pre-tensioned slabs, the post-tensioned have ordinary reinforcement, which absorbs shear forces in the anchoring zone and ensures that the strain differences do not give undesired cracking. Pre-tensioned concrete does not contain any reinforcement other than prestressed reinforcement and therefore only has a load-bearing capacity in one direction. All loads are thus transferred to the arrangements at each end of the elements [13].

Gullhaug Torg has a challenging architectural design, making good use of the benefits of post-tensioned slabs. The thin slabs make for a more considerable net roof height, ensuring a good and stable indoor climate based on natural air conditioning. The heigh is necessary to let in cold outdoor air through horizontal hatches under the slab and mix it with the warm indoor air. Longer spans utilize the reduced required number of columns and open for a more flexible décor. When considering the material-technical benefits, post-tensioning reduces cracks and requires less concrete, leading to cost savings, reduced CO_2 emissions, and increased construction progress [14].

Figure 2. Post-tensioned slab cast at Gullhaug Torg 2A

2.2. Curing technology

Concrete is a material that builds up its strength and durability over time. The conditions in the first days after casting are critical considering the long-term properties of the material. The conditions need to be balanced. Today's construction practice is characterised by high demands for rapid progress, which can be at the expense of the finished concrete product. The chemical process of hydration is exothermic, characterised by high heat generation, and under controlled conditions, this self-heating will provide technical advantages. On the other hand, curing heat can also cause problems. Concrete is often considered a maintenance-free material, but this is only the case if the execution and measures in advance are done correctly. An essential prerequisite for a rational construction process is that it can occur almost regardless of weather conditions. Norway has a climate that requires well-adapted concrete work at several degrees below 0°C. At the same time, the use of solid structures requires solutions that prevent too high temperatures and temperature gradients [15].

Current material knowledge can ensure the necessary progress while the inherent properties of the concrete are safeguarded. A common term for this is curing technology. Curing technology is adapted to describe the relationship between temperature level and hydration rate in hardening concrete based on reaction kinetics. Curing technology systemises planning, concrete production, casting, and finishing based on the industry's acquired knowledge, which is especially important within winter casting [15].

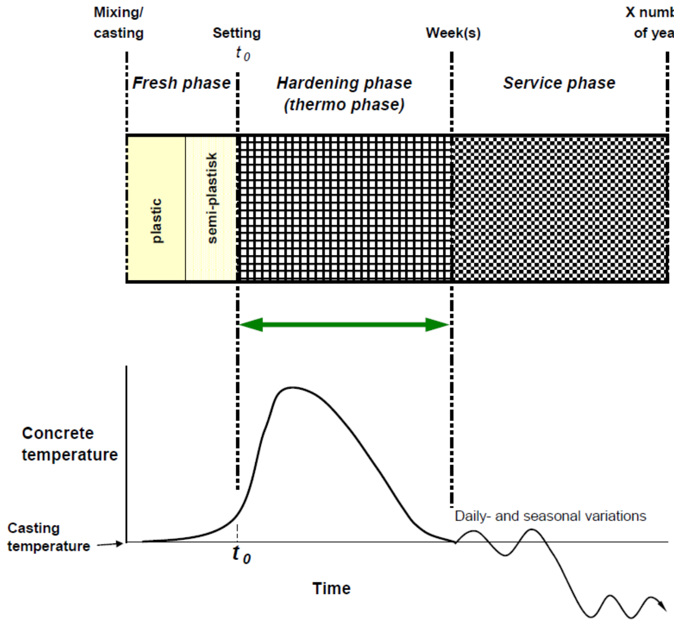


Figure 3. Schematic representation of the different phases of concrete [16].

The life of concrete can be divided into three phases, as illustrated in figure 3. The fresh phase consists of mixing, transport, casting, and the onset of hardening (plastic stage). The hydration process develops at a slow initial pace in this period, controlled by adding small amounts of gypsum (calcium sulphate) as a retarding agent. Gradually, the cast concrete loses all workability (semi-plastic stage) and enters the bonding stage, in which sufficient hydration development leads to measurable mechanical properties. Most mechanical properties are developed in the hardening phase with the hydration process. The hardening phase ends when the concrete is in thermal equilibrium with the surroundings, entering the service phase.

2.2.1. Winter casting

Casting work in the winter can lead to operational implications. Norway has a climate characterised by significant variations between different parts. In Köppen-Geiger's climate classification, Oslo is defined as a "temperate/humid continental climate (Dfb)", characterised by short summers and long winters. Also, the monthly average temperature never exceeds 22°C. Low temperatures can lead to significant heat loss from the curing concrete to the surroundings, slow and unpredictable development of strength, and the risk of permanent damage to the concrete. As mentioned above, a rational construction process should proceed regardless of weather conditions [17].

Winter casting sets strict requirements. Based on the concrete composition, we can predict which properties the concrete has in terms of solidification time, strength- and heat development, and how these properties depend on the temperature. At the construction site, these conditions are considered in terms of construction type, dimensions, formwork type, air temperature and wind conditions. NS-EN 13670+NA sets requirements for winter casting of concrete. Adjacent elements must have a satisfactory temperature so that the concrete does not freeze until it has achieved sufficient strength. If the ambient temperature at the casting time or the curing period is below 0°C, adequate curing measures must be carried out. The curing measures must ensure that the concrete does not fall below 0°C until it has reached a strength of at least 5 MPa. Experience has shown that concrete suffers permanent damage if it freezes before sufficient maturity has been acquired. Water that freezes to ice expands by about 9%. If the water in fresh concrete freezes, the concrete expands by about 2%. At the same time, the hydration of the cement will not start until the water is thawed. The consequence is porous concrete with significantly reduced strength and durability. In the case of slabs, premature freezing can lead to crumbling of the surface and the need for additional treatment before pouring [15]. Measures to limit the heat loss in the concrete include insulating the formwork, covering the slab with tarps, ordering concrete at higher temperatures, or using gas burners under the slab formwork. Curing measures can be very costly both financially and in terms of time and, at the same time, steal production capacity. Combined with temperature measurement and maturity calculation, this can provide reasonable control of strength development and time for the demolition of formwork. The curing measures to solve the winter casting problems are usually many and depend on several factors. The goal is to implement the most straightforward and cheapest measures [7].

2.2.2. Curing measures

Curing measures are determined based on what is to be cast and when it is to be cast. According to this, the most important factors are the type of construction, concrete composition, and weather conditions. NS-EN 13670+NA give comprehensive descriptions concerning the curing conditions. Good curing conditions are first and foremost necessary for the coverage zone to develop in the best possible way. It is this part of the structure that will protect the reinforcement. The design basis shall describe requirements for the curing measures and specify the curing class, which provides answers to the curing time. The concrete must be ensured good curing conditions and be protected at an early stage:

- to minimise shrinkage.
- to ensure sufficient firmness in the surface layer.
- to ensure sufficient durability properties for the surface layer of the structure.
- against harmful weather conditions and freezing.
- against harmful vibrations, shocks, and damage.

The duration of the curing measures must be adapted to the development of the concrete's properties in the surface layer. The development is described by curing classes defined by the curing period or the specified characteristic compressive strength percentage after 28 days, as shown in table 1, according to table 4 in NS-EN 13670+NA. Unless otherwise described, curing class 3 applies to Norway [18].

Table 1. Curing classes according to table 4 in NS-EN 13670+NA [19]

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

[a] Provided the setting time does not exceed 5 hours, and the surface temperature of the concrete is equal to or higher than 5°C.

The curing measures are an essential part of the planning before the casting starts. The measures must be carried out during and after the casting. Solidification and hardening accelerators can be added during casting, and the formwork can be insulated. The curing measures are thus dependent on seasonal variations. The purpose of curing measures in the summer is to keep the temperature down during the curing phase and protect fresh concrete from water evaporation to avoid plastic shrinkage cracks. During winter, the purpose is to keep the temperature up in the surface layer, preventing the concrete from freezing and thus preventing water evaporation. As mentioned in the previous chapter, the concrete must not freeze until it has reached a strength of at least 5 MPa. On the other hand, the concrete must not exceed a maximum temperature of 70°C during the curing period. Assessment of the concrete's property development in the surface layer should be based on the relationship between compressive strength and maturity [20]. These subjects of curing technology are explained in later chapters.

There are opportunities to optimise curing measures in advance of casting by using planning tools and simulating the curing process in the construction. The program used in this master's is CrackTeSt COIN and is further explained in the next chapter.

2.2.3. Computer-based curing technology

Curing technology consists of several complex and resource-intensive calculations, which cannot be performed manually. Based on this, special FEM-based computer programs have been developed to conduct these analyses. This thesis makes calculations with the computer-based curing technology program “CrackTeSt COIN”. CrackTeSt COIN can analyse mechanical properties, maturity, strength, and temperature development. The program is typically used in the planning phase of projects, estimating the risk of cracking, and conducting traditional curing technology calculations regarding compressive strength and temperature development. The latter is in focus regarding this thesis.

CrackTeSt COIN is a modified version of the Swedish analysis program ConTeSt PRO, adjusted to the Norwegian practice for modelling and concrete mix design through COIN. Jan Erik Jonasson, who also developed the software HETT97, is the program developer. CrackTeSt COIN is a FEM-based calculation program for curing technology and is defined as 2 ½-dimensional. The constructions are modelled in two dimensions, provided that the heat transport in the third dimension can be neglected. Having the same temperature field in all cross-sections is considered an accurate approximation, as only the ending parts of the construction are subjected to heat exchange. At the same time, it is possible to set criteria for maintaining translation in the z-direction and rotation around the x- and y-axes as a simplification to calculate principal stress out of the plane. These criteria are essential regarding cracking issues and are why the program is denoted as 2 ½D. The program is used to simulate and analyse the temperature histories and distribution in curing concrete constructions and property development of the concrete based on the maturity method. Material composition and boundary conditions are input values selected by the user in order for the program to calculate stresses that arise due to the thermal and autogenous dilation and the restraining effects. CrackTeSt COIN has an interface of two different methods for calculating stresses: *plane surface (PS)* analysis and *linear line* (LL) analysis. Using the PS over the LL is recommended as it is a simplified method that utilises symmetry in the model. The PS analysis is beneficial as the method simultaneously considers the curvature in several directions [16].

The program has several fields of application, including analysis and assessment of the risk of cracking in the curing phase. CrackTeSt COIN is an important planning tool in projects where it is imperative to cast concrete structures without continuous cracking caused by retaining thermal and autogenous dilation. In recent years, the program has also shown its usefulness in analysing the curing process of new concrete compositions. The program has been used for pure temperature calculations and traditional analysis and simulation of compressive strength and temperature development in such contexts.

An overview of the program's appropriate fields of use can be given:

- Simulation of temperature history, development of compression and tension.
- Choice of curing measures for different weather conditions.
- Calculation of stresses based on retention effects.
- Calculation of crack index based on the calculation of tensile stresses in the structure and the tensile strength in the concrete material.

Table 2. Commercial simulation programs and their respective dimensions

Dimension /Program	1D	2D (2 ½D)	3D
HETT97	X		
4C-Temp&Stress		X	
ConTeSt		X	
CrackTeSt COIN		X	
B4cast			X
DIANA			X

Table 2 lists available commercial simulation programs commonly used in Nordic countries. Various programs offer complete sets of material input data based on experimental documentation of a set of "default" concretes. Temperature and stress calculations depend on the material data quality, making CrackTeSt COIN a valuable tool for mapping crack risk in concrete structures and conducting traditional curing technology calculations of temperature and strength development [21]. Data concerning property development needs to consider the actual concrete in their respective building projects when simulating the temperature and strength development. Typical input data considering the curing concrete properties are:

- Hydration heat, density, specific heat, binder content, thermal conductivity.
- Coefficient of thermal expansion.
- Autogenous shrinkage.
- E-modulus.
- Creep.
- Tensile strength.
- Compressive strength.
- Poisson’s ratio.

2.2.4. Heat development

The exothermic chemical process of hydration contributes to the development of strength and heat in the concrete, mainly in the hardening phase. This hydration is very temperature sensitive. High temperatures provide fast hydration and thus rapid strength development. Conversely, low temperature will result in slow hydration. This is especially important to deal with in connection with winter casting. NS-EN 13670 requires that the concrete does not freeze until it has a strength of 5 MPa. We also need to know the strength development to determine whether we can tension the prestressed slabs. Concrete that freezes prematurely has reduced strength and durability. Concrete damaged by frost early in the curing process has often highlighted dark discolouration.

At the same time, the Standard requires that the curing temperature in structures exposed to wet or cyclically wet environments must not exceed 70°C. This requirement is based on the fact that there may be a risk of delayed ettringite formation at higher curing temperatures [19]. A construction concrete can have an adiabatic temperature rise of 50°C. For any initial temperature above 20°C, it may be necessary to implement measures limiting heat generation or lowering the initial temperature. The Standard does not set requirements for temperature differences between the concrete's core and surface or between separate casting sections. Temperature differences that occur here can lead to thermal dilation and cracking. This discovery was concluded in 1978-79 as the Danish Building Research Institute did practical in-situ tests observing critical temperature differences. It was discovered that temperature differences exceeding 20°C were critical regarding surface cracking [16]. The NPRA has, in handbook 026, nevertheless given requirements for temperature differences [22].

The heat development depends on many factors, including fineness of cement (Blaine-value), mass ratio and clinker composition. Curing conditions such as temperature, humidity and time also play an essential role. The higher the Blaine value, the higher the degree of hydration. In terms of mass ratio, a level lower than 0.40 will lead to the cement not being completely hydrated, which results in a reduced amount of heat [7]. The concrete's heat of hydration, based on the density and heat of hydration of the cement, can be converted to an adiabatic temperature increase concrete:

$$\Delta\theta = \frac{Q_\infty \cdot C}{\rho_r \cdot c_b} \tag{2}$$

Where:

$\Delta\theta$ = adiabatic temperature increase [°C]
Q_∞ = amount of heat developed per cement unit [kJ/kg cement]
C = amount of binder [kg/m^3]
c_b = specific heat capacity of concrete [kJ/(kg·°C)]
ρ_r = density of concrete [kg/m^3]

By adding the initial temperature with the temperature rise, we get the theoretical maximum temperature in the concrete. It should be said that heat exchange with the surroundings has not been considered here. In the case of real castings, it will never take place under adiabatic conditions. Where there are temperature differences in a system, there will always be heat transport from high-temperature areas to low-temperature areas. This isotherm process happens via heat conduction, convection, or radiation transport mechanisms.

2.2.5. Maturity

The maturity function, or rate of hydration, expresses the reaction rate of cement hydration at arbitrary temperatures relative to the rate at 20°C. In the Norwegian context, it is usually implied that the function is based on the Arrhenius equation, describing the relationship between a rate constant in a chemical reaction and the absolute temperature. The function indicates the rate of hydration at a temperature level relative to the speed at 20°C. Standardised laboratory tests are performed at 20°C, which has resulted in a dimensionless function value equal to 1.0 at this temperature. The rate of hydration is expressed as shown in equation 3.

$$H(\theta) = \exp\left(\frac{E(\theta\ )}{R} \cdot \left(\frac{1}{293} - \frac{1}{273 + \theta}\right)\right) \quad (3)$$

Where:

$H(\theta)$	=	rate of hydration $[-]$
$E(\theta)$	=	activation energy [J/mol]
Θ	=	temperature [°C]
R	=	universal gas constant, 8.314 [J/mol · °C]

The activation energy regulates the temperature sensitivity as a bilinear function of the empirical constants, A and B:

$$E(\theta) = A + B \cdot (20 - \theta_i), \qquad if\ \theta_i > 20°C \rightarrow B = 0 \quad (4)$$

The empirical constants are determined via curve fitting of the strength development at 20°C up to approximately 50% of 28-days strength. They can also be determined if we know the strength development of the concrete composition at different temperature levels by calibrating the hydration function. They are thus dependent on the cement type, pozzolan content, and to a certain extent, the mass ratio. Figure 4 below illustrates the activation energy as a function of temperature for a typical construction concrete with 20% fly-ash, a concrete based on Portland cement [7] and the hybrid concrete used at Gullhaug Torg with a pozzolan content of 65%. The activation energy can be considered an expression of the temperature sensitivity of the reaction.

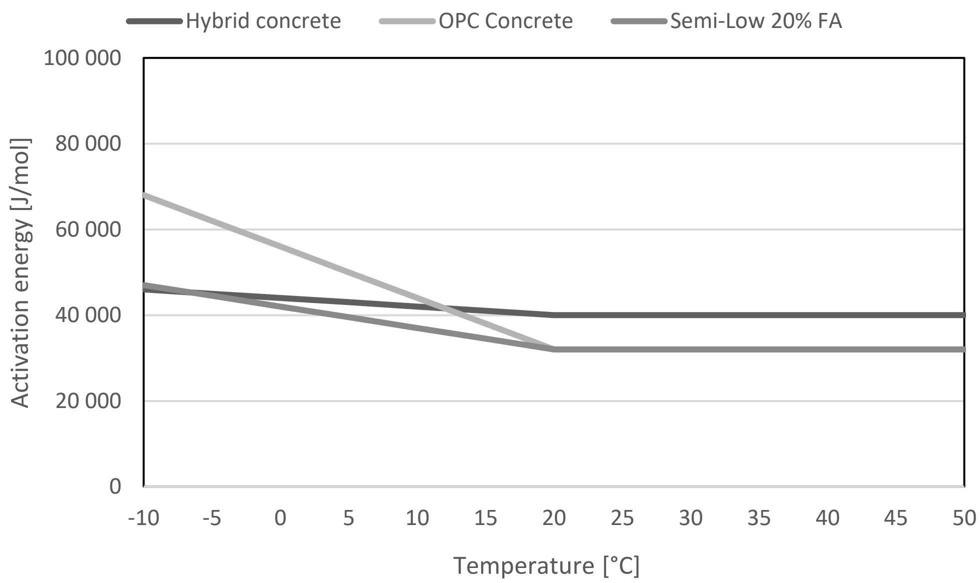


Figure 4. Activation energy as a function of temperature

An important notice when comparing the values of different types of concrete is that the rate of hydration describes the relative rate of hydration according to the rate at 20°C and is thus only suitable for describing the effect of temperature changes.

Time and temperature are two of the most critical factors affecting the strength development of concrete. Due to the temperature sensitivity of the hydration process, the property development cannot be unambiguously described as a function of time. This sensitivity is the background for introducing the concept of maturity, which compares time and temperature to equivalent curing time at 20°C. The maturity unit, M, is calculated as a time integral of the rate of hydration. In most cases, the temperature development is a measured course, making it correspondingly more useful to use numerical calculations in favour of the time integral [7]. Concrete that has hardened at an arbitrary temperature, T_1, for a specific time, Δt_1, then has maturity:

$$M_1 = H(T_1) \cdot \Delta t_1 \tag{5}$$

The numerical calculations of the maturity unit are calculated by dividing the curing process into a certain number of intervals of a specific time at a constant temperature. The constant temperature in each interval is calculated as an average based on time. The average temperature then gives the hydration rate associated with the given time interval. The product of time interval and rate of hydration determine the growth in the maturity of the concrete.

$$M = \sum_{i=1}^{i=n} H(\theta_i) \cdot \Delta t_i \tag{6}$$

Where:

M	=	maturity time
n	=	number of time intervals
H	=	rate function
θ_i	=	the average temperature at each interval
Δt_i	=	time interval

The instantaneous level of strength can be assessed by comparing the maturity with the development of strength at 20°C. The model provides accurate answers within a wide temperature range and covers critical times and scenarios such as frost safety, removal of formwork, and tension.

2.2.6. Strength development

The heat of hydration can be used to express mechanical properties such as compressive strength, tensile strength, and E-modulus. The development of strength depends on maturity. When the maturity of concrete at a given age has been calculated, one can relate this to strength measured at 20°C and find the actual strength of the concrete. It is generally acceptable to determine the strength using linear interpolation between test times. In cases where there is no good data for the strength development, it is acceptable to use empirical form functions that describe the connection with reasonable accuracy. The empirical equation 7 below can be used to describe the relationship, which is a modified version of the equation in CEB-FIP Model Code 90 [23], with reference to Kanstad et al. [24] and Bjøntegaard [16]. The parameter t_0 was first introduced by Kanstad et al. [24], and the parameter t_0^* was introduced later in CrackTest COIN [25]. Both parameters are related to the “final setting” and represent the distinguished time when the strength and stiffness are still defined to be zero, where significant values develop after. The implementation of such a parameter is convenient for material models where the setting time is being adjusted, i.e., different mix temperatures or with the use of retarding or accelerating admixtures [24].

$$f_c(M) = f_{c28} \cdot e^{\left[s\cdot\left(1-\sqrt{\frac{672-t_0^*}{M-t_0}}\right)\right]^{n_c}}, where\ n_c = 1 \quad (7)$$

Where:

$f_c(M)$	=	Compressive strength as a function of maturity [MPa]
f_{c28}	=	modelled strength at 28 days [MPa]
M	=	maturity time [hours]
t_0	=	Start time for stress development [hours], $t_0 = t_0^*$
s	=	function parameter
n_c	=	function parameter

Strength development determined by interpolation and adaptation of the function in a logarithmic coordinate system is illustrated in figures 5 and 6 below.

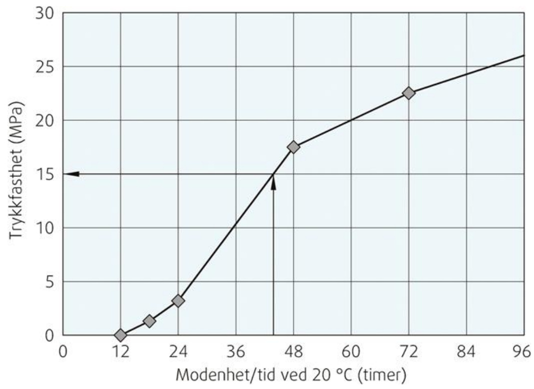


Figure 5. Interpolated strength development [22]

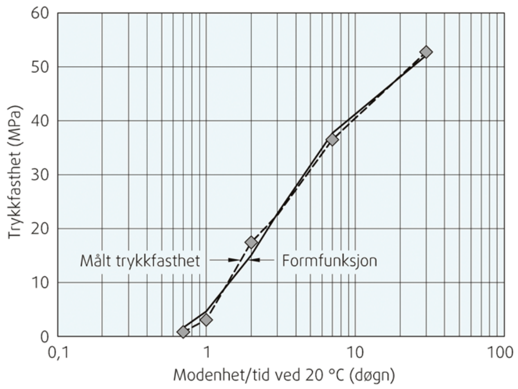


Figure 6. Adaption to measured strength development [22]

2.3. LCA and EPDs

During the lifespan of every project in the buildings and construction sector, they consume significant amounts of resources and energy and are eventually demolished. With the increasing environmental interest rapidly growing, more attention has been paid to sustainable housing technologies and construction methods. The environmental effects in the value chains of product processes must be recognised. We have to investigate every life cycle activity to answer and quantify the environmental impacts. An evaluation method called LCA is used. The method has been widely adopted due to the national and international regulations regarding the environment. The LCA has been frequently applied to products, but the principle simultaneously applies to buildings. The assessment examines products from the origin of raw materials to the consumption of energy and resources during useful life to the impact of the end of life. This process has become known as "cradle to grave" [26]. Furthermore, the LCAs also address the impacts of recycling and reuse, extending the assessment to what is known as "cradle-to-cradle".

By looking at concrete as an example, concrete requires, among other things, cement. Raw materials are processed and refined, often in several steps. Furthermore, cement consists of several resources that must undergo processes to achieve the desired quality. In each stage of each process, the use of resources causes emissions to the environment. We follow the product through an LCA from beginning to end, assessing each stage's environmental and resource conditions. Thus, LCAs provide knowledge to determine how resources can be used most efficiently and improve a product's environmental performance. LCAs are a viable and essential tool in construction projects with requirements concerning, for example, environmental certification through BREEAM, as is the case for Gullhaug Torg, where hybrid concrete plays an important role. In order to make the impacts caused by materials visible, EPDs are therefore prepared.

An EPD is a concise third-party verified and registered document with transparent and comparable information on products' environmental performance throughout the life cycle. The document provides a life-cycle-based account in which we map the resource consumption and potential environmental impacts. Independent third parties approve the EPDs. The declarations are comparable, publicly available, and combinable to form assessments for large projects. This information can assess the products' environmental properties in a building context, contributing to complete documentation of a building's environmental impact. EPDs are essential to more environmentally friendly choices through product and material comparisons. Furthermore, manufacturers can document the environmental effects of their product development and optimise the associated emissions. EPDs create an open and quantitative source of information and an environmentally significant basis for competition.

The underlying LCAs and EPDs are always based on international standards, and the environmental declaration is thus standardised. They meet requirements for environmental documentation for both private and public purchasers. EPDs are typically valid for five years and are based on ISO 14025 regarding environmental labels and declarations and ISO 21930, especially considering building materials. LCAs are based on the principles and framework in ISO 14040 and the requirements for conduction in ISO 14044.

Concrete components in a construction project are neither climate nor energy-friendly in production and manufacturing. The Norwegian Institute for Sustainability Research, NORSUS, has under the auspices of The Norwegian Ready Mixed Concrete Association, FABEKO, developed a calculation tool for EPDs that apply to ready-mixed concrete. The EPDs focus on the carbon footprint and the energy needed to produce and deliver the concrete. The Concrete Association (BEF) has developed a similar tool that applies to concrete elements [7]. EPDs for ready-mixed concrete based on the calculation tool cover the life cycle from "cradle to gate with options", i.e., up to and including production in the mixing plant, modules A1 to A4. Description of the modules according to NS-EN 15804:

- A1 – raw material extraction and processing, processing of secondary material input
- A2 – transport to the manufacturer
- A3 – manufacturing
- A4 – transport to the building site

These EPDs can be either product-specific or project-specific. In this lies that a product-specific EPD is registered with the Norwegian EPD Foundation, while a project-specific EPD is prepared by the concrete manufacturers following the guidelines described. An essential difference in transport contribution to the building site (A4) is that product-specific uses a generic value while project-specific

EPDs are based on the actual transport contribution. However, this contribution shall not be included in connection with the class limits for low-carbon concrete.

2.3.1. Environmental performance

Table 3 and the associated figure 7 provide a general overview of the environmental performance of the various concrete recipes concerning embodied energy and GWP contribution. The recipes are based on concrete produced by Unicon at Sjursøya in Oslo. The declared unit is 1 m^3 concrete, valid from phases A1 to A4. The EPDs apply to a concrete delivery between Sjursjøa and Gullhaug Torg 2A. The EPDs are in their entirety, provided in Appendix C. The value of embodied energy represents TRPE, "Total use of non-renewable primary energy resources". In other words, energy consumption from renewable energy sources is not included in figure 7. This consumption can be found in a separate row in the EPD found in the Appendix as TPE, "Total use of renewable primary energy resources".

The result shows that of the concrete recipes, only H65 satisfies the set emission requirement corresponding to 180 kg CO_2-eq/m^3 concrete. This level is otherwise the requirement for low-carbon class Plus regarding concrete in strength class B55 according to the low-carbon classes defined in NB37. According to these classes, which are given in table 4, H65 will be included as low-carbon class Plus, while H50 will be included as low-carbon class A, where the requirement is 230 kg CO_2-eq/m^3 concrete concerning strength class B55.

It should be mentioned that no specific requirements have been set for the concrete's embodied energy in this project. However, it is important data and a good indication for future projects. Furthermore, reference is made to Powerhouse Brattørkaia, which has had environmental ambitions in the same calibre as Gullhaug Torg. At Brattørkaia, post-tensioned slabs with corresponding requirements for compressive strength were also used. In contrast, the project operated with a goal of concrete with a maximum of 1500 MJ/m^3 embodied energy. This objective is also why slag concrete was not used at Brattørkaia. The results in table 3 show that both concrete recipes on Gullhaug Torg had satisfied a corresponding hypothetical objective.

Table 3. Quantitative presentation of the environmental performance of H65 and H50

Recipe	Embodied energy [MJ/m^3]	GWP-value [kg CO_2-eq/m^3]
H65	1327.0	166.9
H50	1473.0	206.4

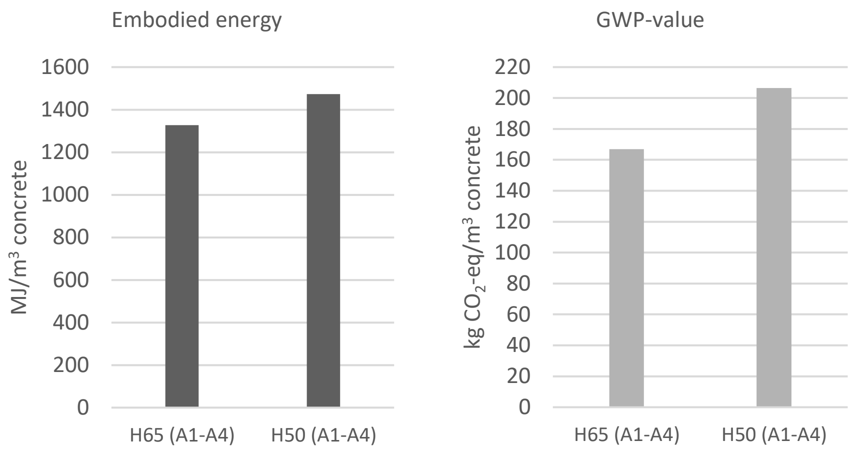


Figure 7. Overview of embodied energy and GWP contributions for H65 and H50

Regarding the energy consumption associated with the curing measures, this is reflected in the GHG accounts through the use of heating and additives. The energy consumption associated with heating is included in the life cycle module A5, *installation into the building*, in connection with the final documentation in BREEAM-NOR Mat 01, sustainable material choices. Energy consumption of construction sites for buildings typically makes up a small part of the total, in the order of approximately 1%, when energy consumption in operations and materials is taken into account. The consumption becomes even less if transport in operation is to be included. Experience has shown that heating in connection with curing constitutes a small amount of the construction site's total energy consumption. The use of additives affects the EPD, but the amounts are ordinarily small and affect emissions to a lesser extent [27].

Energy consumption is considered an ongoing follow-up of consumption, where there are standard prerequisites for this in, among other things, the reference buildings in OneClick LCA. It should be said that these assumptions vary widely. The energy consumption at Gullhaug Torg is registered through the documentation for BREEAM-NOR Man 03, responsible construction practice [27].

The emissions regarding the concrete used at Gullhaug Torg amount to around a quarter of the emissions from materials in the life cycle modules A1-A3 when technical systems are excluded. The preliminary greenhouse gas emissions are calculated against FutureBuilt documentation requirement V1.0 [27].

2.4. Legal framework and regulations

The legal framework is subject to the Planning and Building Act. It can be defined as a comprehensive hierarchy between law, regulation and standards considering all aspects of the buildings and construction sector. The comprehensive and detailed framework designed for the building and construction sector provides an essential starting point for safe, economical, and sustainable construction. The framework ensures concrete structures with satisfactory reliability and durability [28]. The compilation of current Norwegian Standards for concrete structures is displayed in figure 8 below.

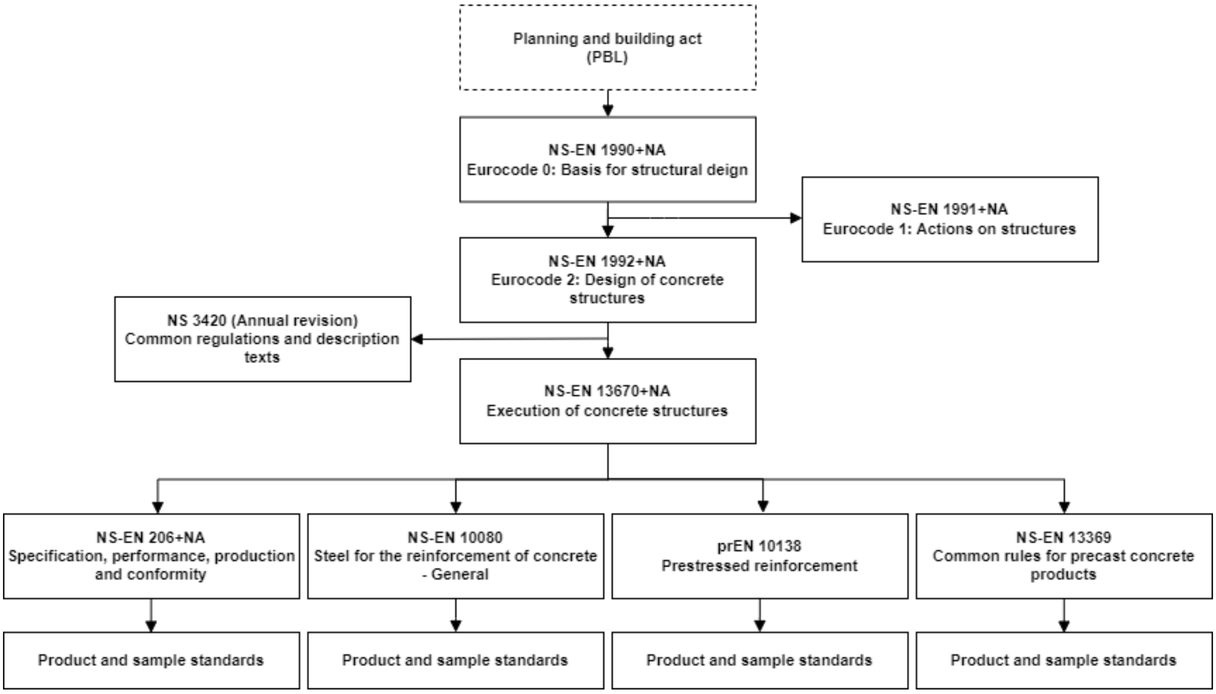


Figure 8. Compilation of the current Norwegian Standard for concrete structures [28]

2.4.1. Concrete framework

Through Standards, the framework provides guidelines for the design and execution of concrete work. They are purely technical and do not contain provisions on the division of roles between the individual actors in the construction process, contractual relationships, or conditions on financial settlements. The standards also design Eurocodes, an established European series of Standards for the design of buildings and documentation of products' load-bearing capacity and strength for construction purposes.

NS-EN 13760 is a Standard considering execution of concrete structures. As for a further assessment of requirements associated with concrete with light aggregate, additive materials or when using special technologies, this must be specified in the production documentation. There are requirements regarding the design of formwork, reinforcement, prestressing, and casting to name but a few. Furthermore, the Standard contains references to normative Standards where this is necessary. The normative references apply to NS-EN 206+NA, which considers specification, properties, production, and conformity in concrete [7].

To ensure the durability of concrete, the legal framework sets requirements for concrete sub-materials, properties of fresh and hardened concrete and detection of these, limitations in concrete composition, concrete specification, delivery of fresh concrete, production control routines, and conformity criteria and evaluation. Considering the standard NS-EN 206+NA, it is ensured that the concrete has a composition (through requirements for specification) and is produced (through requirements for manufacture) so that the desired properties are achieved. Rules have also been issued to check that the produced concrete has the expected properties. Consulting engineers use the Standard to ensure that assumptions in the design related to the concrete's properties result in specified requirements for the concrete manufacturer [29].

NS-EN 206+NA refers to several normative references that deal with requirements for aggregates, SCMs, additives, and several test standards. The regulations for fly ash, silica fume, and slag in concrete can be found in the national annexes. Each of the mentioned SCMs has its Standard in which they need to satisfy:

- NS-EN 13263-1 – “Silica fume for concrete"
- NS-EN 450-1 – "Fly ash for concrete"
- NS-EN 15167-1 – "Ground granulated blast furnace slag for use in concrete, mortar and grout"

2.5. Low-carbon concrete

Low-carbon concrete is a concept that has been developed as a result of the growing environmental focus in the construction industry. Concrete has great potential to reduce the large emissions associated with it. In this context, GHG emissions are defined as CO_2-equivalents, where the contribution is weighted according to GWP. OPC produced in Norway, such as "Norcem Industrisement", can have a total carbon footprint of approximately 800 kg CO_2-eq/t cement. The calcination amounts to approximately 480 kg CO_2/t cement. In a global context, this is considered a moderate emission. The opportunities to reduce emissions are the context for the major efforts, especially in Northern Europe, regarding energy consumption and carbon footprint in cement production. Today, many companies demand and require energy and carbon accounts for their projects, as they have invested in environmental management systems certified according to NS-EN ISO 14001. The environmental profile of the products is characterised by the use of EPDs, explained in chapter 2.3 [7].

Cement production and the significant CO_2 emissions that follow are the biggest environmental impact on concrete. This impact can be significantly reduced, especially for normal strength concrete. By using superplasticisers, highly reactive cement, optimising the distribution of particle size and reducing the water content, the amount of OPC clinker in the cement and concrete can be reduced. Essential is the already attainable substitution of natural residual products such as silica fume, fly ash and slag, otherwise known as SCMs. The replacement of clinker is the most significant contribution to reducing the emissions associated with cement. These SCMs are further explained in chapter 2.7. They are residual products from other industries, and as the carbon footprint is associated with the primary productions, SCMs are considered neutral in cement's carbon and energy accounts. This is, of course, with omitted transport contribution. It is impossible to reduce the emissions regarding the calcination process. Thus, the use of these pozzolanic and hydraulic materials provides environmental benefits. The use of SCMs also leads to new properties for the concrete, both positive and negative. These new properties entail new challenges for the concrete industry that require more experience and knowledge [30].

When using SCMs, it is a prerequisite that the concrete composition satisfies the requirements of NS-EN 206+NA for all low-carbon classes. Rules for mixed cement are given in table NA.12 (Appendix A), with stated limiting values for dosing pozzolanic and hydraulic binders in the various resistance classes. Further rules are given for how the mentioned binders are included in the concrete's mass ratio when checking the durability classes' requirements. Where it is necessary to deviate from the material composition set in the Standard in order to achieve a given low-carbon class, this must be clarified with the client. When calculating the proportion of the different SCM in the concrete, an efficiency factor (k-value) is used. The k-value is in accordance with the Standards of the respective SCMs. The highest amount of added SCM that can be considered when calculating mass ratios and the least effective amount of binder is given by the requirement [28]:

$$\frac{\mathrm{SCM}_{\mathrm{added}} + \mathrm{SCM}_{\mathrm{cement}}}{\mathrm{Total\ binder}} \cdot 100\% = \mathrm{SCM\ content} \tag{8}$$

It should be noted that the supplements are calculated separately. For fly ash, the maximum allowable amount is 35%, while for silica fume, it is 11%, calculated based on mass. The maximum proportion of slag depends on whether only slag and clinker are included as the main component in the cement or whether it is combined with fly ash. Combined with fly ash, the amount is 80%, and without it is 60% based on mass. Furthermore, chapter NA.5.3.2(902) in the Standard provides the opportunity to document conformity with the requirements of the durability classes by direct functional testing of relevant binder compositions. This criterion makes it possible to set new criteria for mass ratios and binder compositions otherwise not given as pre-accepted solutions in the Standard [28].

Low-carbon concrete is characterised by low heat generation and longer curing time, comparable to low-heat concrete. The difference is that low-carbon concrete is defined by limiting values concerning GHG emissions. There are no set Standards for low-carbon concrete. However, the Norwegian Concrete Association’s (Norsk Betongforening, NB) publication, NB37, defines the term and makes an industry-standard through a classification system with specific limiting values for GHG emissions [30]. The term is defined in NB37 as "a structural concrete produced according to the rules in NS-EN 206+NA, where measures have been taken to limit GHG emissions" [30]. Table 4 below presents these low-carbon classifications with their respective limiting values. The values are based on the Norwegian Ready Mixed Concrete Association's (FABEKO) EPD model and are limited to the production stage (A1-A3) of the life cycle as given in NS-EN 15804:2012+A2:2019. The class boundaries are differentiated based on strength and durability class. They are updated regularly so that the environmental goals for construction projects continuously align with the product range available in the Norwegian concrete market. The industry reference represents a realistic value regarding GHG emission, considering ordinary production in regions with the least favourable conditions. It is based on generic Norwegian values from 2019, obtained from EPDs from several concrete producers in all regions, which can estimate savings in GHG emissions by using low-carbon concrete. NB37 was first published in 2015 before the first revision was made in 2019, and then a minor update was carried out in 2020. The revision reduced the industry reference values by a minimum of 40 kg CO2-eq/m^3. The improvement is due to the concrete industry's environmental focus and significant measures to reduce its carbon footprint.

Table 4. Low-carbon concrete classes with limiting values for greenhouse gas emissions [30]

Strength class/ Low-carbon class	B20	B25	B30	B35	B45	B55	B65
The maximum permitted greenhouse gas emissions [kg CO_2-eq. pr. m^3 concrete]							
Industry reference	240	260	280	330	360	370	380
Low-carbon B	190	210	230	280	290	300	310
Low-carbon A	170	180	200	210	220	230	240
Low-carbon Plus	-	-	150	160	170	180	190
Low-carbon Extreme	-	-	110	120	130	140	150

The limiting values, as a result of the combination between low-carbon and strength class, is not necessarily available from all suppliers or even in all regions. The emissions that can be achieved depend on local parameters in terms of availability, quantities, transport, and competence. When defining the level of ambition regarding GHG accounts, the most prominent parameters to consider are:

- Strength class.
- Low-carbon class.
- Construction design.
- Span width.
- Cross-sectional dimension.
- Exposure class.

These parameters significantly impact the total concrete consumption and thus the GHG accounts, requiring good cooperation between the designers and contractors [30].

The two most ambitious classes, Plus and Extreme, can only be achieved by using particular types of cement and by adding large amounts of slag or fly ash, preferable in combination with a large amount of silica fume. The limiting value for low-carbon Plus is set so that, in practice, it represents the lowest GHG level that can be achieved by using fly ash as an SCM within the framework given in NS-EN 206+NA. Similarly, the limiting value for low-carbon Extreme is set using slag. The ambitious objective of reaching the class of low-carbon Plus is made possible by designing the concrete with large proportions of the pozzolans fly ash and silica fume. These concretes have a slow development of strength but a greater compressive strength in the long run compared to concrete with a higher proportion of Portland cement [30]. Such properties open up the possibility of moving the conformity criterion for the current strength class from 28 to 56 days. In practice, the conformity criterion at 28 days is reduced, corresponding to the documented aftergrowth between 28 and 56 days. Such an adaptation of the conformity criterion for the strength classes is not found in the Standards. The principle is nevertheless generally recognised, where the Norwegian Public Roads Administration (NPRA) provides rules for such an adaptation in handbook R762, chapter 84.4b. Reduction of the conformity criterion allows for a reduction in the amount of binder, which contributes positively to limiting GHG emissions beyond what can be achieved from a purely prescription point of view [14].

Through the overall quality criteria that follow the FutureBuilt program, the invested projects must be innovative, socio-ecologically sustainable, and have high quality. At the same time, the projects must, as a general rule, be located close to high-frequency public transport services. Regarding GHG emissions, the projects, as mentioned in subchapter 1.1.2, must have at least 50% reduced GHG emissions from materials, construction processes, energy use and transport compared with a reference building [31]. These are all criteria that Gullhaug Torg works to acquire. At the same time, no formal requirement has been specified for the GWP value of the concrete. Instead, it must be documented which of the minimum requirements from BREEAM-NOR are satisfied, or a GHG account must be carried out. The most ambitious requirement in BREEAM-NOR in terms of sustainable material requires 40% reduced greenhouse gas emissions from materials compared to the reference building, highlighting the significant environmental commitment to the project [32].

At Gullhaug Torg, the post-tensioned slabs are designed with concrete in strength class B55, which can be considered an unusually high strength class for this type of construction. The slabs in the project are planned to be made with a pozzolanic content of 65% and 50%, respectively. The concrete with 50% pozzolanic content will act as a "substitute" for the concrete with 65%, where exposed construction parts have difficulty achieving the desired strength due to challenging conditions [14]. Both have the potential to satisfy strength class B55 with an adapted conformity criterion. Furthermore, the prescribed mixes can probably be further optimised concerning the carbon footprint [14]. The choice is triggered by the need for increased shear capacity contribution from the concrete material by the columns. The post-tensioned slabs at the project stand for a significant proportion of the total concrete volume, and emphasis has therefore been placed on limiting the GHG emissions for these concrete structures. The objective is to satisfy the requirement for low-carbon Plus in accordance with NB37, indicating with the strength class of B55 a maximum allowed GHG emission of 180 kg CO_2-eq/m^3 [30]. Such concrete compositions are referred to as "hybrid concrete" and are explained further in the next chapter.

2.6. Hybrid concrete

The positive course of development regarding the concrete industry has created a vision of zero-emission concrete and has already come a long way. Together with several active commercial drivers, the industry has undergone tests with low-carbon concrete and reduced the carbon footprint. The ambitions are now significantly increased as there are opportunities for concrete products with significantly lower emissions. Some of these are available in the Norwegian market but are not currently used commercially in building constructions. These are concrete compositions that climatically go far beyond low-carbon concrete in class A, which is perceived as the industry's best practice today. The fly ash dosage is higher than that which can react with the $Ca(OH)_2$. Therefore, the extra strength contribution is due to the polymerisation of fly ash, in the same way as in geopolymers. This two-part binder effect is thus named "hybrid concrete", with opportunities of reaching categories such as low-carbon concrete class Plus, with reference to NB37 [30]. This new composition challenges the material-technical basis due to the high content of pozzolanic binders. Concrete with a high fly ash content has a slow development of strength, reduced heat development, and increased temperature sensitivity. These traits make the concrete more challenging during winter casting. As for the post-tensioned slabs, the concrete must achieve a given compressive strength before tensioning. When using hybrid concrete, this requires extensive knowledge regarding curing technology and accompanying measures in order not to delay the progress plan.

Gullhaug Torg, as a FutureBuilt project, has GHG gas ambitions that make it suitable for this concept. The established Standard work focuses primarily on durability, which means that part of the objective at Gullhaug Torg is to demonstrate that the concrete materialistic measures do not violate the Standard's assumptions concerning a long life for the concrete structures. The project's objective has been to develop post-tensioned concrete slabs with concrete containing approximately 50% fly ash. This content corresponds to a 35% reduction in GHG emissions compared to low-carbon class A and approximately a 60% reduction compared to the industry standard concrete. The hybrid concrete used in the project is, per definition, a low-carbon concrete, but the name of choice is an indication that the industry has taken a step forward. The name is set because the material is on the border between traditional Portland cement-based concrete and geopolymers. The latter has a binder that only contains fly ash, activated by adding large amounts of alkalis [33]. The thesis consists of a smaller literature study regarding the adoption of geopolymer technology in chapter 2.8.

Skanska has used a similar concept regarding hybrid concrete in constructing Powerhouse Brattørkaia in Trondheim. From this project, valuable experience and measurements are passed on to Gullhaug Torg. The results from Trondheim already show that the climate ambitions are within reach for the project at Nydalen. The temperature-sensitive concrete has properties that can affect the progress. At Powerhouse Brattørkaia, various curing measures were implemented, of which the effect of these will be suitable lessons to bring forward. To ensure efficient curing, heated concrete from the mixing plant was used. All free concrete surfaces were covered, and the underlying floors were heated using hot air units based on district heating or biodiesel. Weather conditions and variations have an increased impact that must be taken into account, which at the same time links an element of uncertainty to energy costs. The additional cost for the hybrid concrete is estimated at NOK 100 more per m^3 compared with traditional concrete [33].

2.7. Supplementary cementitious materials

In the composite material that concrete is, cement is the most prominent binder. Invented in 1824 by Joseph Aspdin, Portland cement has become the common term for the product that comes out of cement production. Today, there is a growing tendency for Portland cement clinker to be mixed with other materials to improve the concrete's environmental and technical aspects. These are SCMs such as silica fume, fly ash, slag, natural pozzolans, burnt slate or limestone. In this thesis, the two relevant SCMs are silica fume and fly ash, the main focus areas. Fly ash can be distinguished between natural pozzolanic material and an industrially produced material. The latter is in question when referring to fly ash in this thesis.

Pozzolans are a common term for amorphous silica- and alumina-containing (SiO_2 and Al_2O_3) materials that can react chemically with alkalis and the reaction product calcium hydroxide ($Ca(OH)_2$) from cement hydration to form a product with binder properties, as shown in formula 9. The premise for the pozzolanic reaction is that the hydration process first forms $Ca(OH)_2$, which can react with SiO_2. Therefore, the strength development from the pozzolanic reaction starts somewhat later. The delayed reaction is the most important reason why the early strength of concrete with added pozzolanic binders is lower than pure OPC-based concrete.

$$\underset{\text{Silicon dioxide}}{SiO_2} \rightarrow \underset{\text{Calcium hydroxide}}{Ca(OH)_2} + \text{Water} = \underset{\text{Calcium silica hydrate}}{\text{C-S-H}} \quad (9)$$

2.7.1. Silica fume

Silica fume is a by-product resulting from the reduction of quartz with coal in electric arc furnaces in silicon or ferrosilicon alloy production. The material is very fine-grained, with particles in the range of 0.1 to 0.5 microns (µm), approximately the size range of SARS-CoV-2-virions [34]. The particle size corresponds to a 20.000 m^2/kg specific surface area. The fine-grained particle size makes it challenging to handle; thus, alternative forms have been developed. Suppliers either handle silica fume as a slurry with water, in compact form or as a powder [7].

Silica fume is an amorphous, highly reactive pozzolanic material, indicating, as mentioned above, that the silica (SiO_2) reacts chemically with the calcium hydroxide ($Ca(OH)_2$) from the hydration process. The reaction product is calcium silicate hydrate (C-S-H), the most important binder in OPC concrete. Silica fume thus increases the amount of the desired binder.

The pozzolanic reaction leads to an increased heat development compared to OPC alone. Both are also temperature dependent, but silica to a greater extent. The response shows that the pozzolanic reaction proceeds slowly at low temperatures and rapidly at high temperatures, thus having consequences for practical use [7].

Further, the material has essential features improving the rheological and mechanical properties of the concrete, with three prominent roles. Firstly, the filling effect improves the packing density of particles. Secondly, the spherical nature of the particles makes for a lubricating effect enhancing the rheological properties. Thirdly, as mentioned above, the production of additional C-S-H enhances the mechanical properties [35].

In fresh concrete, the effect of silica makes the concrete somewhat stiffer. Due to the specific surface area, concrete with silica has an increased water demand, which reduces the tendency of separation. The reduced tendency results from silica fume always being added in combination with plasticising additives, making the concrete more homogeneous. As a practical solution, increasing the slump to gain the same workability as concrete without silica fume is common. Furthermore, the form and small size of the silica fume particles make for a good filler effect, pervading the voids between the larger cement particles. The combination of filler effect and plasticising additives gives the concrete increased stability as water physically binds to the surface area of the particles. On the negative side of things, it increases the risk of the concrete surface drying out, which can cause plastic shrinkage.

In curing concrete, the pozzolanic reaction considering silica fume is more temperature-dependent compared to the reaction regarding cement and water. The difference can be seen when comparing concrete with and without silica fume - at low curing temperatures, silica concrete experiences lesser strength in the early phase. On the other hand, high curing temperatures lead to high early strengths. Silica concrete is more robust when exposed to high curing temperatures, mainly because of the reduced development of porous reaction products. The challenge of silica concrete thus applies especially to winter casting as the concrete is exposed to the opposing sides that low temperatures entail [15].

In addition to the effects on fresh and hardening concrete, silica fume impacts the mechanical properties and durability. The silica fume positively affects adhesion, the pore structure becomes finer, and the concrete becomes denser. The increased density, a reduced amount of calcium hydroxide, and a more stable C-S-H phase increase the concrete's resistance to leaching, sulphate, and acid attack. Regarding reinforcement corrosion, silica fume has both positive and negative effects, of which the positive ones are dominant, which results in increased resistance to reinforcement corrosion.

2.7.2. Fly ash

Fly ash is a by-product of coal-burning furnaces at thermal power plants, and the name derives from the process of being transported from the combustion chamber by exhaust gases. The incombustible materials fuse, forming mainly spherical amorphous silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO). The properties differ significantly depending on the coal composition and the conditions at the plant. NS-EN 197-1 defines two types of fly ash: siliceous (V) and calcareous (W) fly ash. The former has pozzolanic properties, while the latter has hydraulic and pozzolanic properties. Only siliceous fly ash is used in Norway, i.e., the calcium content is less than 10% by mass [36].

Furthermore, in Norway, the material is most commonly used to produce fly ash cement but is also to some degree used as an additive to concrete at the mixing plant. Fly ash production is significantly larger than silica fume on a global level. The material consists of fine-grained spherical particles, predominantly cenospheres, and is included in approximately the same size range as cement, between 1 and 100 microns (µm). Fly ash thus has about the same specific surface area as cement, 300-600 m^2/kg, due to fly ash containing small amounts of residual carbon [7].

The chemical effects are similar to silica fume due to the amorphous silica and reactive pozzolanic material. Even though these effects are similar, the properties might vary to a greater extent as the chemical activity is smaller than it is for silica fume. The variation in properties is a consequence of coarser particles and a lower content of SiO_2 compared to silica fume. The favourable properties and heat development of fly ash thus develop slowly in concrete. Due to this slow heat development, cement with fly ash is often referred to as "low heat cement" [7].

In fresh concrete, the fly ash contributes to a higher matrix volume, increasing the workability due to a lower density than cement. Fly ash increases the number of fine particles, giving the concrete better stability but also contributing to making it somewhat stiffer. It can be concluded that fly ash has a similar effect on fresh concrete as silica fume.

The same applies to curing concrete. Fly ash reacts more slowly compared to cement, a feature often compensated by grinding the cement finer, making the early reaction faster. The early phase is identified by lower strength, but the pozzolan reaction will increase the strength in the long term. The concrete will also become more robust against high temperatures in the same way as silica fume. In the long run, concrete with fly ash will develop higher strength than some concrete without fly ash, provided that the mass ratio is equal. Fly ash increases the positive effect of adhesion on the concrete composition, caused by a more homogeneous concrete with an increased amount of the strong C-S-H-product.

Similar to silica fume, fly ash impacts the mechanical properties and durability. The fly ash positively affects the adhesion. The pore structure becomes finer, making the concrete denser. Concrete containing fly-ash has increased resistance to leaching, sulphate, and acid attacks due to the increased density and a reduced amount of calcium hydroxide and a more stable C-S-H phase. A recent study by Ishizuka et al. [37] concluded that a low-carbon concrete with large amounts of slag and fly ash had excellent sulphur-acid resistance with no loss in compressive strength.

2.7.3. Efficiency factor

For concrete with pozzolans, a practical approach to the effect of SCM on the strength of Portland cement systems and their resistance against carbonation and chloride penetration is by using the SCM efficiency factor (or k-value). The k-value is defined as the part of the SCM in a pozzolanic concrete that can be considered equivalent to Portland cement, having the same properties as the concrete without SCM. The quantity of the SCM in the mixture can be multiplied by the k-value to estimate the equivalent cement content, which can be added to the existing cement content to determine the water-to-cement ratio [38].

2.8. Alternative binder systems

This chapter consists of a brief literature study regarding the adoption of alternative binder systems.

2.8.1. Alkali-activated material

In AAM systems, the chemistry consists of glassy aluminosilicate phases with calcium from fly ash, slag, calcined clay, or volcanic ash. These calcium materials react with alkalis or a combination of reagents to form phases similar to zeolite. AAM is the most wide-ranging categorisation of binders regarding alkali activation technology. It includes any binder system derived from the reaction of an alkaline salt with a solid silicate powder. These salts can consist of alkali hydroxides, aluminates, carbonates, oxides, silicates, or sulphates. Their objective is to raise the pH of the reaction mixture and accelerate the dissolution of the solid precursor. The solid silicate powder can be calcium silicate or a precursor rich in aluminosilicates such as metallurgical slag or fly ash [39]. Considering the binder known as alkali-activated fly ash (AAFA), concrete with this binder can replace the entirety of the OPC with fly ash and the mixing water with an alkaline solution. The activation of fly ash with alkali is a chemical process where the glasslike component of this residual product is converted to a material with cementitious characteristics. The product formed in the main reaction is a three-dimensional alkaline aluminosilicate gel. The silicon tetrahedra of the reaction product are coordinated with aluminium tetrahedra [40]. The AAM concrete is characterised by good resistance against acid and fire. Such concrete does not produce the same high reaction heat as OPC concrete, leading to cost-reduction possibilities.

2.8.2. Geopolymers

Geopolymers are defined as a subclass of the broader alkali-activated binders. The geopolymers have been implemented into various niche applications. However, they have become a primary application as a binder in construction. The reason is the possibility of generating reliable, high-performance geopolymer with alkaline activation of fly ash or other pozzolanic binders. The discovery of the geopolymers was based on a controversial theory postulating that the Pyramids in Egypt were made of blocks cast in place, creating artificial zeolitic rocks. This controversy led to the conduction of experimental programs to prove the theory, resulting in the discovery of geopolymers as a family of mineral binders. The name derives from its similarities with organic condensation polymers regarding hydrothermal synthesis conditions. Therefore, geopolymer is considered as amorphous to semi-crystalline equivalents to particular synthetic zeolites. The geosynthesis considers the science of manufacturing artificial rock at temperatures below 100°C. This manufacturing obtains natural characteristics such as hardness, longevity, and heat stability [41]. Joseph Davidovits introduced the term "geopolymers" in the late 1970s to classify solid materials geosynthesized by the reaction of an aluminosilicate powder with an alkaline solution. The result was the production of a ceramic-like inorganic polymeric material. The reactive aluminosilicate powder is often metakaolin (calcined kaolinite clay) or fly ash [42]. The dissolution of this aluminosilicate powder leads to the formation of the sialate monomer, which is the material framework of polymeric Si-O-Al. The framework consists of alternatively linked SiO_4 and AlO_4 tetrahedra as they share all the O atoms. To maintain electric neutrality in the matrix, there is a presence of cations in the likes of K^+, Na^+ and Ca^{2+}. The reason is that Al is coordinated in four ways with respect to oxygen [41]. The binding phase is essentially entirely aluminosilicate, and the reacting components' available calcium content is usually low to form the gel in the primary binding phase. This low calcium content substitutes C-S-H's chain characteristics and enables the quasi-zeolitic network structure formation. Even though the calcium content in the reacting components is low, it does not imply that it corresponds with the overall content of the material. Geopolymer-type gel formations do in fact favour design mixes of low calcium content [39].

There are some distinct differences between geopolymerisation and the curing of the OPC. In cement, the primary reaction associated is the chemical hydration process, involving the formation of C-S-H and $Ca(OH)_2$. Another essential reaction is the ettringite formation from the gypsum to retard the initial hydration. Fly ash and other pozzolans are often added to the mix to increase durability and decrease shrinkage. The pozzolans react with the lime from the hydration and form more of the synthesized C-S-H and calcium aluminate hydrates. The primary distinction between the forming reactions of cement and pozzolans is that the pozzolanic reactions are accelerated due to temperature increase and the presence of an alkali metal hydroxide. Simultaneously, the pozzolans have the ability to serve as a reagent for geopolymer synthesizing. In this case, the reaction path is different, where the reaction occurs between the pozzolanic material and an alkaline media together with a water-solvent solution of polysilicates [43].

Geopolymer concrete is an advanced form of concrete with advantages such as improved strength and durability properties. It has high early strength and a rapid curing time, which reduces construction time. The strength gaining process is dependent on the geopolymerisation, and the properties are controlled by the choice of binder, alkali-activated solution, and curing measures. The amount of aluminium in the source materials controls the setting time, and the amount of silicon dioxide and aluminium oxide controls the rate of strength. This type of concrete is considered the green version of OPC-based concrete, as industrial by-products such as fly ash and slag are binders well suited with the geopolymers, utilizing the ability to reuse waste materials. The geopolymer cement is not reliant on the calcium carbonate's calcination process and therefore generates a minimal amount of manufactured CO_2 [44]. Several studies comparing energy consumption and CO_2 emissions of OPC and geopolymer cement have been conducted. Davidovits [44] compared OPC with rock-based geopolymer cement, as presented in table 5 below. The difference between slag as a by-product and a manufactured product is that the former has no additional energy needed.

Table 5. Energy needs and CO_2 emissions considering 1 tonne of OPC and rock-based geopolymer cement.

Energy needs [MJ/tonne]	Calcination	Crushing	Silicate sol.	Total	Reduction
Ordinary Portland cement	4270	430	0	4700	0 %
GP-cement, slag by-product	1200	390	375	1965	59 %
GP-cement, slag manufactured	1950	390	375	2715	43 %
CO_2 emissions [tonne]	Calcination	Crushing	Silicate sol.	Total	Reduction
Ordinary Portland cement	1.000	0.020	0	1.020	0 %
GP-cement, slag by-product	0.140	0.018	0.050	0.208	80 %
GP-cement, slag manufactured	0.240	0.018	0.050	0.308	70 %

The increasing global interest and concern regarding the rise in climate change and the growth in scientific understanding have provided a lift in the development of geopolymer concrete. The geopolymer technology is nothing new for the cement and concrete industry, as it has been around for nearly 50 years. Even so, there has been limited commercial awareness regarding the subject up until recently. The GHG emissions and its concern are not enough to develop such a change in the industry. Supply chains and scales of the economy must be developed, and local naturally occurring raw materials must be utilized. There are predominantly two barriers preventing geopolymer technology from further implementation in the building and construction industry. First is the need for Standards, where the development of such is a progressive process to be implemented in each governmental jurisdiction. The second barrier considers the question of durability regarding geopolymer concrete, as such data is not available for any newly developed material [39]. Geopolymer cement cures more rapidly than OPC and gains most of its strength within the first 24 hours. The combination of suitable properties combined with the environmental aspect makes geopolymers an exciting product to follow in the future.

2.9. The environmental ambition incentive

After conversations with the external supervisor, it is determined that the concrete prices that Skanska pays in the project remain within the company. As mentioned in chapter 2.6, the additional cost for the hybrid concrete is estimated at NOK 100 more per m^3 compared to traditional concrete. The additional cost will be the most relevant factor considering the incentive to implement environmental ambitions. From the received Solibri-file from Skanska, containing the BIM (building information modelling) model, the post-tensioned slabs' total volume was calculated. The total volume of the post-tensioned slabs and the additional cost is presented in table 6 below.

Table 6. The total volume of the post-tensioned slabs and additional cost at Gullhaug Torg

Parameter	High rise Volume [m3]	Low rise Volume [m3]
Post-tensioned slabs	1734	493
Additional cost	NOK 222,758.00	

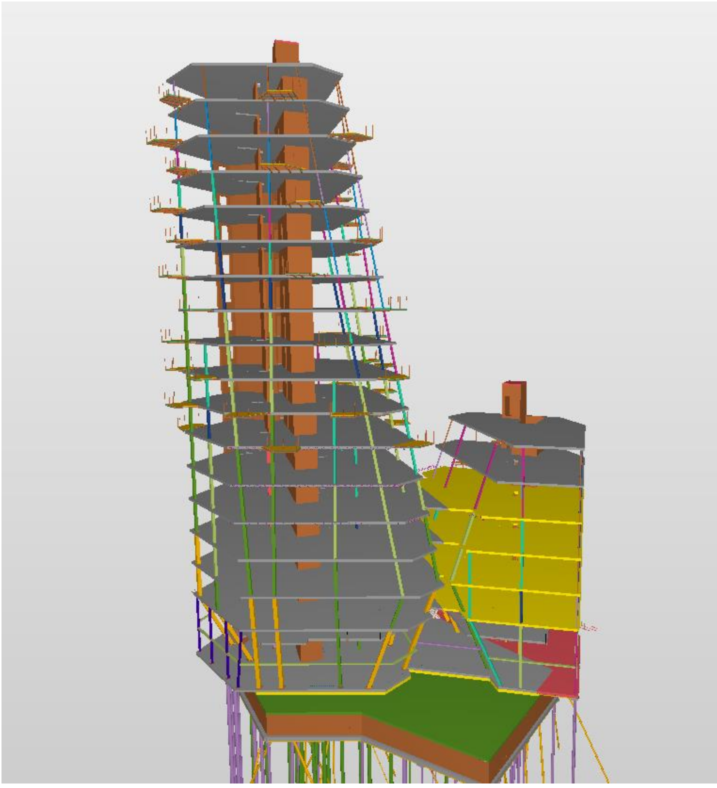


Figure 9. The post-tensioned slabs modelled in Solibri

Regardless of the size of the additional cost, the environmental ambitions require a client with a willingness to pay. When it comes to the ambitions associated with concrete and the goal of making it more environmentally friendly, new solutions will be costly to implement. Avantor as a client, contributes as an environmentally friendly urban developer with said willingness. The ambitions require a common goal for the new solutions to succeed, where all parties must understand the prerequisites and the risk. Costs associated with new solutions are often more significant for the initial projects, but the costs will be reduced for each project that later on implements these solutions. This is due to the increased competence that follows. The knowledge that has already started with the construction of the Powerhouse Brattørkaia, which has been passed on to Gullhaug Torg, is invaluable competence that reduces costs and opens the way for further development.

3. Method

This study will present the procedures used to analyse and evaluate the curing of the post-tensioned "hybrid concrete" slabs at Gullhaug Torg. The chapter will explain the terminology and the operating procedure and present the concrete compositions and curing measures conducted under various weather conditions. The analyses are based on data regarding three concretes with different contents of pozzolanic material: the two concretes related to Gullhaug Torg and a reference concrete. The analyses have been performed with the computer-based curing technology program "CrackTeSt COIN", which relies on mathematical models, requiring good material input data to illustrate the development of properties as accurately as possible. Skanska Teknikk has obtained these material data in collaboration with Unicon in advance of the thesis. Furthermore, fieldwork has been conducted considering casting a post-tensioned slab at the project.

3.1. Background for the analyses

With the environmental aspect as a cornerstone, the concrete industry constantly evolves. In order to lay the foundation for the aim of an emission-free concrete, potential decarbonization pathways are required. The use of industrial by-products as alternative clinker substitutes, or SCMS, is one such pathway and is the direction of this thesis. The term "hybrid concrete" is derived from the two reaction effects due to the high proportion of pozzolanic materials in the concrete. The reaction effects are partly pozzolan and partly a polymerization, hence the name "hybrid concrete". The use of this concrete entails changes in the material properties, where this task deals with the development of strength and temperature. As a FutureBuilt project, it requires the use of environmentally friendly concrete at Gullhaug Torg. The hybrid concrete considered for the post-tensioned slabs aims to achieve a compressive strength of 25 MPa within 3 days of curing. The development of strength is critical for the project. The requirement applies to the time of tensioning of the slabs and is therefore linked to the construction progress. The waiting time before the concrete achieves the required strength quickly becomes downtime as further work will take place on top of the slabs.

The thesis is mainly performed through an experimental method as a means to describe, control, and simulate the phenomena of interest. The thesis considers the simulations of the curing process with various curing measures performed using the two-dimensional FEM-based program, "CrackTeSt COIN". The simulations make it possible to optimise the curing process by comparing the effect of different measures and deciding which are applicable based on the conditions at casting. These preparations categorise the thesis as part of the project's planning phase. The fieldwork considering the casting is performed with temperature sensors to measure the temperature and compressive strength development of the post-tensioned slab on the 2nd floor of the low-rise building.

The weather is an essential factor concerning the construction phase of in-situ concrete. It influences the efficiency of labour productivity and the property development of concrete during the curing process. In this thesis, the latter will be in focus. The use of hybrid concrete as an environmentally friendly alternative entails changes in behaviour during curing. The positive sides of using concrete with a reduced carbon footprint also require comprehensive knowledge regarding weather conditions and their impact on concrete curing. These factors have shaped the goal and scope of the thesis and made it experimental by analysing the extent to which the concretes have a satisfactory property development and whether they can be used at challenging ambient temperatures and wind speeds. As mentioned in the paragraph above, compressive strength development is the decisive target parameter to determine whether or not to tension the prestressed slabs. As explained in subchapter 2.2.4, NS-EN 13670 requires that the concrete does not freeze until it has gained a strength of 5 MPa and that the curing temperature in the structure does not exceed 70°C. These are reference points that will negatively affect the property development of the concrete.

The most crucial target parameters are the strength and temperature development when exposed to different weather conditions. Consequently, the behaviour of the concrete can define the necessary measures and recommended use of concrete in actual weather conditions during construction. The effects of the weather conditions play an essential role in the progression of construction projects. Accordingly, concrete needs to be protected during casting to achieve the requirements concerning strength development before the removal of formwork. The thesis has defined different strategies of curing measures, which will be described in the later chapters. The experiments conducted throughout the thesis are defined in the course of three phases: planning, design, and analysis.

3.2. Planning

The planning phase of the thesis started as part of the initial definition of the thesis' framework with the external supervisor. Through discussions with both supervisors, it continued to make a robust and transparent base. The research question and problems to consider were firmly stated, and the independent variables were chosen. The experiment is quantitative, with fixed factors determined based on representative conditions. The object of the thesis' planning phase is to provide a basis for the material parameters and the boundary conditions used in the analyses conducted in CrackTeSt COIN.

3.2.1. Material properties and boundary conditions

Three different concretes compositions have been applied for comparison in the simulation program. The material data have been computed for the two concrete compositions following the ones used for the post-tensioned slabs at Gullhaug Torg. Both are coined as hybrid concretes, with 50% and 65% pozzolanic material, respectively. Their constituents are presented in table 7 below. After consultation with the external supervisor, the reference concrete used is chosen from the material library in CrackTeSt COIN. The reference concrete represents a construction concrete based on Norcem's concrete "Anlegg FA" developed from R&D projects at NTNU and SINTEF [45]. The three concretes used are:

- Hybrid concrete (M60B55, CEM II/A-V with 65% pozzolanic material), referred to as "H65".
- Hybrid concrete (M60B55, CEM II/A-V with 50% pozzolanic material), referred to as "H50".
- Semi low-heat concrete (CEM II/A-V with 20% fly ash), referred to as "SL20".

Table 7. Constituents of the hybrid concretes

Constituent	Description	H50 [kg/m^3]	H65 [kg/m^3]
Cement	Aalborg Rapid FA	239.6	181.8
Fly ash	FA Norcem (K=0.0)	41.3	123.9
Fly ash	FA Norcem (K=1.0)	90.9	68.6
Silica	Silica fume (K=0.0)	41.3	7.8
Silica	Silica fume (K=1.0)	-	3.1
Sand	0-8 mm	962.3	987.8
Stone	0-16 mm	363.8	354.8
Stone	16-22 mm	472.9	504.1
Superplasticiser	MasterEase 1020	4.8	4.7
Water	-	142.0	123.7
Total	-	2358.9	2388.2

The concrete mixtures will be simulated at several representative boundary conditions to simulate their behaviour with different implemented curing measures. The total period of simulation is set to 168 hours, corresponding to 7 days. In this way, the simulations deal with the most relevant three first days of curing and simultaneously indicate how the concrete properties further develop. The environmental temperature is simulated in a range from -10°C to 25°C in increments of 5°C. The initial concrete temperature is set to 15°C for environmental temperatures ranging from -10°C to 10°C, defined as Norwegian winter conditions. The environmental temperature is further set to 20°C for environmental temperatures from 15°C to 25°C, defined as Norwegian summer conditions. The concrete temperature is based on the produced concrete having a temperature of 20°C at the concrete factory at Sjursøya. The temperature is reduced by approximately 5°C when the environmental temperature is below 15°C. The reduction in concrete temperature results from the transport to the project site [14]. The wind is simulated in a range from 2 m/s to 8 m/s in increments of 2 m/s. This range is considered representative of conditions to occur in the project. The high-rise building consists of 18 stories, and it is not uncommon with wind speeds of 8 m/s on the upper floors. The concrete casting will be postponed when the wind speed exceeds 8 m/s, making this a natural end-value to study [45]. An overview of the calculation presumptions is presented in table 8 and below.

Table 8. Calculation presumptions: temperatures and formwork removal

	Summer	Winter
Ambient temperature	15 – 25°C	-10 – 10°C
Initial concrete temperature	20°C	15°C
Removal of formwork	3 days	3 days

Columns support the post-tensioned slabs, and the slab formwork is made with temporary horizontal and vertical moulds. The formwork consists of 21 mm plywood, removed after 72 hours. CrackTeSt COIN is modelling the constructions in 2D, and in order to carry out an appropriate simulation, coordinates are selected in the modelled construction for obtaining results. The convection coefficients for the boundary conditions are presented in table 9 below.

Table 9. Convection coefficients for the concrete boundaries

	U-value [W/m^{2}K]	Boundary
Formwork	6.67	21 mm plywood
Free surface	1000	Free surface

The slab edge with the active anchor will be considered adiabatic. The coordinates selected as measuring points take into account the location of the tendons and the passive anchor on the dead end. The slab considered in the analyses is modelled 6 meters wide with a thickness of 0.25 meters. The slab is illustrated in figures 10 and 11 below, where the measure points are marked in red in figure 11. The origin is defined at the lower-left edge in figure 11, the side with the active anchor, and the boundary here is set as adiabatic. The most considerable local tensile stresses resulting from the tendons will occur above the centre line, approximately 4 meters from the active anchor. This zone is considered the highest placement of the tendons in the cross-section. It will also be relevant to examine the strength and temperature development at the right end of the modelled slab, an exposed location.

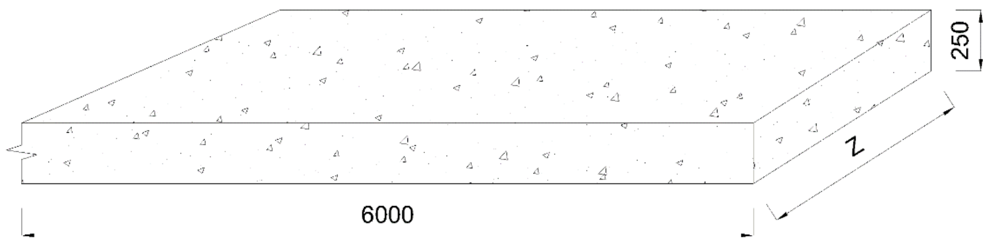


Figure 10. The post-tensioned slab used for temperature calculations [mm]

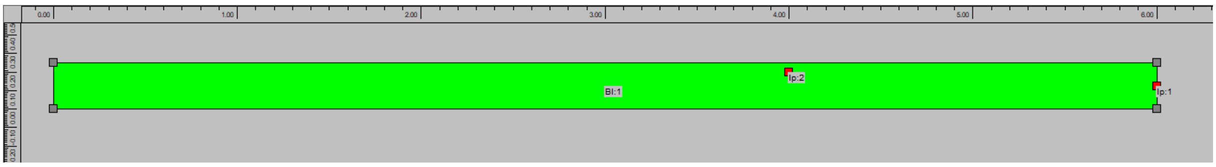


Figure 11. Illustration of the post-tensioned slab modelled in CrackTeSt COIN.

3.2.2. Curing measures

In response to the adverse effects of cold weather conditions, it is necessary to employ different curing measures to ensure the concrete property development is not too affected. Therefore, it has been conducted 7 different strategies of curing measures, separately or in combination, as well as a starting strategy considering only the formwork. The first strategy will give reasonable indications of how the different measures influence the strength and temperature development and how their effect is affected by various weather conditions. The curing measures considered in this thesis consist of using a curing accelerator, covering the top slab, covering and heating underneath the slab, increasing the temperature of the delivered concrete, and increasing the temperature at the edge of the slab by using heating cables. The different curing measures can be implemented in CrackTeSt COIN by defining the effect each of the measures has on the various concrete properties and outer boundaries in the program. The effects are presented in table 10 below.

Table 10. Curing measures and their influence on the parameters of CrackTeSt COIN

Curing measure	Value	Unit	Description
Cover top	8	h	The top of the slab will be covered with Ethafoam mats (expanded polyethylene) after 8 hours of casting.
Accelerator	5	h	The top of the slab will be covered with Ethafoam mats (expanded polyethylene) after 5 hours of casting.
Accelerator	-2	h	The final setting time of the concrete is adjusted and reduced by 2 hours.
Cover and heating underneath	0	m/s	The wind simulated at the formwork underneath is set as calm.
Cover and heating underneath	+10	°C	The environmental temperature is increased by 10°C at the formwork underneath.
Increased delivered concrete temperature	20	°C	Sjursjøa can deliver concrete with temperatures up to 25°C. Considers 20°C for environmental temperatures between -10 and 10°C. Considers 25°C for environmental temperatures between 15 and 25°C.
Heating cables end of the slab	+10	°C	Two heating cables are placed at the edge of the slab, 5 and 30 cm from the edge, respectively.
Heating cables end of the slab	30	W/m	The heating cables have an effect of 30 W/m until the removal of formwork (72 hours)

The hydration process is affected by the initial concrete temperature, the environmental temperature, the concrete dimensions, and the mix design. The adverse effects caused by the two matters of temperature can be counteracted by implementing curing measures to ensure the hydration process proceeds as desired. The strategies of curing measures defined and implemented in CrackTeSt COIN are presented in table 11. Regarding the choice of strategies consisting of separate and combined measures, efforts have been made to understand the curing measures' efficiency. The methods are based on generally adopted practical measures used in the construction industry. The correlation to the industry is deemed essential as the results of the simulations and analyses must be applicable in future construction projects, either for comparison or as a starting point for further experiments.

Table 11. Strategies of curing measures used in CrackTeSt COIN

Strategy	Curing measures
1	No measures
2	Cover top
3	Cover top, cover and heating underneath
4	Cover top, cover and heating underneath, curing accelerator
5	Cover top, cover and heating underneath, increased delivered concrete temperature
6	Cover top, cover and heating underneath, curing accelerator, increased delivered concrete temperature
7	Cover top, cover and heating underneath, heating cables
8	Cover top, cover and heating underneath, curing accelerator, heating cables

3.3. Design

It was early determined to use CrackTeSt COIN to simulate and analyse the data, entering into the design phase. The choice of manipulative independent variables from the planning phase led to the conduction of 768 unique simulations, distributed between the different concretes, ordered by the wind speeds, the environmental temperatures, and the various curing measures. The rigid independent variables of each concrete remain fixed throughout the experiment, while the manipulative variables define the differences in the simulations. In the following subchapter, the mathematical methods and factors will be explained as well as the procedure in CrackTeSt COIN.

3.3.1. Compression strength and heat development

There have not been conducted separate laboratory experiments for this thesis. This data was already conducted by Skanska beforehand. The property data for the two actual concretes used at Gullhaug Torg was thus achieved directly from them. The established material parameters result from heat development from semi-adiabatic calorimeter tests. The temperature development in the concrete samples is measured and converted to heat development as a function of maturity, i.e., isothermal heat development at 20°C. Calculation of activation energy is done by using the principle expressing that equal maturity gives equal compressive strength. For both H65 and H50, compressive strength tests have been performed in advance at 5°C, 20°C and 35°C. The procedure used to find the two empirical parameters, A and B, as shown in equation 4, is as follows: the compressive strength model, equation 7, is adapted to the compressive strength test result at 20°C. Furthermore, the maturity time scale is adjusted by first changing parameter A so that the 35°C test results match the graph of the 20°C test results. Next, parameter B is changed so that the 5°C test results match the 20°C test results graph.

The concrete compositions used in the project have been developed with given values and models for different material properties stored in a material library in CrackTeSt COIN. This master's thesis is associated with the project's planning phase by analysing the concrete's strength and temperature development prior to casting. The material data quality is decisive for how accurate the calculations will be. With good material data, CrackTeSt COIN becomes a valuable tool for mapping the concrete's behaviour at different temperature conditions and implementing the proper curing measures. Little testing is required to achieve reasonable accuracy when documenting concrete properties to calculate strength and temperature development. Such calculations are therefore easy to perform even with new binder combinations.

The temperature of the concretes during the hardening phase is typically measured using a curing box. Other less applicable and commonly used methods are isothermal heat conduction calorimeters and adiabatic calorimeters. The curing box, also called a semi-adiabatic calorimeter, measures the temperature development in the concrete sample with a thermometer and a data logger. The temperature development is then converted to heat development as a function of maturity.

The heat development can also be described mathematically. In Norway, it is common to consider the empirical shape function that Freiesleben-Hansen introduced in Denmark:

$$Q(M) = Q_\infty \cdot e\left[-\left(\frac{\tau}{M}\right)^{\alpha}\right] \quad (10)$$

Where:

$Q(M)$ = heat generation as a function of maturity time [J/kg]
Q_∞ = final heat generation after infinite time [J/kg]
M = maturity [h]
τ = curve fitting parameter [h]
α = curve fitting parameter [−]

CrackTeSt COIN is made in Sweden, where the Swedish exponential function is applied:

$$Q(M) = W_\infty \cdot e\left(-\lambda_1 \cdot \ln\left(1 + \frac{M}{t_1}\right)\right)^{-\kappa_1} \quad (11)$$

Where:

$Q(M)$ = heat generation as a function of maturity time [J/kg]
W_∞ = final heat generation after infinite time [J/kg]
M = maturity [h]
λ_1 = curve fitting parameter [−]
t_1 = curve fitting parameter [h]
κ_1 = curve fitting parameter [−]

Table 12. Parameters in CrackTeSt COIN for estimating heat development

Parameter	H65	H50	SL20
Density, ρ_r	2381 [kg/m^3]	2400 [kg/m^3]	2335 [kg/m^3]
Total amount of binder, C	413 [kg/m^3]	448 [kg/m^3]	389 [kg/m^3]
Effective amount of binder	281 [kg/m^3]	372 [kg/m^3]	400 [kg/m^3]
Effective water amount	127 [kg/m^3]	146 [kg/m^3]	162.3 [kg/m^3]
Mass ratio	0.45 [-]	0.39 [-]	0.41 [-]
Heat capacity	980 [J/kg·K]	1000 [J/kg·K]	1000 [J/kg·K]
Developed amount of heat, Q_∞	280 [kJ/kg]	320 [kJ/kg]	350 [kJ/kg]
Curve fitting parameter, t_1	13 [h]	13 [h]	11.16 [h]
Curve fitting parameter, κ_1	1.1 [-]	1.53 [-]	1.53 [-]
Curve fitting parameter, α_1	1.0 [-]	1.0 [-]	1.0 [-]

The estimation of compressive strength in CrackTeSt COIN is a modified CEB-FIP model code formulation. The empirical function is advantageous as the program does not handle deterministic data [16].

$$f_c(M) = f_{c28} \cdot \left\{ e\left(s \cdot \left(1 - \sqrt{\frac{672 - t_0}{M - t_0}} \right) \right) \right\}^{n_c}, where\ n_c = 1 \tag{12}$$

Where:

$f_c(M)$	=	compressive strength as a function of maturity time [MPa]
f_{c28}	=	compressive strength at 28 days (= 672 hours) [MPa]
t_0	=	initial strength development [hours]
M	=	maturity [h]
s	=	curve fitting parameter [−]
n_c	=	curve fitting parameter [−]

The parameter t_0 in the FIB model corresponds to the "final setting". It can be considered the starting time for both heat generation and the development of mechanical properties, as described in subchapter 2.2.6. The transition from the plastic phase to hardening material is, in reality, more diffuse. In CrackTeSt COIN, it is prepared to be able to take this into account by defining a set-off period delimited by $t_{initial}$ and t_{Final}. In practice, this has little significance for the thesis results, and it is common to assume that t_{Final} and t_0 are equal. The aim is to settle for a more realistic strength development during the plastic phase, and as the FIB model function is applied from the "final setting", the transition does not influence the thesis results. The value of $t_{Initial}$ does not matter as long as it is less than t_{Final}.

Table 13. Parameters for estimating compression strength in CrackTeSt COIN

Parameter	H65	H50	SL20
f_{c28}	67.2 MPa	80.0 MPa	50.7 MPa
$t_{Initial}$	1.0 h	1.0 h	8.0 h
$t_{Final} = t_0$	7.8 h	7.8 h	11.0 h
s	0.31 [-]	0.31 [-]	0.211 [-]

The activation energy regulating the temperature sensitivity of the concrete is a bilinear function as presented in subchapter 2.2.5. The constants A and B depend on the type of cement, pozzolanic material, and mass ratio. The constants are estimated based on the principle that the same relative compressive strength should give the same relative maturity. When the strength development in some concrete is known for three different temperature levels, the activation energy constants can be adjusted to follow the same graph in terms of maturity. Firstly, the constant A is adjusted for any temperature levels from 20°C onwards until an acceptable coincidence between strength developments when time is expressed as maturity. The adjustments can be estimated through iteration using the least square method based on measured data. Secondly, the constant B is adjusted similarly for temperatures below 20°C. The order of the adjustments is based on the activation energy being constant at temperatures above 20°C, i.e., B is equal to 0 in this range. The activation energy parameters show that the value of A increases with increasing fly ash content while the value of B decreases. This is experienced in the R&D projects at NTNU, where, among other things, the hydraulic binder of slag has shown to have an even higher value of A in the area of 50 000 J/mol [45].

Table 14. Parameters for activation energy

Parameter	H65	H50	SL20
A	40 000 J/mol	40 000 J/mol	32 000 J/mol
B	200 J/mol·°C	200 J/mol·°C	500 J/mol·°C

3.3.2. Procedure

To see how far it is possible to extend in terms of weather conditions and still cast to achieve satisfactory quality, simulations have been carried out within a relevant range area, as described in chapter 3.2. The worst-case scenario is considered with an ambient temperature of -10° and wind speed of 8 m/s. On the contrary, the best-case curing scenario is considered with an ambient temperature of 25°C and a wind speed of 2 m/s. These extremes will provide an acceptable range to analyse the emerging changes in development. As part of the planning phase of a project, the conditions simulated in the computer-based curing technology program must be representative of actual plausible conditions.

Prior to this master's thesis, Skanska Teknikk, in collaboration with Unicon, carried out strength and temperature documentation and generated EPDs of the respective concrete compositions. The curing technology parameters specified through extensive laboratory testing have been used to design the concrete properties of CrackTeSt COIN. Table 15 gives an overview of the working methodology and procedures performed in CrackTeSt COIN, from the input of rigid independent and manipulative variables to the export and collection of desired data.

Table 15. Overview of working methodology and procedures of CrackTeSt COIN

Procedure	Details	Note
Modelling	The construction to be analysed is modelled in 2 dimensions.	The construction can be drawn as a preliminary design with all the required nodes. It can then be detailed by changing the coordinates of the nodes in the model.
Finite element mesh	The size of the elements can be changed according to the desired accuracy. The model has an element size of 0.05 meters. When generating the mesh, the element size corresponds to 5 elements across the cross-section.	A rule of thumb is to have at least three elements across the cross-section, leading to faster simulations but at the expense of quality. The model is therefore modelled with 5 elements across the cross-section.
Simulation time	The simulation time must be accounted for, setting it to 168 hours, corresponding to 7 days.	It is the time interval for which calculations are to be performed. As the analysis focuses on the strength and temperature profile, the time interval may be shorter than if stress analyses are performed. The reason is that the crack indices can occur far into the curing process.
Material	The modelled construction part is linked to the three concretes considered in this thesis.	The concrete materials are either custom or from the program's material library. In this case, two custom materials are used in the form of the hybrid concrete for Gullhaug Torg and a reference concrete from the program's material library.
Parameters	The concrete is given a starting temperature based on the ambient temperature for the specific scenarios.	The material properties of the concrete can be changed if desired to achieve a better adaptation to the conditions of a project. This change will not be the case here.
Curing measures	The bottom and vertical sides are modelled with 21mm plywood removed after 72 hours. The top is insulated with 10mm expanded polyethylene (Ethafoam mats) 8 hours after casting and removed after 72 hours. The scenarios are implemented as described in subchapter 3.2.2. by changing: 1.the final setting time in heat properties 2.the starting temperature of the concrete 3.the environmental temperature 4.the time of insulation 5.the wind speeds.	The curing measures are modelled by their effect on the heat loss and are entered by specifying boundary conditions for the surfaces. The effects are specified directly in transmission or wind speeds, and various insulation materials are selected from the program's database. The boundary conditions can be time-dependent, making it possible to include the removal of formwork, the effects this entails, and the insulation application.
Calculations	When everything has been modelled, the temperature calculations can be run. When this is done, the strength calculations can be run.	The calculation results can be presented as curves or colour charts for temperature, maturity, strength, stress, and crack index.
Results	The results are obtained for chosen points in the construction; (4000, 0.200) and (6000, 0.125). For this thesis, curves and colour charts are extracted for compressive strength and temperature over the entire time interval. Deterministic data for the two parameters are also collected.	The results are retrieved either as figures of the curves and colour maps or as text files with deterministic data in tabular form. The program also can design a complete report of all the procedures and results.

3.4. Fieldwork – the casting of hybrid 65 at the construction site

In connection with the construction of Gullhaug Torg 2A, this thesis has included fieldwork belonging to the first cast of the post-tensioned slabs on the project. The first casting of the post-tensioned slabs was carried out on 12.05.22 over the 2nd floor of the low-rise building. The aim of the fieldwork was to document temperature and strength development at an early age. The project used a wired solution from Maturix, called Gaia 200 [46], with thermocouple sensors attached to rebars which then were placed at the desired measuring points and embedded into the concrete. The thermocouple is plugged into a wireless transmitter to start the continuous data transmission. The concrete is then cast, and the monitoring in the software can be followed in real-time during the curing process. The data transmitter is placed outside the concrete, where the real-time collected data is continuously sent to the cloud at transmission intervals of 15 minutes. Figures 12 and 13 show the thermocouples and transmitters measuring at a passive anchor and the top of a tendon. The sensors were installed to measure the ambient temperatures and the concrete temperatures in exposed areas. Thus, the sensors were located at a passive anchor and at the minimum cover from tendon to top of the slab. With reference to subchapter 3.2.1, this corresponds to the measuring points used in CrackTeSt COIN and will therefore result in good comparable measurements. The measured ambient temperature and wind during the process will be implemented in CrackTeSt COIN to see the correspondence between measured and simulated data.

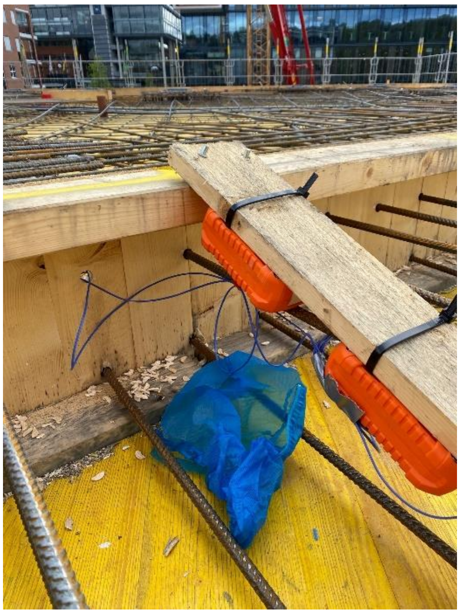


Figure 12. Thermocouples and transmitters before casting

Figure 13. Thermocouples and transmitters after casting

The aim was still to achieve sufficient strength after 3 days of curing, meaning that the formwork would be removed 15.05.22. As this was a Sunday, the time of removal was extended one day. The cast slab was in the order of 80 m^3, of which most of the deliveries were 7 m^3. The concrete trucks were ordered at 15-minute intervals, and the ordered concrete had a target slump of 240 mm and a flow of 500 mm.

To examine the properties of the concrete on the project, the temperature sensors, together with the software, will automatically calculate the maturity and thus the strength development based on the logged data and the concrete composition. In this way, the strength development process can be followed continuously.

At the same time, concrete cubes were taken out to carry out the cube test and find the compressive strength after 28 days. This will occur after the submission deadline for the master's thesis and will thus not be included as part of the result. It must be pointed out that this is a result that is not necessary for the task but would be relevant to have included as a comparison to the parameters for mechanical properties used in CrackTeSt COIN.

3.5. Analysis

The analyses of all the simulations require the collection of relevant data to be computed transparently. The relevant data is, first and foremost, the compressive strength and temperature development after 3 days of curing. The desire is to achieve the compressive strength of 25 MPa within 72 hours. Once the slab is tensioned, the formwork and most of the support can be removed. Then further work on top of the slab can begin. The third day of curing is thus considered the target time when the formwork should be removed. Any delays in formwork removal extend the construction duration, where corrective measures are often costly and hard to employ.

Further, the time when the strength development reaches 25 MPa is essential to understand how the concretes early property development behaves under challenging conditions. The simulations consist of 3 types of concrete, 4 different wind speeds, 8 different environmental temperatures and 8 strategies, corresponding to 768 completed simulations. The high number insinuates the importance of emphasizing good underlying planning. Therefore, curing measures and representative weather conditions were reviewed concerning the project's design and location. Regarding the fieldwork following the casting of the slab above the second level of the low-rise building, the measured data will be implemented in CrackTeSt COIN. The measured ambient temperature and wind will be simulated in detail by plotting the variations during the curing time.

As mentioned in table 15, every temperature calculation performed in CrackTeSt COIN takes place in a two-dimensional plane. The heat analysis results available are:

- Temperature development
- Maturity time
- Compressive strength
- Boundary heat flow

The heat flow results are automatically converted to input data for the structural analysis. As mentioned in subchapter 2.2.3, CrackTeSt COIN offers two different stress conditions, linear line analysis and plane surface analysis. Both conditions are based on the Navier-Bernoulli hypothesis, i.e., plane sections remain plane [25]. In the calculations throughout this thesis, the plane surface model has been used, meaning that the results vary in the two-dimensional plane in accordance with the boundary conditions. The structural analysis results available are:

- Compressive strength development
- Tensile strength development
- Stress development (due to thermal dilation and autogenous deformation)
- Stress/strength ratio (crack index)
- Strain ratio

The results from CrackTeSt COIN will be compared with the results from the fieldwork. This is an important part that provides the opportunity to verify the results of the curing technology program against the actual results of casting on the project.

In this thesis, the relevant results from the heat and structural analysis are temperature and strength development. The interpretation and evaluation of the property development will be assessed in the following chapter regarding the results.

4. Results

This chapter considers a systematic review of research data regarding the results from the conducted simulations and the casting at the cite. Relevant associated parameters will also be accounted for. The results will then be compared against each other concerning the theory from chapter 2. The results will be presented in subchapters based on curing measures and weather conditions and will form the basis of the following discussion chapter.

4.1. Simulations

As mentioned in subchapter 3.2.2, the simulations are based on 8 different strategies of measures, where the first strategy only consists of formwork. The three concretes are exposed to different weather conditions, consisting of wind speeds and ambient temperatures deemed representative of the project's location. Casting procedures will also be put on hold when the wind speed exceeds 8 m/s.

Table 16. Overview of manipulative variables

Wind speed	Temperature	Curing measure strategies	Simulations
2 – 8 m/s Increments: 2	-10 – 25°C Increments: 5	8	768

The number of unique simulations ended at a total of 768. Each concrete was simulated with the 8 different curing measures and tested for the 4 different wind speeds and the 8 different ambient temperatures. The main objective at Gullhaug Torg related to the post-tensioned concrete slabs is to reach a compressive strength of 25 MPa after 3 days of curing. Through the simulations, this has been the threshold level, which either is unattainable or obtainable with or without measures.

4.2. Heat development

As explained in subchapter 2.2.4, the heat development is calculated for the 3 concretes. The calculation of the two hybrid concretes is based on data from their respective concrete recipes, and the amount of heat development per cement unit is obtained from CrackTeSt COIN, see table 17. The concrete recipes are presented in Appendix B. The reference semi low-heat concrete calculation is based solely on data from CrackTeSt COIN, either from material data or recipe information in the description.

Table 17. Parameters of developed heat amount in CrackTeSt COIN

Parameter	H65	H50	SL20
Developed heat amount, Q_∞	280 [kJ/kg]	320 [kJ/kg]	350 [kJ/kg]

Regarding the specific heat capacity of the concrete, this mainly depends on the water content. The absolute heat capacity can be estimated using the recipe numbers and assuming that the concrete's water has a specific heat capacity of 4.2 kJ/(kg·°C). The remaining sub-materials have a specific heat capacity of 0.8 kJ/(kg·°C). Most concrete has a specific heat capacity between 1.00 and 1.10 kJ/(kg·°C).

Therefore, it is accepted and commonly used 1.05 kJ/(kg·°C) as a standard value for all structural concrete [7].

It is essential to point out that full conversion of the curing heat can only take place under adiabatic conditions. In the case of casting, heat loss will always occur to a greater or lesser degree. The data and calculations are presented in tables 18-21 below. The binder includes the cement and the pozzolanic material multiplied by their respective efficiency factor.

Table 18. Specific heat capacity of H65

Constituents	Amount [kg/m^3]	Specific heat capacity [kJ/(kg·°C)]	Absolute heat capacity [kJ/(m^3·°C)]
Binder	281	0.80	225
Water	127	4.20	533
Aggregate	1847	0.80	1477
Total	2388	1.05*	2236

* Standard value for all construction concrete

Table 19. Specific heat capacity of H50

Constituents	Amount [kg/m^3]	Specific heat capacity [kJ/(kg·°C)]	Absolute heat capacity [kJ/(m^3·°C)]
Binder	372	0.80	298
Water	146	4.20	613
Aggregate	1799	0.80	1439
Total	2359	1.05*	2350

* Standard value for all construction concrete

Table 20. Specific heat capacity of SL20

Constituents	Amount [kg/m^3]	Specific heat capacity [kJ/(kg·°C)]	Absolute heat capacity [kJ/(m^3·°C)]
Binder	400	0.80	320
Water	162	4.20	682
Aggregate	1773	0.80	1418
Total	2335	1.05*	2373

* Standard value for all construction concrete

By inserting the relevant parameters from tables 17 and 18-20 into equation 2 from subchapter 2.2.4, the temperature rise of the concrete is calculated, presented in table 21. Including an initial concrete temperature of 25°C, the highest initial temperature that Unicon can deliver, gives the theoretical maximum temperatures. Regarding NS-EN 13670, section 8.5 concerning protective and curing measures, the maximum temperature of the concrete in a component exposed to wet or cyclically wet exposure shall not exceed 70°C. The calculated maximum is only a theoretical maximum temperature as a complete conversion of the curing heat to a rise in temperature in the concrete only can take place under adiabatic conditions. The simulations are run with ambient temperatures from -10 to 25°C, and there will thus be high degrees of heat loss to the surroundings. Therefore, the temperature rise is to be regarded as within the limit. From table 21, H65 has a temperature rise of 33°C, which is the lowest in comparison.

When using silica fume in the concrete, the requirement concerning a maximum temperature of 70°C during curing can be somewhat increased. The use of pozzolanic materials, mainly silica fume, reduces the risk of sulphate attack. The sulphates react with calcium hydroxide and the aluminate minerals, especially tricalcium aluminate (C_3A). The reaction product is ettringite, which is undesirable when there is no more reactive gypsum. It must be emphasized that this primarily applies to constructions with massive cross-sections and, therefore, will not be a problem in post-tensioned slabs.

Table 21. Theoretical temperature rises of the concrete

Parameter	H65	H50	SL20
Temperature rise, $\Delta\theta$	33°C	48°C	57°C
Theoretical max. temperature, $\Delta\theta_{t.max}$	58°C	73°C	82°C

4.3. Activation energy

The determination of the model parameters A and B, as explained in subchapter 3.3.1, was carried out in advance of the master's thesis. Therefore, it is of interest to check the validity of the test result Skanska achieved. This validity has been reviewed by considering the results from the compressive strength and temperature development performed in CrackTeSt COIN at 5°C, 20°C and 25°C, together with the maturity calculated using equations 3, 4, and 6. Figures 14 and 15 present the compressive strength against time for H65 and H50, respectively, while figures 16 and 17 present the effect of the activation energy, and the compressive strength is thus illustrated against maturity hours. The graph named FIB defines the form-function, as described in equation 7.

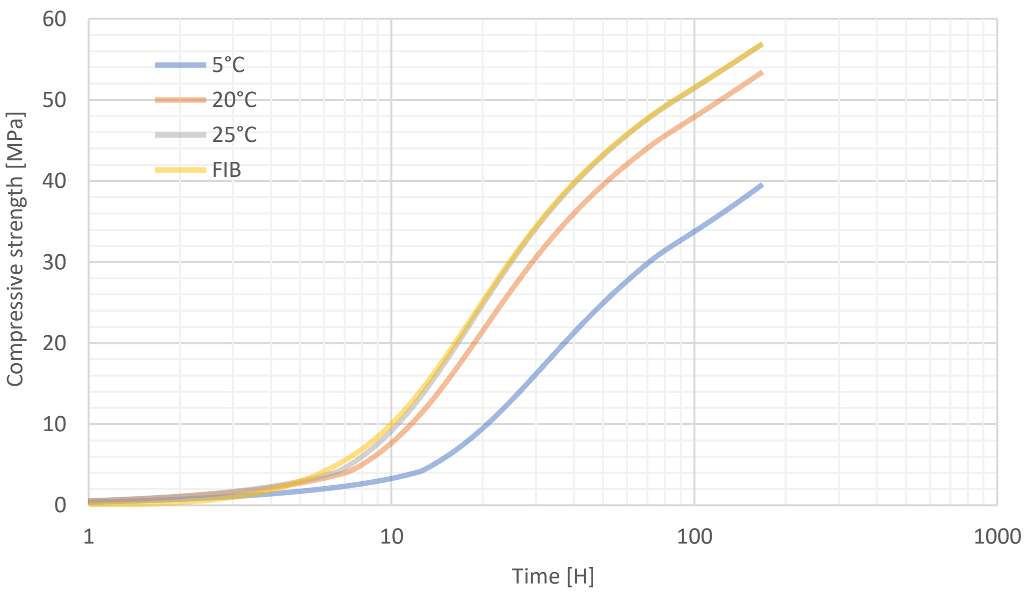


Figure 14. Compressive strength development versus time for H65

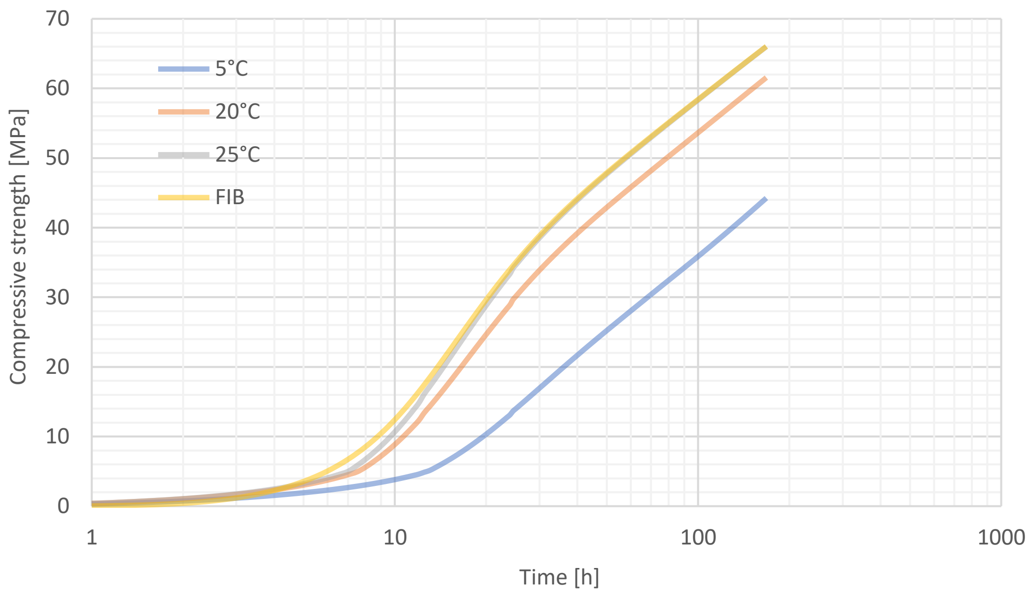


Figure 15. Compressive strength development versus time for H50

When the parameters regarding the activation energy are found, the compressive strength model parameters can be determined. By fitting equation 7 to the 20°C test results, t_0 is found. Now equation 7 can be adjusted to fit the compressive strength test results of all the temperatures, defining f_{c28} and *s*, based on the previously adjusted activation energy. According to the graphs presented in figures 16 and 17, it can be concluded that the obtained value of parameters regarding activation energy and compressive strength has been calibrated and attained an overall high accuracy. By observing the compressive strength model of equation 7 compared to the compressive strength results from CrackTeSt COIN, it can be seen a slight difference in the convex curve of the graph between the form-function and the results from CrackTeSt COIN. The most significant difference indicates that the results from CrackTeSt COIN are 1.8 MPa lower after 8 hours. An assumption is that this is due to the wind speed of 2 m/s. The effect of the wind speed is even more prominent for H50.

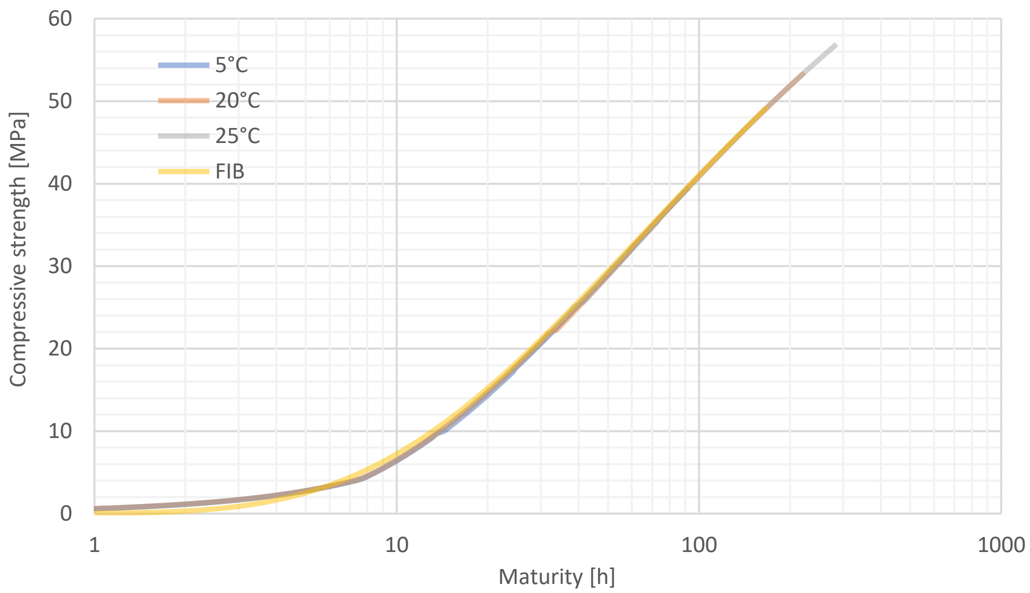


Figure 16. Compressive strength versus maturity for H65

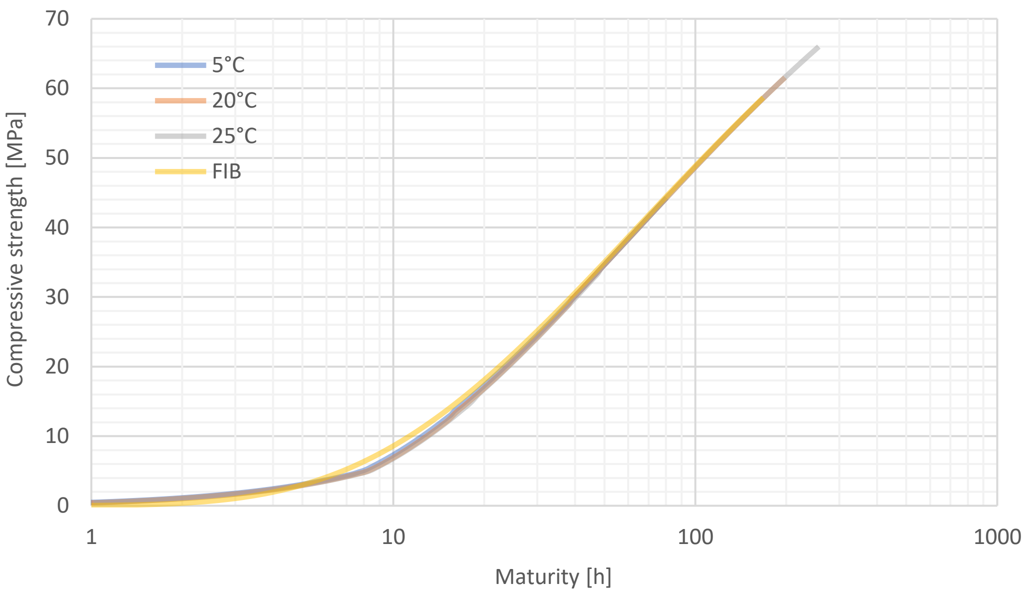


Figure 17. Compressive strength versus maturity for H50

4.4. Compressive strength and temperature development

This chapter and the accompanying subchapters will systematically review the development of compressive strength and temperature of the concrete under various simulated conditions. The compressive strength and temperature development of H65, H50 and SL20 were calculated for 7 days. Through CrackTeSt COIN, the results have been extracted as graphs, deterministic data, and colour maps. Deterministic data are obtained after 72 hours of curing, as well as the time when 25 MPa strength is achieved. These are the two most interesting times in terms of possible demoulding. The results are presented as values collected from coordinate points in the construction [21]. The compressive strength is simulated at two points in the modelled post-tensioned slab as defined in table 22.

Table 22. Dimensions and measuring points of the construction modelled in CrackTeSt COIN

	Dimensions [m]		Coordinates	
Construction	Thickness	Length	MP1	MP2
Slab	0.250	6000	(4000, 0.200)	(6000, 0.125)

Following NS-EN 13670+NA, several of the simulations showed concrete that did not reach a compressive strength of 5 MPa before the surface temperature of the concrete dropped below 0°C. The details of the simulations will be presented in more detail in the coming subchapters.

The three concretes and their respective development of mechanical properties will be presented in the following subchapters. For the tables regarding 72-hour compressive strength development, the presented values are collected from measuring point 2 (MP2), (6000, 0.125). The point is selected to show the full effect of the heating cables in this area. Furthermore, the point is presumed vulnerable as it is the most exposed point in terms of weather conditions; thus, it is concluded that if this measuring point achieves sufficient compressive strength, then it will apply throughout the whole construction. Note that this is only the case without using heating cables, i.e., strategies 7 and 8 are factored out. When the compressive strength is sufficient at MP2 in the two abovementioned strategies, it is crucial to check the adequacy of measuring point 1 (MP1), (4000, 0.200). The negligible effect of the heating cables at MP1 indicates that this point has corresponding curing measures as strategies 3 and 4. The tables are further presented in which the curing processes that do not satisfy NS-EN 13670 regarding achieved early strength before the surface temperature falls below 0°C are marked to indicate the non-applicable cases. For strategies 7 and 8, as explained above, the values from measuring point 1 are decisive. The values are shown in parentheses and illustrate the importance of individual measuring points in cases of local curing measures. When heating cables are used as curing measures in the whole of the concrete structure, only measuring point 2 would be relevant. The table is colour-indicated to show which curing strategies meet the requirement of 3-day compressive strength.

Considering the NS-EN 13670 dictating that the concrete must achieve a compressive strength corresponding to 5 MPa before the surface temperature drops below 0°C, it is still possible to reach the limit compressive strength of 25 MPa. However, as explained in subchapter 2.2.1, it is unsuitable and will not be used. According to the following tables, it can simultaneously be concluded that for all scenarios where this is the case, the required compressive strength of 25 MPa is not achieved within 3 days. It can thus further be concluded that the project-specific criteria comply with NS-EN 13670 and, at the same time, set more demanding criteria.

In order to provide a good and clear presentation of the results concerning the validity of the various concretes, diagrams regarding compressive strength and temperature development will be presented for each of the specific ambient temperatures. The temperature becomes the prominent variable at the construction site, with the wind as a sub-variable. The choice of curing strategy is chosen as a result of these variables. For each increment, the strategies will be presented to show and compare the effect of the curing measures regarding the compressive strength and temperature development. The presentation will consider the development of mechanical properties at MP2 to illustrate the effect of heating cables used in strategies 7 and 8. Because the effect of the different wind speeds will be presented in tables regarding the 72-hour compressive strength, it is chosen to illustrate the strength development at a wind speed of 2 m/s.

4.4.1. Hybrid 65%

The following compressive strength and temperature presentation are based on the description in the last three sections of chapter 4.4. From an ambient temperature of 10°C, no further curing measures are required other than formwork to satisfy the compressive strength criteria, as illustrated in table 23. The effect of wind speed appears to be increasing with decreasing ambient temperature. In order to illustrate this effect, it can be observed that wind speed makes strategy 2 insufficient at an ambient temperature of 5°C only at 8 m/s. At wind speeds above 8 m/s, the casting will be interrupted due to the risk it entails, regardless of whether the criteria are met. Strategy 3 is at ambient temperatures of 0°C, only satisfactory in calmer wind conditions of 2 m/s.

The use of covering at the top of the slab with ethafoam mats, as strategy 2 considers, increases the compressive strength by an average of 2.7 MPa compared to strategy 1 at 5°C, making it a sufficient curing measure for all wind speeds except 8 m/s. Strategy 3 combines covering of the top slab with heating underneath the slab, with an average increased compressive strength of 3.3 MPa compared to strategy 2. The combination of curing measures makes it sufficient for 0°C with a wind speed of 2 m/s. Further, strategy 4-6 has an increase of approximately 0.5 MPa compared to the previous strategy.

Table 23. 72-hour compressive strength development for H65 at measuring point 2

Compressive strength after 72 hours (Criterium: Concrete strength > 25 MPa) Freezing constraint: Concrete strength > 5 MPa when air temp. < 0°C. Otherwise, "N/A"									
Wind [m/s]	Temp. [°C]	Strategies							
		1	2	3	4	5	6	7	8
2	-10	9.0*	10.8*	14.4	15.1	16.2	17.1	33.2(20.2)	33.9(21.6)
	-5	13.5*	15.8	19.8	20.4	21.5	22.2	37.8(25.6)	38.4(26.7)
	0	18.6	21.3	25.2	25.6	26.6	27.2	42.1(30.7)	42.6(31.5)
	5	23.9	26.6	30.3	30.6	31.5	31.9	46.0(35.3)	46.4(35.8)
	10	29.1	31.8	35.0	35.2	36.0	36.3	49.7(39.6)	49.9(39.9)
	15	34.5	37.2	40.2	40.5	41.2	41.5	53.5(44.8)	53.8(45.1)
	20	39.0	41.4	44.2	44.3	45.0	45.3	56.5(48.2)	56.7(48.4)
	25	43.1	45.3	47.9	47.9	48.5	48.8	59.2(51.4)	59.4(51.5)
4	-10	8.0*	9.5*	13.0*	13.7*	14.2	15.2	31.3(18.1)	32.1(19.7)
	-5	12.5*	14.4	18.4	19.0	19.8	20.6	36.2(23.9)	36.8(25.2)
	0	17.6	20.0	24.0	24.5	25.2	25.8	40.7(29.4)	41.2(30.3)
	5	22.9	25.6	29.3	29.6	30.3	30.8	44.8(34.4)	45.2(35.0)
	10	28.2	30.8	34.2	34.4	35.0	35.4	48.6(39.0)	48.9(39.3)
	15	33.7	36.3	39.4	39.7	40.2	40.6	52.6(44.1)	52.9(44.6)
	20	38.2	40.7	43.5	43.7	44.2	44.5	55.7(47.8)	56.0(48.1)
	25	42.5	44.8	47.4	47.5	47.9	48.2	58.6(51.1)	58.8(51.3)
6	-10	7.5*	8.8*	12.1*	12.8*	13.3*	14.1	30.1(16.7)	31.0(18.4)
	-5	11.9*	13.8*	17.6	18.2	18.7	19.6	35.2(22.8)	35.9(24.1)
	0	17.0	19.4	23.3	23.7	24.3	25.0	39.8(28.6)	40.4(29.6)
	5	22.4	25.0	28.7	29.1	29.6	30.1	44.1(33.8)	44.5(34.5)
	10	27.7	30.4	33.7	34.0	34.5	34.8	48.0(38.6)	48.4(39.0)
	15	33.2	35.9	39.0	39.3	39.6	40.1	52.0(43.7)	52.4(44.2)
	20	37.8	40.3	43.2	43.4	43.7	44.1	55.2(47.5)	55.5(47.9)
	25	42.1	44.5	47.1	47.2	47.5	47.8	58.2(50.9)	58.4(51.2)
8	-10	7.3*	8.5*	11.6*	12.3*	12.8*	13.6*	29.6(16.0)	30.5(17.7)
	-5	11.7*	13.4*	17.2	17.8	18.2	19.1	34.7(22.2)	35.4(23.6)
	0	16.8	19.1	22.9	23.4	23.9	24.5	39.4(28.2)	40.0(29.2)
	5	22.2	24.8	28.4	28.8	29.2	29.7	43.8(33.5)	44.2(34.2)
	10	27.5	30.2	33.5	33.7	34.2	34.6	47.8(38.4)	48.1(38.8)
	15	33.0	35.6	38.7	39.0	39.3	39.8	51.7(43.5)	52.1(44.1)
	20	37.6	40.1	43.0	43.2	43.5	43.9	55.0(47.4)	55.3(47.8)
	25	41.9	44.3	46.9	47.1	47.3	47.7	58.0(50.9)	58.2(51.1)

(-) Strength development in measuring point 1 which is decisive
* N/A in accordance with NS-EN 13670

The worst-case scenario regarding temperature indicates that the H65 will not achieve the required compressive strength after 3 days of curing at an ambient temperature of -10°C. The wind speed also plays an essential role in deciding which curing strategy to be considered. With a wind speed of 4 m/s, the concrete can withstand an ambient temperature of -5°C by using strategy 8, considering heating cables. At an ambient temperature of 10°C, the H65 can cure without the use of curing measures, that is, the first temperature level above the defined winter casting. The compressive strength at 5°C considered for every curing strategy is presented in figure 18 below.

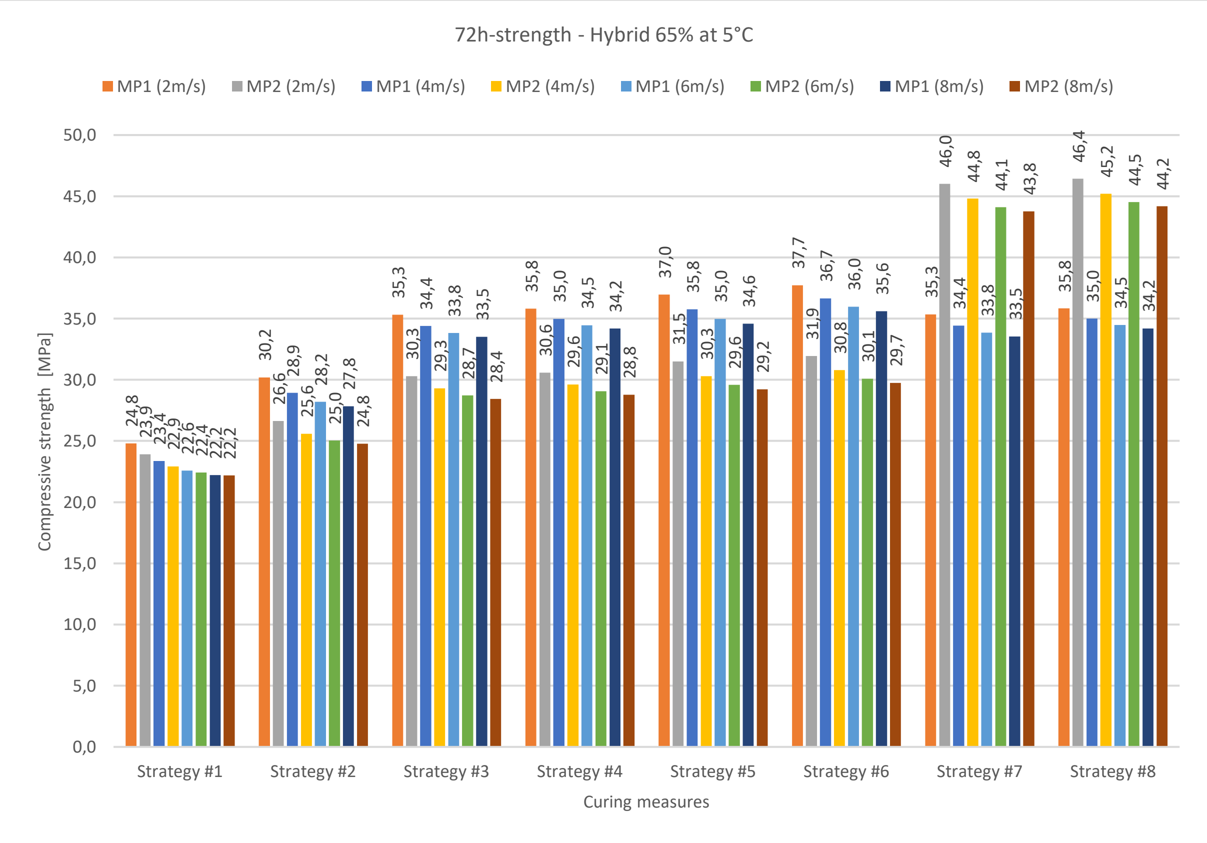


Figure 18. Compressive strength of H65 after 72 hours at 5°C

4.4.1.1. -10°C

Figure 19 presents the slow compressive strength development of H65 during winter casting at -10°C. The figure clearly illustrates the effect of the heating cables in strategies 7 and 8, with a considerably higher strength development compared to the other strategies. When using strategies 7 and 8, the adequacy of measuring point 1 must always be checked, as explained in chapter 4.4. Table 23 indicate that the strategies do not achieve sufficient strength. Therefore, whether the H50 can be used as a substitute in these conditions must be considered.

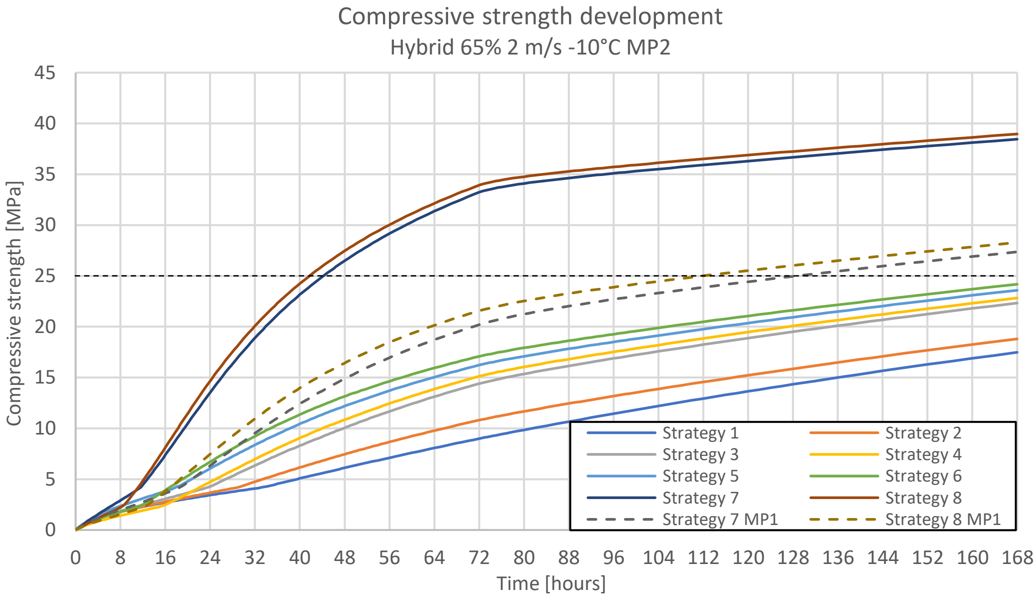


Figure 19. Compressive strength development for H65 at -10°C

Regarding table 23, strategies 1 and 2 do not comply with the NS-EN 13670 regarding minimum strength before the surface temperature drops below 0°C.

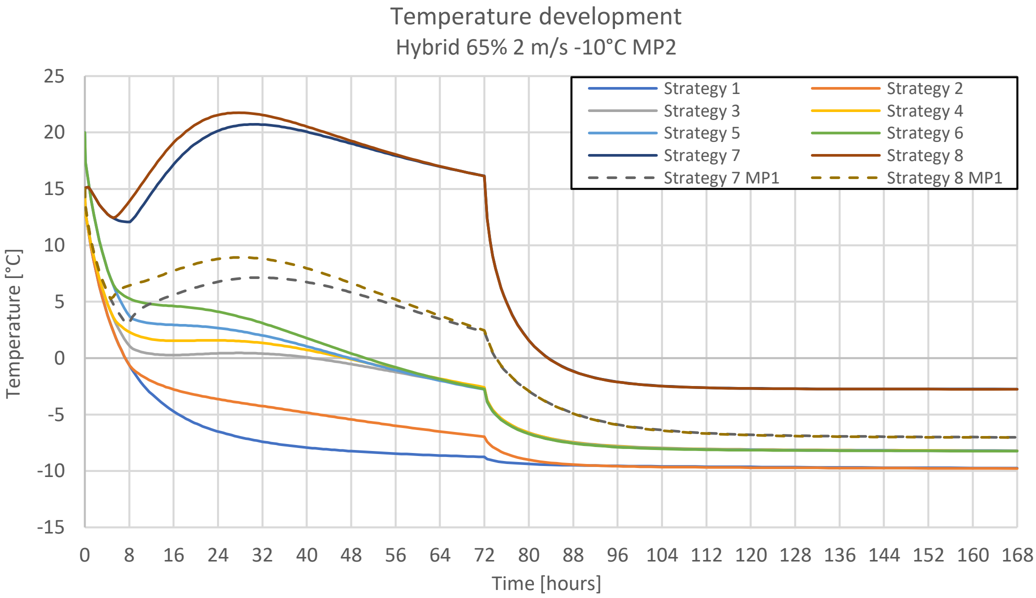


Figure 20. Temperature development for H65 at -10°C

4.4.1.2. -5°C

Figure 21 presents the still slow-moving compressive strength development of H65 during winter casting at -5°C. Similar to the conditions at -10°C, the effect of the heating cables in strategies 7 and 8 can be observed, with a considerably higher strength development compared to the other strategies. When checking the adequacy of measuring point 1, as explained in chapter 4.4, table 23 indicates that the strategies achieve sufficient strength, whereas strategy 8 can remove the formwork after 64 hours.

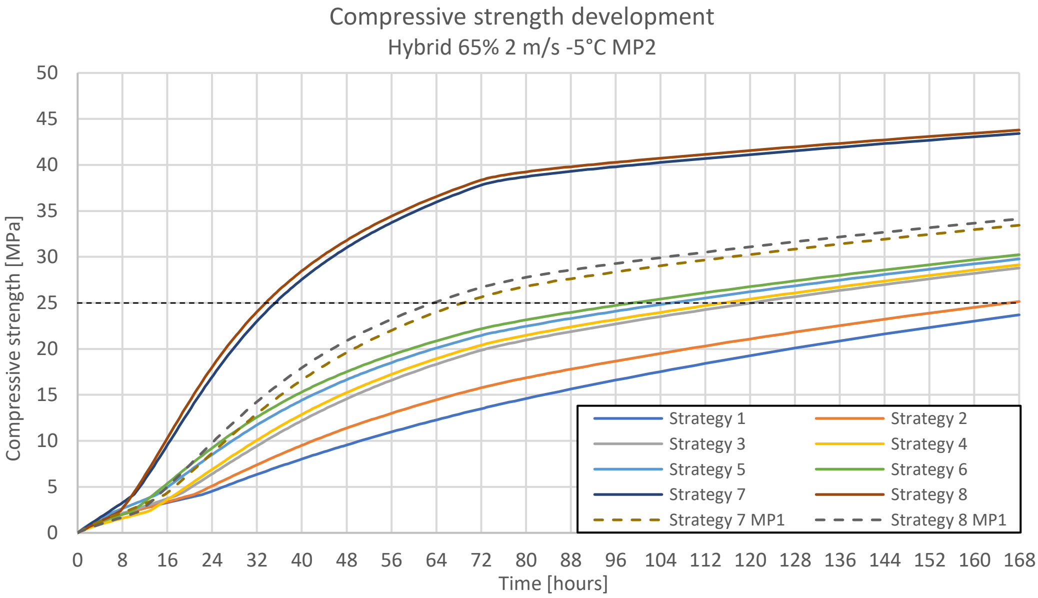


Figure 21. Compressive strength development for H65 at -5°C, MP1

Figure 22 illustrates the low heat development at -5°C. Strategy 1 does not achieve a compressive strength of 5 MPa before the surface temperature drops below 0°C.

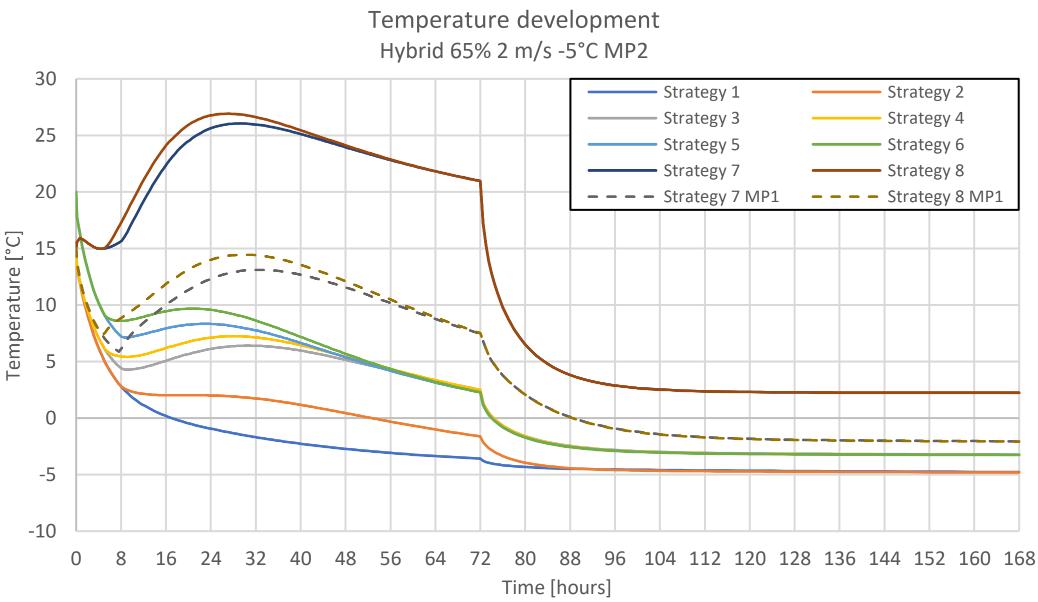


Figure 22. Temperature development for H65 at -5°C

4.4.1.3. 0°C

Figure 23 illustrates that at 0°C, more strategies can achieve adequate strength development. Strategy 3 can be applied as it reaches a compressive strength of 25 MPa after 71 hours. By making use of heating cables, strategy 7 can remove formwork after 2 days of curing.

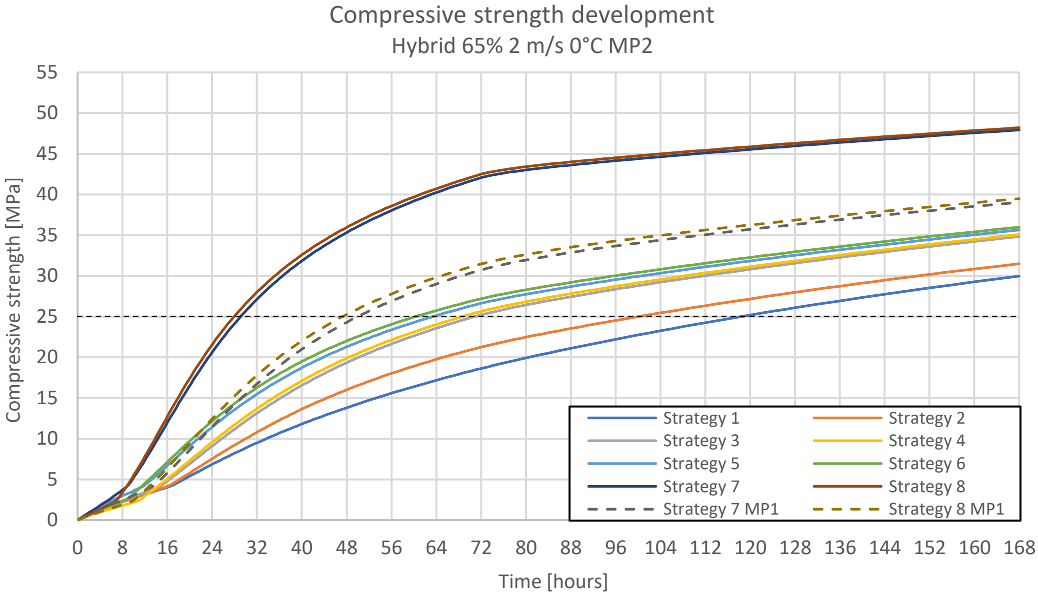


Figure 23. Compressive strength development for H65 at 0°C

From 0°C onwards, the surface temperature of the concrete will not reach minus degrees, and the requirement in NS-EN 13670 will be maintained at the following temperature conditions. Figure 24 still illustrates the low heat development of the H65, but a slight increase can be observed.

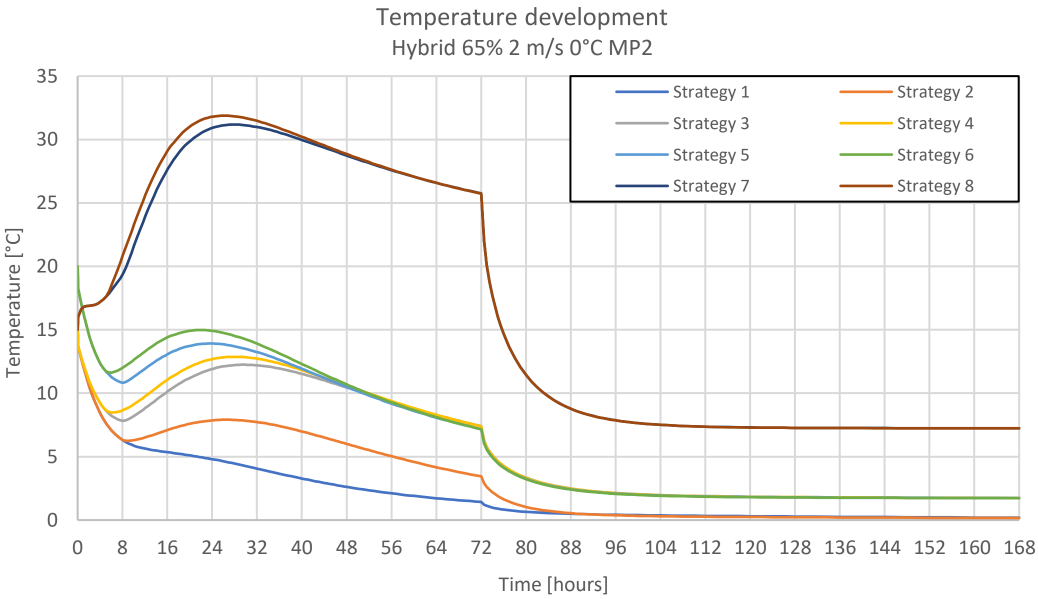


Figure 24. Temperature development for H65 at 0°C

4.4.1.4. 5°C

Figure 25 presents the gradually evolving compressive strength development of H65 during the last degree of winter casting at 5°C. Similar to the previous conditions, the effect of the heating cables in strategies 7 and 8 can be observed. Simultaneously the gap between the strategies with and without heating cables is becoming visibly smaller. At 5°C, strategy 2 is sufficient. It should be mentioned that at 8 m/s, strategy 2 achieves a compressive strength of 24.8 MPa, which in table 23 is deemed as insufficient. In varying weather conditions, the strength can either increase or decrease, emphasising the importance of calculating the actual conditions if this strategy is used.

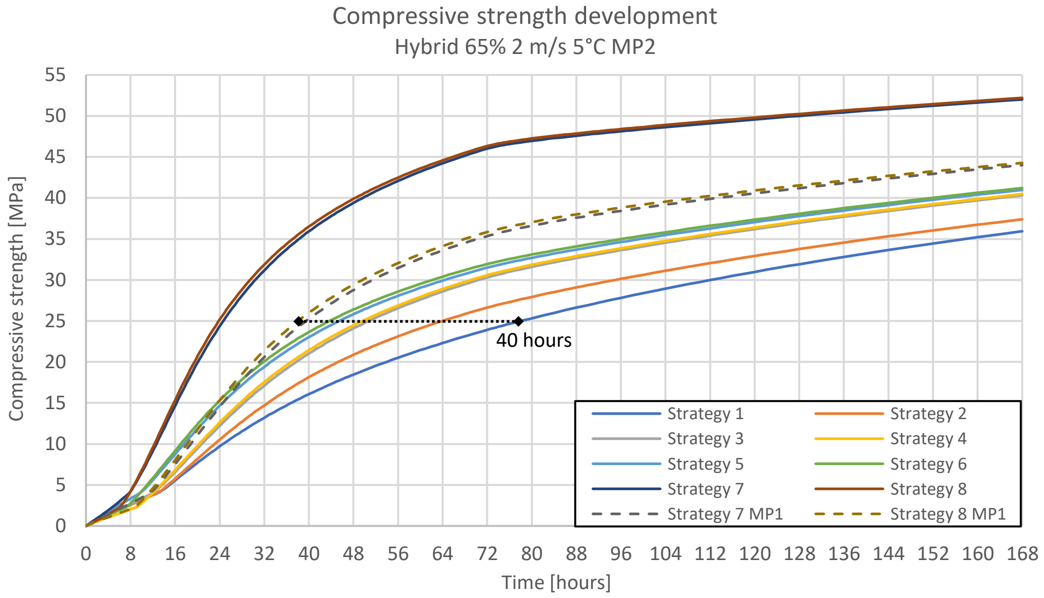


Figure 25. Compressive strength development for H65 at 5°C

Figure 26 illustrates the gradual increase in heat development, although the effect of the fly ash content is still prominent to observe. Strategy 6 has a temperature gradient corresponding to 5.8°C in the first 24 hours.

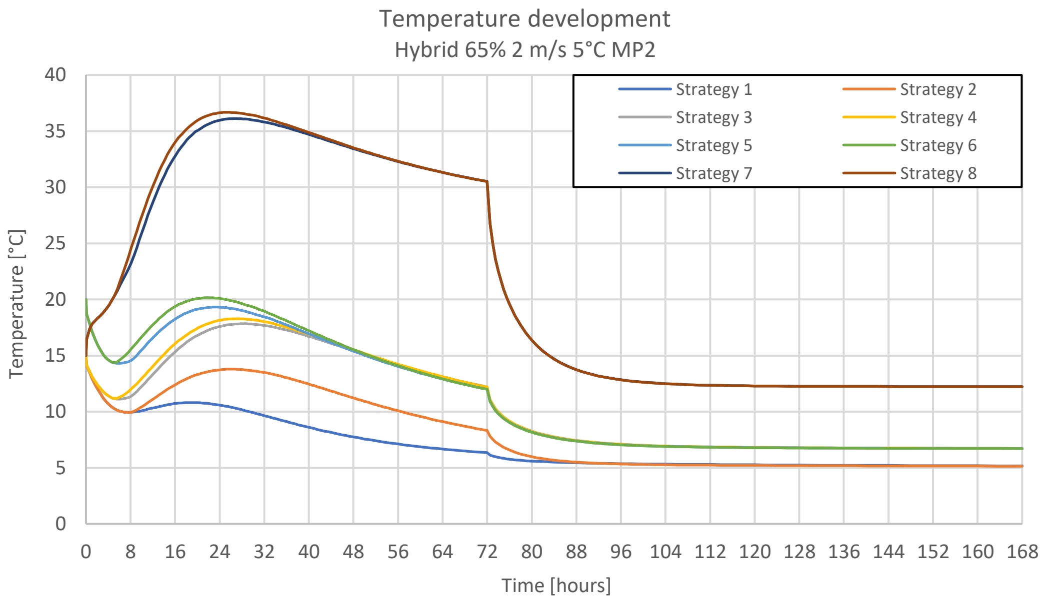


Figure 26. Temperature development for H65 at 5°C

4.4.1.5. 10°C

Figure 27 presents the compressive strength development of H65 at 10°C, the first level above the winter casting. It can be observed that the time gap in which the curing strategies from 1 to 8 reach a compressive strength of 25 MPa, reduces from 40 hours at 5°C to 22 hours at 10°C. At 10°C, the time gap is thus approximately halved, emphasizing the temperature sensitivity of the H65.

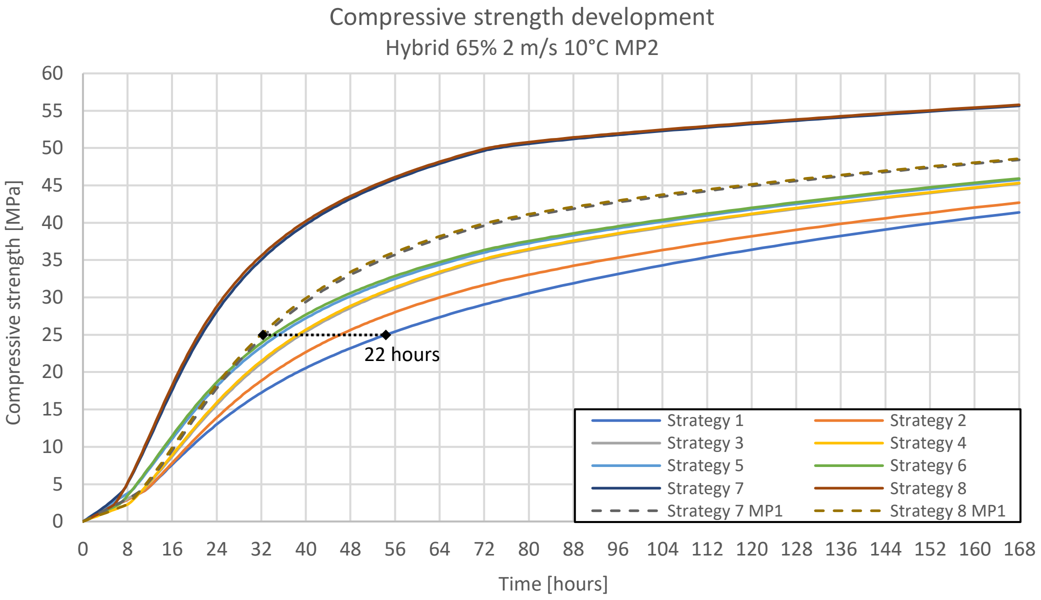


Figure 27. Compressive strength development for H65 at 10°C

Figure 28 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 8.3°C in the first 24 hours.

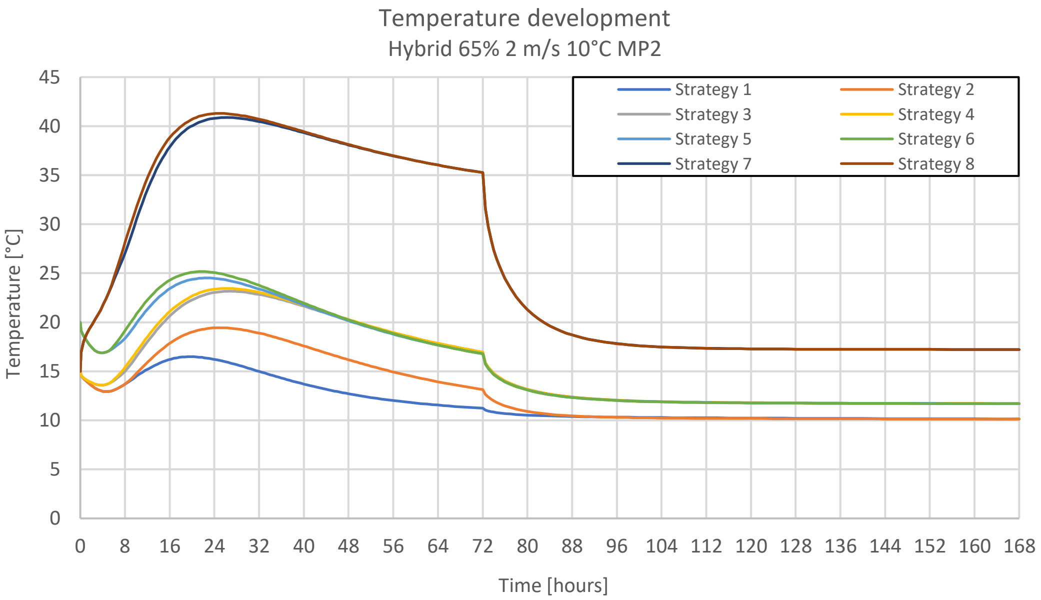


Figure 28. Temperature development for H65 at 10°C

4.4.1.6. 15°C

Figure 29 presents the compressive strength development of H65 at 15°C. Strategies 1 and 8 achieve a strength of 25 MPa after 37 and 24 hours, respectively, a time difference corresponding to 13 hours. It is clear to observe the increasing strength development at higher temperatures.

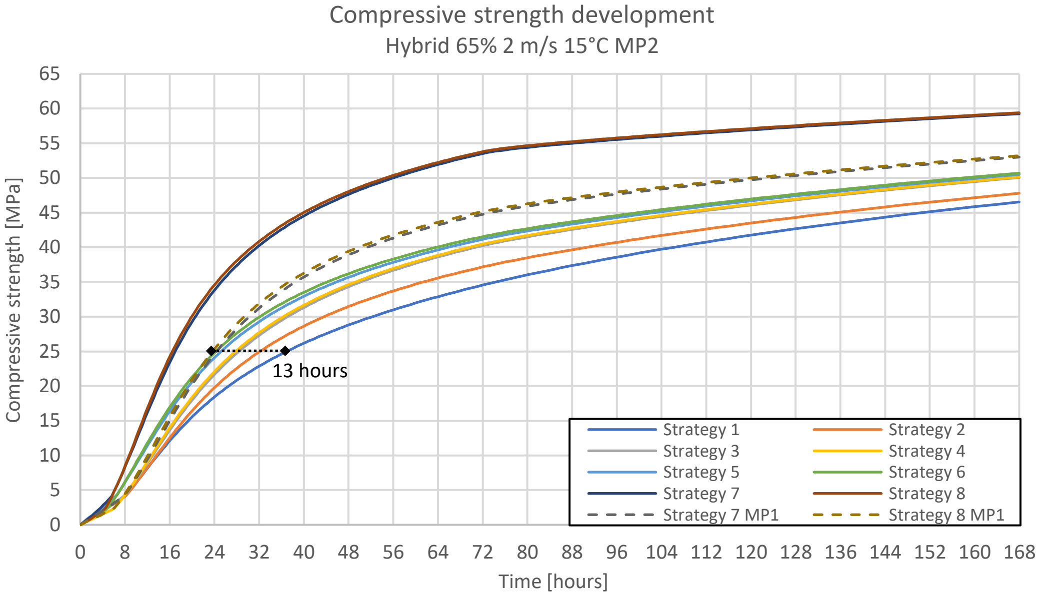


Figure 29. Compressive strength development for H65 at 15°C

Figure 30 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 9.5°C in the first 24 hours. The maximum temperature of strategy 6 corresponds to 32°C, while strategy 8 with heating cables reaches 46.9°C.

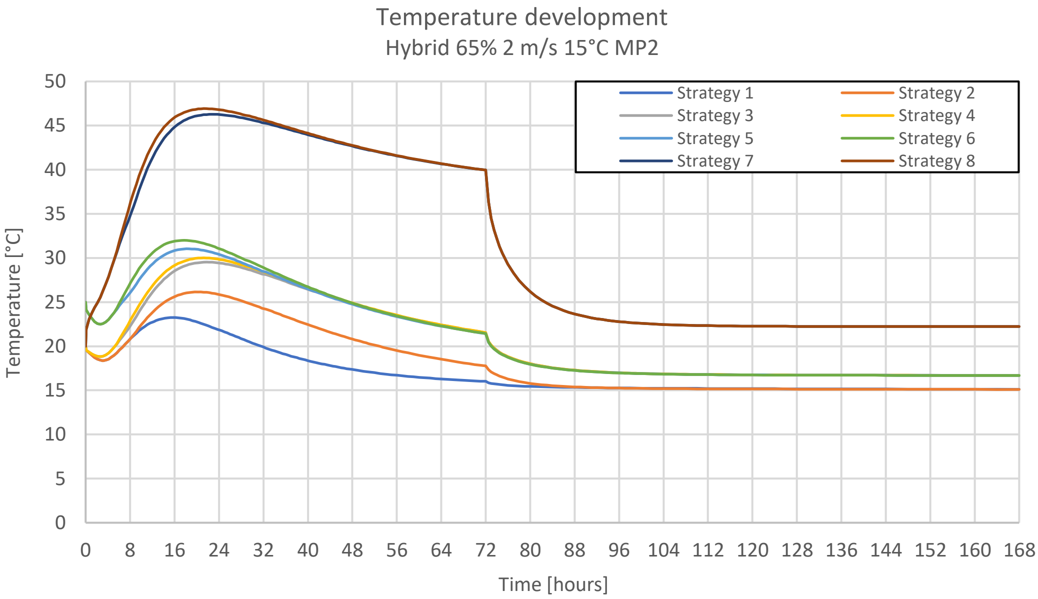


Figure 30. Temperature development for H65 at 15°C

4.4.1.7. 20°C

Figure 31 presents the compressive strength development of H65 at 20°C. At 20°C, it can be observed that strategy 6 reaches a compressive strength of 25 MPa 0.5 hours before strategy 8, indicating the lesser effect of heating cables at higher ambient temperatures.

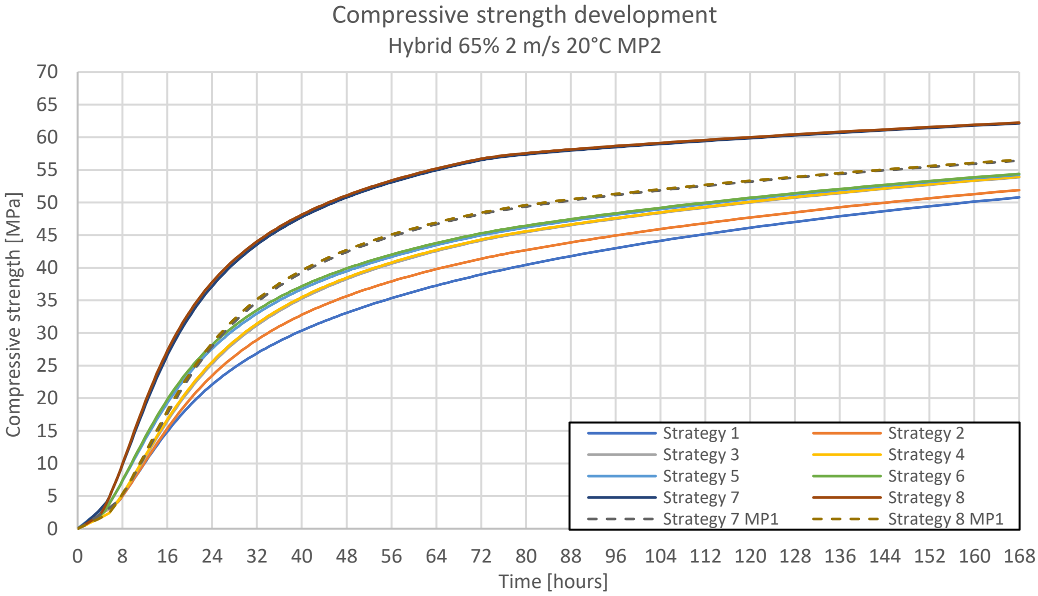


Figure 31. Compressive strength development for H65 at 20°C

Figure 32 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 12.5°C in the first 24 hours. The maximum temperature of strategy 6 corresponds to 36.5°C, while strategy 8 with heating cables reaches 51.2°C.

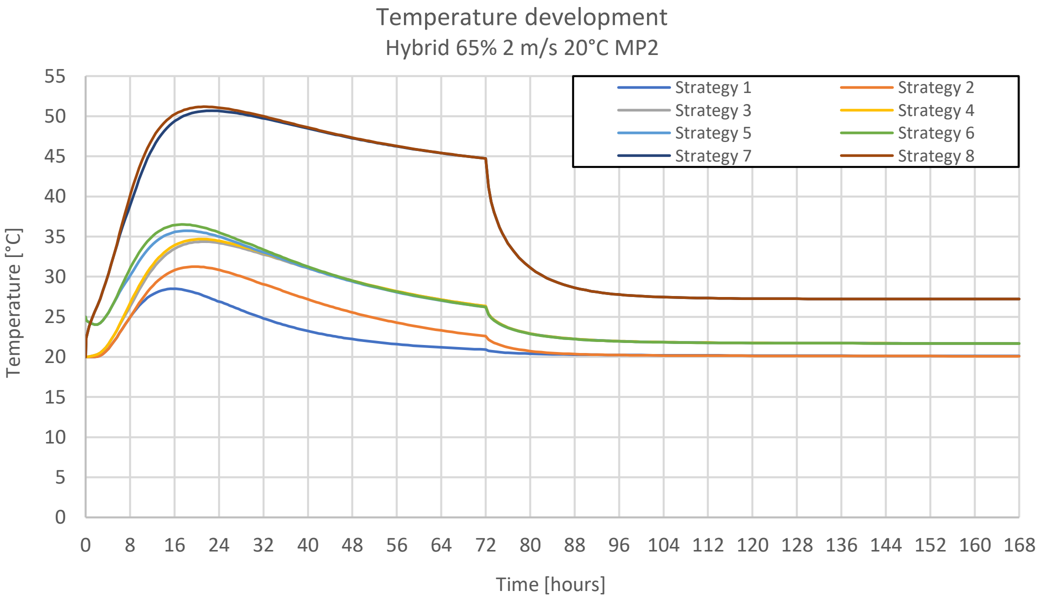


Figure 32. Temperature development for H65 at 20°C

4.4.1.8. 25°C

Figure 33 presents the compressive strength development of H65 at 25°C. Similar to the latter temperature level, it can be observed that strategy 6 reaches a compressive strength of 25 MPa before strategy 8, by 1 hour.

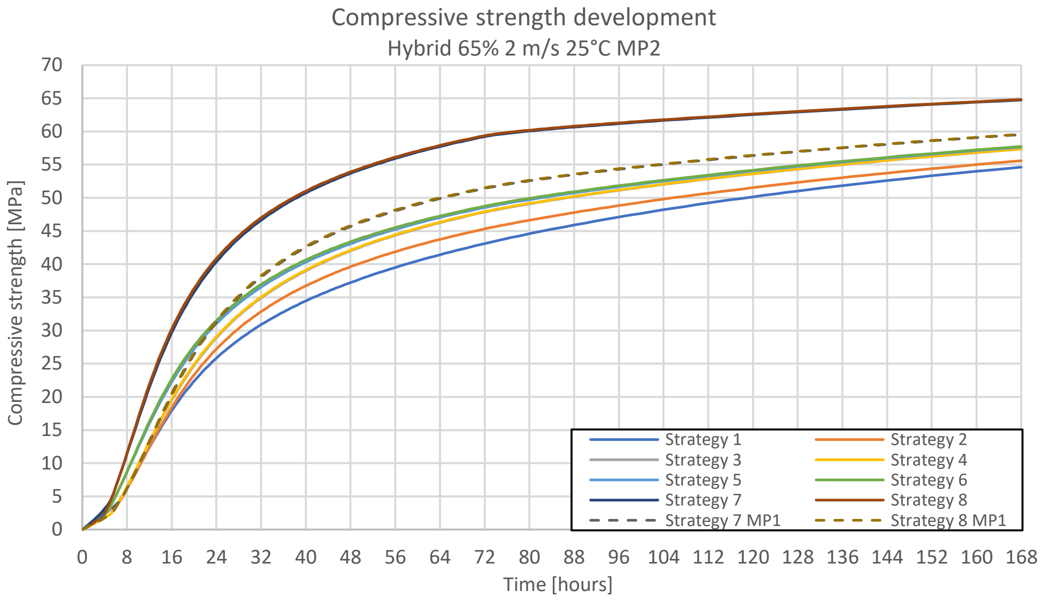


Figure 33. Compressive strength development for H65 at 25°C

Figure 34 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 15.9°C in the first 24 hours. It can be observed that strategies 3 and 4 are more or less developing the same amount of compressive strength and heat at higher temperatures. The only difference in curing measures is the use of accelerator in strategy 4.

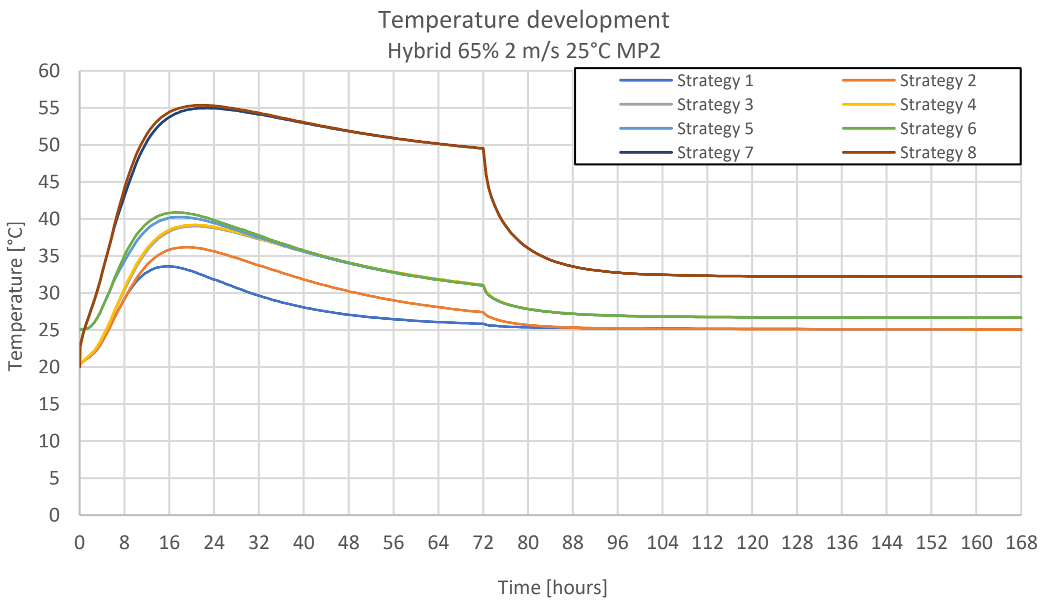


Figure 34. Temperature development for H65 at 25°C

4.4.2. Hybrid 50%

The following compressive strength and temperature presentation are based on the description in the last three sections of chapter 4.4. From an ambient temperature of 5°C, no further curing measures are required other than formwork to satisfy the compressive strength criteria, as illustrated in table 24. The effect of wind speed appears to be increasing with decreasing ambient temperature. In order to illustrate this effect, it can be observed that wind speed makes strategy 2 insufficient at an ambient temperature of 0°C only at 6 m/s and 8 m/s. At wind speeds above 8 m/s, all casting will be interrupted due to the risk it entails, regardless of whether the criteria are met. Strategy 3 is at ambient temperatures of -5°C, only satisfactory in calmer wind conditions of 2 m/s.

The use of covering at the top of the slab with ethafoam mats, as strategy 2 considers, increases the compressive strength by 4.0 MPa compared to strategy 1 at 5°C, making it a sufficient curing measure for all wind speeds. Strategy 3 combines covering of the top slab with heating underneath the slab, with an average increased compressive strength of 4.4 MPa compared to strategy 2. The combination of curing measures makes it sufficient for 0°C with a wind speed of 2 m/s. Further, strategy 4-6 has an average increase of 0.6 MPa compared to the previous strategy.

Table 24. 72-hour compressive strength development for H50 at measuring point 2

Compressive strength after 72 hours (Criterium: Concrete strength > 25 MPa) Freezing constraint: Concrete strength > 5 MPa when air temp. < 0°C. Otherwise, "N/A"									
Wind [m/s]	Temp. [°C]	Strategies							
		1	2	3	4	5	6	7	8
2	-10	11.2*	13.9*	18.9	19.7	21.2	22.3	41.6(27.0)	42.5(28.8)
	-5	16.7	20.3	25.7	26.4	27.7	28.7	47.1(33.8)	47.8(35.1)
	0	23.1	27.1	32.2	32.8	34.0	34.8	52.1(39.9)	52.6(40.8)
	5	29.5	33.6	38.3	38.7	39.8	40.4	56.7(45.5)	57.1(46.1)
	10	35.7	39.7	43.9	44.1	45.2	45.6	61.0(50.5)	61.2(50.8)
	15	42.3	46.3	50.1	50.4	51.2	51.8	65.5(56.5)	65.8(57.0)
	20	47.5	51.2	54.7	54.9	55.7	56.1	68.9(60.5)	69.1(60.8)
	25	52.5	55.8	59.0	59.1	59.8	60.1	72.0(64.0)	72.2(64.2)
4	-10	9.9*	12.0*	16.2*	17.7	18.6	19.9	39.1(24.2)	40.2(26.3)
	-5	N/A	18.4	23.7	24.5	25.4	26.5	45.0(31.6)	45.8(33.2)
	0	21.6	25.4	30.6	31.2	32.0	32.9	50.3(38.3)	50.9(39.4)
	5	28.1	32.2	37.0	37.4	38.2	38.8	55.2(44.2)	55.7(45.0)
	10	34.4	38.5	42.8	43.0	43.8	44.3	59.7(49.6)	60.0(50.1)
	15	41.0	45.0	49.0	49.4	49.9	50.5	64.2(55.6)	64.7(56.3)
	20	46.4	50.2	56.4	54.1	54.6	55.1	67.8(59.8)	68.2(60.3)
	25	51.4	55.0	58.2	58.4	58.9	59.3	71.1(63.6)	71.4(63.9)
6	-10	9.2*	11.1*	15.5*	16.3*	16.8*	18.4	37.6(22.3)	38.7(24.6)
	-5	14.6*	17.2*	22.5	23.4	24.1	25.2	43.7(30.2)	44.5(31.9)
	0	20.8	24.4	29.6	30.2	30.9	31.8	49.2(37.2)	49.2(37.2)
	5	27.4	31.4	36.2	36.6	37.2	37.9	54.3(43.5)	54.8(44.3)
	10	33.7	37.8	42.1	42.4	43.0	43.5	58.9(49.1)	59.3(49.6)
	15	40.3	44.3	48.4	48.8	49.1	49.8	63.5(55.1)	64.0(55.8)
	20	45.7	49.6	53.3	53.6	53.9	54.5	67.2(59.4)	67.6(60.0)
	25	50.9	54.5	57.8	58.0	58.3	58.8	70.6(63.3)	70.9(63.7)
8	-10	8.9*	10.6*	14.9*	15.9*	16.5*	17.6	36.9(21.4)	38.0(23.7)
	-5	14.3*	16.5*	22.0	22.8	23.4	24.5	43.1(29.4)	43.9(31.2)
	0	20.5	24.0	29.1	29.7	30.3	31.2	48.7(36.7)	49.4(37.9)
	5	27.0	31.0	35.8	36.2	36.8	37.4	53.8(43.1)	54.4(43.9)
	10	33.4	37.5	41.8	42.1	42.6	43.2	58.5(48.8)	58.9(49.3)
	15	39.9	45.0	48.0	48.5	48.7	49.4	63.1(54.8)	63.6(55.6)
	20	45.4	49.3	53.0	53.4	53.6	54.2	66.9(59.2)	67.3(59.8)
	25	50.6	54.3	57.6	57.9	58.0	58.6	70.3(63.2)	70.7(63.6)

(-) Strength development in measuring point 1 which is decisive
* N/A in accordance with NS-EN 13670

The H50 concrete is a substitute for the more environmentally friendly but also more temperature-sensitive concrete, H65. As table 24 presents, it is possible to take advantage of and use the H50 when H65 does not sufficiently achieve the desired compressive strength. The concrete can be considered in even more challenging conditions, the toughest being an ambient temperature of -10° combined with a wind speed of 4 m/s. The table transparently illustrates the effect that wind causes as an environmental condition. Although the difference between the obtained compressive strength and the project-specific criterion is slight, it is still enough so that a wind speed of 6 m/s makes the concrete insufficient at -10°C. Comparing H50 to H65 indicates that the former of the two can withstand more challenging conditions, making it a crucial substitute for keeping the progression intact. At an ambient temperature of 5°C, which is one level below H65, the H50 can cure without the use of curing measures; that is the first temperature level defined as "winter casting".

Regarding an ambient temperature of -10°C, the worst-case scenario indicates that the H50 will achieve the required compressive strength after 3 days of curing with strategies 7 and 8. Strategy 7 is sufficient at wind speeds of 2 m/s, while strategy 8 is sufficient up to 4 m/s. The wind speed plays an essential role in deciding which curing strategy can be considered. With a wind speed of 8 m/s, the concrete can withstand an ambient temperature of -5°C by using strategies 7 and 8, considering heating cables. At an ambient temperature of 5°C, the H50 can cure without the use of curing measures; that is the last temperature level considered as winter casting. The compressive strength at 0°C considered for every curing strategy is presented in figure 35 below.

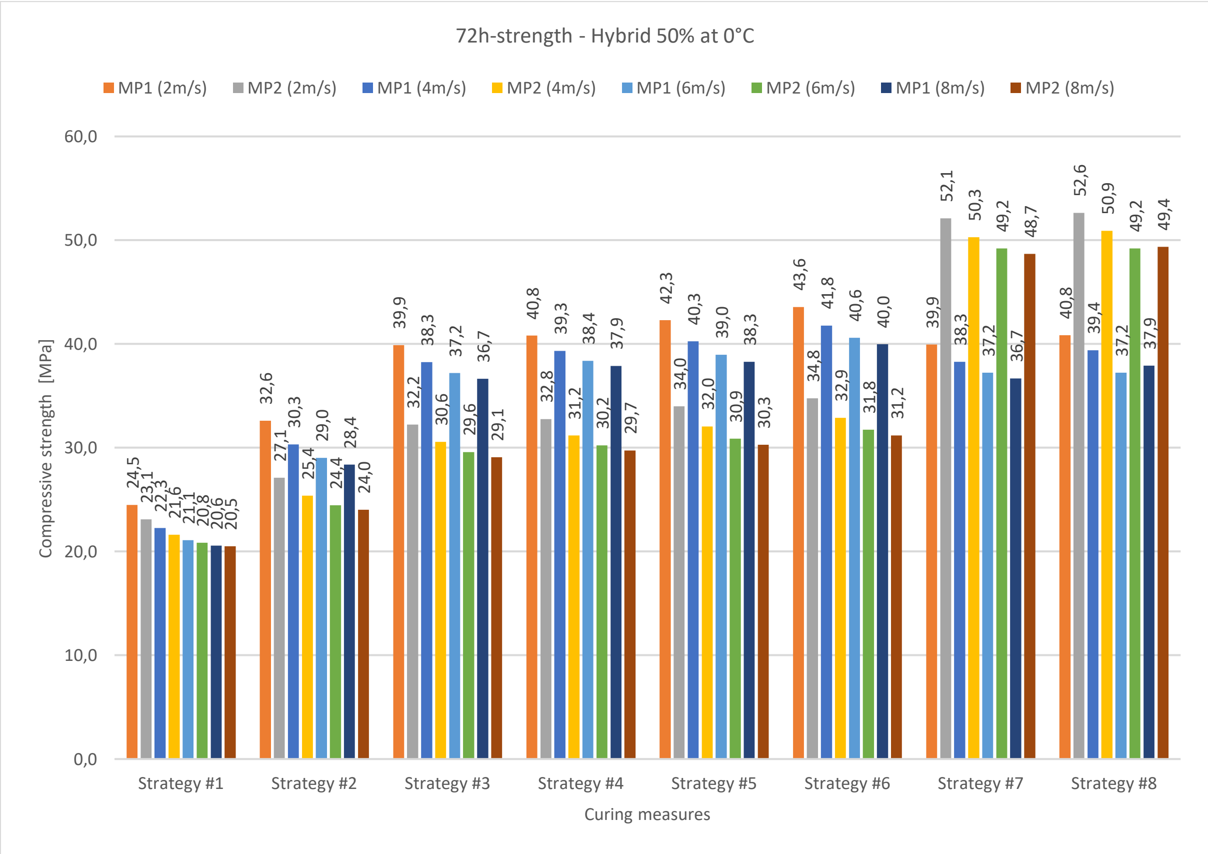


Figure 35. Compressive strength of H50 after 72 hours at 0°C

4.4.2.1. -10°C

Figure 36 presents the slow compressive strength development of H50 during winter casting at -10°C. The figure clearly illustrates the effect of the heating cables in strategies 7 and 8, with a considerably higher strength development compared to the other strategies. When using strategies 7 and 8, the adequacy of measuring point 1 must always be checked, as explained in chapter 4.4. In contrast to the H65, table 24 indicates that the strategies achieve sufficient strength for the H50. Therefore, at -10°C, it is possible to cast and maintain progress by using the substitute concrete for which the H50 is meant.

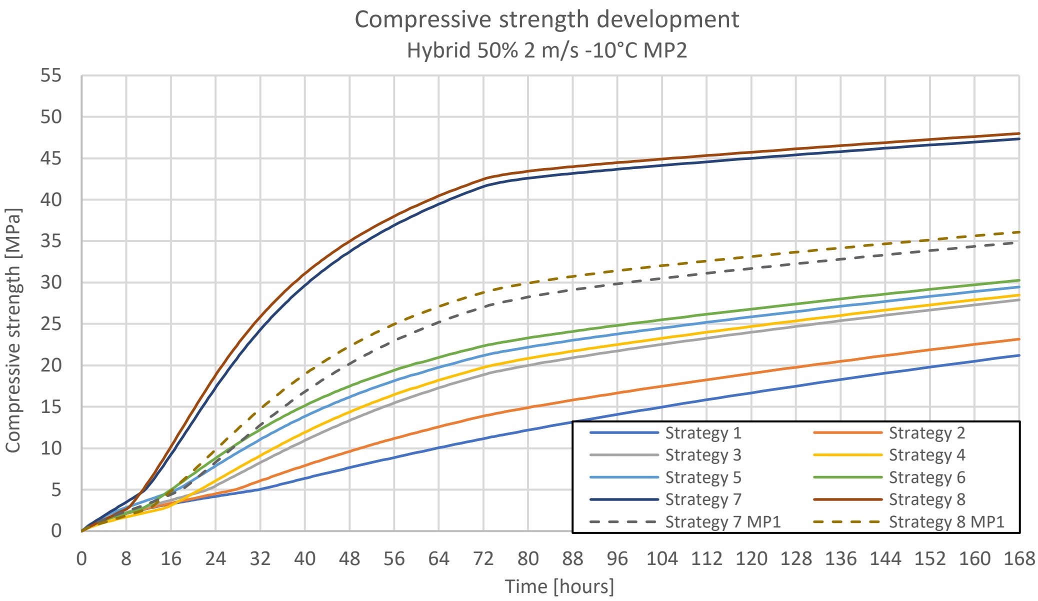


Figure 36. Compressive strength development for H50 at -10°C

Regarding table 24, strategies 1 and 2 do not comply with NS-EN 13670 regarding minimum strength before the surface temperature drops below 0°C.

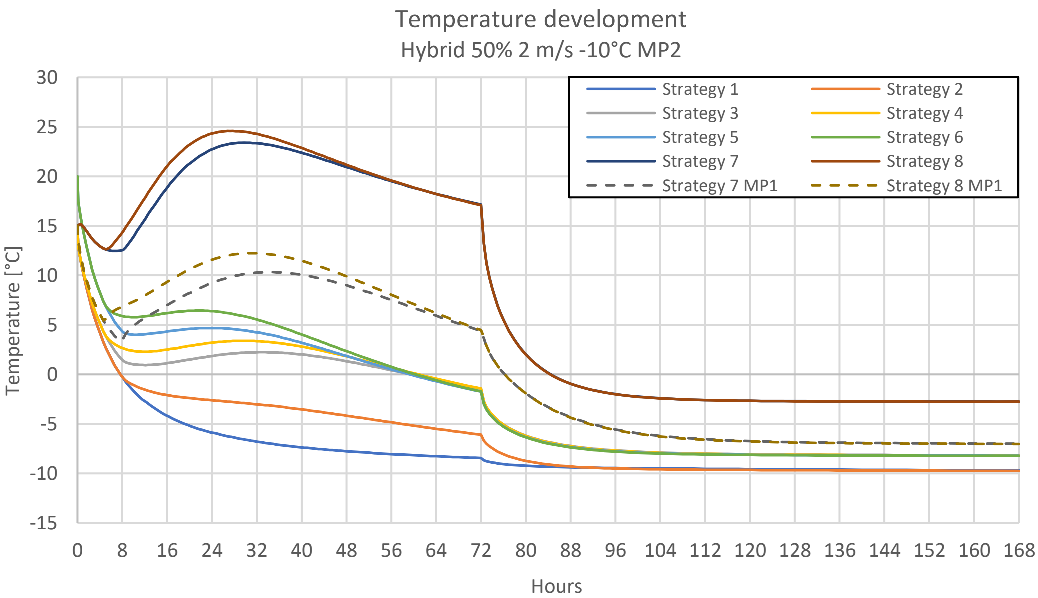


Figure 37. Temperature development for H50 at -10°C

4.4.2.2. -5°C

Figure 38 presents the still slow-moving compressive strength development of H50 during winter casting at -5°C. Although the development is slow compared to the H65, the H50 achieves sufficient strength development from strategy 3, where H65 is dependent on the use of heating cables.

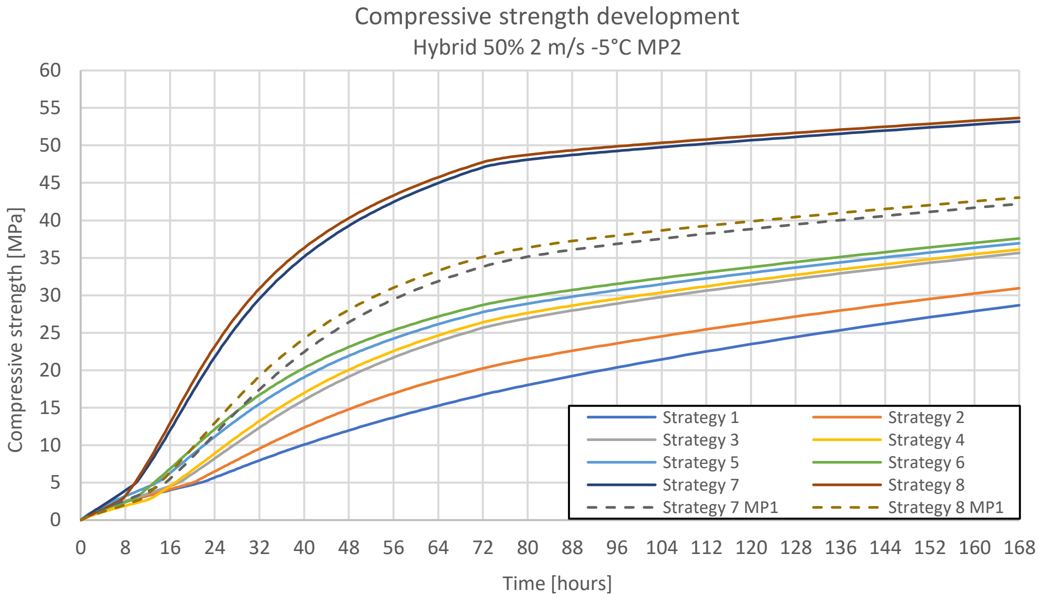


Figure 38. Compressive strength development for H50 at -5°C

Figure 39 illustrates the low heat development at -5°C. The potential of the surface temperature dropping below 0°C is present. Therefore, it is a risk that the H50 does not satisfy the requirement in NS-EN 13670 of not achieving a compressive strength of 5 MPa before the surface temperature drops below 0°C. Regarding table 24, the H50 nevertheless acquires sufficient strength.

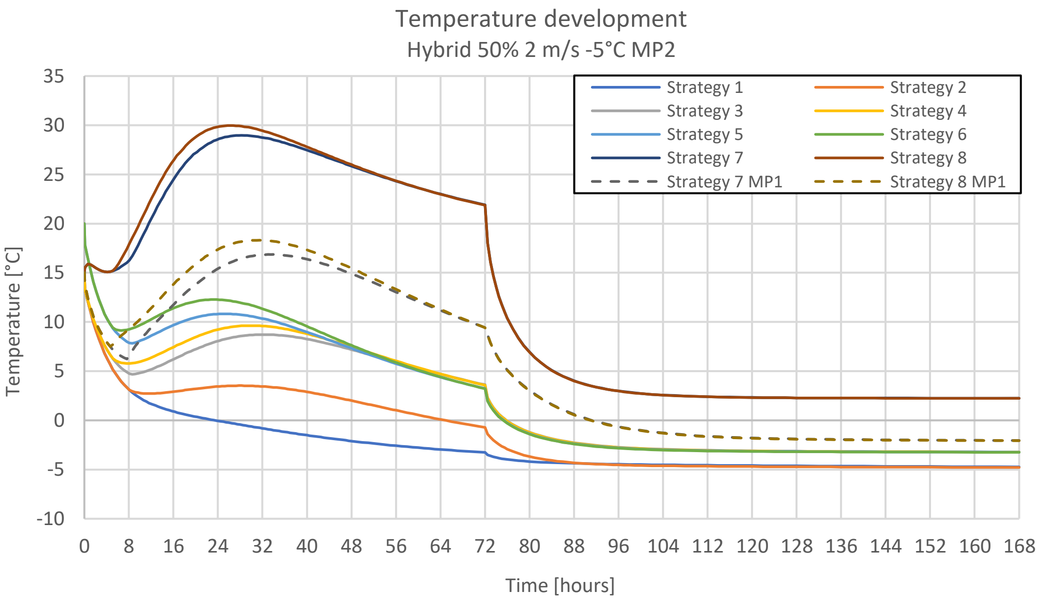


Figure 39. Temperature development for H50 at -5°C

4.4.2.3. 0°C

Figure 40 illustrates that at 0°C, strategy 2 achieves adequate strength development for the first time. The strategy reaches a compressive strength of 25 MPa after 63 hours. By utilizing strategy 3, however, the acquired strength is developed in 47.5 hours. In comparison, this is a reduction corresponding to 15.5 hours.

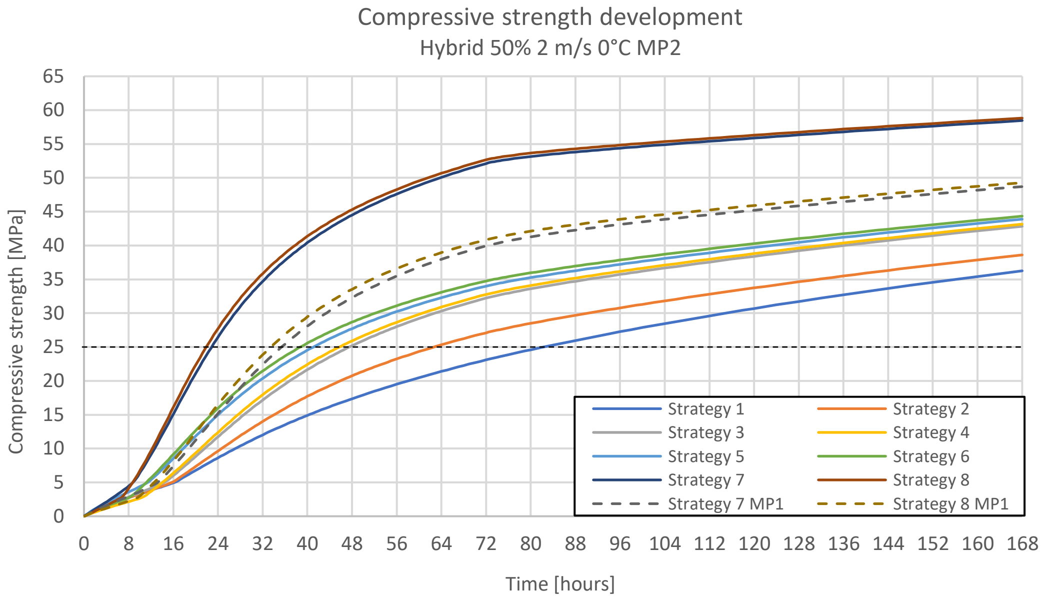


Figure 40. Compressive strength development for H50 at 0°C

From 0°C onwards, the surface temperature of the concrete will not reach minus degrees, and the requirement in NS-EN 13670 will be maintained at the following temperature levels. Figure 41 still illustrates the low heat development of the H50, but a slight increase can be observed.

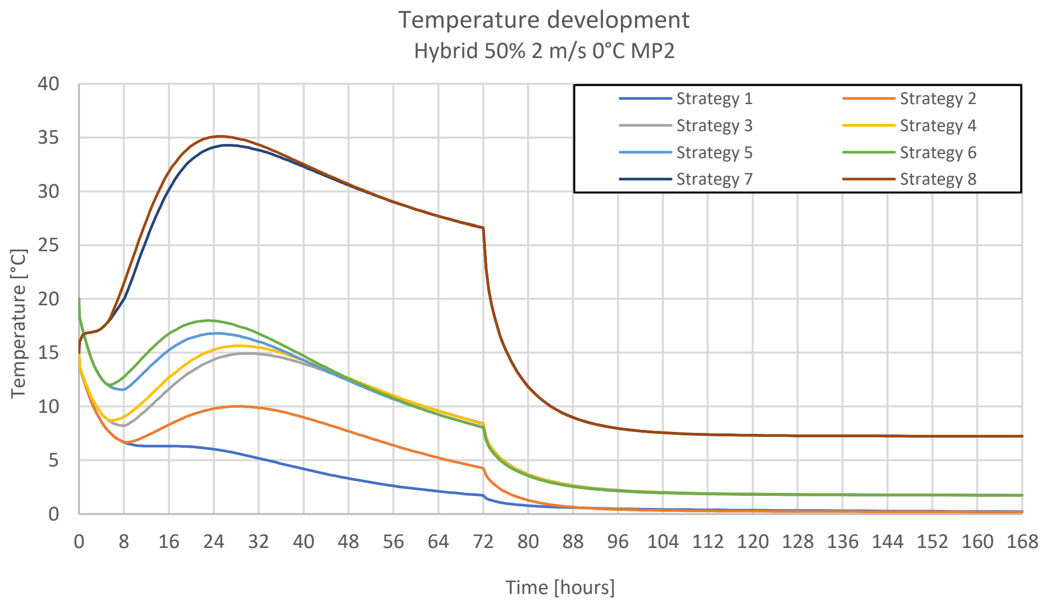


Figure 41. Temperature development for H50 at 0°C

4.4.2.4. 5°C

Figure 42 presents the gradually evolving compressive strength development of H50 during the last degree of winter casting at 5°C. Similar to the previous conditions, the effect of the heating cables in strategies 7 and 8 can be observed. Simultaneously the gap between the strategies with and without heating cables is becoming visibly smaller. At 5°C, all strategies are sufficient, independent of wind speed. As the first temperature level where strategy 1 can be used, the strength difference between a wind speed of 2 m/s and 8 m/s after 72 hours is 2.5 MPa.

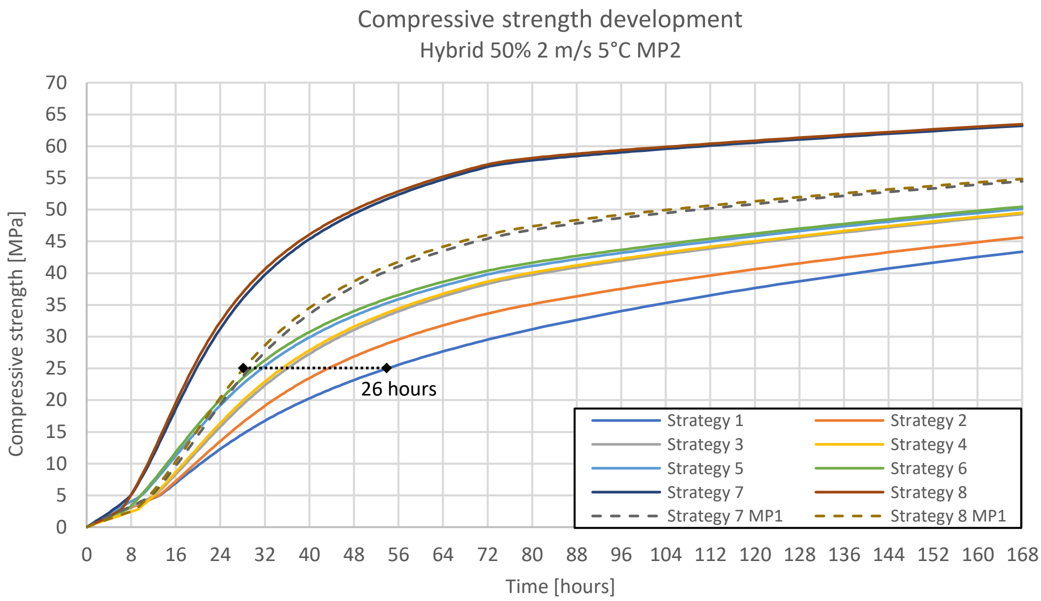


Figure 42. Compressive strength development for H50 at 5°C

Figure 43 illustrates the gradual increase in heat development, although the effect of the fly ash content is still prominent to observe. Strategy 6 has a temperature gradient of 8.7°C in the first 24 hours. That is 2.9°C higher than H65 under the same conditions.

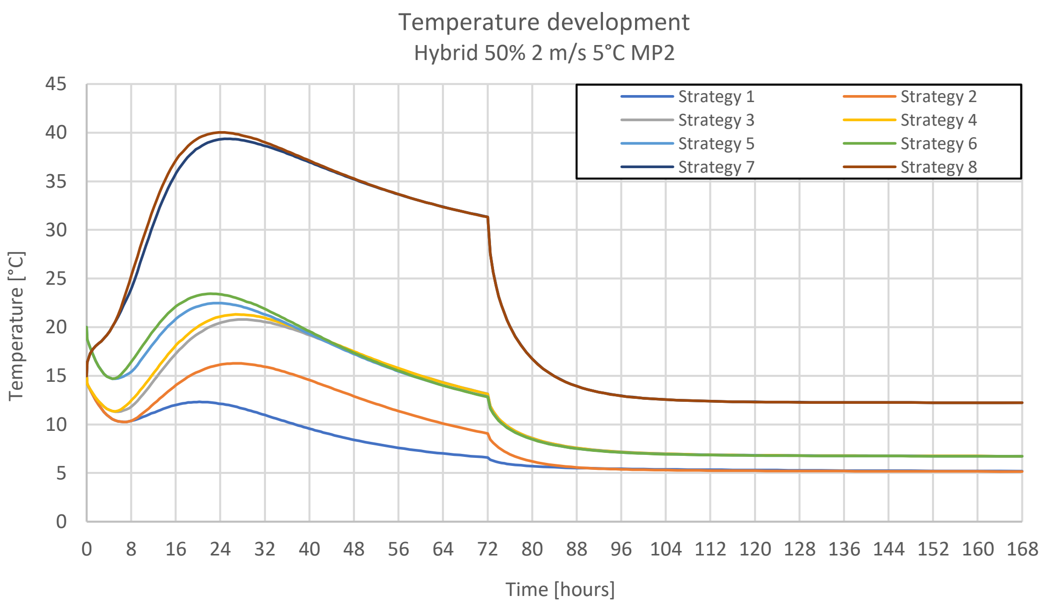


Figure 43. Temperature development for H50 at 5°C

4.4.2.5. 10°C

Figure 44 presents the compressive strength development of H50 at 10°C, the first level above the winter casting. It can be observed that the time gap in which the curing strategies from 1 to 8 reach a compressive strength of 25 MPa, reduces from 26 hours at 5°C to 13,5 hours at 10°C. At 10°C, the time gap is thus approximately halved, emphasizing the temperature sensitivity of the H50.

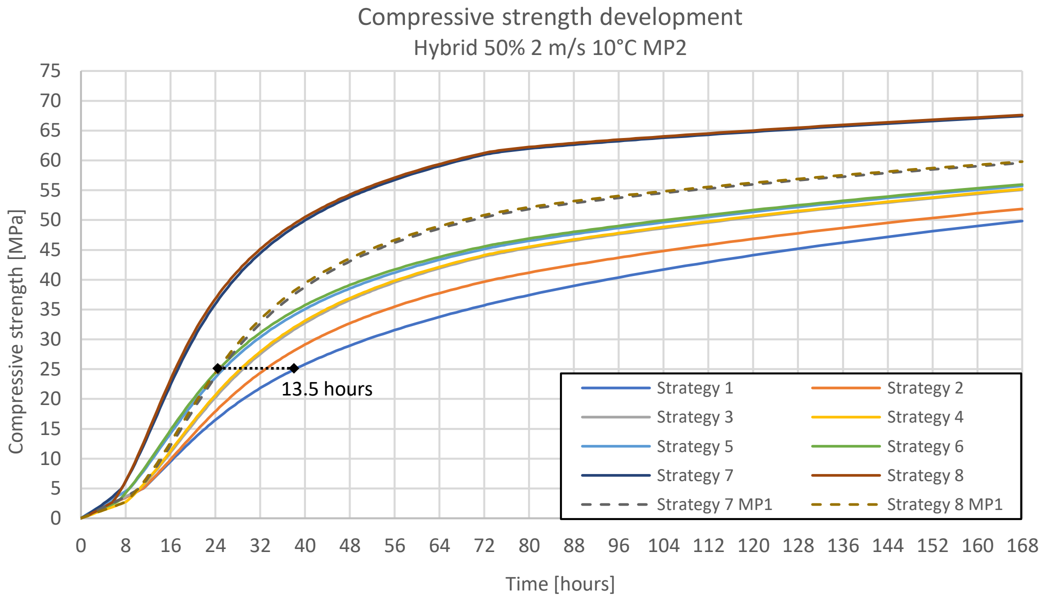


Figure 44. Compressive strength development for H50 at 10°C

Figure 45 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient corresponding to 11.6°C in the first 24 hours. That is 3.3°C higher than H65 under the same conditions.

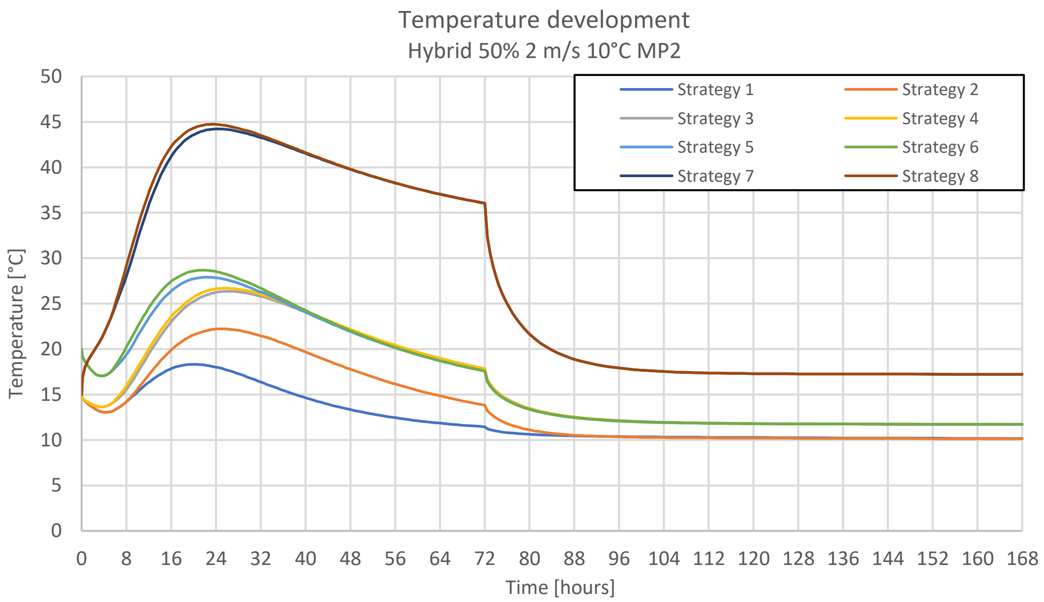


Figure 45. Temperature development for H50 at 10°C

4.4.2.6. 15°C

Figure 46 presents the compressive strength development of H50 at 15°C. Strategies 1 and 8 achieve a strength of 25 MPa after 26 and 18 hours, respectively, a time difference corresponding to 8 hours. Both strategies 6 and 8 reach a compressive strength of 25 MPa after 18 hours. It is clear to observe the increasing strength development at higher temperatures and the smaller strength gap between the different strategies.

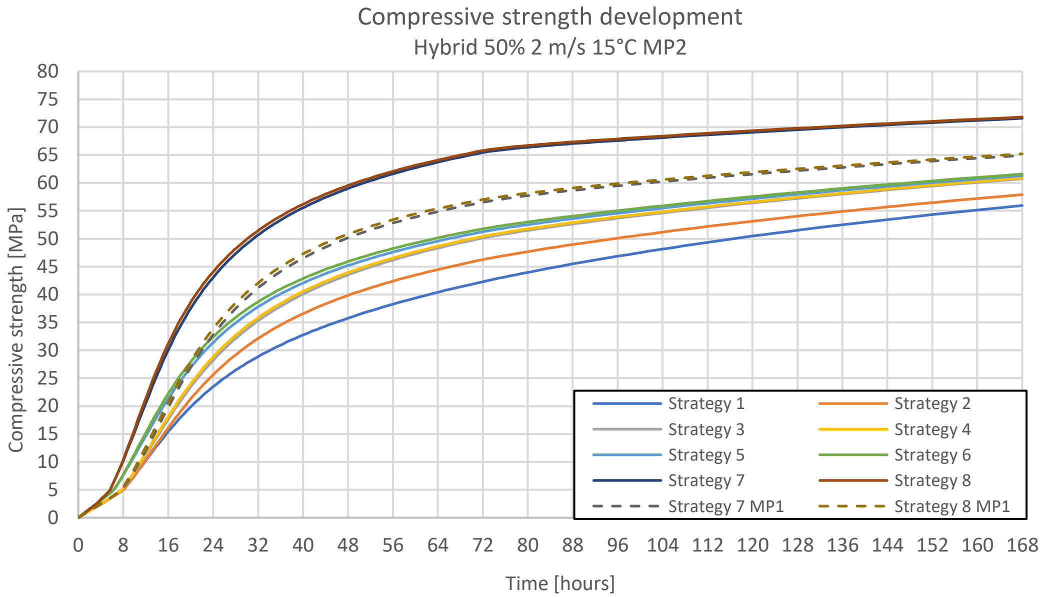


Figure 46. Compressive strength development for H50 at 15°C

Figure 47 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient corresponding to 13.3°C in the first 24 hours. The maximum temperature of strategy 6 corresponds to 36°C, while strategy 8 with heating cables reaches 50.6°C.

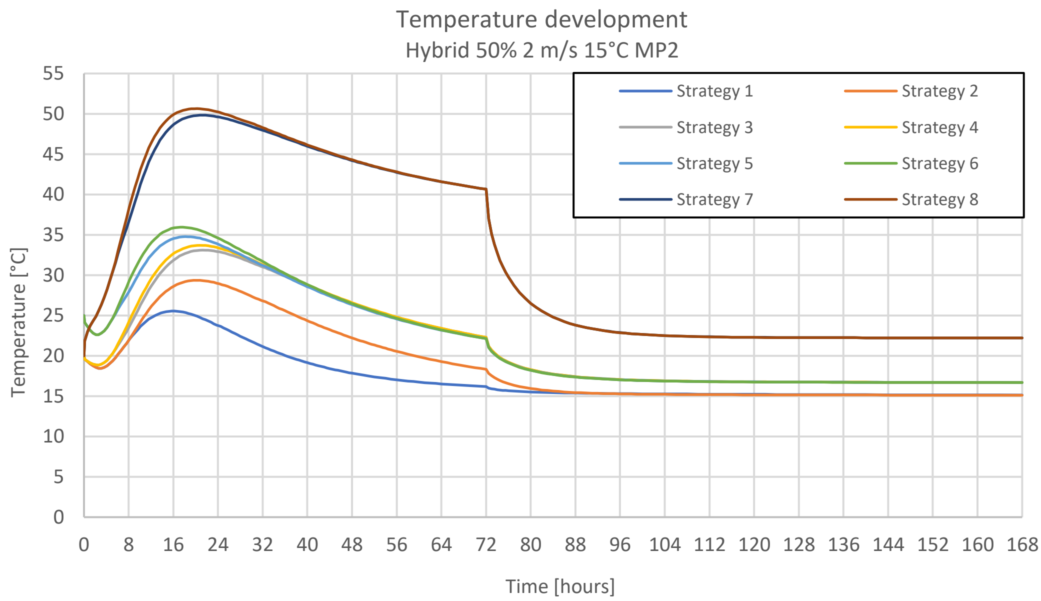


Figure 47. Temperature development for H50 at 15°C

4.4.2.7. 20°C

Figure 48 presents the compressive strength development of H50 at 20°C. At 20°C, it can be observed that strategy 6 reaches a compressive strength of 25 MPa 1 hour before strategy 8, indicating the lesser effect of heating cables at higher ambient temperatures.

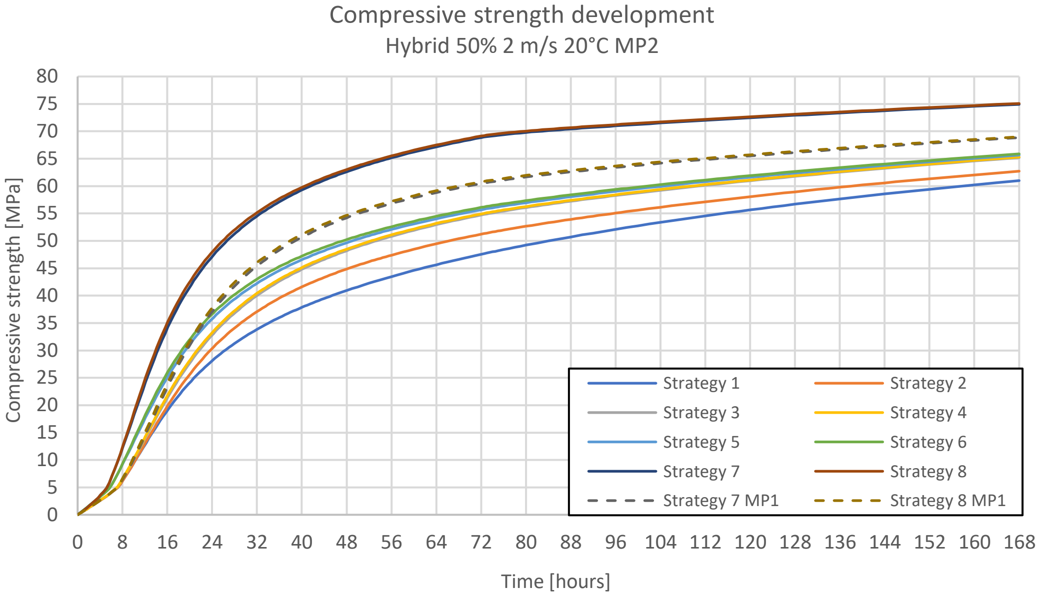


Figure 48. Compressive strength development for H50 at 20°C

Figure 49 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 16.5°C in the first 24 hours. The maximum temperature of strategy 6 corresponds to 40.6°C, while strategy 8 with heating cables reaches 54.9°C.

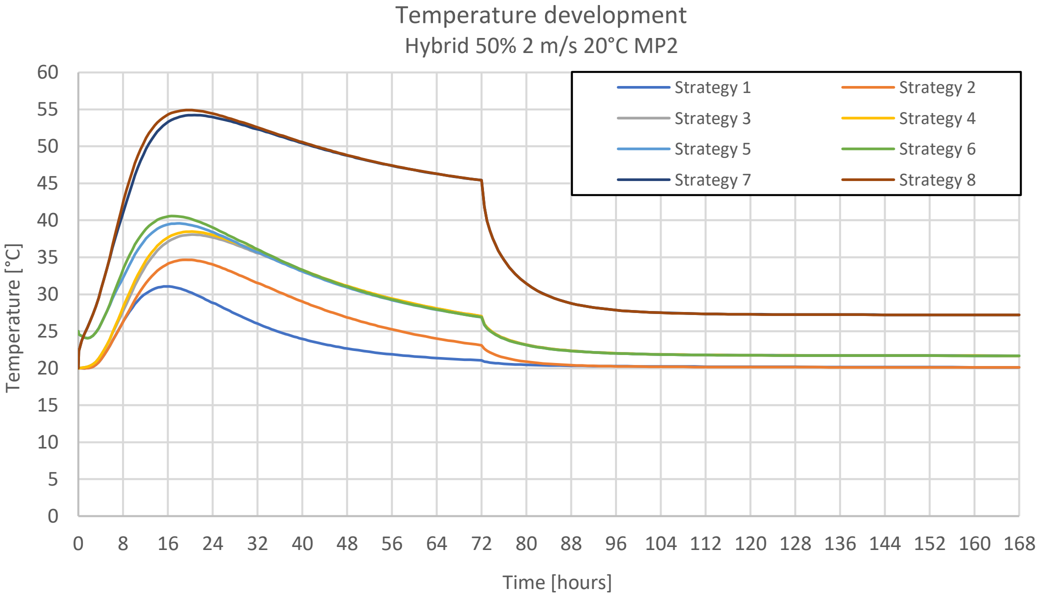


Figure 49. Temperature development for H50 at 20°C

4.4.2.8. 25°C

Figure 50 presents the compressive strength development of H50 at 25°C. Similar to the latter temperature level, it can be observed that strategy 6 reaches a compressive strength of 25 MPa before strategy 8, by 1 hour.

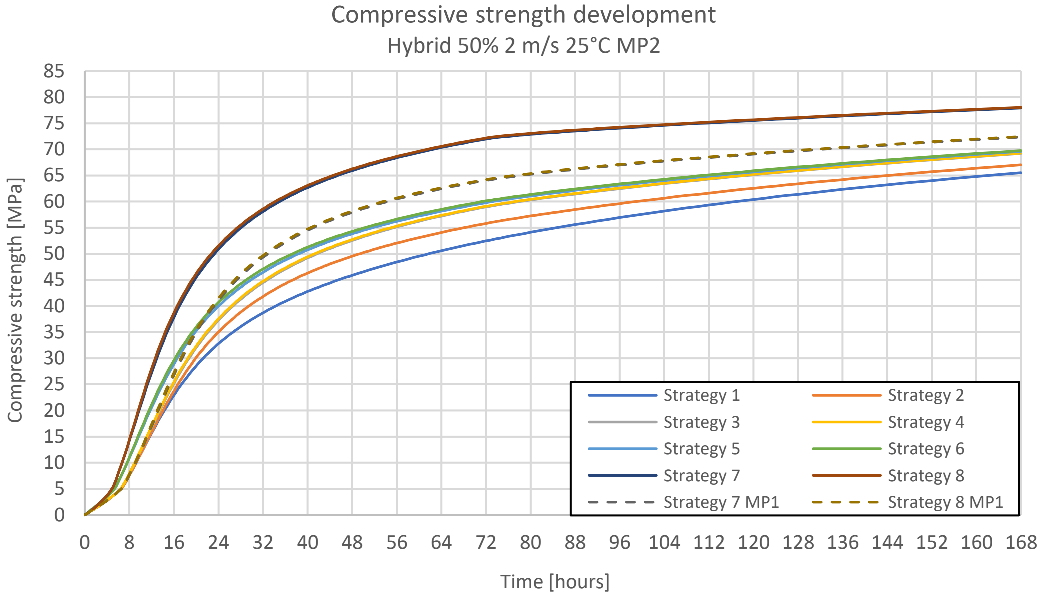


Figure 50. Compressive strength development for H50 at 25°C

Figure 51 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 20°C in the first 24 hours. At higher temperatures, strategies 3 and 4 are more or less developing the same amount of compressive strength and heat. The only difference in their curing measures is the use of accelerator in strategy 4. These properties are similar compared to the H65.

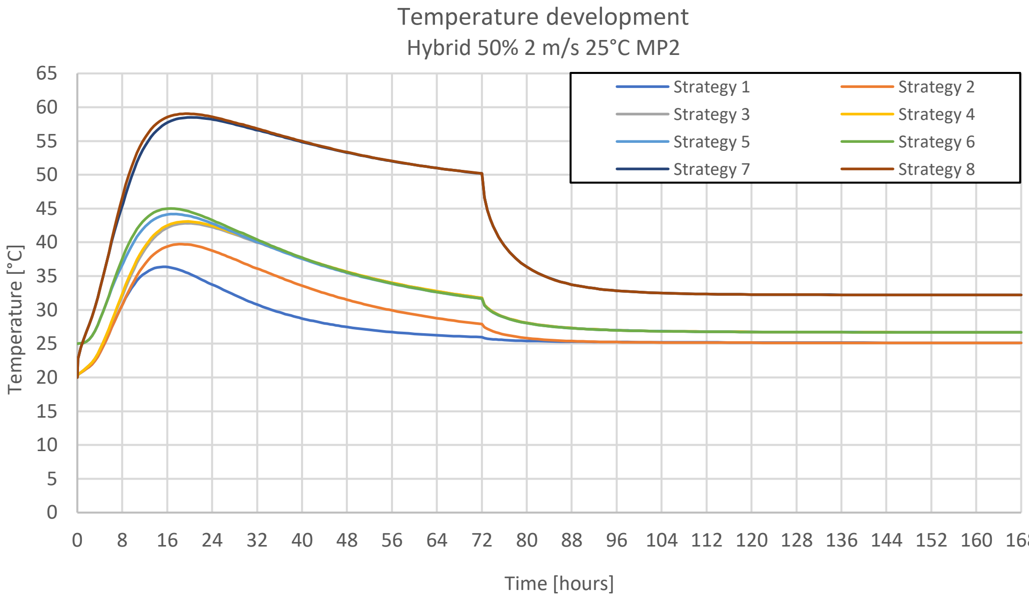


Figure 51. Temperature development for H50 at 25°C

4.4.3. Semi low-heat

The following compressive strength and temperature presentation are based on the description in the last three sections of chapter 4.4. From an ambient temperature of 10°C, no further curing measures are required other than formwork to satisfy the compressive strength criteria, as illustrated in table 25. The effect of wind speed appears to be increasing with decreasing ambient temperature. In order to illustrate this effect, it can be observed that wind speed makes strategy 2 insufficient at an ambient temperature of 5°C only at 8 m/s. At wind speeds above 8 m/s, all casting will be interrupted due to the risk it entails, regardless of whether the criteria are met. Strategy 3 is at ambient temperatures of 0°C, only satisfactory in calmer wind conditions of 2 m/s.

The use of covering at the top of the slab with ethafoam mats, as strategy 2 considers, increases the compressive strength by 2.7 MPa compared to strategy 1 at 5°C, making it a sufficient curing measure for all wind speeds except 8 m/s. Strategy 3 combines the covering of the top slab with heating underneath the slab, with an average increased compressive strength of 3.3 MPa compared to strategy 2. The combination of curing measures makes it sufficient for 0°C with a wind speed of 2 m/s. Further, strategy 4-6 has an increase of approximately 0.5 MPa compared to the previous strategy.

Table 25. 72-hour compressive strength development for SL20 at measuring point 2

Compressive strength after 72 hours (Criterium: Concrete strength > 25 MPa) Freezing constraint: Concrete strength > 5 MPa when air temp. < 0°C. Otherwise, "N/A"									
Wind [m/s]	Temp. [°C]	Strategies							
		1	2	3	4	5	6	7	8
2	-10	6.0*	10.5*	17.6	18.9	20.0	21.1	31.3(24.1)	31.8(25.4)
	-5	13.2*	18.5	23.8	24.4	25.2	25.9	34.0(28.5)	34.3(29.3)
	0	20.1	24.3	28.0	28.4	28.9	29.4	36.3(31.7)	36.5(32.1)
	5	25.0	28.4	31.2	31.4	31.9	32.1	38.3(34.3)	38.5(34.5)
	10	28.8	31.5	33.8	33.8	34.3	34.5	40.1(36.5)	40.2(36.6)
	15	32.1	34.5	36.5	36.6	36.9	37.1	42.0(39.0)	42.1(39.1)
	20	34.5	36.7	38.4	38.5	38.8	38.9	43.4(40.6)	43.5(40.7)
	25	36.7	38.6	40.1	40.1	40.5	40.6	44.7(42.1)	44.8(42.1)
4	-10	3.9*	7.4*	14.8*	16.4*	16.6*	18.4	29.9(21.4)	30.6(23.3)
	-5	11.6*	15.9*	22.1	22.9	23.3	24.2	32.9(27.1)	33.4(28.1)
	0	18.4	22.8	26.9	27.3	27.7	28.2	35.4(30.8)	35.7(31.3)
	5	23.8	27.4	30.4	30.6	31.0	31.3	37.6(33.7)	37.8(34.0)
	10	27.9	30.8	33.2	33.3	33.7	33.9	39.6(36.1)	39.7(36.2)
	15	31.3	33.9	36.0	36.1	36.3	36.6	41.5(38.6)	41.7(38.8)
	20	33.9	36.2	38.0	38.1	38.3	38.5	43.0(40.3)	43.1(40.5)
	25	36.1	38.2	39.8	39.9	40.1	40.2	44.4(41.9)	44.5(42.0)
6	-10	2.9*	5.7*	12.6*	14.4*	14.4*	16.4	29.0(19.3)	29.7(21.7)
	-5	10.6*	14.3*	20.9	21.8	22.0	23.1	32.2(26.0)	32.7(27.2)
	0	17.6	21.9	26.2	26.7	26.9	27.5	34.9(30.2)	35.3(30.8)
	5	23.1	26.8	29.9	30.2	30.4	30.8	37.2(33.3)	37.5(33.6)
	10	27.3	30.4	32.9	33.0	33.2	33.5	39.2(35.8)	39.4(36.0)
	15	30.9	33.5	35.6	35.8	35.9	36.2	41.2(38.3)	41.4(38.6)
	20	33.5	35.9	37.8	37.9	38.0	38.2	42.7(40.2)	42.9(40.3)
	25	35.8	38.0	39.6	39.7	39.8	40.0	44.2(41.8)	44.3(41.9)
8	-10	2.6*	4.9*	10.7*	12.9*	13.0*	15.3*	28.4(18.2)	29.3(20.7)
	-5	10.2*	13.4*	20.2	21.2	21.3	22.4	31.9(25.4)	32.4(26.6)
	0	17.1	21.5	25.8	26.3	26.5	27.1	34.6(29.8)	35.0(30.5)
	5	22.8	26.6	29.7	30.0	30.2	30.5	37.0(33.1)	37.3(33.4)
	10	27.1	30.2	32.7	32.8	33.0	33.3	39.1(35.7)	39.2(35.9)
	15	30.7	33.3	35.5	35.7	35.7	36.0	41.0(38.2)	41.2(38.5)
	20	33.3	35.7	37.6	37.8	37.8	38.1	42.6(40.1)	42.8(40.3)
	25	35.7	37.9	39.5	39.6	39.7	39.9	44.0(41.7)	44.2(41.9)

(-) Strength development in measuring point 1 which is decisive
* N/A in accordance with NS-EN 13670

The SL20 concrete is defined as an industry standard and is thus used as a reference concrete in this thesis [45]. Comparing table 25 with tables 23 and 24 indicates that SL20 can be considered a middle ground between H65 and H50 when considering the 72-hours compressive strength. The time-dependent course of the compressive strength is quite different from the two hybrid concretes. This difference is due to SL20 generating more heat and simultaneously being more temperature-dependent to develop compressive strength. The concrete can be considered in more challenging conditions than H65, but not at the level of H50. The lowest ambient temperature while still achieving sufficient compressive strength is -10°C combined with a wind speed of 2 m/s. At all the other wind speeds, the course of strategies providing sufficient 72-hours compressive strength is the same. The difference in achieved strength is slight, indicating that SL20 is temperature-sensitive to a minor degree. At an ambient temperature of 5°C and a wind speed of 2 m/s, SL20 can cure without the use of curing measures. At the other wind speeds, an ambient temperature of 10°C leads to the same conclusion.

Regarding an ambient temperature of -10°C, the worst-case scenario indicates that the SL20 will only achieve the required compressive strength after 3 days of curing with strategy 8. However, the strategy is only adequate at wind speeds of 2 m/s. The wind speed plays an essential role in deciding which curing strategy can be considered. Comparing the strength development of strategy 8 at 2 m/s and 8 m/s indicates a difference of 4,7 MPa. At an ambient temperature of 5°C, strategies 5 to 8 are sufficient at 2 m/s. Strategies 7 and 8 concerning heating cables are sufficient in all other wind conditions. At an ambient temperature of 5°C and a wind speed of 2 m/s, the SL20 can cure without the use of curing measures. This temperature level is considered winter casting. The compressive strength at 0°C considered for every curing strategy is presented in figure 52 below.

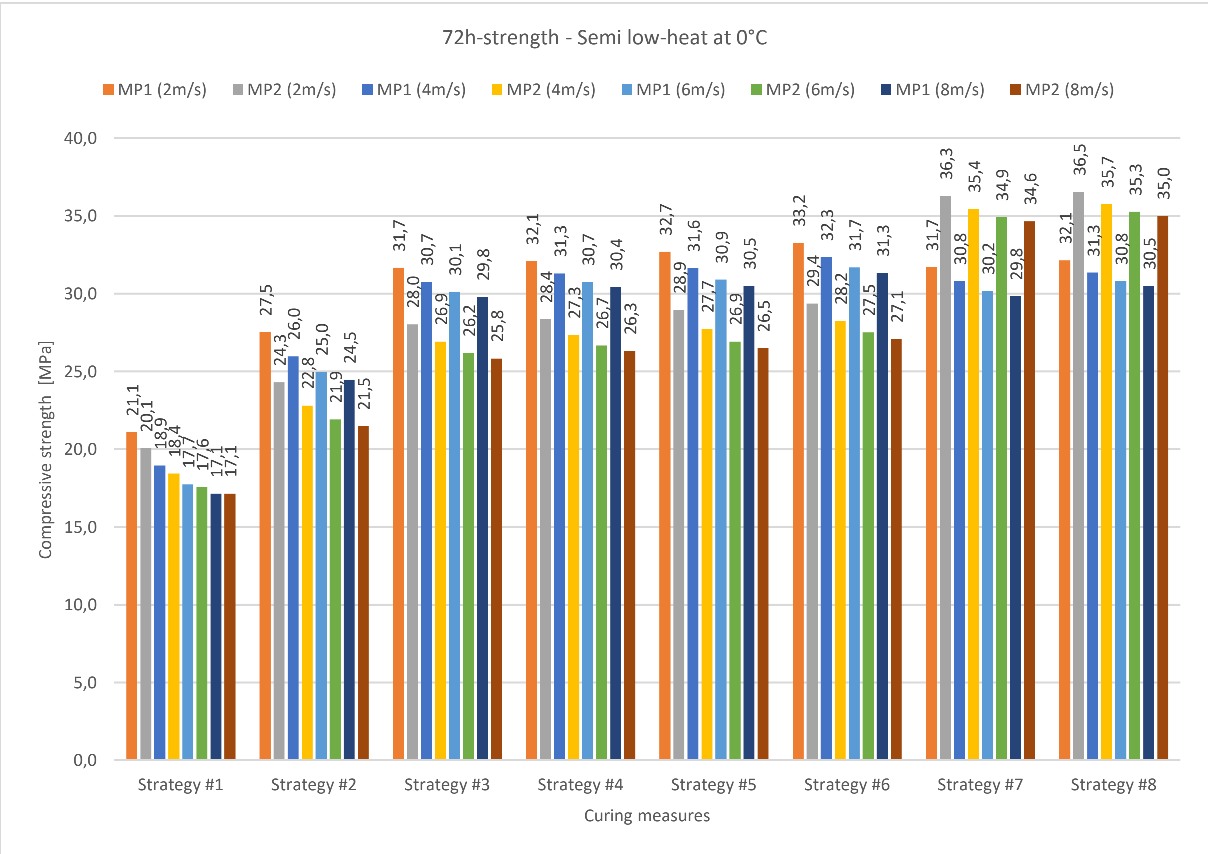


Figure 52. Compressive strength of SL20 after 72 hours at 0°C

4.4.3.1. -10°C

Figure 53 presents the compressive strength development of SL20 during winter casting at -10°C. The figure clearly illustrates a more rapid curve than the hybrid concretes, but the compressive strength after 7 days indicates a lower long-term strength. This implies correctness as f_{c28} for SL20 is the lowest of the three, as presented in table 13. It is evident to observe the significant difference between strategies 1, 2 and 3; however, none of them reaches a compressive strength higher than 25 MPa during the first 7 days of curing. Strategy 8 is the only case in which it reaches adequate strength and does so after 69 hours. Compared to the two hybrid concretes, the development of SL20 is intermediate to them at -10°C.

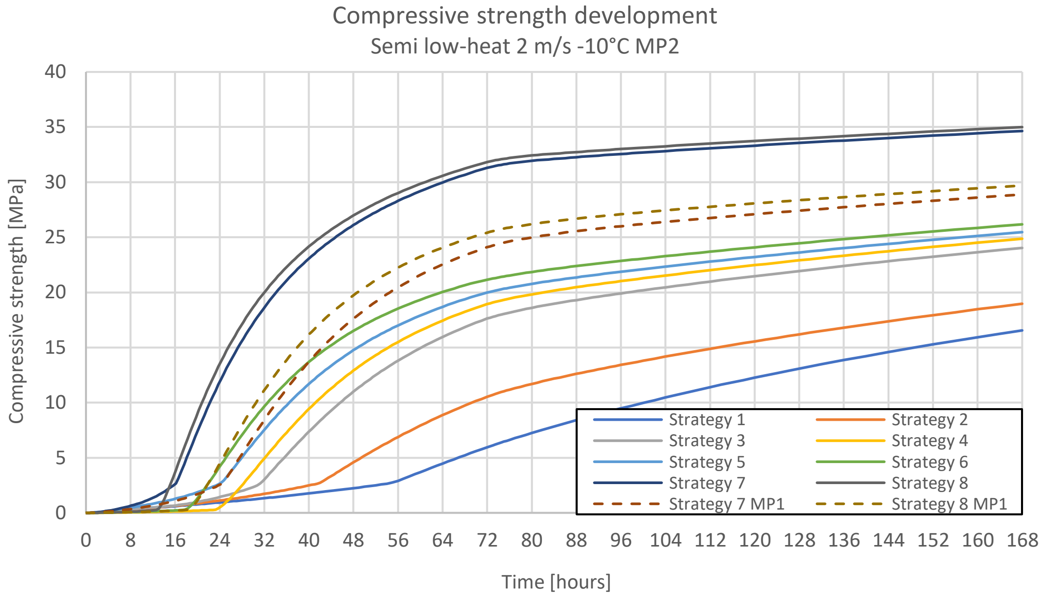


Figure 53. Compressive strength development for SL20 at -10°C

Regarding table 25, strategies 1 and 2 do not comply with NS-EN 13670 regarding minimum strength before the surface temperature drops below 0°C. Figure 54 illustrates how strategies 1 and 2 drops below 0°C after 7 hours.

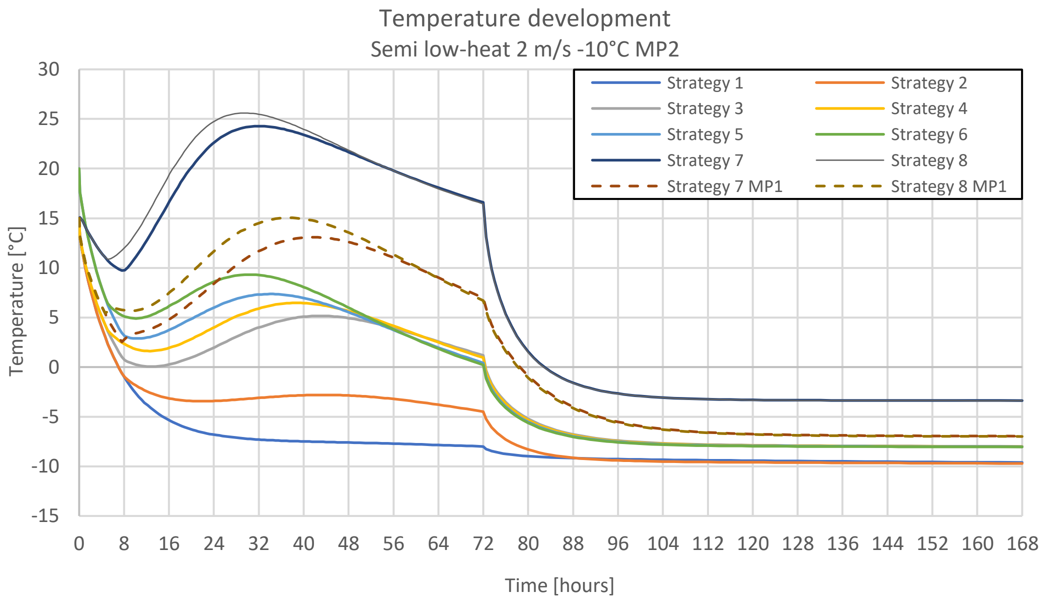


Figure 54. Temperature development for SL20 at -10°C

4.4.3.2. -5°C

Figure 55 presents the compressive strength development of SL20 during winter casting at -5°C. The steep curve of strength development during the first two days, as was the case at -10°C, indicates the reference concrete of SL20 is less temperature sensitive than the hybrid concretes. Although the development is less sensitive compared to H65 and H50, SL20 achieves an all-over lower strength development. The difference in strength development between strategies 1, 2 and 3 is still noteworthy. At 2 m/s, strategies 5 through 8 achieve sufficient strength, the former one hour before the 3 day-mark.

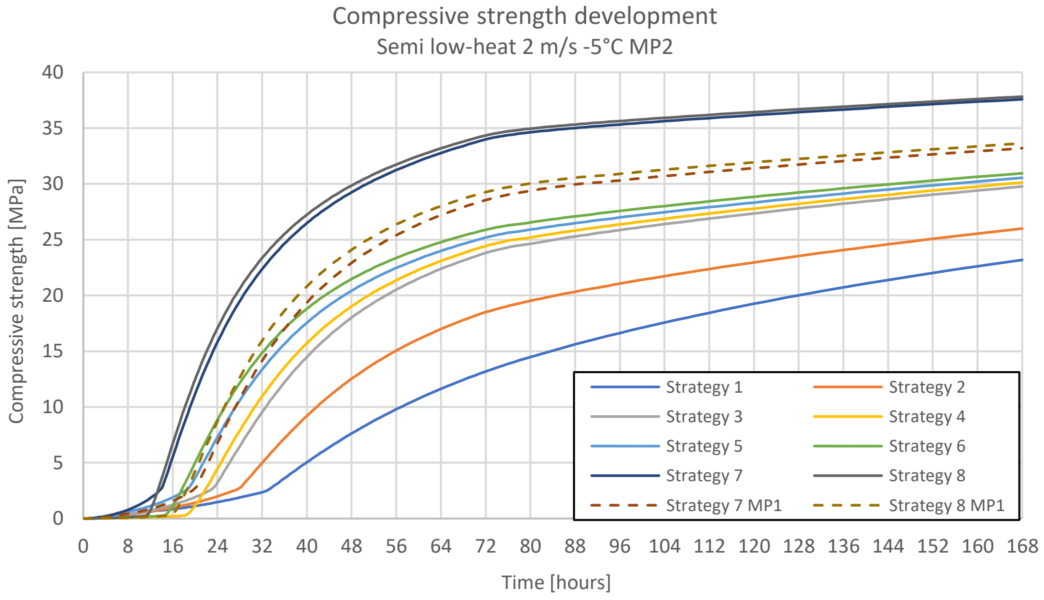


Figure 55. Compressive strength development for SL20 at -5°C

Figure 56 illustrates the heat development at -5°C. The potential of the surface temperature dropping below 0°C is present. Therefore, it is a risk that the SL20 does not satisfy the requirement in NS-EN 13670 of not achieving a compressive strength of 5 MPa before the surface temperature drops below 0°C. With reference to table 25, strategy 1 does not acquire sufficient strength at 2 m/s.

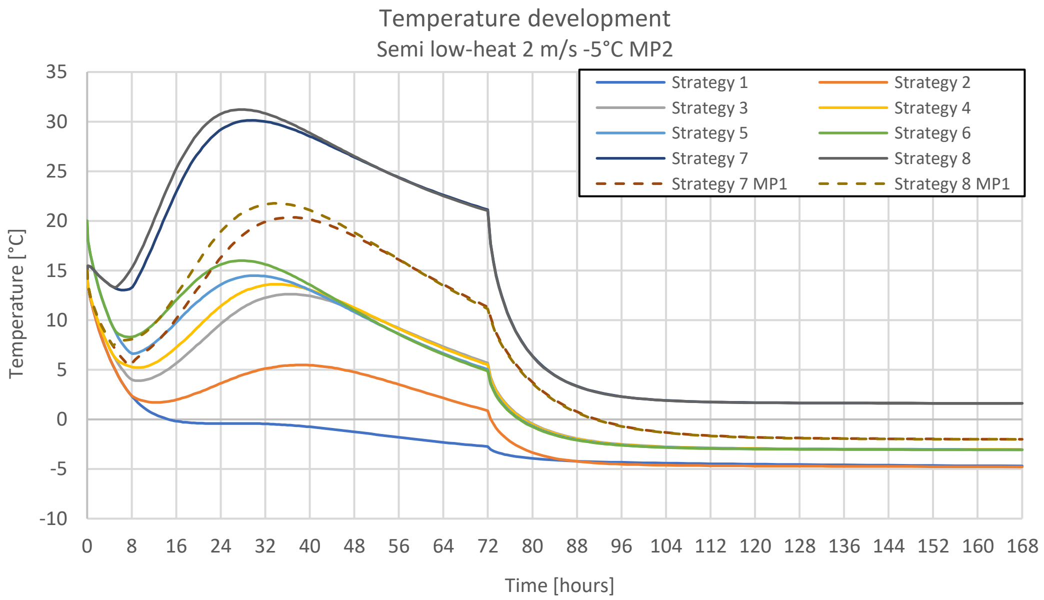


Figure 56. Temperature development for SL20 at -5°C

4.4.3.3. 0°C

Figure 57 illustrates that at 0°C, strategies 2 and 3 are, for the first time achieving adequate strength development, applicable at all the wind speeds. As pointed out in the two abovementioned subchapters, the difference in strength development is starting to decrease but is still significant. The difference in which strategies 1 and 3 reached 25 MPa is 60.5 hours.

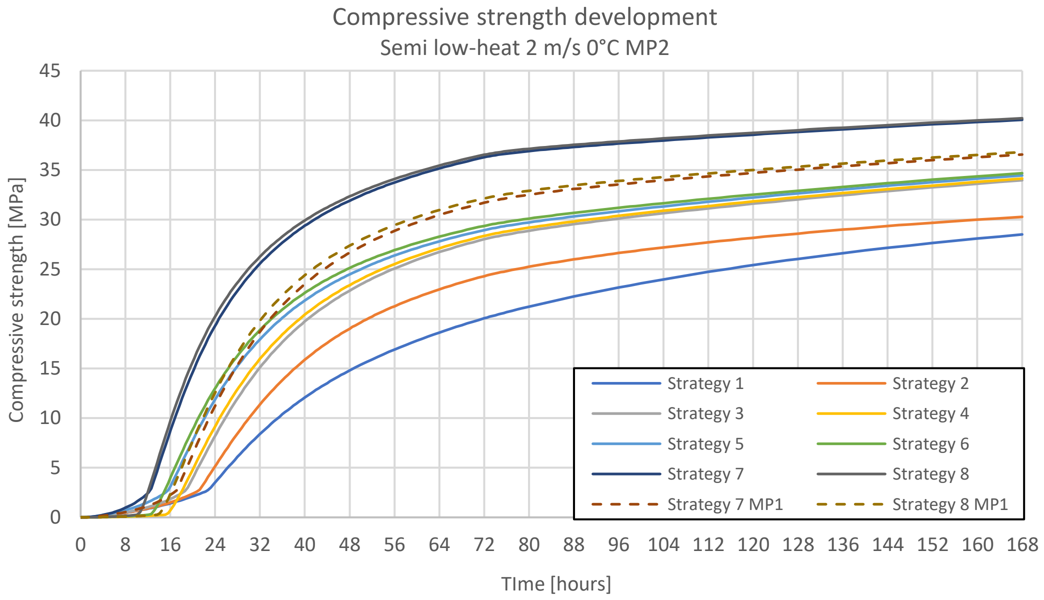


Figure 57. Compressive strength development for SL20 at 0°C

From 0°C onwards, the surface temperature of the concrete will not reach minus degrees, and the requirement in NS-EN 13670 will be maintained at the following temperature levels. Figure 58 illustrates the heat development of the SL20, where an increase compared to the -5°C results can be observed.

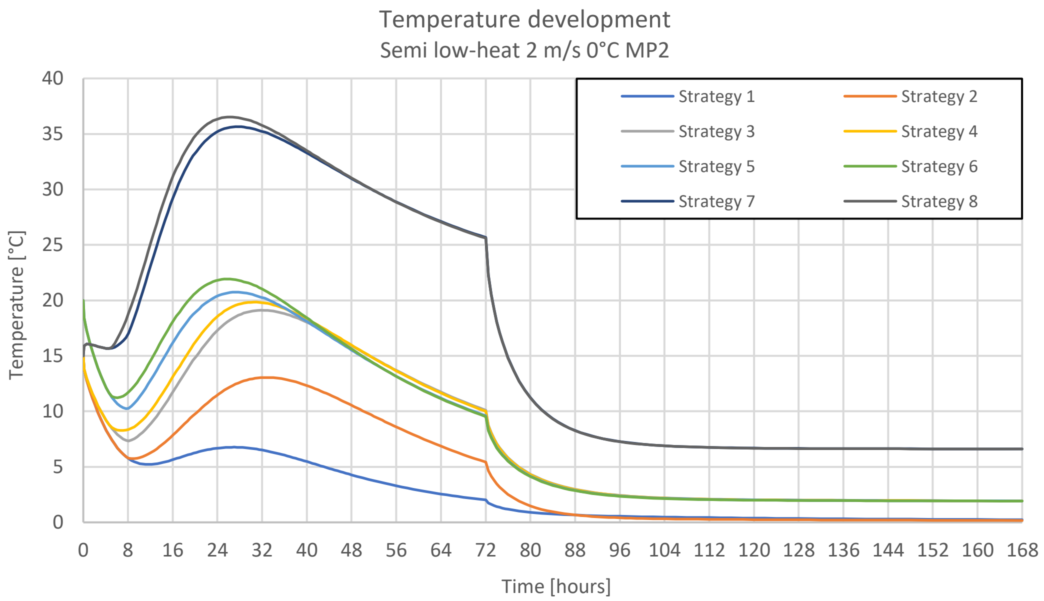


Figure 58. Temperature development for SL20 at 0°C

4.4.3.4. 5°C

Figure 59 presents the gradually evolving compressive strength development of SL20 during the last degree of winter casting at 5°C. Similar to the previous conditions, the effect of the heating cables in strategies 7 and 8 can be observed. Simultaneously the gap between the strategies with and without heating cables is becoming visibly smaller. At 5°C, all strategies are sufficient at a wind speed of 2 m/s. As the first temperature level where strategy 1 can be used, the strength difference between a wind speed of 2 m/s and 8 m/s after 72 hours is 2.2 MPa.

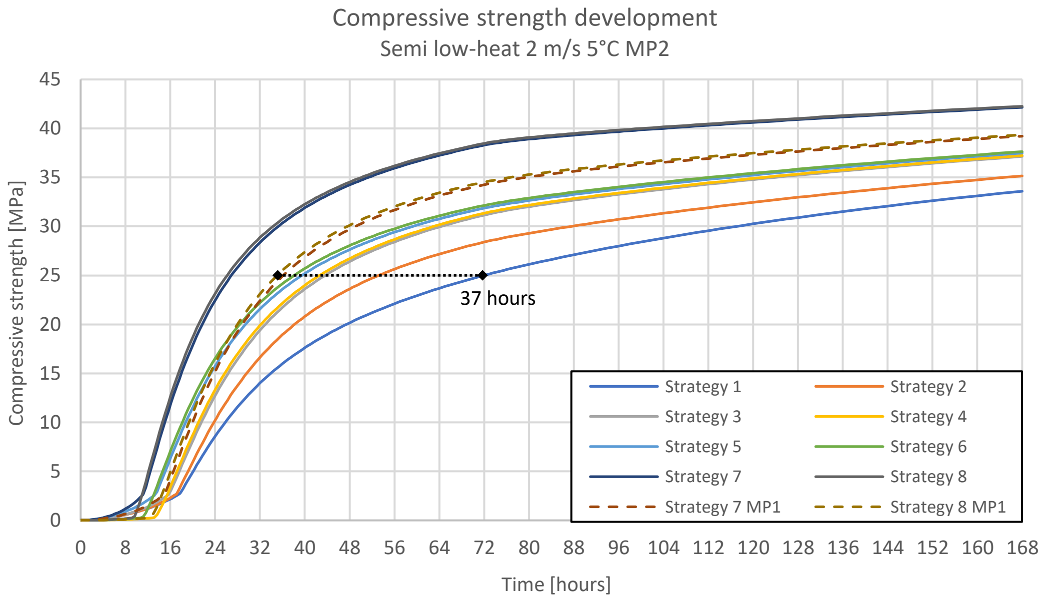


Figure 59. Compressive strength development for SL20 at 5°C

Figure 60 illustrates the gradual increase in heat development. Strategy 6 has a temperature gradient of 13.6°C in the first 24 hours. That is 4.9°C higher than H50 and 7.8°C higher than H65 under the same conditions.

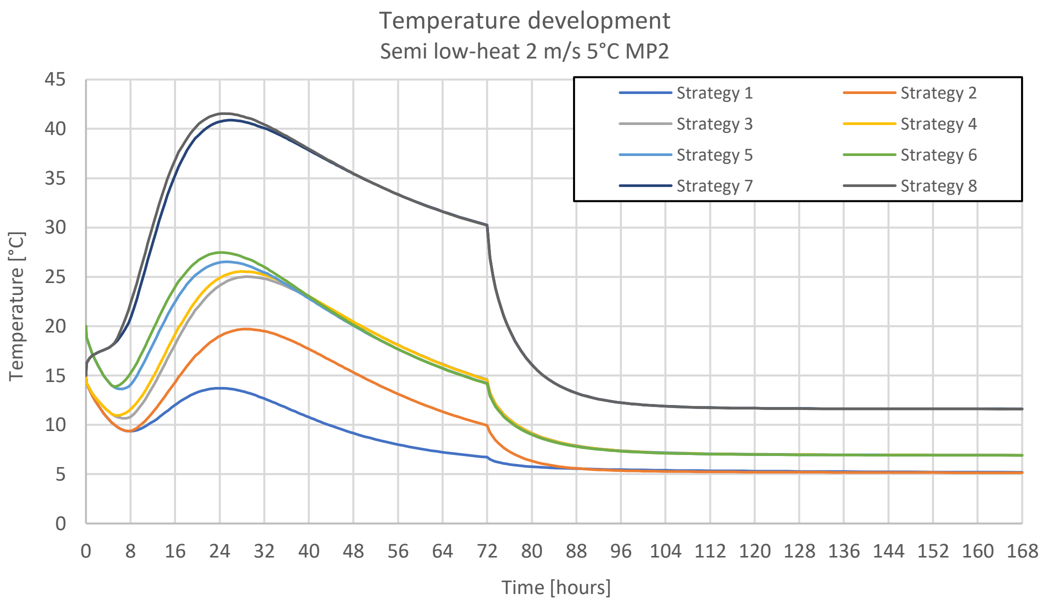


Figure 60. Temperature development for SL20 at 5°C

4.4.3.5. 10°C

Figure 61 presents the compressive strength development of SL20 at 10°C, the first level above the winter casting. It can be observed that the time gap in which the curing strategies from 1 to 8 reach a compressive strength of 25 MPa, reduces from 37 hours at 5°C to 21 hours at 10°C. Compared to H65 and 50 with a difference corresponding to 22 and 13.5 hours, respectively. Furthermore, SL20 reaches a compressive strength of 25 MPa just before H65. Thus, the hybrid concretes present their ability for earlier strength development at higher temperatures, indicating that the difficulty of such concretes lies in the curing during winter conditions.

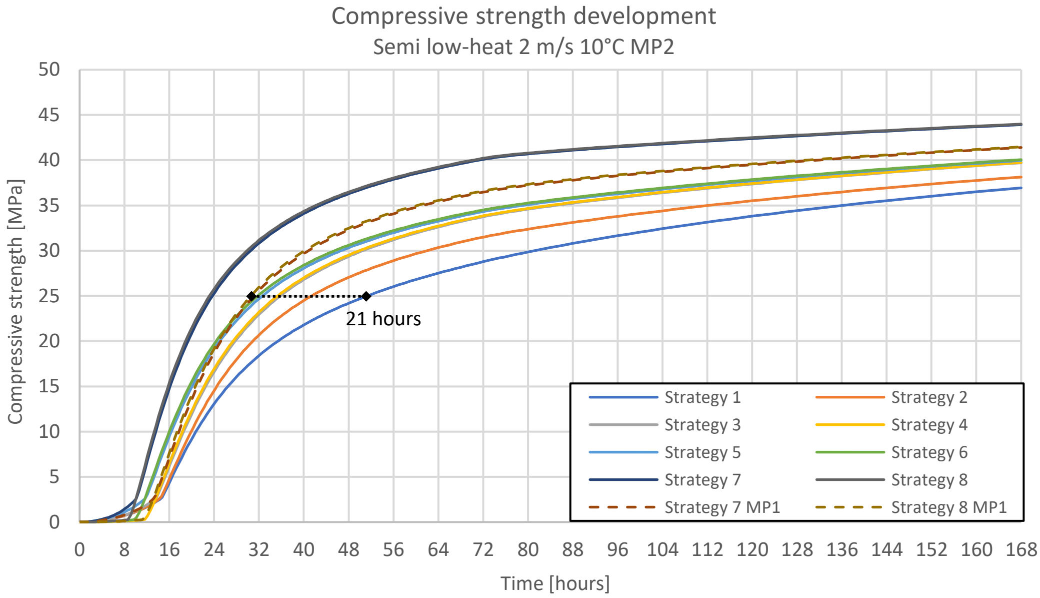


Figure 61. Compressive strength development for SL20 at 10°C

Figure 62 illustrates the gradual increase in heat development, where strategy 6 has a temperature gradient of 16.3°C in the first 24 hours. That is 4.7°C higher than H50 and 8.0°C higher than H65 under the same conditions.

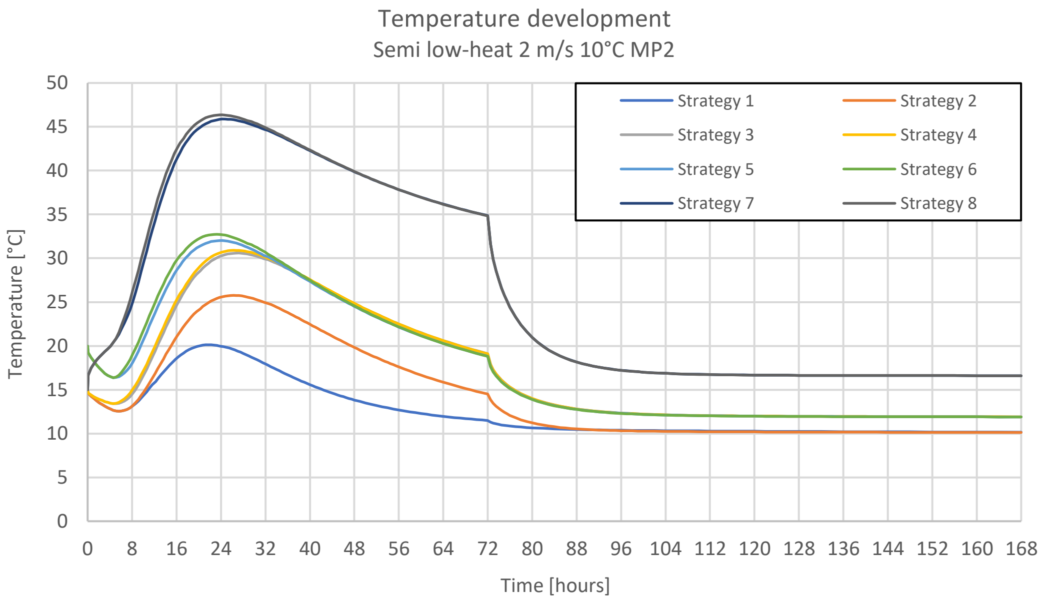


Figure 62. Temperature development for SL20 at 10°C

4.4.3.6. 15°C

Figure 63 presents the compressive strength development of SL20 at 15°C. Strategies 1 and 8 achieve a strength of 25 MPa after 26 and 18 hours, respectively, a time difference corresponding to 8 hours. Both strategies 6 and 8 reach a compressive strength of 25 MPa after 18 hours. It is clear to observe the increasing strength development at higher temperatures and the smaller strength gap between the different strategies.

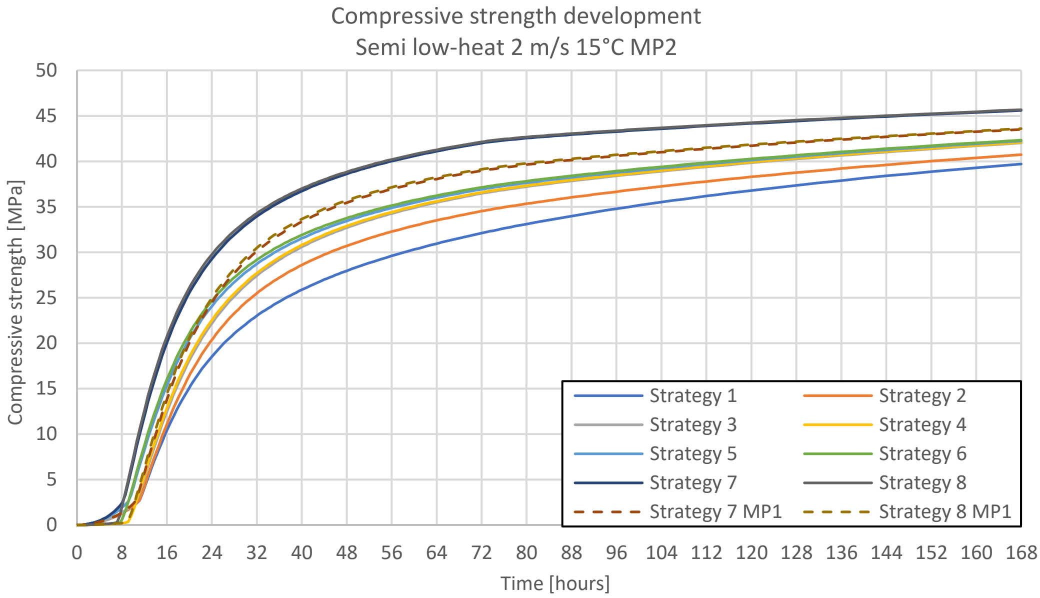


Figure 63. Compressive strength development for SL20 at 15°C

Figure 64 illustrates the gradual increase in heat development, whereas strategy 6 has a temperature gradient of 17.9°C in the first 24 hours. The maximum temperature of strategy 6 corresponds to 39.8°C, while strategy 8 with heating cables reaches 52.5°C.

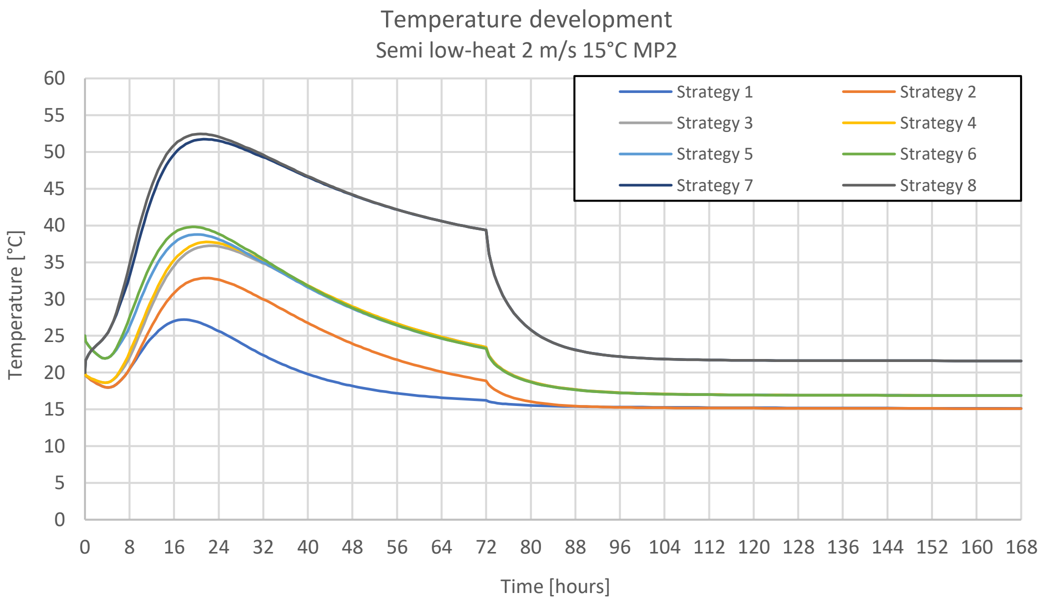


Figure 64. Temperature development for SL20 at 15°C

4.4.3.7. 20°C

Figure 65 presents the compressive strength development of SL20 at 20°C. At 20°C, it can be observed that strategy 6 reaches a compressive strength of 25 MPa 0.5 hours before strategy 8, indicating the lesser effect of heating cables at higher ambient temperatures.

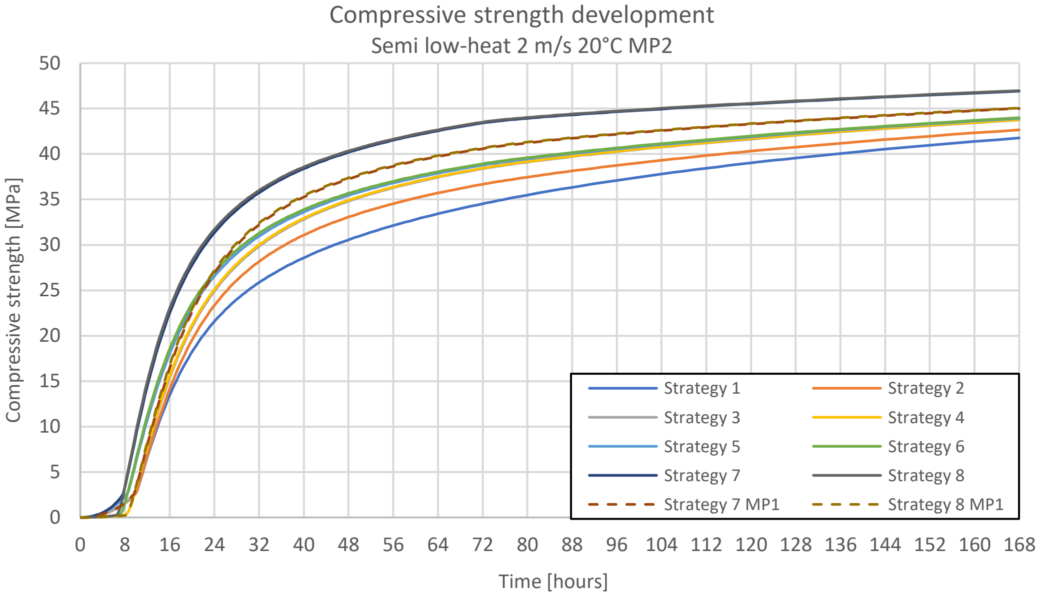


Figure 65. Compressive strength development for SL20 at 20°C

Figure 66 illustrates the gradual increase in heat development, whereas strategy 6 has a temperature gradient of 20.7°C in the first 24 hours. The maximum temperature of strategy 6 corresponds to 44.5°C, while strategy 8 with heating cables reaches 56.8°C.

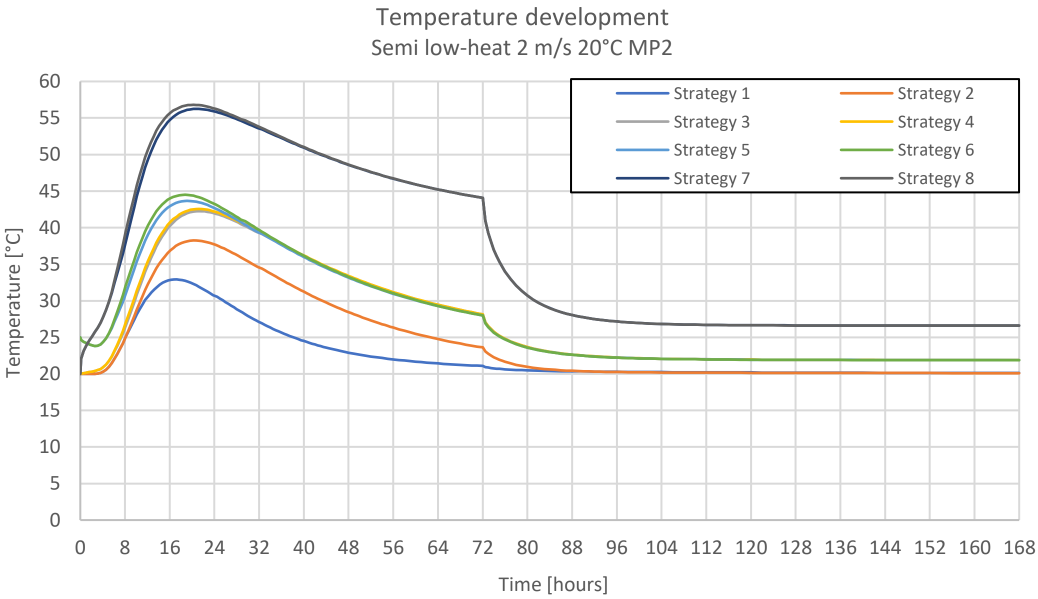


Figure 66. Temperature development for SL20 at 20°C

4.4.3.8. 25°C

Figure 67 presents the compressive strength development of SL20 at 25°C. Similar to the latter temperature level, it can be observed that strategy 6 reaches a compressive strength of 25 MPa before strategy 8, by 0.5 hours.

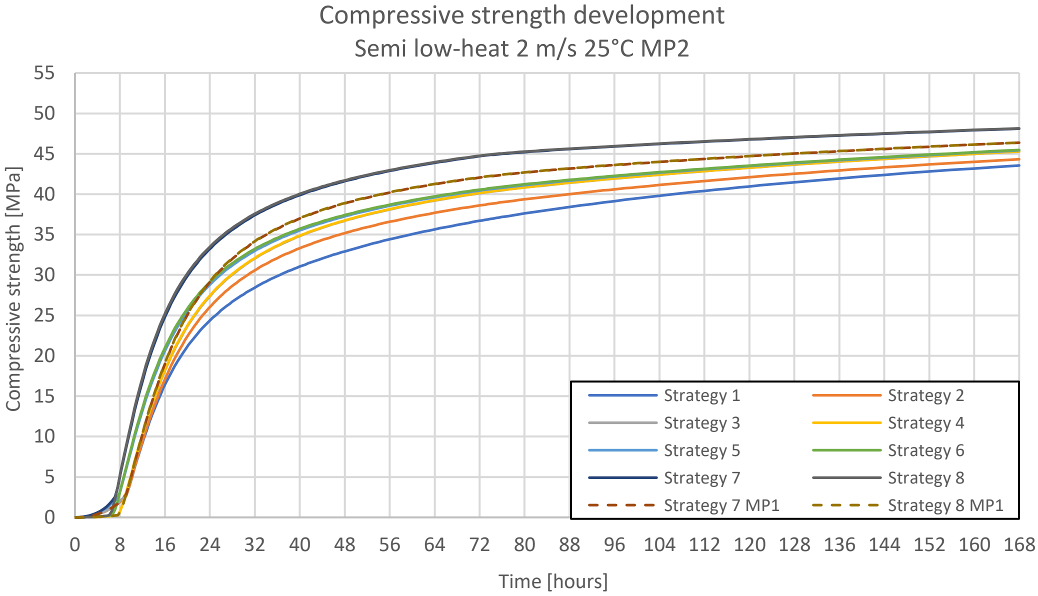


Figure 67. Compressive strength development for SL20 at 25°C

Figure 68 illustrates the gradual increase in heat development, whereas strategy 6 has a temperature gradient of 24.0°C in the first 24 hours. At higher temperatures, strategies 3 and 4 are more or less developing the same amount of compressive strength and heat. The only difference in their curing measures is the use of accelerator in strategy 4. These properties are similar compared to H65 and H50.

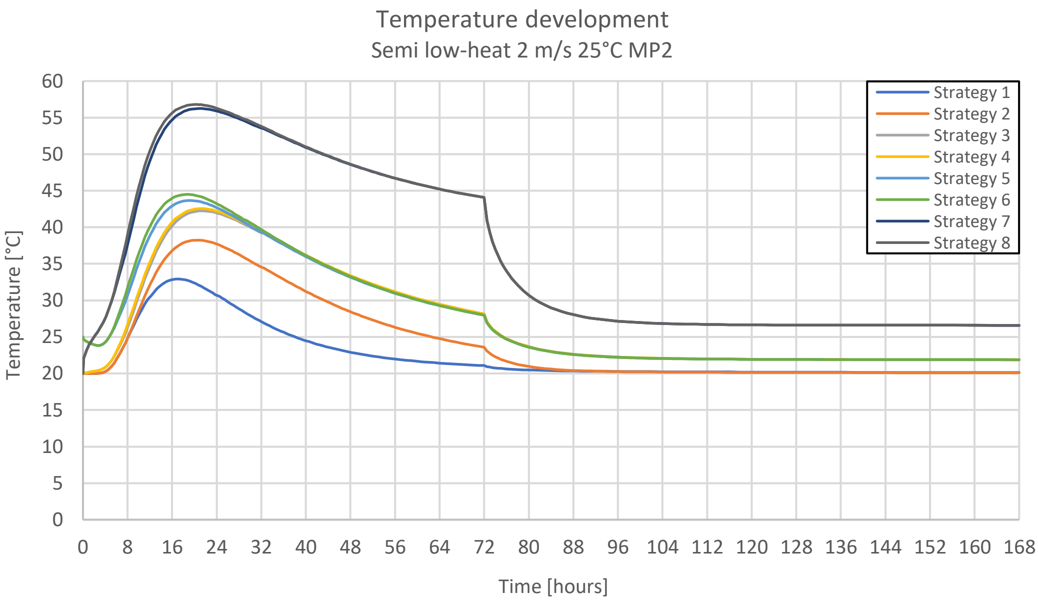


Figure 68. Temperature development for SL20 at 25°C

4.5. Progressive opportunities

This chapter will present the progressive opportunities, explaining the possibilities of utilizing the curing measures to increase the project's progression. The following tables will consider the time when the strategies achieve the required compressive strength of 25 MPa. The presented values are collected from the respective strategies' decisive measuring points. Regarding strategies 1 to 6, measuring point 2 at (6000, 0.125) will be decisive. Regarding strategies 7 and 8, measuring point 1 at (4000, 0.200) will be decisive. The latter is due to heating cables affecting measuring point 2 as a local curing measure.

Regarding NS-EN 13670 and the achieved early strength before the surface temperature falls below 0°C, chapter 4.4 concluded that the project-specific criteria comply with the requirement and are even more demanding. Therefore, the following tables present the curing process cases that do not reach 25 MPa within 168 hours as non-applicable (N/A). Furthermore, the tables are colour-indicated to show which curing strategies meet the 3-days compressive strength requirement.

4.5.1. Hybrid 65

Table 26 presents the time when the different strategies of H65 reach a compressive strength of 25 MPa. The table indicates the effect of the temperature-sensitive concrete. At -10°C, the challenging conditions are recognizable, as H65 does not achieve sufficient compressive strength within the required 3 days. At -5°C, the conditions are still challenging, and the wind speed is decisive. At 4 m/s, strategy 8 achieves 25 MPa at the 3-day mark, while at 2 m/s, both strategies 7 and 8 will suffice. That means the curing measure of heating cables is required.

At 0°C, several more possibilities of accessible strategies open up. Simultaneously this temperature level indicates the imperative effect of the wind speed as a variable. At 8 m/s, H65 requires the use of heating cables, while at 2 m/s, curing strategy 3 will suffice, considering cover at the top together will cover and heating underneath the slab. The average time difference when strategies 1 and 8 achieve sufficient strength is 74.5 hours.

At 5°C, scenario 1, which only considers the formwork, will not achieve sufficient compressive strength, regardless of wind speed. At 8 m/s, strategy 2 will need 73.5 hours to achieve 25 MPa. The average time difference when strategies 1 and 8 achieve sufficient strength is 44.1 hours.

The ambient temperature of 5°C is the last level that requires curing measures to comply with the requirement. The curing measures will nonetheless still impact the progress with the possibility of reaching sufficient strength within a day. At 10°C, the effect of the heating cables is still visible. The average time difference when strategies 1 and 8 achieve sufficient strength is 25.4 hours.

From an ambient temperature of 15°C, the effect of the heating cables does not have the same impact anymore, and the most effective curing measures of choice are defined in strategy 6, considering cover at the top, cover and heating underneath, accelerator and increased delivered concrete temperature. At 15°C, the average time difference when strategies 1 and 6 achieve sufficient strength is 14.3 hours. At 20°C, the average difference is 9.0 hours, and at 25°C, the average difference is 5.6 hours.

Table 26. Time of achieving a compressive strength of 25 MPa for H65

Time when hybrid 65 reaches 25 MPa (Criterium: 25 MPa in maximum 72 hours) Constraint: Concrete strength > 25 MPa after 168 hours. Otherwise, "N/A"									
Wind [m/s]	Temp. [°C]	Scenario							
		1	2	3	4	5	6	7	8
2	-10	N/A	N/A	N/A	N/A	N/A	N/A	128.0	112.0
	-5	N/A	168.0	120.0	115.0	106.0	99.0	69.0	63.5
	0	118.0	100.0	71.0	69.0	63.0	60.5	50.0	47.5
	5	78.0	64.0	50.0	49.5	45.5	43.5	39.5	38.0
	10	54.0	46.0	39.0	38.5	35.0	34.0	33.0	32.0
	15	37.0	31.0	28.5	28.0	25.5	24.5	24.5	24.0
	20	28.5	26.0	23.5	23.5	21.0	20.5	21.5	21.0
	25	23.0	21.5	20.5	20.0	18.0	18.0	19.0	19.0
4	-10	N/A	N/A	N/A	N/A	N/A	N/A	160.0	142.0
	-5	N/A	N/A	136.0	132.0	124.0	118.0	80.0	72.0
	0	126.0	110.0	79.0	75.5	72.0	68.0	54.5	51.0
	5	84.0	69.0	54.5	53.0	50.0	48.0	42.0	40.0
	10	58.0	49.0	41.0	75.5	37.5	36.5	34.0	33.0
	15	40.0	34.0	30.0	29.0	22.0	26.0	25.5	24.5
	20	30.5	27.0	24.5	24.0	27.0	21.5	22.0	21.5
	25	24.0	22.0	20.5	20.0	18.5	18.0	19.0	19.0
6	-10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	164.0
	-5	N/A	N/A	147.0	142.0	137.0	129.0	91.0	78.0
	0	130.0	115.0	85.0	81.0	77.0	72.0	58.0	54.0
	5	88.0	72.0	57.0	55.0	52.5	50.5	43.5	41.5
	10	61.0	50.5	42.0	41.5	39.0	38.0	34.5	33.5
	15	42.0	35.0	30.5	30.0	28.0	27.0	26.0	25.0
	20	31.5	27.5	24.5	24.0	23.0	22.0	22.0	21.5
	25	24.0	22.0	20.5	20.5	19.0	18.5	19.0	19.0
8	-10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	-5	N/A	N/A	152.0	146.0	142.0	135.0	96.5	84.0
	0	132.0	117.0	88.0	84.0	81.0	75.5	59.0	55.5
	5	88.0	73.5	58.0	56.0	54.0	51.5	44.5	42.0
	10	61.0	51.0	43.0	42.0	40.0	38.5	35.0	34.0
	15	42.5	35.5	31.0	30.0	29.0	27.5	26.5	25.0
	20	32.0	27.5	25.0	24.5	23.5	22.5	22.5	21.5
	25	24.5	22.5	21.0	20.5	19.0	18.5	19.0	19.0

4.5.2. Hybrid 50

Table 27 presents the time when the different strategies of H50 reach a compressive strength of 25 MPa. The table illustrates the intended usability of H50 as a substitute concrete in the conditions where H65 do not suffice. H50 is on its side also a temperature-sensitive concrete, and there are conditions of winter casting considered too challenging for H50 as well.

At -10°C, the challenging conditions are recognizable, but to a lesser degree than H65. H65 did not reach 25 MPa within 72 hours, whereas H50 in strategy 8 did so after 56 hours at 2 m/s and after 66.5 hours at 4 m/s. This demonstrates the effectiveness of H50 in combination with heating cables. At -5°C, H65 depends on heating cables, whereas H50 can use strategy 3 at 2 m/s.

At 0°C, strategies 2 and 3 will achieve sufficient compressive strength within 3 days, dependent on the wind speed, as illustrated in table 27. The average time difference when strategies 1 and 8 achieve sufficient strength is 74.9 hours, approximately 20 hours less than H65 under similar conditions.

At 5°C, H50 does not need curing measures to achieve sufficient compressive strength. The average time difference when strategies 1 and 8 achieve sufficient strength is 31.3 hours, approximately 13 hours less than H65 under similar conditions. At 10°C, the effect of the heating cables does not have the same impact anymore, and the most effective curing measures of choice are defined in strategy 6, considering cover at the top, cover and heating underneath, accelerator and increased delivered concrete temperature. At 10°C, the average time difference when strategies 1 and 6 achieve sufficient strength is 16.6 hours. At 15°C, the average difference is 9.6 hours, at 20°C, it is 6.4 hours, and at 25°C, it is 3.9 hours.

Table 27. Time of achieving a compressive strength of 25 MPa for H50

The time when hybrid 50 reaches 25 MPa (Criterium: 25 MPa in maximum 72 hours) Constraint: Concrete strength > 25 MPa after 168 hours. Otherwise, "N/A"									
Wind [m/s]	Temp. [°C]	Scenario							
		1	2	3	4	5	6	7	8
2	-10	N/A	N/A	132.0	124.0	110.0	98.0	93.0	56.0
	-5	132.0	108.0	69.0	66.0	59.0	55.0	45.0	41.5
	0	82.0	63.0	47.5	45.5	41.0	38.5	35.5	33.5
	5	54.0	43.5	36.0	35.0	31.5	30.0	29.5	28.0
	10	38.0	33.0	29.0	28.5	25.5	24.5	25.0	24.5
	15	26.0	23.5	21.5	21.0	18.8	18.0	19.0	18.0
	20	21.0	19.5	18.5	18.0	16.0	15.5	17.0	16.5
	25	17.5	17.0	16.0	16.0	14.0	14.0	15.5	15.0
4	-10	N/A	N/A	164.0	148.0	140.0	128.0	77.0	66.5
	-5	144.0	124.0	81.0	75.0	70.0	65.0	51.0	46.5
	0	92.0	71.0	52.5	50.5	46.5	44.0	38.5	36.0
	5	60.0	47.5	38.5	37.5	34.5	33.0	31.0	26.5
	10	41.5	35.0	30.0	30.0	27.0	26.0	25.5	25.0
	15	28.5	24.5	22.0	21.5	20.0	19.0	19.5	19.0
	20	22.0	20.0	18.5	18.0	16.5	16.0	17.0	17.0
	25	18.0	17.0	16.0	16.0	14.5	14.0	15.5	15.0
6	-10	N/A	N/A	N/A	166.0	162.0	142.0	94.0	74.5
	-5	148.0	132.0	90.0	84.0	79.0	72.0	55.0	50.0
	0	95.0	75.0	55.5	53.0	50.5	47.0	41.0	38.0
	5	63.0	49.5	40.5	39.0	36.5	34.5	32.5	30.5
	10	43.5	36.0	31.0	30.5	28.5	27.0	26.5	25.5
	15	30.0	25.5	23.0	22.0	20.5	19.5	20.0	19.0
	20	23.0	20.5	19.0	18.5	17.0	16.5	17.5	17.0
	25	18.0	17.5	16.0	16.0	14.5	14.0	15.5	15.0
8	-10	N/A	N/A	N/A	N/A	165.0	154.0	105.0	82.0
	-5	150.0	137.0	95.0	88.5	84.0	76.0	57.5	52.0
	0	97.0	77.5	57.0	54.5	52.5	49.0	42.0	39.0
	5	64.0	51.0	41.0	40.0	37.5	35.5	33.0	31.0
	10	44.5	36.5	31.5	31.0	29.0	28.0	27.0	26.0
	15	30.5	25.0	23.5	22.5	21.0	20.0	20.5	19.5
	20	23.5	21.0	19.0	18.5	17.5	16.0	17.5	17.0
	25	18.5	17.0	16.0	16.0	15.0	14.5	15.5	15.0

4.5.3. Semi low-heat

Table 28 presents the time when the different strategies of SL20 reach a compressive strength of 25 MPa. The reference concrete works as a valuable tool to compare the properties of the two hybrid concretes against traditional concrete.

At -10°C, the SL20 depends on the wind speed to achieve sufficient compressive strength using strategy 8. At 2 m/s, strategy 8 reaches 25 MPa after 69 hours. At -5°C, SL20 is dependent on using heating cables from 4 m/s but can utilize strategy 5 at 2 m/s. Strategy 5 considers cover at the top, cover and heating underneath, and increased temperature on the delivered concrete.

At 0°C, strategies 3 and 4 will achieve sufficient compressive strength within 3 days, regardless of the wind speed, as illustrated in table 28. At 5°C and a wind speed of 2 m/s, SL20 does not need curing measures to achieve sufficient compressive strength, achieving 25 MPa at the 3-day mark. At the other wind speeds, strategy 2 will suffice. The average time difference when strategies 1 and 8 achieve sufficient strength is 44.0 hours, similar to H65.

At 10°C, the effect of the heating cables does not have the same impact anymore, and the most effective curing measures of choice are defined in strategy 6, considering cover at the top, cover and heating underneath, accelerator and increased delivered concrete temperature. At 10°C, the average time difference when strategies 1 and 6 achieve sufficient strength is 25.6 hours. At 15°C, the average difference is 15.5 hours, at 20°C, it is 10.5 hours, and at 25°C, it is 7.0 hours. Although the overall development of compressive strength and temperature is different from the two hybrid concretes, the time of reaching a compressive strength of 25 MPa is similar to H65.

Table 28. Time of achieving a compressive strength of 25 MPa for SL20

The time when semi low-heat reaches 25 MPa (Criterium: 25 MPa in maximum 72 hours) Constraint: Concrete strength > 25 MPa after 168 hours. Otherwise, "N/A"									
Wind [m/s]	Temp. [°C]	Scenario							
		1	2	3	4	5	6	7	8
2	-10	N/A	N/A	N/A	N/A	157.0	140.0	80.0	69.0
	-5	N/A	152.0	84.5	77.5	71.0	65.5	54.5	51.0
	0	115.5	78.0	56.0	54.0	50.0	47.5	43.5	41.5
	5	72.0	53.5	44.0	43.0	39.5	38.0	36.5	35.0
	10	51.5	41.5	36.0	35.5	33.0	32.0	31.0	30.5
	15	37.5	31.5	28.0	27.5	25.5	24.5	24.5	24.0
	20	30.0	26.5	24.5	24.0	21.5	21.5	22.0	22.0
	25	25.0	23.0	21.5	21.5	19.5	19.5	20.0	20.0
4	-10	N/A	N/A	N/A	N/A	N/A	N/A	126.0	95.0
	-5	N/A	N/A	107.0	98.0	93.0	81.0	62.0	57.0
	0	133.0	93.5	61.5	59.0	57.0	54.0	47.0	44.5
	5	81.0	58.5	46.5	45.5	43.0	41.5	38.5	37.0
	10	57.0	44.0	37.5	37.0	35.0	34.0	32.5	31.5
	15	41.0	33.0	29.0	28.0	27.0	26.0	25.5	24.5
	20	32.5	27.0	24.5	24.5	23.0	22.0	22.5	22.0
	25	26.5	23.0	21.5	21.5	20.0	19.5	20.0	20.0
6	-10	N/A	N/A	N/A	N/A	N/A	N/A	164.0	128.0
	-5	N/A	N/A	123.0	113.0	110.0	97.0	67.0	61.0
	0	154.0	109.0	65.5	62.5	61.0	57.5	50.0	47.0
	5	85.0	61.5	48.5	47.0	45.5	43.5	39.5	38.0
	10	59.5	45.5	38.5	38.0	36.0	35.0	33.0	32.0
	15	43.5	34.0	29.5	29.0	28.0	26.5	26.0	25.0
	20	34.0	27.5	25.0	25.0	23.5	23.0	22.5	22.0
	25	27.5	23.5	22.0	21.5	20.5	20.0	20.0	20.0
8	-10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	146
	-5	N/A	N/A	132.0	120.0	119.0	106.0	70.0	64.0
	0	N/A	121.0	67.5	64.5	63.5	59.5	51.5	48.0
	5	87.0	63.0	49.5	48.0	47.0	44.5	40.5	39.0
	10	61.0	46.0	39.0	38.5	37.0	35.5	33.0	32.5
	15	44.5	34.5	30.5	29.5	28.5	27.5	26.5	25.5
	20	35.0	28.0	25.5	25.0	24.0	23.0	23.0	22.5
	25	28.0	23.5	22.0	21.5	21.0	20.0	20.0	20.0

4.6. Fieldwork – the casting of hybrid concrete at the construction site

As mentioned in chapter 3.4 regarding the method of the fieldwork, the formwork was removed after 4 days, on Monday 15.05.22. The cast slab was in the order of 80 m^3, of which most of the deliveries were 7 m^3. There were some discrepancies between ordered and received workability, which led to delivery delays, as described in chapter 3.4. However, these deviations will not affect the temperature and strength development of the concrete.

The objective of using the sensors at Gullhaug Torg 2A was to find out when the concrete had reached the requirement of 25 MPa compressive strength, so that tensioning of the tendons could start. The thermocouple sensors embedded in the concrete measured the temperature for a period of approximately 4 days. Table 29 illustrates when the concrete at Gullhaug Torg 2A reaches the target strength of 25 MPa. The measured temperature is calculated with the Arrhenius maturity function to find the compressive strength.

Table 29. The time when the hybrid 65 at Gullhaug Torg 2A reaches the target strength of 25 MPa

Measuring point	The target of 25 MPa reached
Passive anchor 1	51.1 h
Passive anchor 2	50.7 h
Top tendons	54.6 h

In figure 69, the compressive strength development of the fieldwork is illustrated together with the strength development simulated with CrackTeSt COIN considering the same weather conditions. An important notice is that the calculations performed in Maturix have used some different values for the activation energy parameters. The value of A is set to 36000 J/mol, and the value of B is set to 500 J/mol. This deviates to some degree from the values otherwise used in this thesis. In this connection, simulations have been carried out in CrackTeSt COIN with the original parameter values and corresponding values used in Maturix, marked as "adapted" in figure 69. The result indicates that the change in the value of the activation energy parameter makes very little difference. Furthermore, by comparing the results derived from CrackTeSt COIN with the ones of Maturix, the development indicates very good agreement. The report from Maturix is given in Appendix F.

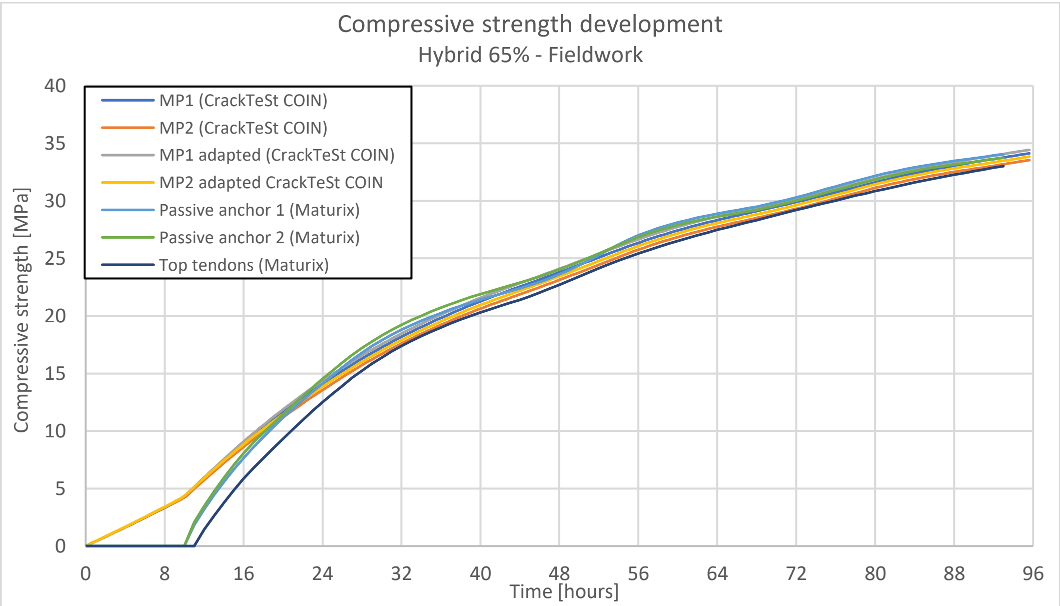


Figure 69. Compressive strength development with conditions of the fieldwork

5. Discussion

This chapter sequentially discusses the various results that emerge from chapter 4. The property development of the concretes and how they are affected by the weather conditions will be discussed. Furthermore, the results from the fieldwork and the impact of the SCMs will be accounted for.

5.1. Heat development

The heat development varies between the concrete and on the basis of the different weather conditions. Regarding weather conditions, the ambient temperature is the most decisive parameter. The pozzolanic material has a significant effect on the heat development of the concrete, where the composition of the hybrid concretes consists of a high dosage of fly ash and silica fume. The pozzolanic reaction with silica fume causes more heat to be generated compared to the use of traditional Portland cement alone. This is especially the case at higher mass ratios. On the other hand, fly ash has a lesser heat development than cement, which is the background for the term "low-heat concrete", belonging to cement with added fly ash. The pozzolanic reaction is simultaneously more temperature dependent than the cement reaction. This temperature sensitivity causes the pozzolanic reaction to proceed slowly at low temperatures and rapidly at high temperatures. These effects are essential for practical use, where winter casting is demanding.

A typical CEM I-cement has a heat generation in the order of 320-360 kJ/kg, dependent on, among other things, the degree of fine grinding and mass ratio. H50 and H65 have a heat generation of 320 kJ/kg and 280 kJ/kg, respectively. In comparison, the SL20 develops 350 kJ/kg, where the cement is the prominent binder. Considering that the silica fume is the pozzolanic material that develops the most heat, H50 illustrates this effect. As mentioned above, the heat generation of silica is higher in high mass ratios. The H50 has a mass ratio of 0.39. The combination of fly ash and the relatively low mass ratio can be thought to be the main reasons for the magnitude of heat development. Furthermore, the H65, with a larger amount of fly ash, show a decrease in heat development. Thus, this indicates that H65 is the most sensitive concrete regarding winter casting, which is evident in the results.

A prominent trend from the results clearly demonstrates that an increasing amount of fly ash leads to lower heat generation. The magnitude of this effect increases simultaneously with decreasing ambient temperature. Another trend that is clear to observe regarding heat development and the various curing measures is that the effect of the curing measures starts already at the final setting. With increasing ambient temperature, the difference between the strategies decreases. Strategy 3-6 has partly different courses, but they all arrive at the same temperature after 72 hours.

The high proportion of fly ash in the H65 can explain the slight temperature increase and that it has the lowest heat development. The temperature-increase results from the exothermic hydration process, where the mass ratio in the concrete is one of the factors that affect the amount of heat developed. For OPC based concrete with a mass ratio lower than 0.40, the total water content of the concrete will be too small for the cement to hydrate completely [7]. Increasing water content leads to increased heat generation. Regarding chapter 2.8, this will not be the case for the concretes in this thesis, as the pozzolanic material can react chemically with alkalis and the reaction product of calcium hydroxide from the hydration process. In the chemical process, fly ash contributes to far less heat generation than cement, hence the term "low-heat concrete". The H65 has a mass ratio of 0.45, which implies a relatively low value. H50 and SL20 have mass ratios of 0.39 and 0.41, respectively, indicating that the slight differences compared to H65 have a lesser effect than the amount of developed heat per cement unit, Q_∞, regarding the temperature rise.

5.1.1. Activation energy

As mentioned in subchapter 2.2.5, the activation energy is part of the hydration rate function regulating the temperature sensitivity. Figure 70 illustrates the influence of the pozzolanic materials, in particular the activation energy parameters of the fly ash and their effect in terms of relative hydration rate. The activation energy for temperatures above 20°C, represented by parameter A, increases with increasing fly ash content. The final strength of concrete using pozzolans or hydraulic binders is less affected by curing temperatures than pure Portland cement-based concrete. This is decisive for parameter B decreasing with increasing pozzolanic material. It can be seen that the hydration rate below 20°C is relatively equal for all the concrete, while the hydration rate increases with an increasing amount of fly ash.

Regarding the fieldwork, where the calculations performed in Maturix used activation energy parameters that deviated to a small degree from the ones used in CrackTeSt COIN, the results showed that the changes constituted minimal differences. Figure 70 illustrates the values of the hydration rate functions graphically, indicating the minor differences influencing the concrete. The difference between the respective hydration rates can be seen more notable at higher temperatures.

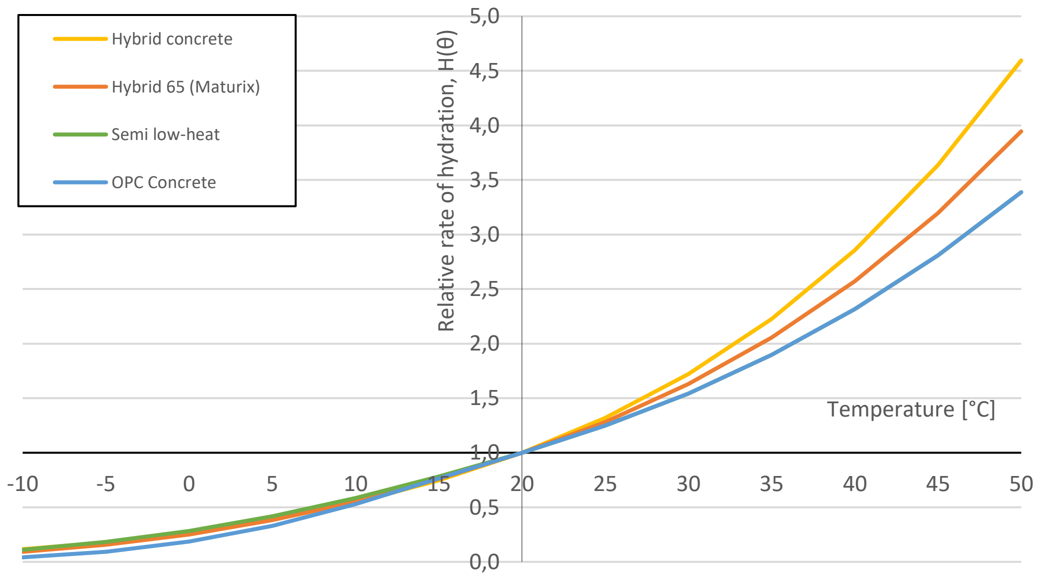


Figure 70. Hydration rate function, $H(\theta)$ versus temperature

5.1.2. Ambient temperature

Concrete curing is a self-reinforcing process if the released heat is allowed to lead to an increase in temperature in the structure. The temperature-sensitive hybrid concrete generates less heat at low temperatures, making it all the more important to utilize the generated heat. Furthermore, this temperature sensitivity entails the importance of using curing measures in winter conditions so that the concrete develops the desired strength. High curing temperature can reduce the final strength, but the pozzolanic materials help make the concrete more robust against this.

The results from the various ambient temperatures illustrate their effect on the heat development of the concrete. The development of strength is directly linked to the development of heat, which is apparent when comparing the different temperatures. From an ambient temperature of 10°C, the heat development of both hybrid concretes is in the order of magnitude to achieve the desired strength before 3 days have elapsed. The concrete is then independent of curing measures to maintain the desired heat development, and the objective of the curing measures will solely be to accelerate the progress. On the other hand, the need for curing measures in winter casting is prominent. Without curing measures, the results show that the heat development of the hybrid concretes during winter casting will decline throughout the simulated period. At -10°C, the effect of the weather conditions on H65 is challenging, and only the heating cables are able to increase the temperature in the concrete. The heat development is nevertheless too slow for the concrete to achieve the required strength within the desired time. The ambient temperature has a similar effect on H50. However, the specific heat development of the concrete as a result of the lower proportion of fly ash gives the concrete sufficient heat development with heating cables to comply with the requirement for strength.

The difference in heat development is especially prominent at ambient temperatures of -5°C. With reference to figure 70, the hydration rate indicates that the hybrid concretes are less temperature sensitive than traditional OPC-based concrete, but the relative strength development is generally slower. Therefore, from a progression perspective, it is necessary to adapt the curing measures to the weather situation, for which the calculations provide a reasonable basis.

5.2. Compressive strength

With reference to chapter 2.7, both silica fume and fly ash are pozzolanic materials. The pozzolanic reaction does not start until the hydration process has developed the calcium hydroxide ($Ca(OH)_2$), which chemically reacts with the silica (SiO_2) to form the C-S-H. Since the pozzolanic reaction depends on the hydration process, this causes the mechanical properties and strength gain due to the SiO_2 not starting until after a few days. Silica fume has high reactivity that gives the concrete increased strength, especially in the early phase. This is based on the high SiO_2 content and the fine-grained particles that provide a high specific surface, as explained in subchapter 2.7.1. This leads the silica fume to react first in the pozzolanic reaction of H65 and H50. In principle, fly ash has the same chemical properties, but the chemical activity is smaller due to the coarser particles and a lower content of SiO_2. The positive effects of fly ash are therefore developed more slowly. By comparing the H65 with the H50, this effect is evident. The H65 has a more significant fly ash proportion than the H50, resulting in slower strength development. This means that the concrete is more demanding in achieving compressive strength requirements at lower temperatures. By comparing the hybrid concretes with the reference concrete, it is clear to observe that the reference concrete with 20% fly ash and 2.9% silica fume has a more rapid development of strength from the start of the hardening phase.

Furthermore, the developed strength after 7 days indicates that the hybrid concrete is likely to develop a higher strength in the long term, illustrated in figure 71, where one can observe the more declining curve of SL20 relative to the hybrid concretes. With reference to Maage et al. [7], the ultimate strength development of concrete with the addition of pozzolanic material may reach and even exceed the strength developed of ordinary Portland cement-based concrete. However, this thesis has not considered the long-term effect of mechanical properties, whereas the early strength in the first 3 days has been the centre of evaluation. This is thus not enough time to study these effects.

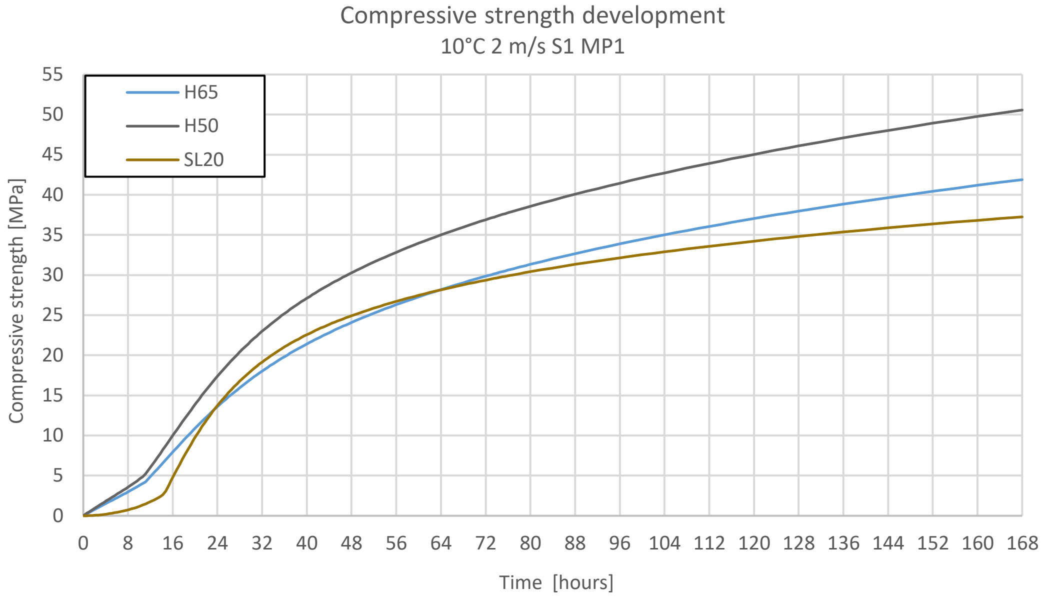


Figure 71. Comparison of strength development at 10°C between H65, H50 and SL20

The results make it clear to observe the relationship between heat and compressive strength development. The 3-days compressive strength illustrates that H50 develops a higher strength than H65 and SL20. This advantage is at the expense of the environmental benefits that follow with using H65 and why H50 is considered the second choice only to be used when H65 is not sufficient. Furthermore, the tables describing when the concretes achieve the requirement of compressive strength corresponding to 25 MPa, indicate that the time when H65 and SL20 reach this milestone is quite similar. For ordinary Portland-based concrete, it is customary to see a high early strength and a further decreasing strength development up to 28 days. The lack of early strength development is particularly evident in increasing fly ash dosage, which is illustrated by comparing the concretes in the results.

5.2.1. Winter casting

Considering the criteria in NS-EN 13670 dictating the concrete must achieve a compressive strength corresponding to 5 MPa before the surface temperature drops below 0°C, it is still possible to reach the limit compressive strength of 25 MPa. However, it is unsuitable to use concrete where this is the case. It is essential to ensure the quality of the concrete and make sure that it does not freeze before it can withstand this. If the concrete freezes before it has achieved the required strength, it will suffer permanent damage in loss of strength and reduced durability. The significant loss of strength when the concrete freezes before it has set, i.e., strength less than 1-2 MPa, causes ice needles to form in the concrete. When these needles thaw, a cavity is formed between the aggregate and the binder.

The permanent loss of strength will be visible in the long-term strength development. This is thus not displayed in the test results of this thesis, whereas the 7 days of strength development is not enough time in order to study the effect of the freezing condition. It is nevertheless important to point out the cases where the concrete does not meet the criterion. The positive effect of the curing measures illustrates that at -5°C, freezing will not be a problem. At -10°C, H65 is most exposed, where the concrete is dependent on heating cables to avoid freezing. H50 solves the problem with heating underneath the slabs.

5.2.2. SCMs

The hybrid concretes in this thesis illustrate the effect of silica fume and fly ash, dictated by slow strength development. Silica fume has a high proportion of amorphous SiO_2, which have the ability to participate in the pozzolanic reaction. As mentioned in subchapter 2.7.1, the silica fume has a large specific surface area of 20,000 kg/m^2. These two factors lead to silica fume having a high chemical activity. What still causes the strength gain to be postponed for a few days is that the pozzolan reaction does not start until calcium hydroxide ($Ca(OH)_2$) has been formed from the hydration process. Fly ash has the same chemical effects due to the amorphous silica. However, the chemical activity is less as the content of SiO_2 is lower than for silica fume, and the particles are coarser, giving a specific surface corresponding to the cement of 300-600 kg/m^2. The low chemical activity leads to the positive effects of fly ash taking months to be fully achieved. These effects seem reasonable as to why H65, with the highest amount of fly ash, is more temperature-dependent and generally achieves lower strength.

When it comes to heat generation, the two pozzolanic materials are at opposite ends of the scale, where the properties of cement are considered the norm. Silica fume generates more heat than OPC, especially at higher mass ratios, while fly ash generates far less. The pozzolanic reaction with silica fume is more temperature dependent than cement, while with fly ash, the relative reaction rate is higher independent of temperature. It must be pointed out that this is relative, where the reaction rate regarding fly ash-based concrete is generally lower than for OPC-based concrete. The results from the experimental tests indicate that the H65 has a lower overall heat development, which is prominent during the winter casting.

6. Conclusion

The overall aim of the thesis has been to investigate how the temperature and compressive strength of concrete with high pozzolanic material behaves during different weather conditions and the influence of different curing measures. Furthermore, the thesis aims to contribute as a reference considering planning procedures with new concrete compositions. The aim has been approached experimentally and analytically through extensive experimental testing in the computer-based curing technology program, CrackTeSt, and fieldwork at Gullhaug Torg through casting with temperature sensors.

The main conclusions are in the following, presented concerning the defined objectives:

- Examine the behaviour of the different concrete compositions.

The reaction of the cement with water is a reliable and predictable chemical process. When other types of binders are added, such as pozzolanic materials in this case, it leads to new chemical reactions with a change in properties. Therefore, it is essential, especially when post-tensioning, to know when it is possible to stress the cables and remove the formwork – both in terms of safety and not to delay the project's progress. This further emphasizes the importance of validating the material model in the curing technology program. Evaluating the validity of the material model has not been part of the thesis' research question. At the same time, good agreement is shown between the temperature and strength development results from the fieldwork and CrackTeSt COIN. This supports the validity of the calculation approaches.

In order to investigate the effects of the pozzolanic materials of the hybrid concretes, that is, fly ash and silica fume, the thesis has performed extensive experimental testing through CrackTeSt COIN as well as fieldwork with casting together with temperature sensors. The aim has been to investigate the temperature, and compressive strength development of two hybrid concretes and compare the results from CrackTeSt COIN with the results from the casting at Gullhaug Torg. The results showed that both the hybrid concretes, H65 and H50, have low heat and slow strength development, whereas the development decreased with increasing pozzolanic material.

The use of fly ash and silica fume as pozzolanic material in the two hybrid concretes have significantly impacted the mechanical properties. The study illustrates the positive effect of silica fume during winter casting in the form of higher heat development. Simultaneously, the results from CrackTeSt COIN show that the environmental ambitions can be maintained to a large extent with correct planning and evaluation of curing measures. The most challenging conditions are simulated at an ambient temperature of -10°C, indicating the importance of planning and evaluating the curing measures.

- *Examine the effect of curing measures under representative weather conditions.*

The challenging conditions during winter casting became apparent throughout the simulated ambient temperatures and wind conditions. The likewise challenging hybrid concretes illustrate the need for curing measures during such conditions. With the H50 as the second choice with respect to the environmental ambitions, there are two scenarios in which none of the concretes are considered sufficient regarding the requirement, based on the curing measures regarded in this thesis. That is at an ambient temperature of -10°C and wind speeds of 6 m/s and 8 m/s. Besides this, the required compressive strength of 25 MPa is achieved within 3 days for every combination of weather conditions. The H50, with the lowest amount of pozzolanic material, is independent of curing measures to reach sufficient strength from an ambient temperature of 5°C. For H65, it is independent from -10°C. The curing measures have, through the results, illustrated their effectiveness, with a gradual increase from strategy 1 to 8. When the measurements show that the requirement of 25 MPa can be achieved earlier than 3 days, this data can be used to consider accelerating the time of tensioning and thus save time.

- Optimisation of curing measures to achieve 25 MPa compressive strength prior to 3 days.

Time is valuable in the buildings and construction sector, especially when several companies and contractors collaborate on extensive projects. Gullhaug Torg 2A requires optimal adjustments and continuous workflow coordination to keep up with the progress plan. Concrete is the most used material, where the estimation of curing can be a challenging process, with particular focus on the post-tensioned slabs in the means of safety and progression. As mentioned above, the pozzolanic effect of the hybrid concretes significantly impacts the mechanical properties. The concrete is also highly affected by the external influences of weather and wind, emphasizing the importance of a good planning phase. Knowing the temperature and compressive strength development and how the concrete behaves in different weather conditions beforehand is essential in keeping efficiency and not losing valuable redundant waiting time. CrackTeSt COIN has, as a curing technology program, proven to be an invaluable resource as new and more environmentally friendly concrete emerges. The program opens opportunities to control the curing process and optimise in terms of the correct choice of curing measures. The results of the thesis illustrate the effect of the curing measures and present the time when the concrete reaches sufficient compressive strength based on the influence of the weather conditions.

- *Final comments*

For information, changes were made to the concrete recipes used in the project. This was due to a shortage of cement in Denmark, which led Unicon to switch from Aalborg to Norcem cement. The result was that the cement "Rapid FA" from Aalborg was replaced with "Std FA" from Norcem. This shift had a positive effect on CO_2 emissions both in terms of production and transport to Sjursøya. Regarding the mechanical properties relevant to this thesis, the concrete composition will be essentially the same, where the proportion of pozzolanic materials will be unchanged and is thus regarded not to impact the results of the thesis in any way. The concrete recipes are presented in Appendix B.

7. Further work

Conversations with representatives from FutureBuilt, Avantor and Skanska, as well as experiences from the fieldwork, reveal that the hybrid concrete has led to some problematic casting. There are thus more factors than curing and development of mechanical properties that need to be mapped regarding hybrid concrete. There is no point in using more environmentally friendly concrete if it has to be replaced within 20 years because the durability is inadequate. Castability is, therefore, an important matter, which has been a challenge at Gullhaug Torg in areas with tight reinforcement. It will be helpful to find out the sources of the problematic workability.

This thesis has looked exclusively at mechanical properties at an early stage with the objective of reaching a target compressive strength. Concrete with a high pozzolanic content has a slower development of strength but is also a more robust concrete in terms of temperature. It would be helpful to look at the development of mechanical properties of hybrid concrete over a more extended period, document the behaviour during winter conditions, and evaluate the utility potential.

The environmental ambition that the thesis is based on is the incentive of implementing SCMs as constituents in the concrete. Slag is a hydraulically latent SCM that is more temperature-sensitive than the pozzolanic binders. Similarly, it is a residual product that gives the concrete a smaller carbon footprint. As an alternative that is used today and will be used in the future, slag has not made a significant entry into Norway. It will, regardless, be interesting to see how slag-based concrete behaves during winter casting and the effectiveness of curing measures.

The transition from plastic phase to hardening material is more diffuse and not too accurate when simulating the strength development in CrackTeSt COIN. Considering the parameter $t_{0,}$ which corresponds to the "final setting", it would be interesting to study how to improve the early strength development in the curing technology program.

References

1. O'Brien, K., A.L.S. Clair, and B. Kristoffersen, *Climate change, ethics and human security*. 2010: Cambridge University Press.
2. Masson-Delmotte, V., et al., *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 2021, IPCC.
3. Programme, U.N.E., *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. 2021: Nairobi. p. 105.
4. Miljodirektoratet. *Miljømål 5.3*. 2021 [cited 2022 12.01.2022]; Available from: https://miljostatus.miljodirektoratet.no/miljomal/klima/miljomal-5.3/.
5. Landsforening, B., *GRØNT SKIFTE-byggenæringens bidrag til løsning.* BNLs miljø-og energipolitik mot, 2016. **2030**: p. 1-12.
6. Preston, F. and J. Lehne, *Making Concrete Change Innovation in Low-carbon Cement and Concrete*. 2018: Chatham House - The Royal Institute of International Affairs.
7. Maage, M., et al., *Betong Regelverk, teknologi og utførelse*. 2 ed. UTGAVE. OSLO: NORSK BETONGFORENING OG BYGGENÆRINGENS FORLAG. 2015: Byggenæringens Forlag AS.
8. Snohetta, *Gullhaug Torg 2A*, 346f0c58800334d4beaa7ebc08aa0baa_2048w, Editor. 2015, Snohetta/MIR: www.snohetta.com.
9. Danielsberg, A., *Personal communication*. 2022, Avantor.
10. Skanska. *Gullhaug Torg 2A*. 2016 [cited 2022 09.01.2022]; Available from: https://www.skanska.no/hva-vi-gjor/prosjekter/249739/Gullhaug-Torg-2A.
11. Snohetta. *Gullhaug Torg*. 2016 [cited 2022 01.09.2022]; Available from: https://snohetta.com/projects/269-gullhaug-torg.
12. FutureBuilt. *Verikal Nydalen*. 2021 [cited 2022 01.09.2022]; Available from: https://www.futurebuilt.no/Forbildeprosjekter#!/Forbildeprosjekter/Vertikal-Nydalen.
13. Sørensen, S.I., *Betongkonstruksjoner*. 2015: Fagbokforlaget.
14. Hermansen, F., *Personal communication*. 2022, Skanska.
15. Sørpler, B., K. Kjellsen, and T. Fredvik, *Betong: Herdeteknologi.* Herdeteknologi utgitt av Norcem FoU, 2009(3).
16. Bjøntegaard, Ø., *Basis for and practical approaches to stress calculations and crack risk estimation in hardening concrete structures–State of the art FA 3 Technical performance. SP 3.1 Crack free concrete structures.* 2011.
17. data, C. *Klima: Oslo*. 2022 [cited 2022 10.01.2022]; Available from: https://no.climate-data.org/europa/norge/oslo-1190/.
18. Bjøntegaard, Ø., et al., *Forståelse og bruk av håndbok R762, prosess 84.* 2017.
19. Norge, S., *NS-EN 13670:2009+NA:2010 Utførelse av betongkonstruksjoner*. 2010, Norge, Standard.
20. Bjøntegaard, Ø., et al., *Praktiske råd og tiltak mot fastholdingsriss i herdende betongkonstruksjoner*. 2021, Norsk Betongforening: Norsk Betongforening.
21. Skjølsvik, O.B., E. Haram, and S. Smeplass, *Beregning av rissrisiko CrackTeSt COIN: FA: Technical performance: SP 3.1 Crack free concrete structures.* 2015.
22. SINTEF Byggforsk. *520.028 Oppfølging av betongens herdeforløp på byggeplass*. 2011 [cited 2022 10.02.2022]; Available from: https://www.byggforsk.no/dokument/4018/oppfoelging_av_betongens_herdeforloep_paa_byggeplass#i51.
23. Béton, C.E.-I.d., *CEB-FIP model code 1990: Design code*. 1993: Thomas Telford Publishing.
24. Kanstad, T., et al., *Mechanical properties of young concrete: Part II: Determination of model parameters and test program proposals.* Materials and Structures, 2003. **36**: p. 226-230.
25. Klausen, A.B.E., *Early age crack assessment of concrete structures Experimental investigation of decisive parameters.* 2016.

26. Norge, S., *NS-EN ISO 14040:2006 Miljøstyring - Livsløpsvurdering - Prinsipper og rammeverk*. 2006, Standard Norge.
27. Fjeldheim, H., *Personal communication*. 2022, Skanska.
28. Norge, S., *NS-EN 206:2013+A2: 2021+NA:2021 Betong, Spesifikasjon, egenskaper, framstilling og samsvar*. 2021, Standard Norge.
29. Kompen, R., *Betong regelverk: standarder og prosesskode-2 prosess 84.* 2009.
30. Betongforening, N., *Norsk Betongforenings Publikasjon nr. 37:2020 "Lavkarbonbetong"*. 2020.
31. FutureBuilt, *FutureBuilt kvalitetskriterier*. 2021, FutureBuilt.
32. Norwegian Green Building Council, *BREEAM-NOR 2016 for nybygg, Teknisk manual SD5075NOR - ver: 1.2*. 2016: www.byggalliansen.no. p. 338.
33. FutureBuilt. *På vei mot nullutslipp*. 2018 [cited 2022 15.01.2022]; Available from: https://www.futurebuilt.no/Nyheter#!/Nyheter/Paa-vei-mot-nullutslippsbetong.
34. Masters, P.S., *The molecular biology of coronaviruses.* Advances in virus research, 2006. **66**: p. 193-292.
35. Richard Liew, J.Y., M.-X. Xiong, and B.-L. Lai, *Chapter 07 - Special considerations for high strength materials*, in *Design of Steel-Concrete Composite Structures Using High-Strength Materials*, J.Y. Richard Liew, M.-X. Xiong, and B.-L. Lai, Editors. 2021, Woodhead Publishing. p. 125-142.
36. Norge, S., *NS-EN 197-1:2011 Sement Del 1: Sammensetning, krav og samsvarskriterier for ordinære sementtyper*. 2011, Standard Norge.
37. Ishizuka, H., et al. *Experimental study on the sulfuric acid resistance of low carbon concrete*. 2021. ISEC Press.
38. Papadakis, V. and S. Tsimas, *Supplementary cementing materials in concrete: Part I: efficiency and design.* Cement and concrete research, 2002. **32**(10): p. 1525-1532.
39. van Deventer, J.S.J., et al., *Chemical Research and Climate Change as Drivers in the Commercial Adoption of Alkali Activated Materials.* Waste and Biomass Valorization, 2010. **1**(1): p. 145-155.
40. García-Lodeiro, I., A. Palomo, and A. Fernández-Jiménez, *Alkali–aggregate reaction in activated fly ash systems.* Cement and Concrete Research, 2007. **37**(2): p. 175-183.
41. Swanepoel, J.C. and C.A. Strydom, *Utilisation of fly ash in a geopolymeric material.* Applied Geochemistry, 2002. **17**(8): p. 1143-1148.
42. Provis, J.L. and J.S.J. Van Deventer, *Geopolymers: structures, processing, properties and industrial applications*. 2009: Elsevier.
43. Van Jaarsveld, J.G.S., J.S.J. Van Deventer, and L. Lorenzen, *The potential use of geopolymeric materials to immobilise toxic metals: Part I. Theory and applications.* Minerals Engineering, 1997. **10**(7): p. 659-669.
44. Davidovits, J., *Geopolymer Cement a review 2013.* 2013: p. 1-11.
45. S, S., *Personal communication*. 2022.
46. Maturix. *Gaia 200*. 2022 [cited 2022 16.05.2022]; Available from: https://maturix.com/sensors/gaia-200/.

Appendix A: NS-EN 206, table NA.12

Egenskap	Bestandighetsklasse					
	M90	M60	M45	MF45 a,b,c	M40 d	MF40 a,b,c,d
Minste luftinnhold i fersk betong				4 %		4 %
Minste effektive bindemiddelmengde (kg/m^3)	150	200	225	225	225	225
Sementtype	**Største masseforhold f, g, h**					
CEM I	0,90	0,60	0,45	0,45	0,40	0,40
CEM II/A-S, 6-20 % slagg	0,90	0,55	0,45	0,45	0,40	0,40
CEM II/B-S, 21-35 % slagg	0,90	0,55	0,45	-	0,40	-
CEM II/A-D, 6-10 % silikastøv	0,90	0,60	0,45	0,45	0,40	0,40
CEM II/A-V, 6-20 % flygeaske	0,90	0,55	0,45	0,45	0,40	0,40
CEM II/B-V, 21-35 % flygeaske	0,90	0,50	0,45	-	0,40	-
CEM II/A-L, 6-20 % kalksteinfiller L	0,90	0,50	- i	-	- i	-
CEM II/A-LL, 6-20 % kalksteinfiller LL	0,90	0,50	- i	-	- i	-
CEM II/A-M, 12-20 % diverse	0,90	- j, k	- j, k	- k	- j, k	- k
CEM II/B-M, 21-35 % diverse	0,90	- j, k	- j, k	- k	- j, k	- k
CEM III/A, 36-65 % slagg	0,90	0,50	0,45	-	0,40	-
CEM III/B, 66-80 % slagg	0,90	0,45	0,45	-	0,40	-

a For bestandighetsklasse MF40 og MF45 skal det anvendes frostsikkert tilslag (se NA.5.1.3).
b Standarden gir ikke regler for produksjon av frostsikker betong uten bruk av luftinnførende tilsetningsstoffer.
c Standarden gir ikke anvendelsesregler for bestandighetsklassene MF45 og MF40 om den samlede mengden flygeaske og slagg (V + S) er større enn 20 vektprosent i forhold til bindemiddelmengde. Tilfredsstillende frostbestandighet kan likevel dokumenteres iht. NA.5.3.2(902) for sement eller bindemiddelkombinasjoner der samlet innhold (i sement + tilsatt) er over 20 %.
d Bindemidlet skal minst inneholde 6 % silikastøv eller samlet minst 14 % flygeaske, silikastøv og slagg (V + D + S) i bestandighetsklassene MF40 og M40.
e (ikke i bruk)
f Ved bruk av tilsetningsmaterialer gjelder grenseverdien for største masseforhold for den sementtypen som tilsetningsmaterialene tilsettes til.
g Der flere sementtyper som det er gitt anvendelsesregler for blandes, kan største tillatte masseforhold fastsettes som et vektet middel av kravene til de enkelte sementtypene.
h "-" i tabellen betyr at Norsk Standard ikke gir anvendelsesregler for denne kombinasjonen av sementtype og bestandighetsklasse. Det henvises også til NA.5.3.2(902).
i CEM II/A-L og CEM II/A-LL kan anvendes etter reglene for CEM I forutsatt at mengden kalksteinfiller L og LL ut over 5 % ikke tas med i beregningen av masseforholdet.
j CEM II/A-M og CEM II/B-M kan benyttes med grenseverdier som for CEM I, CEM II/A-V og CEM II/A-S, dersom det ved beregning av masseforhold ses bort fra andelen materiale (hovedkomponenter) som bringer sementen over grenseverdiene for hhv. CEM I, CEM II/A-V og CEM II/A-S.
k Det tillates kun sementer som ikke inneholder andre hovedkomponenter enn klinker (K), flygeaske (V), slagg (S) og kalksteinfiller (L og LL).

Figure A. 1. NS-EN 206, table NA.12, limiting values for concrete composition

Appendix B: Concrete recipes

During the current work, the concrete composition used in CrackTeSt COIN was Hybrid 65 and Hybrid 50 with Aalborg Rapid FA cement. The recipes are given in figures B.1 and B.2. The concrete recipe used during the fieldwork of casting at Gullhaug Torg 2A is given in figure B.3.

Unicon A/S

Betongblankett

v.1.13

Side 1   05.01.2022   17:50:39

unicon
CEMENTIR HOLDING

Resept...: UP59D-F000   Fabrikk: Sjursøya--92   Versjon: 0003

SKANSKAB55M60H65FA

Bestandighetsklasse	M45
Fastetsklasse	B45
Kontrolklasse	
Største steinstr.	25
Tilstrebet sætmål	200 mm
Forprøvning. attestnr.	

Sammensetning	Navn	Densitet kg/m³	Mengde kg/m³	Volum l/m3
Sement	Aalborg Rapid FA CEM II/A-V	2.970	181,8	61
Flygeaske	FA Norcem k=0	2.300	123,9	54
Flygeaske	FA Norcem k=1.0	2.300	68,6	30
Silika	Silika ikke med i V/C	2.200	7,8	4
Silika	Silikastøv k=1	2.200	31,0	14
Sand	0-8 Svelviksand	2.650	987,8	373
Stein	8-16 mm Svelviksand	2.705	354,8	131
Stein	16-22 Svelviksand	2.705	504,1	186
Superplast.	UMASTER EASE 1020	1.050	4,7	3
Kaldt vann	Kaldt vann	1.000	123,7	124
Tilstrebet luftinnhold i betong, volum %	2,0			20,0
			2.388	1.000

Kontrolpunkt	**Verdi**	**Beregning**
Tilsatt silika	11 %	100 * 31 / (182 + 31 + 69)
Tilsatt flygeaske	24 %	100 * 69 / (182 + 31 + 69)
Effektiv bindemiddelmengde	281 kg/m³	(1,0 * 181,8) + (1,0 * 68,6) + (1,0 * 31,0)
Effektivt vanninhold	127 kg/m³	3,68 + 123,73
Masseforhold	0,451	127 / 281
Alkaliinnhold	1,77 kg/m³	
Maks. kloridinnhold	0,10 %	100 * 0,295 / (182 + 31 + 69)

Klorid- og alkaliregnskap

Delmateriale	kg/m³	%(Alkali)	kg/m³(Alkali)	%(Klorid)	kg/m3(klorid)
Sement	181,77	0,48	0,87	0,05	0,091
Flygeaske	123,93	0,00	0,00	0,10	0,124
Flygeaske	68,58	0,00	0,00	0,10	0,069
Silika	7,85	1,00	0,08	0,03	0,002
Silika	30,98	2,50	0,78	0,03	0,009
Superplast.	4,65	1,00	0,05	0,01	0,000
Sand	987,76	0,00	0,00	0,00	0,000
Stein	354,76	0,00	0,00	0,00	0,000
Stein	504,13	0,00	0,00	0,00	0,000
Kaldt vann	123,73	0,00	0,00	0,00	0,000
Total	2.388,14		1,77		0,295

Figure B. 1. Concrete recipe for Hybrid 65 used in CrackTeSt COIN

Unicon A/S

Betongblankett

v.1.13

Side 1 05.01.2022 17:48:44

Resept...: UP59E-F000 Fabrikk: Sjursøya--92 Versjon: 0001

SKANSKAB55M60H50FA

Bestandighetsklasse	M60
Fastetsklasse	B55
Kontrolklasse	
Største steinstr.	25
Tilstrebet sætmål	200 mm
Forprøvning. attestnr.	

Sammensetning	Navn	Densitet kg/m³	Mengde kg/m³	Volum l/m3
Sement	Aalborg Rapid FA CEM II/A-V	2.970	239,6	81
Flygeaske	FA Norcem k=0	2.300	41,3	18
Flygeaske	FA Norcem k=1.0	2.300	90,9	40
Silika	Silikastøv k=1	2.200	41,3	19
Sand	0-8 Svelviksand	2.650	962,3	363
Stein	8-16 mm Svelviksand	2.705	363,8	134
Stein	16-22 Svelviksand	2.705	472,9	175
Superplast.	UMASTER EASE 1020	1.050	4,8	4
Kaldt vann	Kaldt vann	1.000	142,0	142
Tilstrebet luftinnhold i betong, volum %	2,5			25,0
			2.359	1.000

Kontrolpunkt	**Verdi**		**Beregning**
Tilsatt silika	11	%	100 * 41 / (240 + 41 + 91)
Tilsatt flygeaske	24	%	100 * 91 / (240 + 41 + 91)
Effektiv bindemiddelmengde	372	kg/m³	(1,0 * 239,6) + (1,0 * 90,9) + (1,0 * 41,3)
Effektivt vanninhold	146	kg/m³	3,80 + 142,03
Masseforhold	0,393		146 / 372
Alkaliinnhold	2,23	kg/m³	
Maks. kloridinnhold	0,07	%	100 * 0,264 / (240 + 41 + 91)

Klorid- og alkaliregnskap

Delmateriale	kg/m³	%(Alkali)	kg/m³(Alkali)	%(Klorid)	kg/m3(klorid)
Sement	239,60	0,48	1,15	0,05	0,120
Flygeaske	41,31	0,00	0,00	0,10	0,041
Flygeaske	90,88	0,00	0,00	0,10	0,091
Silika	41,31	2,50	1,03	0,03	0,012
Superplast.	4,82	1,00	0,05	0,01	0,000
Sand	962,30	0,00	0,00	0,00	0,000
Stein	363,80	0,00	0,00	0,00	0,000
Stein	472,94	0,00	0,00	0,00	0,000
Kaldt vann	142,03	0,00	0,00	0,00	0,000
Total	2.358,99		2,23		0,264

Figure B. 2. Concrete recipe for Hybrid 50 used in CrackTeSt COIN

Unicon A/S

Betongblankett

v.1.13

Side 1 03.05.2022 12:12:18

Resept...: UP59D-D000 Fabrikk: Sjursøya--2 Versjon: 0011

SKANSKAB55M60H65FA

Bestandighetsklasse	M90
Fastetsklasse	B45
Kontrolklasse	
Største steinstr.	25
Tilstrebet sætmål	200 mm
Forprøvning. attestnr.	

Sammensetning	Navn	Densitet kg/m³	Mengde kg/m³	Volum l/m3
Sement	Norcem Std FA CEM II/B-M 42,5R	3.000	199,4	66
Flygeaske	Flyveaske k=0 Eco Zec, Ena	2.300	119,8	52
Flygeaske	Flyveaske k=1.0 Eco Zec, Ena	2.300	68,5	30
Silika	Silika ikke med i V/C	2.200	8,1	4
Silika	Silikastøv k=1	2.200	32,1	15
Sand	0-8 Svelviksand	2.650	969,8	366
Stein	8-16 mm Svelviksand	2.705	348,3	129
Stein	16-22 Svelviksand	2.705	495,0	183
Superplast.	UMASTER EASE 1020	1.050	5,0	4
Kaldt vann	Kaldt vann	1.000	131,9	132
Tilstrebet luftinnhold i betong, volum %	2,0			20,0
			2.378	1.000

Kontrolpunkt	Verdi		Beregning
Tilsatt silika	11	%	100 * 32 / (199 + 32 + 68)
Tilsatt flygeaske	23	%	100 * 68 / (199 + 32 + 68)
Effektiv bindemiddelmengde	300	kg/m³	(1,0 * 199,4) + (1,0 * 68,5) + (1,0 * 32,1)
Effektivt vanninhold	136	kg/m³	3,93 + 131,93
Masseforhold	0,453		136 / 300
Alkaliinnhold	3,81	kg/m³	
Maks. kloridinnhold	0,15	%	100 * 0,448 / (199 + 32 + 68)

Klorid- og alkaliregnskap

Delmateriale	kg/m³	%(Alkali)	kg/m³(Alkali)	%(Klorid)	kg/m3(klorid)
Sement	199,43	1,40	2,79	0,07	0,140
Flygeaske	119,83	0,00	0,00	0,10	0,120
Flygeaske	68,47	0,00	0,00	0,10	0,068
Silika	8,13	2,00	0,16	0,30	0,024
Silika	32,10	2,50	0,80	0,30	0,096
Superplast.	4,98	1,00	0,05	0,01	0,000
Sand	969,82	0,00	0,00	0,00	0,000
Stein	348,32	0,00	0,00	0,00	0,000
Stein	494,99	0,00	0,00	0,00	0,000
Kaldt vann	131,93	0,00	0,00	0,00	0,000
Total	2.378,00		3,81		0,448

Figure B. 3. Concrete recipe for hybrid 65 used during the fieldwork at Gullhaug Torg 2A

Appendix C: Environmental product declarations

Hybrid 65 with Aalborg Rapid FA cement

Ver1 2015

ENVIRONMENTAL PRODUCT DECLARATION

in accordance with ISO 14025, ISO 21930 and EN 15804

Eier av deklarasjonen:	Unicon AS
Programoperatør:	Næringslivets Stiftelse for Miljødeklarasjoner
Utgiver:	Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonsnummer:	Viser til NEPD-1487-500-NO
Publiseringsnummer:	Ikke tildelt
ECO Platform registreringsnummer:	Ikke tildelt
Godkjent dato:	
Gyldig til:	

SKANSKAB55M60H65FA - UP59D-F000 - Sjursøya

Unicon AS

unicon
CEMENTIR HOLDING

www.epd-norge.no

Generell informasjon

Produkt:

SKANSKAB55M60H65FA - UP59D-F000 - Sjursøya

Eier av deklarasjonen:

Unicon AS
Kontaktperson: Berit Gudding Petersen
Telefon: 97171734
e-post: bgpe@unicon.no

Programoperatør:

Næringslivets stiftelse for Miljødeklarasjoner
Pb. 5250 Majorstuen, 0303 Oslo
Phone: +47 23 08 80 00
e-post: post@epd-norge.no

Produsent:

Unicon AS
Prof. Birkelandsvei 27B 1081 Oslo
Norway

Deklarasjonsnummer:

Viser til NEPD-1487-500-NO

Produksjonssted:

Unicon Sjursøya
Norway

ECO Platform registreringsnummer:

Kvalitet/Miljøsystem:

NS-EN 14001 No. S-024

Deklarasjonen er basert på PCR:

EN 15804:2012+A1:2013 tjener som kjerne-PCR
NPCR 020:2018 Part B for Concrete and concrete elements

Org. no.:

No 942822979

Erklæring om ansvar:

Eieren av deklarasjonen skal være ansvarlig for den underliggende informasjon og bevis. EPD Norge skal ikke være ansvarlig med hensyn til produsent informasjon, livsløpsvurdering data og bevis.

Godkjent dato:

Gyldig til:

Deklarert enhet:

1 m3 SKANSKAB55M60H65FA - UP59D-F000 - Sjursøya

Årstall for studien:

2021

Deklarert enhet med opsjon:

A1,A2,A3,A4

Sammenlignbarhet:

EPD av byggevarer er nødvendigvis ikke sammenlignbare hvis de ikke samsvarer med NS-EN 15804 og ses i en bygningskontekst.

Funksjonell enhet:

Miljødeklarasjonen er utarbeidet av:

Deklarasjonen er utarbeidet og verifisert ved bruk av EPDverktøy lca.tools ver EPD2020.11, utviklet av LCA.no AS. EPDverktøyet er integrert i bedriftens miljøstyringssystem, og godkjent av EPD-Norge

EPD er utarbeidet av:

Kaiwan Quadri Koplanto

Bedriftsspesifikke data og EPD er kontrollert av:

Berit Gudding Petersen

Generelt om verifikasjon av EPD fra verktøy:

Uavhengig verifikasjon av data, annen miljøinformasjon og EPD er foretatt etter ISO 14025:2010, kapittel 8.1.3 og 8.1.4. Individuell tredjepartsverifisering av hver EPD er ikke nødvendig når verktøyet er i) integrert i bedriftens miljøstyringssystem, ii) prosedyrer for bruk av verktøyet er godkjent av EPD-Norge og iii) prosessen granskes årlig. Se vedlegg G i EPD-Norges retningslinjer for ytterligere informasjon om EPD-verktøy.

Verifikasjon av EPD-verktøy:

Uavhengig tredjepartsverifikasjon av verktøy, bakgrunnsdata og test-EPD er gjort i henhold til EPD-Norge sine prosedyrer og retningslinjer for verifisering og godkjenning av EPD-verktøy.

Anne Rønning, Norsus AS

(krever ikke signatur)

Godkjent:

Sign

Håkon Hauan, Daglig leder EPD-Norge

Produkt

Produktbeskrivelse:

B55 M60, 22MM, LKP, 65%FA

Produktspesifikasjon:

1m3 ferdigbetong styrkeklasse B55 og bestandighetsklasse M60

Materialer	kg	%
Cement	181,00	7,58
Aggregate	1846,65	77,34
Water	123,73	5,18
Chemicals	3,64	0,15
SCM	232,83	9,75
Totalt:	2387,85	

Tekniske data:

Prosjektspesifik EPD utarbeidet etter retningslinjer gitt av EPD Norge. Godkjent dato og Gyldig til dato fylles ikke ut for Prosjektspesifikke EPD'er.

Markedsområde:

Levetid, produkt:

Levetid, bygg:

LCA: Beregningsregler

Deklarert enhet:

1 m3 SKANSKAB55M60H65FA - UP59D-F000 - Sjursøya

Cut-off kriterier:

Alle viktige råmaterialer og all viktig energibruk er inkludert. Produksjonsprosessen for råmaterialene og energistrømmer som inngår med veldig små mengder (mindre enn 1%) er ikke inkludert. Disse cut-off kriteriene gjelder ikke for farlige materialer og stoffer.

Alle viktige råmaterialer og all viktig energibruk er inkludert. Produksjonsprosessen for råmaterialene og energistrømmer som inngår med veldig små mengder (<1%) er ikke inkludert.

Allokering:

Allokering er gjort iht. bestemmelser i EN 15804. Inngående energi og vann, samt produksjon av avfall i egen produksjon er allokert likt mellom alle produktene gjennom masseallokering. Miljøpåvirkning og ressursforbruk for primærproduksjonen av resirkulerte materialer er allokert til det opprinnelige produktsystemet. Bearbeidingsprosessen og transport av materialet til produksjonssted er allokert til analysen i denne EPDen.

Allokering er gjort I hht bestemmelser I EN 15804
Inngående energi og vann, samt produksjon av avfall i egen produksjon er allokert likt mellom alle produktene gjennom masseallokering.
Påvirkning for primærproduksjonen av resirkulerte materialer er allokert til hovedproduktet der materialet ble brukt. Resirkuleringsprosessen og transport av materialet er allokert til denne analysen.

Datakvalitet:

Spesifikke data for produktsammensetningen er fremskaffet av produsenten. De representerer produksjonen av det deklarerte produktet og ble samlet inn for EPD-utvikling i det oppgitte året for studien. Bakgrunnsdata er basert på registrerte EPDer i henhold til EN 15804, Østfoldforskning sine databaser, ecoinvent og andre LCAdatabaser. Datakvaliteten for råmaterialene i A1 er presentert i tabellen nedenfor.

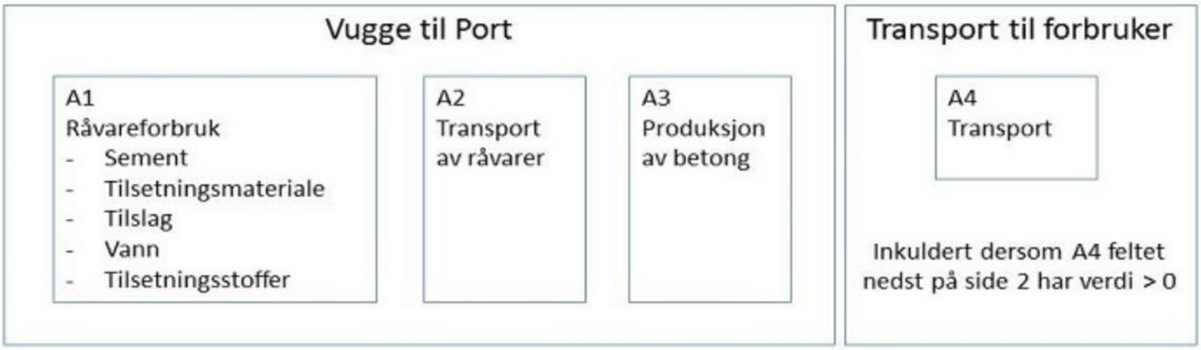
Energiforbruk på fabrikk er gjennomsnitt 2018.

Materials	Source	Data quality	Year
Aggregate	Modified EcoInvent	Database	2012
SCM	TI, Denmark	EPD	2013
Chemicals	EPD-EFC-20150091-IAG1-EN	EPD	2015
Aggregate	Østfoldforskning	Database	2016
Water	ecoinvent 3.4	Database	2017
SCM	ecoinvent 3.6	Database	2019
Cement	RTS_102_21	EPD	2021

Systemgrenser:

Alle prosesser fra råvareuttak til produktet ut fra fabrikkporten er inkludert i analysen.

Flytskjemaet nedenfor illustrerer systemgrensene for analysen:



Teknisk tilleggsinformasjon

Registrert EPD for Unicon: NEPD-1487-500-NO

Prosjektspesifik EPD utarbeidet etter retningslinjer gitt av EPD Norge. Godkjent dato og Gyldig til dato fylles ikke ut for Prosjektspesifikke EPD'er.

LCA: Scenarier og annen teknisk informasjon

Følgende informasjonen beskriver scenariene for modulene i EPDen.

Transport fra produksjonssted til bruker (A4)

Type	Kapasitetsutnyttelse inkl retur %	Kjøretøytype	Distanse km	Brennstoff/Energi forbruk	Enhet	Verdi (l/t)
Bil	53,0 %	Concrete truck, EURO 6	15	0,020216	l/tkm	0,30
Jernbane					l/tkm	
Båt					l/tkm	
Annet					l/tkm	

Scenarier etter A1-A4 er ikke inkludert

Byggefase A5

.	Enhet	Verdi
Hjelpematerialer	kg	
Vannforbruk	m^3	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Materialta[illegible]	kg	
Materiale[illegible]llsbehandling	kg	
Støv i lu[illegible]	kg	
VOC utslipp	kg	

Monterte produkter i bruk (B1)

.	Unit	Value

Vedlikehold (B2)/Repar[illegible]

.	Enhet	Verdi
Vedlikeholdsfrekvens*	-	
Hjelpematerialer	[illegible]	
Andre ressurser	[illegible]	
Vannforbruk	[illegible]	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Materialtap	kg	
VOC utslipp	kg	

Utskifting (B4)/Renovering (B5)

.	Enhet	Verdi
Utskiftingsfrekvens*	stk	
Elektrisitetsforbruk	kWh	
Utskifting av slitte deler	0	

* Tall eller referanselevetid

Driftsenergi (B6) og vannbruk (B7)

.	Enhet	Verdi
Vannforbruk	m^3	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Utstyrets varmeeffekt	kW	

Sluttfase [illegible]

.	Enhet	Verdi
Farlig avfall	kg	
Blandet avfall	kg	
Gjenbruk	kg	
Resirkulering	kg	
Energigjenvinning	[illegible]	
Til deponi	[illegible]	

Transport avfallsbehandling (C2)

Type	Kapasitetsutnyttelse inkl retur %	Kjøretøytype	Distanse km	Brennstoff/Energi forbruk	Enhet	Verdi (l/t)
Bil					l/tkm	
Jernbane					l/tkm	
Båt					l/tkm	
Annet					l/tkm	

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage				Construction installation stage	User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	.	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,43E+02	1,61E+01	4,72E+00	3,05E+00
ODP	kg CFC11 -eq	4,79E-06	2,94E-06	8,32E-07	5,76E-07
POCP	kg C_2H_4-eq	2,26E-02	3,32E-03	9,59E-04	5,40E-04
AP	kg SO_2 -eq	4,54E-01	1,11E-01	3,51E-02	1,07E-02
EP	kg PO_4^{3-} -eq	9,51E-02	2,29E-02	7,55E-03	2,23E-03
ADPM	kg Sb -eq	4,11E-04	1,33E-05	4,51E-06	6,73E-06
ADPE	MJ	9,30E+02	2,29E+02	6,73E+01	4,65E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Ressursbruk (Resource use)

Parameter	Unit	A1	A2	A3	A4
RPEE	MJ	8,31E+01	2,87E+01	2,25E+01	7,15E-01
RPEM	MJ	0,00E+00	0,00E+00	0,00E+00	2,19E-01
TPE	MJ	8,31E+01	2,87E+01	2,25E+01	9,34E-01
NRPE	MJ	9,56E+02	2,36E+02	6,95E+01	4,75E+01
NRPM	MJ	1,75E+01	0,00E+00	0,00E+00	0,00E+00
TRPE	MJ	9,74E+02	2,36E+02	6,95E+01	4,75E+01
SM	kg	1,94E+02	0,00E+00	0,00E+00	0,00E+00
RSF	MJ	0,00E+00	0,00E+00	3,81E-03	0,00E+00
NRSF	MJ	0,00E+00	0,00E+00	0,00E+00	0,00E+00
W	m^3	2,96E+00	3,50E-02	2,49E-01	4,23E-02

RPEE Renewable primary energy resources used as energy carrier; RPEM Renewable primary energy resources used as raw materials; TPE Total use of renewable primary energy resources; NRPE Non renewable primary energy resources used as energy carrier; NRPM Non renewable primary energy resources used as materials; TRPE Total use of non renewable primary energy resources; SM Use of secondary materials; RSF Use of renewable secondary fuels; NRSF Use of non renewable secondary fuels; W Use of net fresh water

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Livsløpets slutt - Avfall (End of life - Waste)

Parameter	Unit	A1	A2	A3	A4
HW	kg	3,55E+00	1,31E-04	3,61E-05	3,60E-05
NHW	kg	8,48E+01	4,72E+00	5,91E-01	4,70E+00
RW	kg	INA*	INA*	INA*	INA*

HW Hazardous waste disposed; NHW Non hazardous waste disposed; RW Radioactive waste disposed

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Livsløpets slutt - Utgangsfaktorer (End of life - Output flow)

Parameter	Unit	A1	A2	A3	A4
CR	kg	0,00E+00	0,00E+00	1,10E-02	0,00E+00
MR	kg	4,36E-04	0,00E+00	0,00E+00	0,00E+00
MER	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00
EEE	MJ	INA*	INA*	INA*	INA*
ETE	MJ	INA*	INA*	INA*	INA*

CR Components for reuse; MR Materials for recycling; MER Materials for energy recovery; EEE Exported electric energy; ETE Exported thermal energy

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Norske tilleggskrav

Klimagassutslipp fra bruk av elektrisitet i produksjonsfasen

Nasjonal produksjonsmiks fra import, lavspenning (inkludert produksjon av overføringslinjer, i tillegg til direkte utslipp og tap i nett) er brukt for anvendt elektrisitet i produksjonsprosessen (A3). Bakgrunnsdata er presentert i tabellen under. Karakteriseringsfaktorer fra EN 15804:2012+A1:2013 er benyttet.

Elektrisitetsmiks	Datakilde	Mengde	Enhet
El-mix, Norway (kWh)	ecoinvent 3.4	31,04	g CO2-ekv/kWh

Farlige stoffer

Produktet er ikke tilført stoffer fra REACH Kandidatliste eller den norske prioritetslisten.

Inneklima

Produktet har ingen påvirkning på inneklima.

Bibliografi

NS-EN ISO 14025:2010 Miljømerker og deklarasjoner - Miljødeklarasjoner type III
NS-EN ISO 14044:2006 Miljøstyring - Livsløpsvurderinger - Krav og retningslinjer
NS-EN 15804:2012+A1:2013 Bærekraftig byggverk - Miljødeklarasjoner
ISO 21930:2017 Sustainability in buildings and civil engineering works
ecoinvent v3, Allocation, cut-off by classification, Swiss Centre of Life Cycle Inventories.
Iversen et al., (2018) eEPD v3.0 - Background information for EPD gen. system. LCA.no OR 04.18
Vold et al. (2014) EPD-generator for betongindustrien, bakgrunnsinformasjon for verifisering, OR 04.14, Østfoldforskning,
NPCR Part A: Construction products and services. Ver. 1.0. April 2017, EPD-Norge.

- PCR for Precast Concrete Products, NPCR 20.2011, www.epd-norge.no
- Vold M. og Edvardsen T. (2014); EPD-generator for betongindustrien, Bakgrunnsinformasjon for verifisering, OR 04.14 Østfoldforskning, Fredrikstad, Januar 2014.
- Vold M. og Edvardsen T. (2014); EPD-generator for betongindustrien, Brukerveileding, OR 05.14 Østfoldforskning, Fredrikstad, Januar 2014.

	Programoperatør og utgiver Næringslivets Stiftelse for Miljødeklarasjoner PostBoks 5250 Majorstuen, 0303 Oslo,Norge	Telefon: e-post: web:	+47 23 08 80 00 post@epd-norge.no www.epd-norge.no
unicon CEMENTIR HOLDING	**Eier av deklarasjon** Unicon AS Prof. Birkelandsvei 27B 1081 Oslo	Telefon: e-post: web:	97171734 bgpe@unicon.no
Østfoldforskning	**Forfatter av livsløpsrapporten** Østfoldforskning AS Stadion 4 1671 Kråkerøy	Telefon: e-post: web:	+47 69 35 11 00 post@ostfoldforskning.no www.ostfoldforskning.no
LCA.no	**Utvikler av EPD-generator** LCA.no AS Dokka 1C 1671 Kråkerøy	Telefon: e-post: web:	+47 916 50 916 post@lca.no www.lca.no

Hybrid 50 with Aalborg Rapid FA cement

Ver1 2015

ENVIRONMENTAL PRODUCT DECLARATION

in accordance with ISO 14025, ISO 21930 and EN 15804

Eier av deklarasjonen:	Unicon AS
Programoperatør:	Næringslivets Stiftelse for Miljødeklarasjoner
Utgiver:	Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonsnummer:	Viser til NEPD-1487-500-NO
Publiseringsnummer:	Ikke tildelt
ECO Platform registreringsnummer:	Ikke tildelt
Godkjent dato:	
Gyldig til:	

SKANSKAB55M60H50FA - UP59E-F000 - Sjursøya

Unicon AS

www.epd-norge.no

Generell informasjon

Produkt:

SKANSKAB55M60H50FA - UP59E-F000 - Sjursøya

Eier av deklarasjonen:

Unicon AS
Kontaktperson: Berit Gudding Petersen
Telefon: 97171734
e-post: bgpe@unicon.no

Programoperatør:

Næringslivets stiftelse for Miljødeklarasjoner
Pb. 5250 Majorstuen, 0303 Oslo
Phone: +47 23 08 80 00
e-post: post@epd-norge.no

Produsent:

Unicon AS
Prof. Birkelandsvei 27B 1081 Oslo
Norway

Deklarasjonsnummer:

Viser til NEPD-1487-500-NO

Produksjonssted:

Unicon Sjursøya
Norway

ECO Platform registreringsnummer:

Kvalitet/Miljøsystem:

NS-EN 14001 No. S-024

Deklarasjonen er basert på PCR:

EN 15804:2012+A1:2013 tjener som kjerne-PCR
NPCR 020:2018 Part B for Concrete and concrete elements

Org. no.:

No 942822979

Erklæring om ansvar:

Eieren av deklarasjonen skal være ansvarlig for den underliggende informasjon og bevis. EPD Norge skal ikke være ansvarlig med hensyn til produsent informasjon, livsløpsvurdering data og bevis.

Godkjent dato:

Gyldig til:

Deklarert enhet:

1 m3 SKANSKAB55M60H50FA - UP59E-F000 - Sjursøya

Årstall for studien:

2021

Deklarert enhet med opsjon:

A1,A2,A3,A4

Sammenlignbarhet:

EPD av byggevarer er nødvendigvis ikke sammenlignbare hvis de ikke samsvarer med NS-EN 15804 og ses i en bygningskontekst.

Funksjonell enhet:

Miljødeklarasjonen er utarbeidet av:

Deklarasjonen er utarbeidet og verifisert ved bruk av EPDverktøy lca.tools ver EPD2020.11, utviklet av LCA.no AS. EPDverktøyet er integrert i bedriftens miljøstyringssystem, og godkjent av EPD-Norge

EPD er utarbeidet av:

Kaiwan Quadri Koplanto

Bedriftsspesifikke data og EPD er kontrollert av:

Berit Gudding Petersen

Generelt om verifikasjon av EPD fra verktøy:

Uavhengig verifikasjon av data, annen miljøinformasjon og EPD er foretatt etter ISO 14025:2010, kapittel 8.1.3 og 8.1.4. Individuell tredjepartsverifisering av hver EPD er ikke nødvendig når verktøyet er i) integrert i bedriftens miljøstyringssystem, ii) prosedyrer for bruk av verktøyet er godkjent av EPD-Norge og iii) prosessen granskes årlig. Se vedlegg G i EPD-Norges retningslinjer for ytterligere informasjon om EPD-verktøy.

Verifikasjon av EPD-verktøy:

Uavhengig tredjepartsverifikasjon av verktøy, bakgrunnsdata og test-EPD er gjort i henhold til EPD-Norge sine prosedyrer og retningslinjer for verifisering og godkjenning av EPD-verktøy.

Anne Rønning, Norsus AS

(krever ikke signatur)

Godkjent:

Sign

Håkon Hauan, Daglig leder EPD-Norge

Produkt

Produktbeskrivelse:

B55 M60, 22MM, LKP, 50%FA

Produktspesifikasjon:

1m3 ferdigbetong styrkeklasse B55 og bestandighetsklasse M60

Materialer	kg	%
Cement	239,60	10,16
Aggregate	1799,03	76,30
Water	142,03	6,02
Chemicals	3,76	0,16
SCM	173,50	7,36
Totalt:	2357,93	

Tekniske data:

Prosjektspesifik EPD utarbeidet etter retningslinjer gitt av EPD Norge. Godkjent dato og Gyldig til dato fylles ikke ut for Prosjektspesifikke EPD'er.

Markedsområde:

Levetid, produkt:

Levetid, bygg:

LCA: Beregningsregler

Deklarert enhet:

1 m3 SKANSKAB55M60H50FA - UP59E-F000 - Sjursøya

Cut-off kriterier:

Alle viktige råmaterialer og all viktig energibruk er inkludert. Produksjonsprosessen for råmaterialene og energistrømmer som inngår med veldig små mengder (mindre enn 1%) er ikke inkludert. Disse cut-off kriteriene gjelder ikke for farlige materialer og stoffer.

Alle viktige råmaterialer og all viktig energibruk er inkludert. Produksjonsprosessen for råmaterialene og energistrømmer som inngår med veldig små mengder (< 1%) er ikke inkludert.

Allokering:

Allokering er gjort iht. bestemmelser i EN 15804. Inngående energi og vann, samt produksjon av avfall i egen produksjon er allokert likt mellom alle produktene gjennom masseallokering. Miljøpåvirkning og ressursforbruk for primærproduksjonen av resirkulerte materialer er allokert til det opprinnelige produktsystemet. Bearbeidingsprosessen og transport av materialet til produksjonssted er allokert til analysen i denne EPDen.

Allokering er gjort I hht bestemmelser I EN 15804
Inngående energi og vann, samt produksjon av avfall i egen produksjon er allokert likt mellom alle produktene gjennom masseallokering.
Påvirkning for primærproduksjonen av resirkulerte materialer er allokert til hovedproduktet der materialet ble brukt. Resirkuleringsprosessen og transport av materialet er allokert til denne analysen.

Datakvalitet:

Spesifikke data for produktsammensetningen er fremskaffet av produsenten. De representerer produksjonen av det deklarerte produktet og ble samlet inn for EPD-utvikling i det oppgitte året for studien. Bakgrunnsdata er basert på registrerte EPDer i henhold til EN 15804, Østfoldforskning sine databaser, ecoinvent og andre LCAdatabaser. Datakvaliteten for råmaterialene i A1 er presentert i tabellen nedenfor.

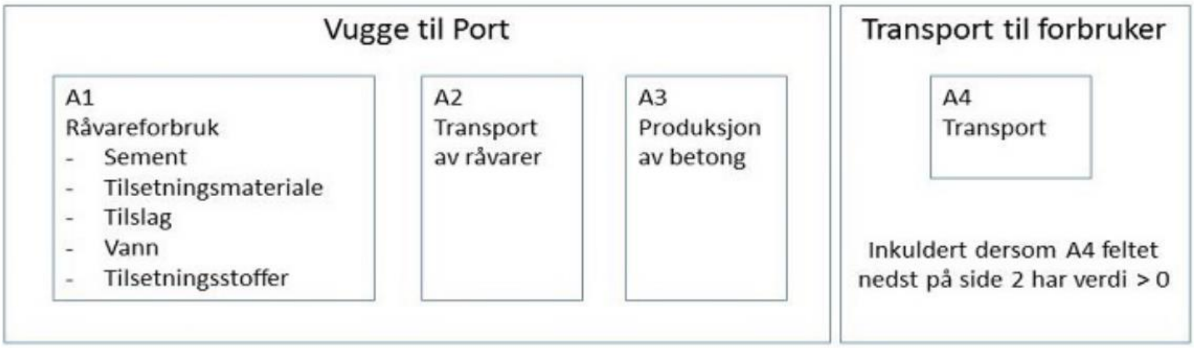
Energiforbruk på fabrikk er gjennomsnitt 2018.

Materials	Source	Data quality	Year
Aggregate	Modified EcoInvent	Database	2012
SCM	TI, Denmark	EPD	2013
Chemicals	EPD-EFC-20150091-IAG1-EN	EPD	2015
Aggregate	Østfoldforskning	Database	2016
Water	ecoinvent 3.4	Database	2017
SCM	ecoinvent 3.6	Database	2019
Cement	RTS_102_21	EPD	2021

Systemgrenser:

Alle prosesser fra råvareuttak til produktet ut fra fabrikkporten er inkludert i analysen.

Flytskjemaet nedenfor illustrerer systemgrensene for analysen:



Teknisk tilleggsinformasjon

Registrert EPD for Unicon: NEPD-1487-500-NO

Prosjektspesifik EPD utarbeidet etter retningslinjer gitt av EPD Norge. Godkjent dato og Gyldig til dato fylles ikke ut for Prosjektspesifikke EPD'er.

LCA: Scenarier og annen teknisk informasjon

Følgende informasjonen beskriver scenariene for modulene i EPDen.

Transport fra produksjonssted til bruker (A4)

Type	Kapasitetsutnyttelse inkl retur %	Kjøretøytype	Distanse km	Brennstoff/Energi forbruk	Enhet	Verdi (l/t)
Bil	53,0 %	Concrete truck, EURO 6	15	0,020216	l/tkm	0,30
Jernbane					l/tkm	
Båt					l/tkm	
Annet					l/tkm	

Scenarier etter A1-A4 er ikke inkludert

Byggefase A5

.	Enhet	Verdi
Hjelpematerialer	kg	
Vannforbruk	m^3	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Materialta[illegible]	kg	
Materiale[illegible]llsbehandling	kg	
Støv i lu[illegible]	kg	
VOC utslipp	kg	

Monterte produkter i bruk (B1)

.	Unit	Value

Vedlikehold (B2)/Repa[illegible]

.	Enhet	Verdi
Vedlikeholdsfrekvens*	.	
Hjelpematerialer	[illegible]	
Andre ressurser	[illegible]	
Vannforbruk	[illegible]	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Materialtap	kg	
VOC utslipp	kg	

Utskifting (B4)/Renovering (B5)

.	Enhet	Verdi
Utskiftingsfrekvens*	stk	
Elektrisitetsforbruk	kWh	
Utskifting av slitte deler	0	

* Tall eller referanselevetid

Driftsenergi (B6) og vannbruk (B7)

.	Enhet	Verdi
Vannforbruk	m^3	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Utstyrets varmeeffekt	kW	

Sluttfase ([illegible]

.	Enhet	Verdi
Farlig avfall	kg	
Blandet avfall	kg	
Gjenbruk	kg	
Resirkulering	kg	
Energigjenvinning	[illegible]	
Til deponi	[illegible]	

Transport avfallsbehandling (C2)

Type	Kapasitetsutnyttelse inkl retur %	Kjøretøytype	Distanse km	Brennstoff/Energi forbruk	Enhet	Verdi (l/t)
Bil					l/tkm	
Jernbane					l/tkm	
Båt					l/tkm	
Annet					l/tkm	

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage				Construction installation stage	User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	.	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,86E+02	1,26E+01	4,72E+00	3,05E+00
ODP	kg CFC11 -eq	5,52E-06	2,30E-06	8,32E-07	5,76E-07
POCP	kg C_2H_4-eq	2,76E-02	2,64E-03	9,59E-04	5,40E-04
AP	kg SO_2 -eq	5,59E-01	8,40E-02	3,51E-02	1,07E-02
EP	kg PO_4^{3-} -eq	1,16E-01	1,72E-02	7,55E-03	2,23E-03
ADPM	kg Sb -eq	5,18E-04	1,27E-05	4,51E-06	6,73E-06
ADPE	MJ	1,12E+03	1,79E+02	6,73E+01	4,65E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Ressursbruk (Resource use)

Parameter	Unit	A1	A2	A3	A4
RPEE	MJ	1,03E+02	3,02E+01	2,25E+01	7,15E-01
RPEM	MJ	0,00E+00	0,00E+00	0,00E+00	2,19E-01
TPE	MJ	1,03E+02	3,02E+01	2,25E+01	9,34E-01
NRPE	MJ	1,15E+03	1,86E+02	6,95E+01	4,75E+01
NRPM	MJ	1,81E+01	0,00E+00	0,00E+00	0,00E+00
TRPE	MJ	1,17E+03	1,86E+02	6,95E+01	4,75E+01
SM	kg	1,32E+02	0,00E+00	0,00E+00	0,00E+00
RSF	MJ	0,00E+00	0,00E+00	3,81E-03	0,00E+00
NRSF	MJ	0,00E+00	0,00E+00	0,00E+00	0,00E+00
W	m^3	2,94E+00	3,14E-02	2,49E-01	4,23E-02

RPEE Renewable primary energy resources used as energy carrier; RPEM Renewable primary energy resources used as raw materials; TPE Total use of renewable primary energy resources; NRPE Non renewable primary energy resources used as energy carrier; NRPM Non renewable primary energy resources used as materials; TRPE Total use of non renewable primary energy resources; SM Use of secondary materials; RSF Use of renewable secondary fuels; NRSF Use of non renewable secondary fuels; W Use of net fresh water

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Livsløpets slutt - Avfall (End of life - Waste)

Parameter	Unit	A1	A2	A3	A4
HW	kg	4,70E+00	1,12E-04	3,61E-05	3,60E-05
NHW	kg	1,08E+02	4,67E+00	5,91E-01	4,70E+00
RW	kg	INA*	INA*	INA*	INA*

HW Hazardous waste disposed; NHW Non hazardous waste disposed; RW Radioactive waste disposed

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Livsløpets slutt - Utgangsfaktorer (End of life - Output flow)

Parameter	Unit	A1	A2	A3	A4
CR	kg	0,00E+00	0,00E+00	1,10E-02	0,00E+00
MR	kg	5,77E-04	0,00E+00	0,00E+00	0,00E+00
MER	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00
EEE	MJ	INA*	INA*	INA*	INA*
ETE	MJ	INA*	INA*	INA*	INA*

CR Components for reuse; MR Materials for recycling; MER Materials for energy recovery; EEE Exported electric energy; ETE Exported thermal energy

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Norske tilleggskrav

Klimagassutslipp fra bruk av elektrisitet i produksjonsfasen

Nasjonal produksjonsmiks fra import, lavspenning (inkludert produksjon av overføringslinjer, i tillegg til direkte utslipp og tap i nett) er brukt for anvendt elektrisitet i produksjonsprosessen (A3). Bakgrunnsdata er presentert i tabellen under. Karakteriseringsfaktorer fra EN 15804:2012+A1:2013 er benyttet.

Elektrisitetsmiks	Datakilde	Mengde	Enhet
El-mix, Norway (kWh)	ecoinvent 3.4	31,04	g CO2-ekv/kWh

Farlige stoffer

Produktet er ikke tilført stoffer fra REACH Kandidatliste eller den norske prioritetslisten.

Inneklima

Produktet har ingen påvirkning på inneklima.

Bibliografi

NS-EN ISO 14025:2010 Miljømerker og deklarasjoner - Miljødeklarasjoner type III
NS-EN ISO 14044:2006 Miljøstyring - Livsløpsvurderinger - Krav og retningslinjer
NS-EN 15804:2012+A1:2013 Bærekraftig byggverk - Miljødeklarasjoner
ISO 21930:2017 Sustainability in buildings and civil engineering works
ecoinvent v3, Allocation, cut-off by classification, Swiss Centre of Life Cycle Inventories.
Iversen et al., (2018) eEPD v3.0 - Background information for EPD gen. system. LCA.no OR 04.18
Vold et al. (2014) EPD-generator for betongindustrien, bakgrunnsinformasjon for verifisering, OR 04.14, Østfoldforskning,
NPCR Part A: Construction products and services. Ver. 1.0. April 2017, EPD-Norge.

- PCR for Precast Concrete Products, NPCR 20.2011, www.epd-norge.no
- Vold M. og Edvardsen T. (2014); EPD-generator for betongindustrien, Bakgrunnsinformasjon for verifisering, OR 04.14 Østfoldforskning, Fredrikstad, Januar 2014.
- Vold M. og Edvardsen T. (2014); EPD-generator for betongindustrien, Brukerveileding, OR 05.14 Østfoldforskning, Fredrikstad, Januar 2014.

	Programoperatør og utgiver Næringslivets Stiftelse for Miljødeklarasjoner PostBoks 5250 Majorstuen, 0303 Oslo,Norge	Telefon: e-post: web:	+47 23 08 80 00 post@epd-norge.no www.epd-norge.no
unicon CEMENTIR HOLDING	**Eier av deklarasjon** Unicon AS Prof. Birkelandsvei 27B 1081 Oslo	Telefon: e-post: web:	97171734 bgpe@unicon.no
Østfoldforskning	**Forfatter av livsløpsrapporten** Østfoldforskning AS Stadion 4 1671 Kråkerøy	Telefon: e-post: web:	+47 69 35 11 00 post@ostfoldforskning.no www.ostfoldforskning.no
LCA.no	**Utvikler av EPD-generator** LCA.no AS Dokka 1C 1671 Kråkerøy	Telefon: e-post: web:	+47 916 50 916 post@lca.no www.lca.no

Hybrid 65 with Norcem Std FA cement

Ver1 2015

ENVIRONMENTAL PRODUCT DECLARATION

in accordance with ISO 14025, ISO 21930 and EN 15804

Eier av deklarasjonen:	Unicon AS
Programoperatør:	Næringslivets Stiftelse for Miljødeklarasjoner
Utgiver:	Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonsnummer:	Viser til NEPD-1487-500-NO
Publiseringsnummer:	Ikke tildelt
ECO Platform registreringsnummer:	Ikke tildelt
Godkjent dato:	03.05.2022
Gyldig til:	

SKANSKAB55M60H65FA- STDFA-SJURSØYA

Unicon AS

www.epd-norge.no

Generell informasjon

Produkt:

SKANSKAB55M60H65FA- STDFA-SJURSØYA

Eier av deklarasjonen:

Unicon AS
Kontaktperson: Berit Gudding Petersen
Telefon: 97171734
e-post: bgpe@unicon.no

Programoperatør:

Næringslivets stiftelse for Miljødeklarasjoner
Pb. 5250 Majorstuen, 0303 Oslo
Phone: +47 23 08 80 00
e-post: post@epd-norge.no

Produsent:

Unicon AS
Prof. Birkelandsvei 27B 1081 Oslo
Norway

Deklarasjonsnummer:

Viser til NEPD-1487-500-NO

Produksjonssted:

Unicon Sjursøya
Norway

ECO Platform registreringsnummer:

Kvalitet/Miljøsystem:

NS-EN 14001 No. S-024

Deklarasjonen er basert på PCR:

EN 15804:2012+A1:2013 tjener som kjerne-PCR
NPCR 020:2018 Part B for Concrete and concrete elements

Org. no.:

No 942822979

Erklæring om ansvar:

Eieren av deklarasjonen skal være ansvarlig for den underliggende informasjon og bevis. EPD Norge skal ikke være ansvarlig med hensyn til produsent informasjon, livsløpsvurdering data og bevis.

Godkjent dato:

03.05.2022

Gyldig til:

Deklarert enhet:

1 m3 SKANSKAB55M60H65FA- STDFA-SJURSØYA

Årstall for studien:

2021

Deklarert enhet med opsjon:

A1,A2,A3,A4

Sammenlignbarhet:

EPD av byggevarer er nødvendigvis ikke sammenlignbare hvis de ikke samsvarer med NS-EN 15804 og ses i en bygningskontekst.

Funksjonell enhet:

Miljødeklarasjonen er utarbeidet av:

Deklarasjonen er utarbeidet og verifisert ved bruk av EPDverktøy lca.tools ver EPD2020.11, utviklet av LCA.no AS. EPDverktøyet er integrert i bedriftens miljøstyringssystem, og godkjent av EPD-Norge

EPD er utarbeidet av:

Kaiwan Quadri Koplanto

Bedriftsspesifikke data og EPD er kontrollert av:

Tony Strand

Generelt om verifikasjon av EPD fra verktøy:

Uavhengig verifikasjon av data, annen miljøinformasjon og EPD er foretatt etter ISO 14025:2010, kapittel 8.1.3 og 8.1.4. Individuell tredjepartsverifisering av hver EPD er ikke nødvendig når verktøyet er i) integrert i bedriftens miljøstyringssystem, ii) prosedyrer for bruk av verktøyet er godkjent av EPD-Norge og iii) prosessen granskes årlig. Se vedlegg G i EPD-Norges retningslinjer for ytterligere informasjon om EPD-verktøy.

Verifikasjon av EPD-verktøy:

Uavhengig tredjepartsverifikasjon av verktøy, bakgrunnsdata og test-EPD er gjort i henhold til EPD-Norge sine prosedyrer og retningslinjer for verifisering og godkjenning av EPD-verktøy.

Anne Rønning, Norsus AS

(krever ikke signatur)

Godkjent:

Sign

Håkon Hauan, Daglig leder EPD-Norge

Produkt

Produktbeskrivelse:

B55M60- 65%FA
D-MAX 22mm
konsistens 200

Produktspesifikasjon:

1m3 ferdigbetong styrkeklasse B55 og bestandighetsklasse M60

Materialer	kg	%
Cement	199,43	8,43
Aggregate	1802,97	76,18
Water	131,61	5,56
Chemicals	4,29	0,18
SCM	228,53	9,66
Totalt:	2366,83	

Tekniske data:

Prosjektspesifik EPD utarbeidet etter retningslinjer gitt av EPD Norge. Godkjent dato og Gyldig til dato fylles ikke ut for Prosjektspesifikke EPD'er.

Markedsområde:

Levetid, produkt:

Levetid, bygg:

LCA: Beregningsregler

Deklarert enhet:

1 m3 SKANSKAB55M60H65FA- STDFA-SJURSØYA

Cut-off kriterier:

Alle viktige råmaterialer og all viktig energibruk er inkludert. Produksjonsprosessen for råmaterialene og energistrømmer som inngår med veldig små mengder (mindre enn 1%) er ikke inkludert. Disse cut-off kriteriene gjelder ikke for farlige materialer og stoffer.

Alle viktige råmaterialer og all viktig energibruk er inkludert. Produksjonsprosessen for råmaterialene og energistrømmer som inngår med veldig små mengder (< 1%) er ikke inkludert.

Allokering:

Allokering er gjort iht. bestemmelser i EN 15804. Inngående energi og vann, samt produksjon av avfall i egen produksjon er allokert likt mellom alle produktene gjennom masseallokering. Miljøpåvirkning og ressursforbruk for primærproduksjonen av resirkulerte materialer er allokert til det opprinnelige produktsystemet. Bearbeidingsprosessen og transport av materialet til produksjonssted er allokert til analysen i denne EPDen.

Allokering er gjort I hht bestemmelser I EN 15804
Inngående energi og vann, samt produksjon av avfall i egen produksjon er allokert likt mellom alle produktene gjennom masseallokering.
Påvirkning for primærproduksjonen av resirkulerte materialer er allokert til hovedproduktet der materialet ble brukt. Resirkuleringsprosessen og transport av materialet er allokert til denne analysen.

Datakvalitet:

Spesifikke data for produktsammensetningen er fremskaffet av produsenten. De representerer produksjonen av det deklarerte produktet og ble samlet inn for EPD-utvikling i det oppgitte året for studien. Bakgrunnsdata er basert på registrerte EPDer i henhold til EN 15804, Østfoldforskning sine databaser, ecoinvent og andre LCAdatabaser. Datakvaliteten for råmaterialene i A1 er presentert i tabellen nedenfor.

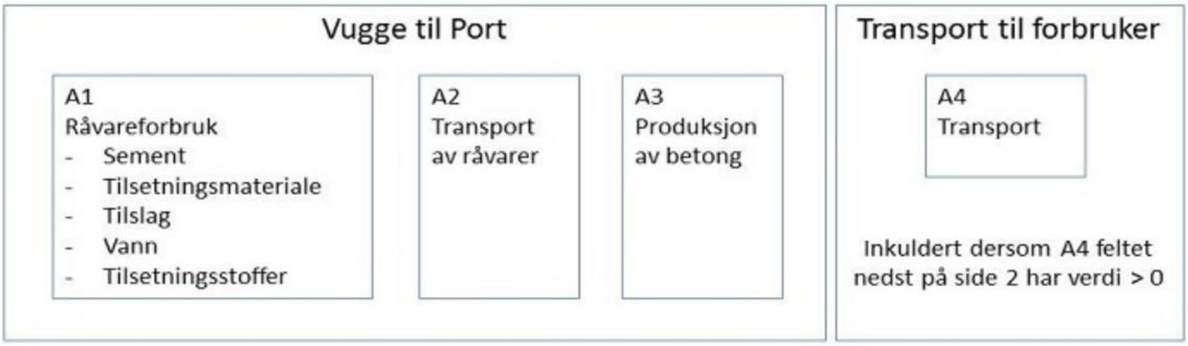
Energiforbruk på fabrikk er gjennomsnitt 2018.

Materials	Source	Data quality	Year
Aggregate	Modified EcoInvent	Database	2012
SCM	TI, Denmark	EPD	2013
Chemicals	EPD-EFC-20150091-IAG1-EN	EPD	2015
Aggregate	Østfoldforskning	Database	2016
Water	ecoinvent 3.4	Database	2017
SCM	ecoinvent 3.6	Database	2019
Cement	NEPD-2275-1028-NO	EPD	2020

Systemgrenser:

Alle prosesser fra råvareuttak til produktet ut fra fabrikkporten er inkludert i analysen.

Flytskjemaet nedenfor illustrerer systemgrensene for analysen:



Teknisk tilleggsinformasjon

Registrert EPD for Unicon: NEPD-1487-500-NO

Prosjektspesifik EPD utarbeidet etter retningslinjer gitt av EPD Norge. Godkjent dato og Gyldig til dato fylles ikke ut for Prosjektspesifikke EPD'er.

LCA: Scenarier og annen teknisk informasjon

Følgende informasjonen beskriver scenariene for modulene i EPDen.

Transport fra produksjonssted til bruker (A4)

Type	Kapasitetsutnyttelse inkl retur %	Kjøretøytype	Distanse km	Brennstoff/Energi forbruk	Enhet	Verdi (l/t)
Bil	53,0 %	Concrete truck, EURO 6	10	0,020216	l/tkm	0,20
Jernbane					l/tkm	
Båt					l/tkm	
Annet					l/tkm	

Scenarier etter A1-A4 er ikke inkludert

Byggefase A5

.	Enhet	Verdi
Hjelpematerialer	kg	
Vannforbruk	m^3	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Materialta[illegible]	kg	
Materiale[illegible]llsbehandling	kg	
Støv i lu[illegible]	kg	
VOC utslipp	kg	

Monterte produkter i bruk (B1)

.	Unit	Value

Vedlikehold (B2)/Repar[illegible]

.	Enhet	Verdi
Vedlikeholdsfrekvens*	-	
Hjelpematerialer	[illegible]	
Andre ressurser	[illegible]	
Vannforbruk	[illegible]	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Materialtap	kg	
VOC utslipp	kg	

Utskifting (B4)/Renovering (B5)

.	Enhet	Verdi
Utskiftingsfrekvens*	stk	
Elektrisitetsforbruk	kWh	
Utskifting av slitte deler	0	

* Tall eller referanselevetid

Driftsenergi (B6) og vannbruk (B7)

.	Enhet	Verdi
Vannforbruk	m^3	
Elektrisitetsforbruk	kWh	
Andre energikilder	MJ	
Utstyrets varmeeffekt	kW	

Sluttfase [illegible]

.	Enhet	Verdi
Farlig avfall	kg	
Blandet avfall	kg	
Gjenbruk	kg	
Resirkulering	kg	
Energigjenvinning	[illegible]	
Til deponi	[illegible]	

Transport avfallsbehandling (C2)

Type	Kapasitetsutnyttelse inkl retur %	Kjøretøytype	Distanse km	Brennstoff/Energi forbruk	Enhet	Verdi (l/t)
Bil					l/tkm	
Jernbane					l/tkm	
Båt					l/tkm	
Annet					l/tkm	

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage				Construction installation stage	User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	.	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,29E+02	9,58E+00	4,79E+00	2,03E+00
ODP	kg CFC11 -eq	2,97E-06	1,72E-06	8,35E-07	3,84E-07
POCP	kg C_2H_4-eq	1,97E-02	1,98E-03	9,78E-04	3,60E-04
AP	kg SO_2 -eq	1,23E-01	5,66E-02	3,54E-02	7,15E-03
EP	kg PO_4^{3-} -eq	8,09E-02	1,12E-02	7,59E-03	1,49E-03
ADPM	kg Sb -eq	8,99E-05	1,46E-05	5,82E-06	4,49E-06
ADPE	MJ	5,62E+02	1,35E+02	6,78E+01	3,10E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Ressursbruk (Resource use)

Parameter	Unit	A1	A2	A3	A4
RPEE	MJ	1,27E+02	2,92E+01	3,23E+01	4,77E-01
RPEM	MJ	0,00E+00	0,00E+00	0,00E+00	1,46E-01
TPE	MJ	1,27E+02	2,92E+01	3,23E+01	6,23E-01
NRPE	MJ	5,75E+02	1,42E+02	7,07E+01	3,16E+01
NRPM	MJ	2,07E+01	0,00E+00	0,00E+00	0,00E+00
TRPE	MJ	5,95E+02	1,42E+02	7,07E+01	3,16E+01
SM	kg	2,30E+02	0,00E+00	0,00E+00	0,00E+00
RSF	MJ	1,79E+02	0,00E+00	5,51E-03	0,00E+00
NRSF	MJ	2,19E+02	0,00E+00	0,00E+00	0,00E+00
W	m^3	2,84E+00	2,70E-02	3,43E-01	2,82E-02

RPEE Renewable primary energy resources used as energy carrier; RPEM Renewable primary energy resources used as raw materials; TPE Total use of renewable primary energy resources; NRPE Non renewable primary energy resources used as energy carrier; NRPM Non renewable primary energy resources used as materials; TRPE Total use of non renewable primary energy resources; SM Use of secondary materials; RSF Use of renewable secondary fuels; NRSF Use of non renewable secondary fuels; W Use of net fresh water

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Livsløpets slutt - Avfall (End of life - Waste)

Parameter	Unit	A1	A2	A3	A4
HW	kg	6,98E-04	9,55E-05	3,88E-05	2,40E-05
NHW	kg	2,17E+01	4,11E+00	6,99E-01	3,14E+00
RW	kg	INA*	INA*	INA*	INA*

HW Hazardous waste disposed; NHW Non hazardous waste disposed; RW Radioactive waste disposed

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Livsløpets slutt - Utgangsfaktorer (End of life - Output flow)

Parameter	Unit	A1	A2	A3	A4
CR	kg	0,00E+00	0,00E+00	6,00E-03	0,00E+00
MR	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00
MER	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00
EEE	MJ	INA*	INA*	INA*	INA*
ETE	MJ	INA*	INA*	INA*	INA*

CR Components for reuse; MR Materials for recycling; MER Materials for energy recovery; EEE Exported electric energy; ETE Exported thermal energy

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

unicon
CEMENTIR HOLDING

Norske tilleggskrav

Klimagassutslipp fra bruk av elektrisitet i produksjonsfasen

Nasjonal produksjonsmiks fra import, lavspenning (inkludert produksjon av overføringslinjer, i tillegg til direkte utslipp og tap i nett) er brukt for anvendt elektrisitet i produksjonsprosessen (A3). Bakgrunnsdata er presentert i tabellen under. Karakteriseringsfaktorer fra EN 15804:2012 +A1:2013 er benyttet.

Elektrisitetsmiks	Datakilde	Mengde	Enhet
El-mix, Norway (kWh)	ecoinvent 3.4	31,04	g CO2-ekv/kWh

Farlige stoffer

Produktet er ikke tilført stoffer fra REACH Kandidatliste eller den norske prioritetslisten.

Inneklima

Produktet har ingen påvirkning på inneklima.

Bibliografi

NS-EN ISO 14025:2010 Miljømerker og deklarasjoner - Miljødeklarasjoner type III
NS-EN ISO 14044:2006 Miljøstyring - Livsløpsvurderinger - Krav og retningslinjer
NS-EN 15804:2012+A1:2013 Bærekraftig byggverk - Miljødeklarasjoner
ISO 21930:2017 Sustainability in buildings and civil engineering works
ecoinvent v3, Allocation, cut-off by classification, Swiss Centre of Life Cycle Inventories.
Iversen et al., (2018) eEPD v3.0 - Background information for EPD gen. system. LCA.no OR 04.18
Vold et al. (2014) EPD-generator for betongindustrien, bakgrunnsinformasjon for verifisering, OR 04.14, Østfoldforskning,
NPCR Part A: Construction products and services. Ver. 1.0. April 2017, EPD-Norge.

- PCR for Precast Concrete Products, NPCR 20.2011, www.epd-norge.no
- Vold M. og Edvardsen T. (2014); EPD-generator for betongindustrien, Bakgrunnsinformasjon for verifisering, OR 04.14 Østfoldforskning, Fredrikstad, Januar 2014.
- Vold M. og Edvardsen T. (2014); EPD-generator for betongindustrien, Brukerveileding, OR 05.14 Østfoldforskning, Fredrikstad, Januar 2014.

	Programoperatør og utgiver Næringslivets Stiftelse for Miljødeklarasjoner PostBoks 5250 Majorstuen, 0303 Oslo,Norge	Telefon: e-post: web:	+47 23 08 80 00 post@epd-norge.no www.epd-norge.no
unicon CEMENTIR HOLDING	**Eier av deklarasjon** Unicon AS Prof. Birkelandsvei 27B 1081 Oslo	Telefon: e-post: web:	97171734 bgpe@unicon.no
Østfoldforskning	**Forfatter av livsløpsrapporten** Østfoldforskning AS Stadion 4 1671 Kråkerøy	Telefon: e-post: web:	+47 69 35 11 00 post@ostfoldforskning.no www.ostfoldforskning.no
LCA.no	**Utvikler av EPD-generator** LCA.no AS Dokka 1C 1671 Kråkerøy	Telefon: e-post: web:	+47 916 50 916 post@lca.no www.lca.no

Appendix D: Construction drawings, fieldwork

The construction drawings considering post-tensioning of the tendons during the fieldwork at Gullhaug Torg 2A are presented in figures D.1 and D.2.

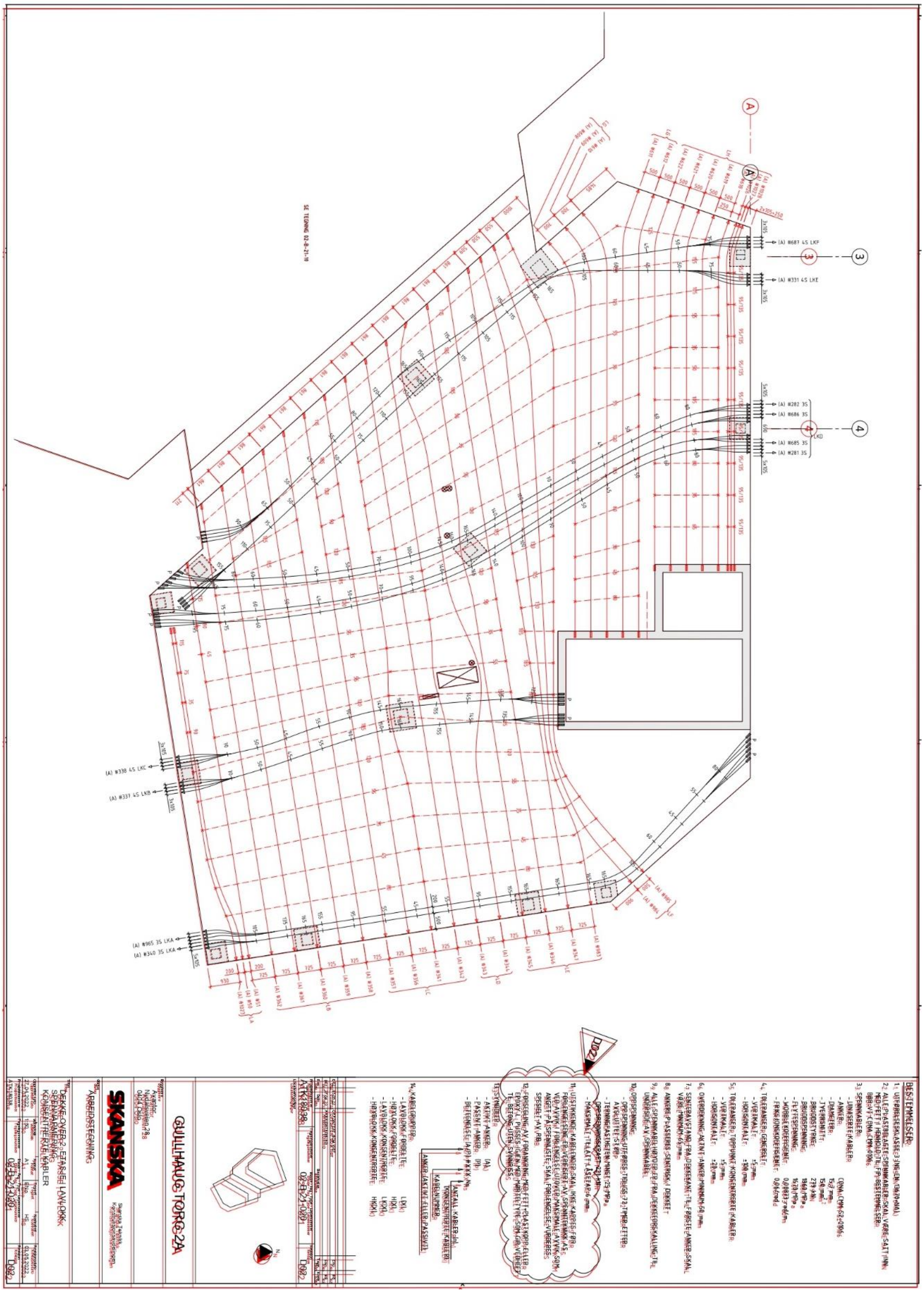


Figure D. 1. Combined work drawings regarding the fieldwork on Gullhaug Torg 2A

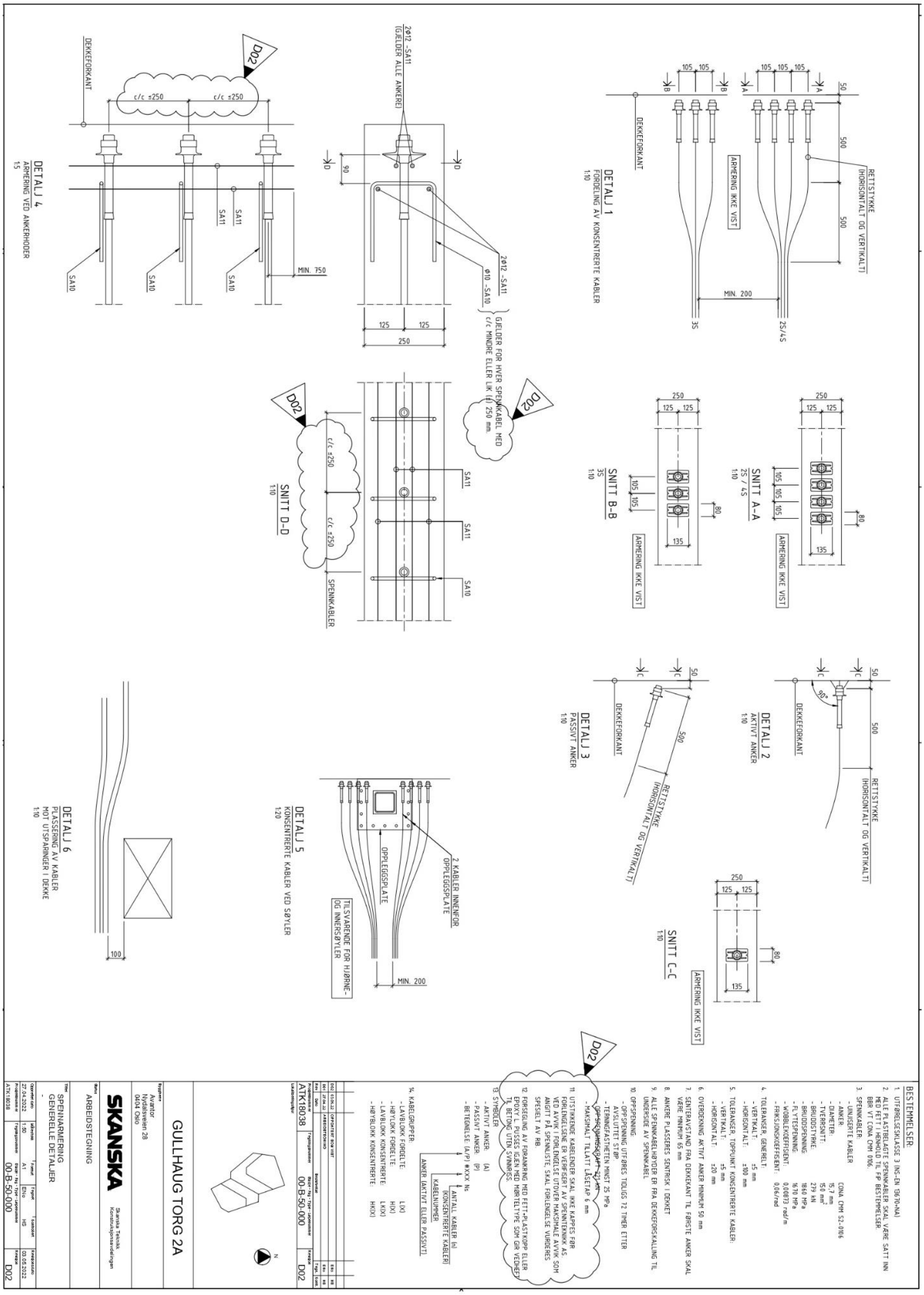


Figure D. 2. Detail drawing regarding the fieldwork on Gullhaug Torg 2A

Appendix E: Report from Maturix

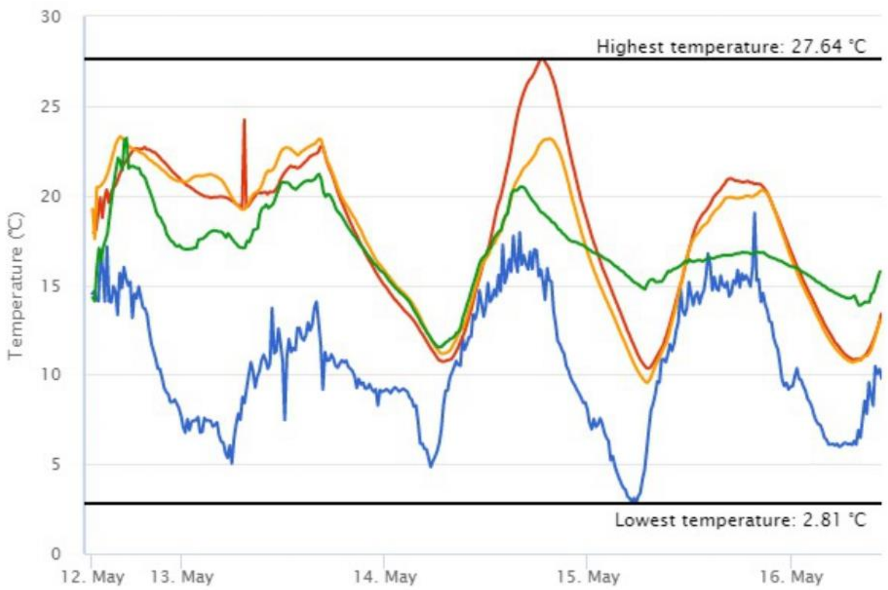
The report from the wireless temperature measurements is presented in the following.

maturix®

Dekke over Plan 2
Gullhaug Torg

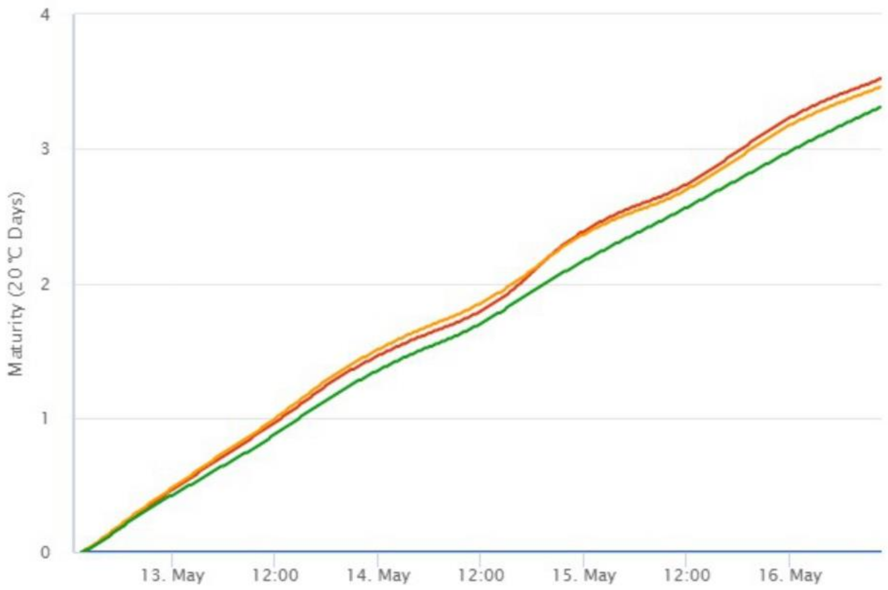
Cast Date: 12/5-2022 - 16/5-2022
LHAUTO-1

Temperature



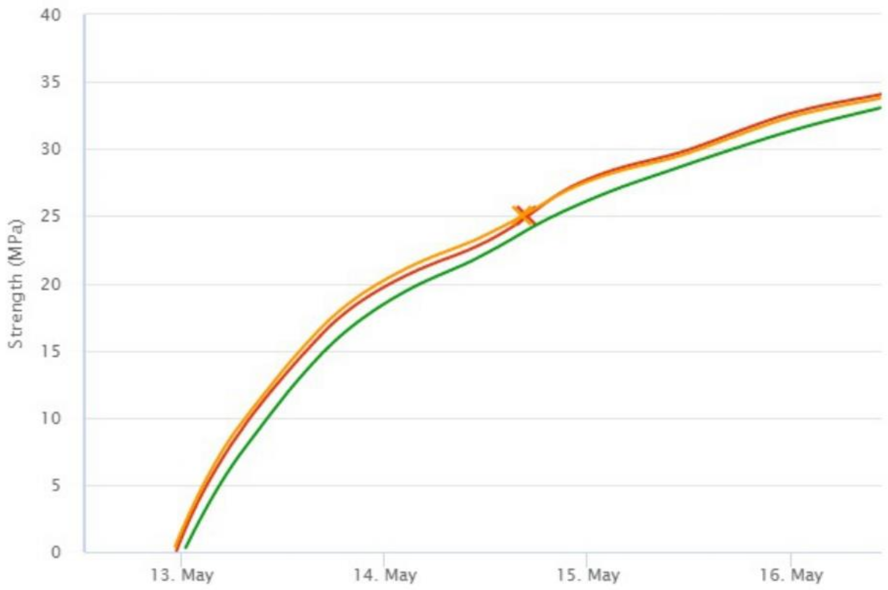
		Monitoring Description	Min	Average	Max	Latest
1	———	Omgivelsestemperatur	2.81 °C	10.58 °C	19.02 °C	9.79 °C
2	———	Passiv anker gruppe	10.34 °C	17.91 °C	27.64 °C	13.38 °C
3	———	Passiv anker singel	9.54 °C	17.63 °C	23.29 °C	13.05 °C
4	———	Kabel høyparti	11.53 °C	16.95 °C	23.2 °C	15.74 °C

Maturity



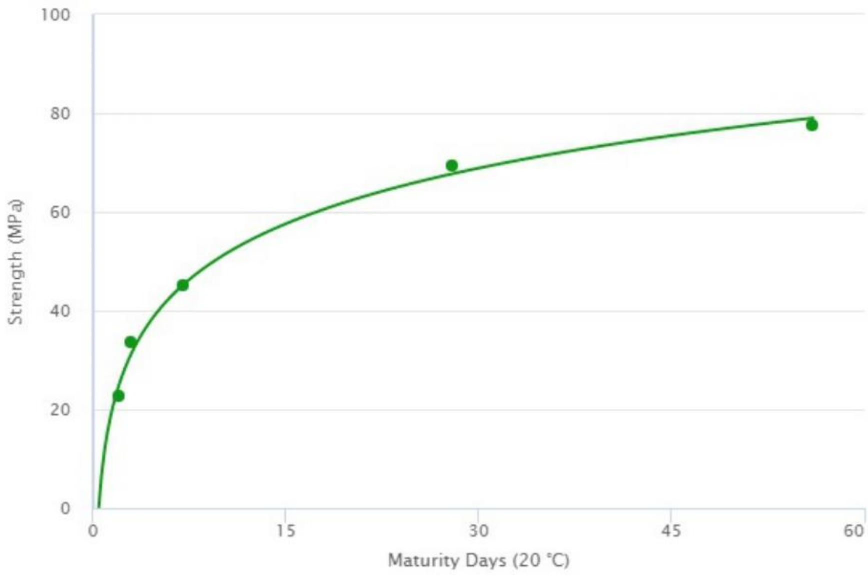
		Monitoring Description	Maturity	Target
1	————	Omgivelsestemperatur		
2	————	Passiv anker gruppe	3.52 Days (20 °C)	
3	————	Passiv anker singel	3.46 Days (20 °C)	
4	————	Kabel høyparti	3.31 Days (20 °C)	

Strength



		Monitoring Description	Strength	Target
1	————	Omgivelsestemperatur		
2	————	Passiv anker gruppe	34.07 MPa	25 MPa
3	————	Passiv anker singel	33.77 MPa	25 MPa
4	————	Kabel høyparti	33.05 MPa	67 MPa

Concrete

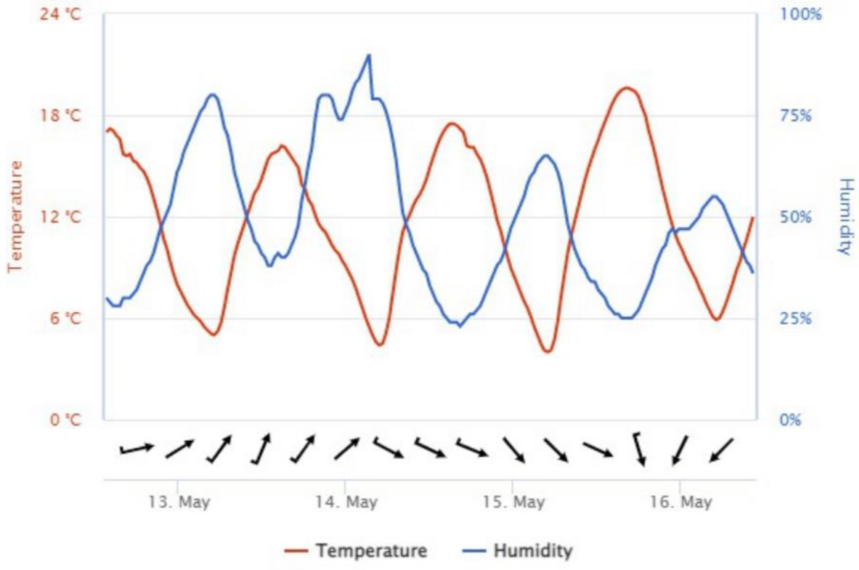


B55 M60 65% hybrid	
Maturity Function	Arrhenius
Activation Energy	36000
Increment Energy	500
Specified temperature	20
Concrete Version	8
Regression Formula	-38.060 + 16.250 × ln(x)

Concrete Details

Maturity	Strength
2 Days (20 °C)	22.7 MPa
3 Days (20 °C)	33.61 MPa
7 Days (20 °C)	45.07 MPa
28 Days (20 °C)	69.4 MPa
56 Days (20 °C)	77.5 MPa

Weather



Appendix F: Report from CrackTeSt COIN

The following attachment is an arbitrary report of the 768 simulation reports conducted in CrackTeSt COIN.

C:Hybrid 65 5 S6.CPR

Report

Contents

1 Software & Project Information

1.1 Software

System name: CrackTeSt COIN
System version: 1.0
Developed by: JEJMS Concrete AB

1.2 Project

Original filename: C:\Users\pette\OneDrive - OsloMet\OsloMet\4. SEM\Master\CrackTest COIN\Scenarios\B55M60H65FA.CPR
Created: 2022.02.19 10.46.43
Created by: petter on AOC-24-CURVED-C
Current filename: C:\Users\pette\OneDrive - OsloMet\OsloMet\4. SEM\Master\CrackTest COIN\Scenarios\Wind 2 ms\Hybrid 65%\4. 5°C\Scenario #6\Hybrid 65 5 S6.CPR
Last change: 2022.05.19 13.05.10
Last change by: petter on AOC-24-CURVED-C

2 Geometry & Time

2.1 Description

2.1.1 Blocks

Block 1: (0.000;0.000) - (6.000;0.000) - (6.000;0.250) - (0.000;0.250)

2.1.2 Computation time

Total time length: 168 (h)

3 Heat Properties

3.1 Description

3.1.3 Block type list

Hybrid 65%: Young concrete
Start temperature:
Constant: 20.0
Material definition: GT2A, Hybrid 65 (str)
Source
Description
Original material parameters
Density: 2381 (kg/m³), Heat cap. 980 (J/(kg·K))
Heat cond. (W/m²K) as piece-wise linear function of equivalent time of maturity (h), (equ. time; heat cond.): (0;2.2), (100;2.2), (124;2.2), (10000;2.2),
C 413 (kg/m³), QInfinite 280000 (J/kg), t1 13 (h), Kappa1 1.1 (-)
te0 0 (h), BetaDIni 1 (-), AIni 40000 (J/mol), BIni 200 (J/mol K)
BetaDSet 1 (-), ASet 40000 (J/mol), BSet 200 (J/mol K), BetaD 1 (-), A 40000 (J/mol), B 200 (J/mol K)
s 0.31 (-), tIni 1 (h), tFin 7.8 (h), nSet 1 (-)
Fset 0.5 (MPa), ncc28d 0.001 (-)
Fcc28 67.2 (MPa)
Following material parameters are changed by the user
tFin 5.8 (h)

Hybrid 50%: Young concrete
Start temperature:
Constant: 15.0
Material definition: GT2A Hybrid 50 (str)
Source
Description
Original material parameters
Density: 2400 (kg/m³), Heat cap. 1000 (J/(kg·K))
Heat cond. (W/m²K) as piece-wise linear function of equivalent time of maturity (h), (equ. time; heat cond.): (0;2.2), (100;2.2), (124;2.2), (10000;2.2),
C 448 (kg/m³), QInfinite 320000 (J/kg), t1 13 (h), Kappa1 1.1 (-)
te0 0 (h), BetaDIni 1 (-), AIni 40000 (J/mol), BIni 200 (J/mol K)
BetaDSet 1 (-), ASet 40000 (J/mol), BSet 200 (J/mol K), BetaD 1 (-), A 40000 (J/mol), B 200 (J/mol K)
s 0.31 (-), tIni 1 (h), tFin 7.8 (h), nSet 1 (-)
Fset 0.5 (MPa), ncc28d 0.001 (-)
Fcc28 80 (MPa)

3.1.4 Block connection list

Block 1: Hybrid 65%

3.1.5 Boundary type list

Vert. forsk. h.
Temperature
Constant 5 (°C)
Wind velocity
Constant 2 (m/s)
Heat transfer coefficient
Piece-wise constant (time (h);htc (W/m²K))
(0:6.66667)
Wood/Plywood 0.021 (m)
(72:1000)
Free surface
Supplied heat

Constant 0 (W/m²)
Forsk. UK dekke
Temperature
Constant 15 (°C)
Wind velocity
Constant 0 (m/s)
Heat transfer coefficient
Piece-wise constant (time (h);htc (W/m²K))
(0:6.66667)
Wood/Plywood 0.021 (m)
(72:1000)
Free surface
Supplied heat
Constant 0 (W/m²)
Forsk. OK dekke
Temperature
Constant 5 (°C)
Wind velocity
Constant 2 (m/s)
Heat transfer coefficient
Piece-wise constant (time (h);htc (W/m²K))
(0:1000)
Free surface
(5:3.6)
Expanded polyethylene 0.01 (m)
(72:1000)
Free surface
Supplied heat
Constant 0 (W/m²)
Moving Boundary: Moving boundary
Temperature
Constant 15 (°C)
Heat transfer coefficient
Constant 30 (W/m²K)
Supplied heat
Constant 0 (W/m²)

3.1.6 Boundary connection list

Boundary segment 1: Forsk. UK dekke
Boundary segment 2: Vert. forsk. h.
Boundary segment 3: Forsk. OK dekke
Boundary segment 4: adiabatic (no heat flow)

3.1.7 Inner point type list

3.1.8 Simulation of filling process for young concrete

Surface position as a piece-wise linear func. of time (time (h); y-coord. (m))
(0;0),

4 Plane-Surface Analysis

4.1 Description

4.1.9 Stress case

Default time stepping
  Translation
    Full restraint (1.000)
  Rotation around X-axis
    Full restraint (1.000)
  Rotation around Y-axis
    Full restraint (1.000)

4.1.10 Block data list

Block 1: Hybrid 65%

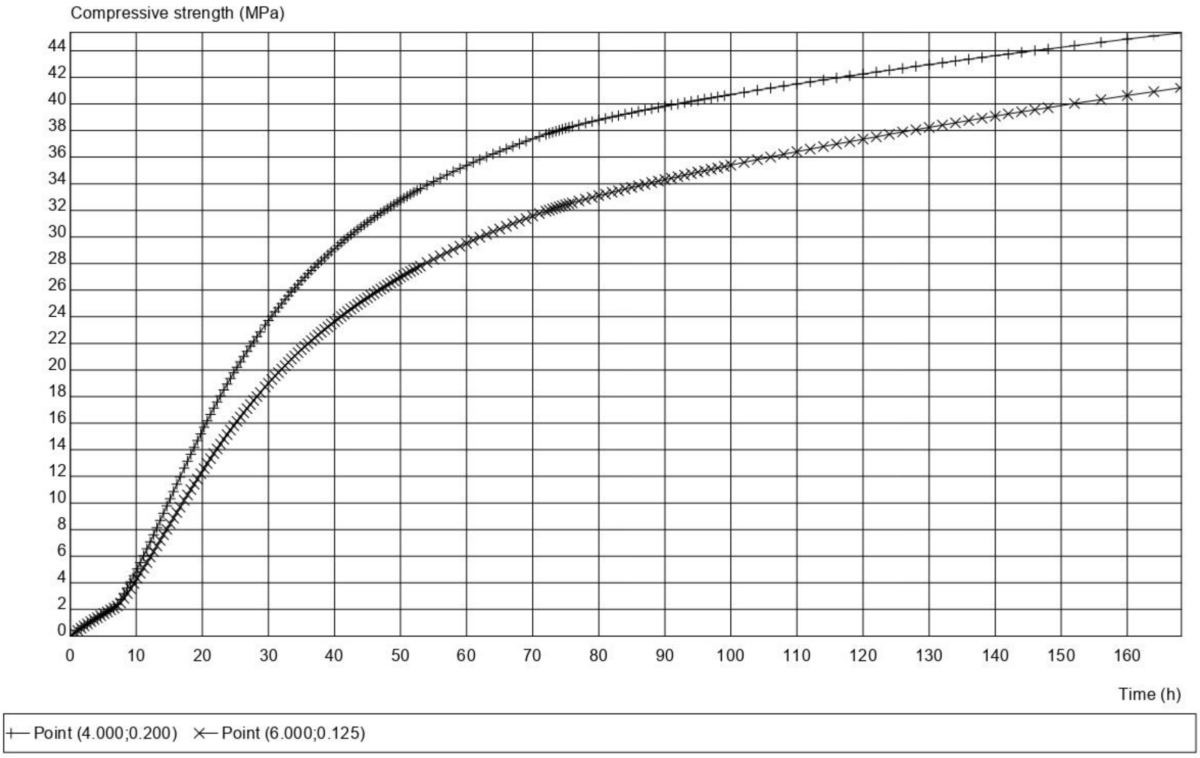
4.1.11 Block type list

Hybrid 65%: Young concrete
  Material definition: GT2A, Hybrid 65 (str)
  Source
  Description
  Original material parameters
    AlfaTemp 9.2e-06 (1/K), Fcc28d 67.2 (MPa), Fct28d 3.5 (MPa), nct 0.5 (-)
    RelaxTime1 0 (d), TimeZero 0 (d)
    Relax: Age 0.499 (d), Units (GPa) 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998
    Relax: Age 0.6 (d), Units (GPa) 0.644261 -0.0445494 4.25397 0.73831 0.384775 0.802989 1.24254 -0.72577
    Relax: Age 1.293 (d), Units (GPa) 1.03113 1.20778 4.07885 2.10966 3.41182 4.13209 7.29994 -4.23395
    Relax: Age 2.785 (d), Units (GPa) 1.03509 1.48553 3.92277 2.8857 4.70211 5.59254 9.92648 -5.7813
    Relax: Age 6 (d), Units (GPa) 0.957097 1.51985 3.59673 3.61301 5.59353 6.61399 11.7332 -6.96048
    Relax: Age 12.927 (d), Units (GPa) 0.845118 1.47618 3.11824 4.33702 6.36231 7.44932 13.188 -8.14913
    Relax: Age 27.85 (d), Units (GPa) 0.7382 1.35859 2.72895 4.49366 6.47902 7.45878 13.138 -6.39564
    Relax: Age 60 (d), Units (GPa) 0.626221 1.16554 2.36805 4.08226 6.08237 6.86512 11.9703 -3.06522
    Relax: Age 129.266 (d), Units (GPa) 0.531293 0.995926 2.04916 3.65283 5.72828 6.4051 10.9534 -0.146848
    Relax: Age 278.495 (d), Units (GPa) 0.451104 0.847758 1.77076 3.22439 5.36661 6.06994 10.0814 2.42074
  Following material parameters are changed by the user

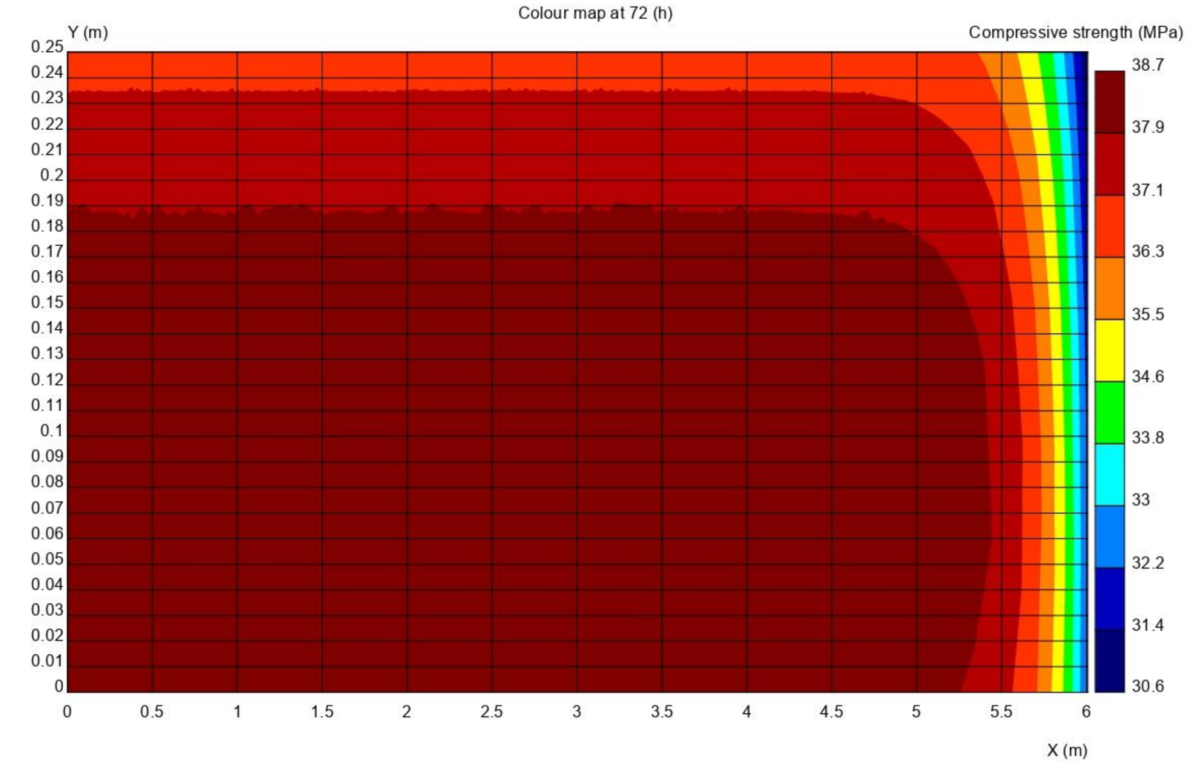
Hybrid 50%: Young concrete
  Material definition: GT2A Hybrid 50 (str)
  Source
  Description
  Original material parameters
    AlfaTemp 9.2e-06 (1/K), Fcc28d 80 (MPa), Fct28d 3.8 (MPa), nct 0.5 (-)
    RelaxTime1 0 (d), TimeZero 0 (d)
    Relax: Age 0.499 (d), Units (GPa) 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998 0.0109998
    Relax: Age 0.6 (d), Units (GPa) 0.644261 -0.0445494 4.25397 0.73831 0.384775 0.802989 1.24254 -0.72577
    Relax: Age 1.293 (d), Units (GPa) 1.03113 1.20778 4.07885 2.10966 3.41182 4.13209 7.29994 -4.23395
    Relax: Age 2.785 (d), Units (GPa) 1.03509 1.48553 3.92277 2.8857 4.70211 5.59254 9.92648 -5.7813
    Relax: Age 6 (d), Units (GPa) 0.957097 1.51985 3.59673 3.61301 5.59353 6.61399 11.7332 -6.96048
    Relax: Age 12.927 (d), Units (GPa) 0.845118 1.47618 3.11824 4.33702 6.36231 7.44932 13.188 -8.14913
    Relax: Age 27.85 (d), Units (GPa) 0.7382 1.35859 2.72895 4.49366 6.47902 7.45878 13.138 -6.39564
    Relax: Age 60 (d), Units (GPa) 0.626221 1.16554 2.36805 4.08226 6.08237 6.86512 11.9703 -3.06522
    Relax: Age 129.266 (d), Units (GPa) 0.531293 0.995926 2.04916 3.65283 5.72828 6.4051 10.9534 -0.146848
    Relax: Age 278.495 (d), Units (GPa) 0.451104 0.847758 1.77076 3.22439 5.36661 6.06994 10.0814 2.42074

5 Plane-Surface Computation Results

5.1 Comp. strength curve chart

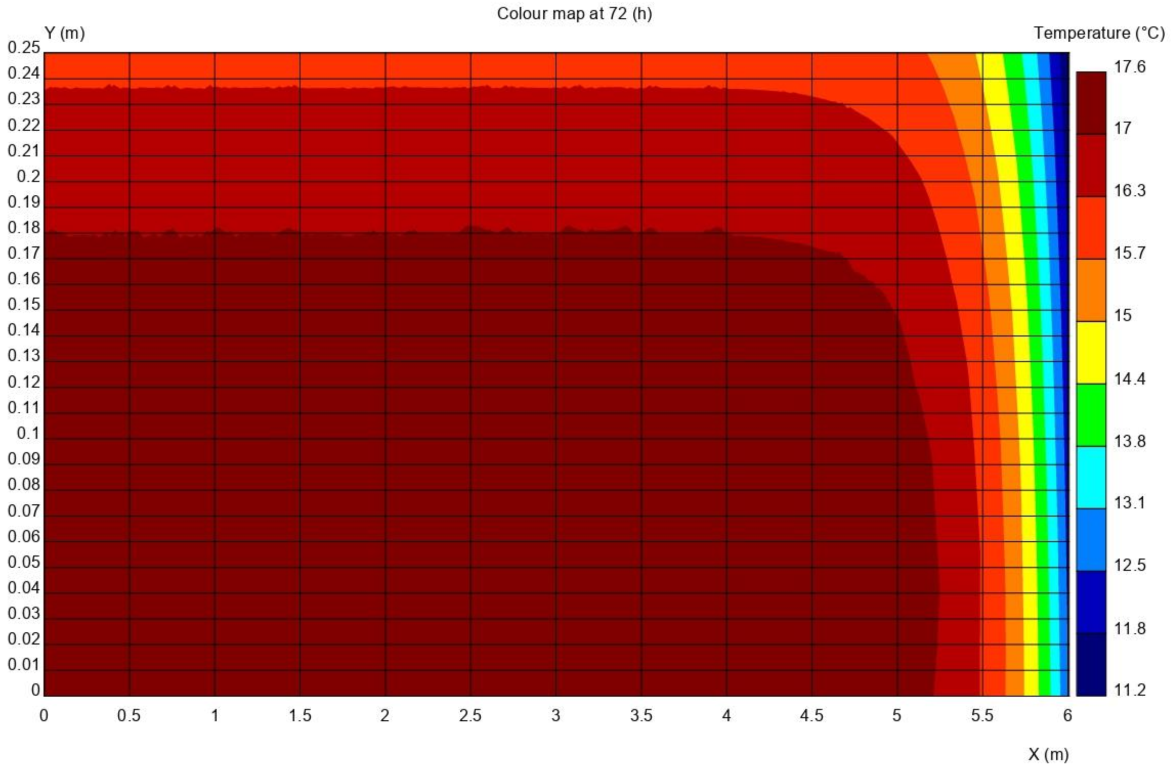


5.2 Comp strength map 72h

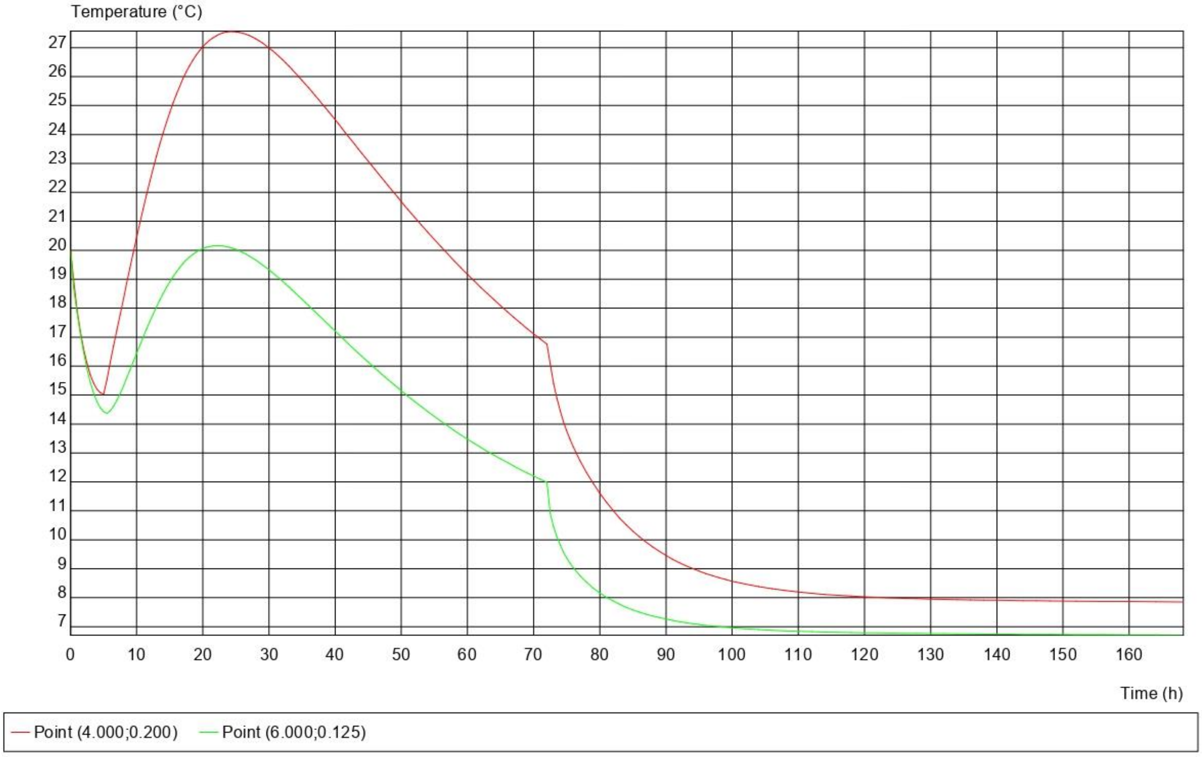

Colour map at 72 (h)
Y (m)
Compressive strength (MPa)
0.25
0.24
0.23
0.22
0.21
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
X (m)
38.7
37.9
37.1
36.3
35.5
34.6
33.8
33
32.2
31.4
30.6

6 Heat Computation Results

6.1 Temperature 72h



6.2 Temp. curve chart


Temperature (°C)
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
Time (h)
Point (4.000;0.200)
Point (6.000;0.125)