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BIM-LCA Construction Project

Case study report

Geopolymer Concrete: A future-oriented concrete

(1) Østfold University College

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Geopolymer Concrete: A future-oriented concrete

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This thesis investigates the durability and properties of self-developed geopolymer concrete, comparing its CO₂-emissions with traditional concrete. The study emphasizes geopolymer concrete as a sustainable alternative, highlighting its lower emissions and excellent properties. The research utilizes BIM modeling and LCA analysis to assess its environmental impact and suitability for precast applications. Overall, the thesis contributes to the knowledge of geopolymer concrete and promotes emission awareness in the construction industry.

3 keywords:

Geopolymer concrete
BIM
LCA

Preface

In this preface, we aim to encapsulate the comprehensive journey of our three-year civil engineering study, spanning from 2020 to 2023. We have gained extensive knowledge in construction-related disciplines, problem-solving, and project work throughout these three years, which have been filled with excitement, challenges, and intriguing ups and downs. Overall, this journey has greatly shaped and prepared us as future civil engineers, offering invaluable experiences.

The participation in the BIM-LCA pilot project through the Erasmus+ workshop in Cartagena UPCT has been an enlightening experience, serving as a kick-off for this bachelor thesis, providing valuable insights and setting the stage for further exploration.

In the beginning, we express our heartfelt gratitude to Susana Garcia Sanfelix for her invaluable assistance in the studies of concrete, chemical aspects, and her guidance throughout our bachelor's thesis journey. Her expertise and support have greatly contributed to our growth and understanding in these areas.

Furthermore, we extend our sincere appreciation to Marius Birkeland and Henrik Røer for their significant contributions to the BIM component and construction subject matter explored within this thesis.

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Abstract

This thesis, titled "Geopolymer Concrete: A future-oriented concrete," addresses the objective of investigating the durability and properties of a self-developed geopolymer concrete. The study also involves a comparison of CO₂-emissions between the production phase of geopolymer concrete and traditional concrete, with the aim of raising emission awareness in the construction and engineering industry through the application of BIM and LCA methodologies.

The thesis primarily focuses on geopolymer as a promising solution for a green transition in the construction and engineering industry. Key components of the study include BIM modeling and LCA analysis. The LCA analysis reveals a positive CO₂-balance, indicating lower emissions for geopolymer concrete compared to traditional concrete, although it also highlights a negative aspect concerning energy consumption.

Extensive laboratory testing conducted by the group demonstrates that geopolymer concrete exhibits excellent properties, enhancing both durability and lifespan. As a result, it is concluded that geopolymer concrete is suitable for precasted applications. The study emphasizes the need for further exploration of potential enhancements in terms of standardizing the use of untraditional concrete.

Overall, this thesis contributes to the knowledge and understanding of geopolymer concrete as a sustainable alternative, while highlighting the importance of emission awareness and promoting environmentally friendly practices in the construction and engineering industry.

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Symbols

Abbreviations

ASR	- Alkali-silica reaction
BFS	- Blast Furnace Slag
BIM	- Building Information Modeling
EFC	- Earth Friendly Concrete
EPD	- Environmental Product Declaration
FA	- Fly Ash
GGBFS	- Ground granulated blast furnace slag
GPC	- Geopolymer concrete
LCA	- Life Cycle Assessment
OPC	- Ordinary Portland cement
PCR	- Product Category Rules
SCC	- Self-consolidating concrete
SF	- Silica Fume

Chemical abbreviations

AgNO ₃	- Silver Nitrate
Al	- Aluminum
Al ₂ O ₃	- Aluminum Oxide
$C_{20}H_{14}O_4$	- Dibenzalacetone
C_2S	- Dicalcium Silicate
C ₃ A	- Tricalcium Aluminate
C_3S	- Tricalcium Silica

C ₄ AF	- Tetracalcium Aluminoferrite
Ca	- Calcium
Ca(OH) ₂	- Calcium Hydroxide
CaSiO ₃	- Calcium Silicate
СН	- Calcium Hydroxide / Portlandite
CH_4	- Methane
СО	- Carbon Monoxide
CO_2	- Carbon Dioxide
Fe	- Iron
H ₂ O	- Water
K	- Potassium
K ₂ O	- Potassium Oxide
K ₂ SiO ₃	- Potassium Silicate
КОН	- Potassium Hydroxide
Li	- Lithium
MgO	- Magnesium Oxide
Na	- Sodium
Na ₂ O	- Sodium Oxide
Na ₂ SiO ₃	- Sodium Silicate
NaCl	- Sodium Chloride
0	- Oxygen
Si	- Silicon

1 Introduction

For every year that passes, the climate is changing. Measurements have shown that the temperature is increasing, glaciers are melting, sea levels are rising and there is more unpredictable extreme weather. This is due to the increase of greenhouse gasses being released into the atmosphere (FN-Sambandet, 2023). The construction industry alone accounts for approximately 38% of the world's emissions (United Nation Environment Programme, 2021). Of these 38%, the production of concrete accounts for a significant 10% of the emissions (Saeed, et al., 2022, pp. 5-9). Due to the excellent properties such as



Figure 1: Global CO₂-emissions by sectors (Ali, 2020, p. 12)

compressive strength, durability, fire resistance and resistance to other mechanical stresses, concrete has become the most widely used material in the construction industry. It is estimated an annual consumption of 12,5 billion cubic meters in 2021 (Seehusen, 2021). Concrete is widely used in prefabricated elements and cast on-site structures, as it has great flexibility to be shaped into challenging forms while still maintaining the desired properties.

Today's greenhouse gas emissions must be minimized to avoid the collapse of society and preserve the environment (FN-Sambandet, 2023). This means that all actors within the various industries must contribute, including the construction industry (FN-Sambandet, 2023).

This group vision is to conduct a thorough examination of geopolymer concrete, to see if traditional concrete is replaceable – by utilizing technical tools that are used in the construction industry.

1.1 Problem statement

In conjunction with the Erasmus+ program and in association with Østfold University College, the group has been engaged in an international BIM-LCA construction project. As a part of this, the bachelor's thesis has been written in collaboration with Jotne Eiendom and Selvaag Bolig. It is focusing on the development of FMV-Vest urban area in Fredrikstad, mainly towards a construction called "Modellageret". This construction has a projected lifespan of 10 years before the new regulatory plan becomes operational. Therefore, the group has chosen to enlighten the green transition within the construction industry by addressing the following problem statement:

The purpose of this thesis is to investigate the durability and properties of a self-developed geopolymer concrete, as well as comparing the CO_2 -emissions from the production phase versus traditional concrete – with the goal of promoting emission awareness in the construction and engineering industry using BIM and LCA.

1.2 Limitations

With the time constraints for the bachelor's thesis, it is appropriate to set the following limitations to ensure that the results are as useful as possible:

Geopolymer concrete

- The properties of the material are the only factors considered and not the aesthetic design.
- Any economic aspects will not be evaluated or included in the decision-making basis.
- The material properties will be tested in the laboratory at Østfold University College and limited to the equipment available.
- Limitations regarding mixing sufficient amount of samples.
- The comparison against traditional concrete is limited to literature and standards.

Potential use of Geopolymer concrete, BIM review

- The influencing forces and statics in the design of the module wall are not a focus of this assignment, *rather* the potential use of the geopolymer concrete.
- Anchoring solution of the module wall will not be considered, but briefly discussed as reusability is a goal.

LCA study

- The values for the LCA study are extracted from the database of SimaPro and the energy consumptions is partly presumed and not a definite value.
- The LCA study is constricted to the production phase of ready mixed concrete.

1.3 Research Method

During the implementation of the bachelor's thesis, the group utilizes various methods of research, as shown in the following points:

- Field trip to Cartagena and workshops related to technical tools.
- Literature search and methodical gathering of information related to the topic.
- Project schedule and progress tracking in Microsoft Project.
- Flow chart of mixing and recipe development in Microsoft Visio.
- Oral information gathering from collaboration partners and supervisors.
- Casting and laboratory related testing.
- Modelling in Revit.
- Life Cycle Assessment in SimaPro.
- Result reporting in Excel.

2 Theory

Concrete is one of the most used materials in the world and plays a crucial role in the construction and engineering industry (Gregory & Logan, 2021). Historically, concrete has been used in various forms for thousands of years, and the development of modern Portland cement-based concrete can be traced back to the 19th century (Kontrollrådet, 2018). Today, concrete remains a popular building material due to its versatile properties, but the production of concrete has a significant environmental impact with large amounts of carbon dioxide emissions (Gregory & Logan, 2021).

In 1978, geopolymer was first introduced as an alternative to ordinary Portland cement, OPC (Parshwanath, Nataraja, & Lakshmanan, 2011). Geopolymer is based on less processed minerals with aluminum silicates. Suitable raw materials for geopolymer can be fly ash, iron slag, or even clay (Betongfokus, 2019). To determine whether geopolymer is an environmentally friendly and durable material, the reader must rely on literature and research-based evidence presented below, including BIM and LCA.

2.1 Traditional Concrete

Concrete is a versatile engineering material consisting of a hydraulic cementing substance, usually OPC, aggregate, water, and often controlled amounts of entrained air. Concrete is initially a plastic, workable mixture which can be molded into a variety of shapes. Strength is developed during the hydration reaction between the cement and water. The products, mainly calcium silicates, calcium aluminates, and calcium hydroxide, are relatively insoluble and bind the aggregate in a hardened matrix (Jahren, 2012, p. 11). The concrete mass acts as a homogeneous fluid, where the matrix phase is surrounding the particle phase (Maage, 2015, p. 143).

2.1.1 Cement

The definition of cement is generally used to describe a dry substance that is yet to be activated. The particle size ranges from 0.5 to 80 μ m, and the color is normally grey, due to the raw materials containing iron (Fe). These raw materials consist mainly of limestone, gypsum and other materials containing high levels of lime and silica. Among these are quartz, slate, sand, or clay (Jahren, 2012, p. 16).

When it comes to the production of cement, limestone is burned with, for example, quartz and shale. The mixture is crushed and heated in rotating kilns at around 1450°C. This results in clinker that is grinded together with gypsum and becomes cement (Heidelberg Materials, n.d.). Limestone consists mainly of the composition of carbon and oxygen, and when heated, calcination process starts where limestone is decomposed in calcium oxide (CaO) and carbon dioxide (CO₂) is released – resulting in extensive CO₂-emissions (Heidelberg Materials, n.d.).

$$CaCO_3 \rightarrow CaO + CO_2$$
 1

It is estimated that around 3 tons concrete being used per human being each year (Gagg, 2014, p. 1).

2.1.2 Hydration process

The OPC consists of mainly four minerals, namely tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetra calcium aluminate ferrite (C_4AF). The unbonded CaO is the most important mineral for the properties, additionally magnesium oxide (MgO), gypsum, potassium oxide (K_2O) and sodium oxide (Na_2O). The ratio between these four minerals, depicts the exothermic, strength, durability and curing properties of the cement (Maage, 2015, p. 83).

Name	Chemical formula	Symbol
Tricalcium silicate	$3CaO \times SiO_2$	C_3S
Dicalcium silicate	$2CaO \times SiO_2$	C_2S
Tricalcium aluminate	$3CaO \times Al_2O_3$	C ₃ A
Tetra calcium aluminate ferrite	$4Ca0 \times Al_2O_3 \times Fe_2O_3$	C ₄ AF

Table 1: The 4 main minerals of OPC (Maage, 2015, p. 83)

Formula of hydration process of C₃S:

 $C_3S + 6H_2O \rightarrow C_3S2 \times 3H_2O + 3Ca(HO)_2$

Formula of hydration process of C₂S:

 $C_2S + 4H_2O \rightarrow C_3S2 \times 3H_2O + 3Ca(HO)_2$

Formula of hydration process of C₃A:

$$C_3A + 6H_2O \rightarrow C_3A \times 6H_2O$$

Formula of hydration process of C₄AF:

$$4C_4AF + 2Ca(HO)_2 + 10H_2O \rightarrow C_3A \times 6H_2O + C_3F \times 6H_2O$$

(Saleh & Eskander, 2020)

The hydration is an exothermic process that release a lot of energy. The process is known as latent hydraulic, and the hydration reaction can continue even when fully submerged, in the absence of air. The reaction is retarded by a small amount of gypsum that must be decomposed in order for the hydration process to start. This ensures the workability of the concrete mix for approximately 2 to 3 hours (Maage, 2015, p. 57). According to Powers' model, the reaction products are calcium silicate hydrate (C-S-H), and portlandite (CH), as well as ettringite. There is, however, not possible to achieve 100% hydration, approximately three quarters will be hydrated after 1 year. The C-S-H creates the gel pores, that is the main source of what gives the cement paste its strength and hardened properties (Maage, 2015, pp. 58-59).



Figure 2: SEM of CH and C-S-H, Mix 8 (Armentrout & Belkowitz, 2009)

2.1.3 Additives

Additives are divided into pozzolans and latent hydraulic materials and aim to replace Portland cement. Based on the desired properties, the different materials can be dosed in varying percentages in relation to Portland cement (Maage, 2015, pp. 92-93). Pozzolan materials are a collective term for materials that react with the reaction product calcium hydroxide (Ca(OH)₂) (Maage, 2015, p. 93).

Silica Fume, 0.01-1µm

Silica Fume, SF, is a byproduct of the production of silicon and ferrosilicon metal. SF is very fine-grained, and the particles are on the order of 1/100 the size of cement particles. In Europe, SF must comply with the standard *NS-EN 13263-1* "*Silica fume for concrete, Part 1: Definitions, requirements and conformity criteria*" (Maage, 2015, pp. 93-99).

Impact on fresh concrete (Maage, 2015, pp. 95-96):

- SF contributes to making the concrete slightly stiffer and reduces the risk of segregation.
- There is higher viscosity and flow shear stress in the concrete with SF, therefore plasticizing agents are always used.
- It contributes to slower strength development and less heat generation.

Impact on cured concrete and mechanical properties (Maage, 2015, pp. 96-98):

- The pozzolanic reaction of SF is more influenced by temperature lower early strength at low temperatures compared to regular concrete and vice versa.
- SF concrete is more resistant to high curing temperatures as it develops less porous products than traditional concrete.
- SF can improve compressive strength, adhesion, and abrasion resistance of concrete than in concrete without it.

Influence on durability (Maage, 2015, pp. 98-99):

- SF reduces the potential for alkali-silica reaction, ASR, as pozzolans will bind the alkalis in the concrete, making them unavailable for later reaction with reactive aggregates.
- The addition of SF results in a finer pore structure in the concrete, leading to denser concrete.
- The ingress of chlorides is significantly reduced by using SF.



Figure 3: Compressive strength of SF containing mortar (Muwashee & Al-Jameel, 2021)

Fly Ash, 1-100 µm

Fly ash, FA, is a byproduct of the cleaning of flue gases in coal fired power plants. *NS-EN 197-1* refers to two types of FA: a silicate-containing and a calcium-containing type. FA usually contains some residual carbon, which is reflected in the slightly darker color of the concrete (Maage, 2015, p. 101). The use of FA in Europe is subject to the standard *NS-EN 450-1: "Fly ash for concrete, Part 1: Definition, specifications and conformity criteria"* (Maage, 2015, p. 101-103).

Influence on fresh concrete (Maage, 2015, p. 102):

- The particles of FA are essentially spherical, and the particle size is similar to OPC. This improves the workability of the concrete.
- FA has lower density than cement. This can contribute to higher matrix volume, which can improve the workability of the concrete.
- FA contributes to good stability.

Impact on hardened concrete and mechanical properties (Maage, 2015, pp. 102-103):

- FA reacts slower than cement, which is compensated for by grinding the cement to a finer state.
- In the long term, the pozzolanic reaction will contribute to concrete with FA developing higher strength than concrete without it.
- The adhesion is positively affected using FA.

Impact on durability (Maage, 2015, p. 103):

- FA has the same impact on durability as SF and the resistance to leaching, sulfate attack, and acid attack is positively influenced using FA.
- Carbonation can propagate faster into the concrete with the amount of FA increases.
- Chloride ingress is strongly reduced, and electrical resistance increases with increasing content of FA.



Figure 4: OPC ratio, compressive strength with % FA (Abushad & Sabri, 2017)

Slag

Slag, or blast-furnace slag, BFS, is a byproduct of the production of raw iron. The collected waste initially consists of relatively large particles and must be crushed and ground to a particle size like cement. Ground Granulated Blast Furnace Slag, GGBFS, is a byproduct of the iron and steel industry that is produced by rapidly quenching and grinding blast furnace slag, and it is commonly used as a supplementary cementitious material in concrete production (GCP, n.d.). GGBFS is commonly referred to as slag in the concrete terminology, and it's a "latent hydraulic" material, meaning that it can chemically react without combination with cement if the pH level is high enough. It consists of 30-50% CaO, 30-40% silicium oxide or silica (SiO₂), 10-25% aluminium oxide or alumina (Al₂O₃), as well as other oxides (Maage, 2015, pp. 103-105). Utilizing slag will reduce emissions associated with concrete and reduce the amount of waste in the steel industry (Samferdsel og infrastruktur, 2019). In Europe, the used standard is *NS-EN 15167-1: "Ground granulated blast furnace slag for use in concrete, mortar and grout, Part 1: Definitions, specifications and conformity criteria"* (Maage, 2015, p. 105).

Impact on fresh concrete (Maage, 2015, p. 105):

- Concrete with slag cement often has improved workability properties and reduced segregation compared to concrete containing only OPC.
- Slag cement in concrete may not necessarily result in reduced heat development.

Impact on hardened concrete and mechanical properties (Maage, 2015, p. 105):

- Slag reacts slowly and the strength will be lower in the first days compared to if OPC had been used. This can be adjusted to some extent by grinding the slag cement to a finer state.
- The reaction of slag cement lasts for a longer period. This means that concrete with slag cement will achieve higher strength than concrete with OPC.

Impact on durability (Maage, 2015, p. 105):

- Slag contributes to reduced chloride ingress, as C-S-H products are formed over time.
- The pore system in the concrete becomes finer, resulting in a denser concrete, thus increasing resistance to alkali reactions and sulfate attacks is positively influenced using slag.
- The fact that the absorption of water in the pore system increases significantly means that concrete with slag cement will have reduced frost resistance.

2.1.4 Admixtures

Below is a table showing the most applied admixtures:

Class of admixtures	Description of the substance's mode of	
	action in concrete	
Water – reducing or plasticizing	Reduces the water requirement in each concrete mixture without affecting the consistency or increase the slump/spread measurement without affecting the water requirement or has both effects simultaneously.	
Highly water – reducing or super plasticizing	Significantly reduces the water requirement in each concrete mixture without affecting the consistency, or significantly increases the slump/spread measurement without affecting the water requirement or has both effects simultaneously.	
Air – entraining	The admixture adds a controlled amount of small, uniformly distributed air bubble during mixing that remain in the mixture after hardening.	
Setting accelerators	Reduces the time before the concrete mixture transitions from a plastic to a hardened state.	
Hardening accelerators	Causes faster development of early strength in concrete, with or without affecting the setting time.	
Setting retarders	Increases the time before the concrete mixture transitions from a plastic to a hardened state.	
Water - repellent	Reduces the capillary water absorption in curing concrete.	
Admixture for reduced water separation	Reduces water loss by reducing water separation <bleeding>.</bleeding>	
Setting – retarding and water – reducing	Provides combined effect of a water – reducing admixture (primary function) and a setting – retarding admixture (secondary function).	
Setting – retarding and high – range water- reducing	Provides combined effects of a water – reducing admixture (primary function) and a setting accelerating admixture (secondary function).	
Accelerating setting and water reducing	Provides combined effects of a water – reducing admixture (primary function) and a setting – retarding admixture (secondary function).	

Table 2: Class of admixtures (SINTEF, 2010)

2.1.5 Mass ratio

The mass ratio depends on the water to cement, additionally additives, along with their respective k-factor (Maage, 2015, p. 100). The mass ratio is the greatest factor the hardened properties, such as strength and durability. Additionally, any admixtures and additives used will affect the other properties (Maage, 2015, p. 13).

Formula for mass ratio (Maage, 2015, p. 155):

$$m = \frac{v}{c} = \frac{v}{(c + \Sigma k * p)}$$

Where:

- Mass lat
III - IVIASS I AL

- v Amount of water
- c Amount of cement
- p Amount of additives
- k Effectiveness factor

2.1.6 Aggregates

Mainly, concrete aggregates are divided into coarse and fine aggregates. An aggregate fraction is defined by the designation d/D, which represents the minimum and maximum nominal particle size. The upper nominal particle size does not represent the maximum actual particle size, which means that there will always be a certain number of oversize particles (Maage, 2015, p. 133). Particle size distribution is documented by sieve analysis according to *NS-EN 933-1* (CEN, 2012).

2.2 Geopolymer concrete

Geopolymer concrete, GPC, has gained a lot of attention in the last years and is a relatively new building material. As with ordinary concrete, GPC is also made with a binder, a liquid, and aggregates. The main difference is that the binder does not contain OPC, and the liquid is mainly alkaline activators. The other big difference between OPC concrete and GPC, is that the utilization of waste materials is much better for the GPC, thus cutting the CO₂-emissions substantially. It is also considered fairly cost effective, providing long life infrastructure and low energy consumption (Ahmed, et al., 2022).

2.2.1 Mass ratio of GPC, L/GB

In 2.1.5 Mass ratio, the concept of mass ratio, as mentioned, also encompasses the liquidto-binder ratio, which represents the mass ratio between the total amount of free water and the water contained within the alkaline solutions, as well as the total mass of the geopolymer solids, including FA, GGBFS, potassium hydroxide (KOH) pellets, and sodium silicate (Na₂SiO₃) solids. This ratio is suggested to have a similar effect as the water-to-cement (W/C) ratio for water and cement (Pilehvar, et al., 2018). However, the proposal term "liquid" is used to encompass the overall quantity of alkaline solutions, additional water, superplasticizers, and geopolymer binders, which include FA and GGBFS (Pilehvar, et al., 2018). By these two proposals, the group settled on using the latter ratio, as the group has defined the entire alkaline solution, superplasticizer, and water as a *liquid*.

2.2.2 Geopolymer as a binder

There is a growing consensus that limestone-based binder is considered the first-generation cement, OPC as the second-generation and geopolymer cement is often referred to as a third-generation cementitious material (Singh, Ishwarya, Gupta, & Bhattacharyya, 2015). It has gained a lot of positive attention in recent years, because of the early compressive strength, good chemical resistance, low permeability, and fire-resistant properties. The word "geopolymer" is a general term that is commonly used to refer to amorphous alkali aluminosilicate, as amorphous describes as a solid which does not exhibit a crystalline structure (Mavračić, Mocanu, Deringer, Csányi, & Elliott, 2018). Furthermore, these are also known by other names such as "geocements", "alkali-activated cements", "inorganic polymers", "alkali-bonded ceramics", "hydro ceramics", and more (Singh, Ishwarya,

Gupta, & Bhattacharyya, 2015). These different terms describe materials utilizing comparable chemistry, despite the variety of the terminology.

The chemical compound generally consists of a repeating unit of sialate monomer. Monomer is a type of chemical connection, where the molecules react within itself to create bigger molecules, given the proper conditions (Helseth, 2021). Sialate monomers is an abbreviated form of alkali silicon-oxo-aluminate, where the alkalis are sodium (Na), potassium (K), lithium (Li) and calcium (Ca). They are characterized by their composition, which includes silicon (Si), aluminium (Al), and oxygen (O) atoms, along with alkali metal cations such as Na or K. Such materials that have been used as raw materials in geopolymer, comprehends feldspar, kaolinite, and industrial solid residues. These includes FA, mining wastes and metallurgical slag. What depicts the reactivity, are characteristics such as chemical make-up, morphology, glassy phase, fineness, and mineralogical composition of these aluminosilicate sources. The common factors that develop the attributes of geopolymer, includes materials that possess sufficient reactive glassy content, high amorphous state, insignificant demand for water and ability to release aluminum readily (Singh, Ishwarya, Gupta, & Bhattacharyya, 2015).

The geopolymerization process generally consists of the following steps (Cong & Cheng, 2021):

- 1. Dissolution of the precursor
- 2. Formation of the initial gel
- 3. Formation of silicate gel network structure

As with OPC, the selection of raw materials and the ratio between them greatly impact the properties of the geopolymer, such as durability, heat development, potential strength, strength development (Maage, 2015, pp. 83-87). As it is used slag and FA as binder, the mineral composition of the materials will be discussed. Table 3 below, shows the composition of the additives that have been used in this project. Also, the Blaine value, or specific surface area, and particle fineness depicts the effectiveness of a pozzolanic material (Taffase & Espinosa-Leal, 2023, p. 2).

MERIT		FA from	FA from Norcem	
	Slag		FA F	
H2O	0,18	H2O	0,54	
CO2	1,41	CO2	1,25	
Na2O	0,55	Na2O	0,86	
MgO	12,79	MgO	1,24	
Al2O3	11,82	AI2O3	21,13	
SiO2	32,12	SiO2	60,59	
SO3	2,69	SO3	0,66	
К2О	0,96	К2О	2,65	
CaO	34,25	CaO	2,04	
TiO2	2,15	TiO2	1,10	
V2O5	0,11	V2O5	0,05	
Cr2O3	0,01	Cr2O3	0,02	
MnO	0,51	MnO	0,09	
Fe2O3	0,21	Fe2O3	7,13	
CuO	0,01	CuO	0,02	
Rb2O	0,00	Rb2O	0,01	
SrO	0,06	SrO	0,06	
Y2O3	0,01	Y2O3	0,01	
ZrO2	0,04	ZrO2	0,06	
Nb2O5	0,00	Nb2O5	0,00	
BaO	0,07	BaO	0,12	
	99,94		99,61	

Table 3: Chemical compositions slag and FA

Slag is activated by Ca(OH)₂, sulphates and alkalis (Maage, 2015, p. 105). In slag, the great amount of CaO and SiO₂, ensures the hydraulic property of reacting with dihydrogen monoxide (H₂O), as well as being able to cure fully submerged. SiO₂, and Al₂O₃, is an amorphous material, thus having pozzolanic properties. When the pH is \geq 11 the Al₂O₃ and SiO₂ becomes soluble, allowing a pozzolanic reaction (Singh, Siddique, & Singh, 2022, pp. 1-29). The SiO₂ must be in an amorphous state to participate in the pozzolanic reaction (Maage, 2015, p. 101). SiO₂ and CaO will form calcium metasilicate (CaSiO₃), as well as C–S–H products, by SiO₂ reacting with the Ca(OH)₂ (Maage, 2015, p. 94).

Pozzolanic reaction (Setina, Gabrene, & Juhnevica, 2013, p. 1006):

$$3Ca(OH)_2 + SiO_2 \rightarrow 3CaO \cdot SiO_2 + 3H_2O$$

FA (type F) in Geopolymer

FA consists mainly of SiO₂ and Al₂O₃ and like slag generates a pozzolanic reaction. The fineness of the FA powder greatly affects the curing and strength development. Ultra-fine FA decreases porosity, generating more durable concrete, but also decreases the setting time (Deb & Sarker, 2016, pp. 1-5). The workability is improved due to the spherical shape and small proportions of the particles (Maage, 2015, p. 101). Additionally, it reduces the porosity, and the water sorptivity will be decreased as a result. It will then increase the chloride diffusion resistance, because of the reduced permeable pores (Saha, 2018, pp. 25-31). However, due to the low content of CaO, and high level of amorphous silica, the early compressive strength development will be lower, and long term will be higher. Also, the FA gradually contributes to the drying shrinkage being reduced, as it has significantly less amount of lime (Saha, 2018, pp. 25-31).

The reason why FA type F is so effective in contributing to less permeability and higher resistance to chloride ion mitigation, is due to the reduction of mainly two transportation methods (Saha, 2018, pp. 25-31):

- Interconnecting voids in concrete.
- Free hydroxyl (HO) ions.

With the higher fineness of FA, the interconnection will be decreased, thus making it difficult for the ions to travel through the concrete. As the FA type F also reduces the ASR, it additionally binds the HO ions in the solution of the pores. Therefore, these two factors are strongpoints in making a more durable concrete, especially because of the reduced chloride permeability (Saha, 2018, pp. 25-31).

Ratio between FA and GGBFS

With greater ratio of FA to GGBFS, the initial setting time is decreased due to the reaction of Ca found in the GGBFS. The workability of the mix is increased in GPC with increasing amount FA because of its small particle size and shape. Due to the fineness and high Blaine value of FA, the pozzolanic reactivity increases and the capillary pores collapses (Ahmed, et al., 2022). This generates lower porosity and higher strength and density, as more material fills the pores that could be filled with air or water. Increasing the ratio of GGBFS, decreases the workability, as the particles have more angular shape than those of FA. The strength development is initially slower, but strength increases up to 180 days (Ahmed, et al., 2022). The ratio of GGBFS to FA of 20 to 80 is optimal according to Ahmed. 25 to 75 ratio of GGBFS and FA is also suggested to have the best mechanical properties (Patil, Karikatti, & Chitawadagi, 2018).



Figure 5: Image a) shows SEM image of slag particles, while b) shows SEM image of fly ash particles (Verma & Dev, 2021)

2.2.3 Alkaline activators

The activators that are being used to make GPC are KOH, sodium hydroxide (NaOH), potassium silicate (K₂SiO₃) and Na₂SiO₃. These are used to activate aluminosilicate substances and produce the hydration products, C-S-H, CH and ettringite. The geopolymerization process generally consists of three consecutive steps (Cong & Cheng, 2021):

- 1. Dissolution of aluminosilicate materials by the alkaline activators.
- 2. Condensation reaction of alumina and silica hydroxyl to form geopolymer gel.
- 3. Condenses further to form a three-dimensional network.

When comparing NaOH to KOH, KOH shows a higher content of alkalinity, however, NaOH appears to show greater capacity to liberate silicate and aluminate monomers (Singh, Ishwarya, Gupta, & Bhattacharyya, 2015). Higher molarity of the alkaline activators, such as NaOH, provides greater compressive strength, although lower workability (Ahmed, et al., 2022). Also, KOH possessed higher compressive strength with higher concentration, up to 14M (Hardjito & Tsen, 2008).

Ratio between the activators

To acquire the highest compressive strength, Detphan and Chindaprasirt, made GPC of rice husk ash and FA, that was activated by a NaOH and Na₂SiO₃ solution. The optimal mass ratio of Na₂SiO₃ to NaOH was 4:1 (Saeed, et al., 2022). Other sources states that the ratio between the two alkaline solutions should be $\frac{Na_2SiO_3}{NaOH} = 2.5$ (Ketana, Reddy, Rao, & Shrihari, 2021). The group has settled for a ratio not too far from these results, although these two differ greatly, 2.5:1 and 4:1. 1.5:1 is what the group will take in account. The rate of workability and setting time, is what the ratio of the alkaline activators will change (Saeed, et al., 2022).
2.2.4 Curing conditions

The optimal curing conditions of FA based GPC, is oven curing in the range of 40°C to 100°C and 20 hours was considered optimal duration of curing in oven (Fadhil, Haruna, Mohammed, & Sha'aban, 2017, p. 32). This is due to the enhanced geopolymer activity during higher temperatures than ambient environment temperature. The bonding between the paste and aggregates are increased, creating an overall increase in strength and durability. Mechanical activation and disintegration rate of the FA particles and morphological transformation are improved, as the curing temperature increases (Fadhil, Haruna, Mohammed, & Sha'aban, 2017, p. 32).

2.2.5 Self-healing properties of GPC

The main reason to some concrete structure failures, is due to rebar corrosion (Rodriguez, Ortega, & Casal, 1997). Furthermore, one common and essential reason to the corrosion of the rebars, are cracks in the concrete. As the main concern regarding the lifespan of a concrete structure depends on its ability to seal and protect the rebars – this self-healing property is rudimentary. Cracks are not uncommon, and will develop due to curing heat, drying shrinkage, plastic shrinkage, deterioration, and applied forces (Maage, 2015, p. 407). These allow chemicals and ions entering the concrete, through water sorption and diffusion. This will destabilize the oxide layer and the steel rebars will start to corrode. Furthermore, this will lead to both decreased cross-sectional area of the rebars, as well as decreased load capacity, and volume expansion of the rebars (Maage, 2015, pp. 218-227). This is due to the corrosion product, creating inner tensile stress that cracks the concrete.

FA type F, as used, have shown self-healing properties. The extent of the healing depends on the damage of the concrete (Ross, Genedy, Juenger, & van Oort, 2022). The FA type F has "autogenous" self-healing, and the repairing process happens because of the incorporation of polymers. The healing mechanism is initiated because of the formation of amorphous aluminosilicate reaction products, as well as a calcite deposition. The ability to closure cracks, to further stop ingression, is what determines a good self-healing ability (Ross, Genedy, Juenger, & van Oort, 2022). The mentioned beneficial properties of FA in GPC can extend the lifespan of the structure.

2.2.6 GPC in use today

One contributor to the slow move over to GPC, is the hazardous environment created by the alkaline activators. Due to the alkaline being highly caustic soda, solutions are hazardous to the operators of the mixing of GPC, as well as the casting-workers (National Center for Biotechnology Information, 2023). Furthermore, when creating a NaOH or KOH solution from pellets with water, the reaction between the two components, i.e., NaOH and H₂O, it is severely exothermic. It will almost reach the boiling temperature of water (BYJU's Learning, 2023). This means that handling great amounts of this liquid, and mixing it, should be done extremely carefully and in a strict manner. Moreover, GPC is being used in a variety of projects with different applications, such as the following:

Queensland University GCI (Global Change Institute)

Australian researched GPC for an extensive period and have already, as the first in the world, incorporated GPC for structural purposes – like the prefabricated plates of the Queensland University Globals Change Institute, GCI, building. This is a 4-story construction, where 3 of the floors involves the use of 33 pre-casted GPC panels. The pre-casted panels are made from slag/FA-based GPC, called Earth Friendly Concrete, EFC, and was designed by Wagners Australia (WAGNERS, n.d.).



Figure 6: 1 of the 33 pre-casted GPC panels (WAGNERS, n.d.)

Brisbane West Wellcamp Airport



(pavement plan - excerpt from ACG Engineers drawings)

Figure 7: Pavement/ runway plan, BWW Airport (Glasby, Day, Genrich, & Aldred, 2015)

BWW Airport became fully operational with commercial flights in 2014. Wagner's Australia supplied the project with approximately 40 000 m³ of geopolymer concrete, making it the largest application of this concrete class in the world at the time. The EFC was well suited for the project due to its high flexural tensile strength, low shrinkage, and workability characteristics (Glasby, Day, Genrich, & Aldred, 2015).

EFC was supplied by Wagners Australia for the construction of the 435 mm thick heavyduty runways as shown in Figure 8 under, in the aircraft turning areas. There were three areas of geopolymer runways including the turning node at the Northern end of the runway, the taxiway on the Western side of the runway and the hangars on the Eastern side of the runway (Glasby, Day, Genrich, & Aldred, 2015).



435 mm concrete, unreinforced, 4.8 MPa flexural strength at 28 days.

Prime coat / debonding layer 200 mm 4% cement modified crushed rock, 5 MPa at 7 days 150 mm capping layer

350 mm shot rock, min CBR 25%

(pavement design by ACG Engineers)

Figure 8: High Strength Concrete Pavement Design Cross Section (Glasby, Day, Genrich, & Aldred, 2015)

The mix of GPC used in this project was developed during a period of 10 years, by the Wagner's to create a commercial concrete that could be produced and handled in similar manner to conventional concrete. The summary mix parameter of this GPC (Glasby, Day, Genrich, & Aldred, 2015):

- Total alumina-silicate binder comprising slag + FA, 415 kg/m³.
- Water: binder ratio: 0.41.
- Nominal 40 mm maximum aggregate size, conforming with 28 mm to AS 2758.1 (3).
- Chemical activator, 37 kg/m³ solids content.
- Proprietary water reducing admixture.

The concrete used in BWW Airport was produced in a twin mobile wet mix plant batch established on the project site, with a maximum supply capacity of 120 m³/hr as shown in Figure 9 (Glasby, Day, Genrich, & Aldred, 2015).



Figure 9: Geopolymer twin batch plant (Glasby, Day, Genrich, & Aldred, 2015)

2.3 Theory related to methodology

To determine the properties of concrete in both fresh and hardened states, the group has utilized various theories associated with the method. This chapter will describe the theory behind the methods used.

2.3.1 Development of recipe

A concrete mix design is proportioned based on the desired properties of the concrete. The main rule is that the matrix composition controls the properties of the hardened concrete, while the aggregate compositions control the properties of the fresh concrete (Maage, 2015, p. 156).

This is a rough rule, which means that it is still possible to adjust the properties of the fresh concrete by slightly changing the matrix properties without simultaneously changing the properties of the hardened concrete (Maage, 2015, p. 156).

2.3.2 Aggregate size

The particle size greatly affects mostly fresh, but also hardened properties of concrete (Maage, 2015, p. 119). Usually, the fractions used in ready-mixed concrete and precast concrete production are divided in 0-8 mm, 8-16 mm, and 16-22 mm fractions in ready mix concrete production (Maage, 2015, p. 130). Fine aggregates have the property of a «filler effect» that fills voids with material rather than air. This generates slightly less workability, but increases stability while lowering bleeding, increasing compressive strength and the degree of compaction is improved (Diagne, Ibrahima, & Gueye, 2021).

To achieve high compressive strength Neville and Aïtcin suggests fractions of the size 10-14 mm for High Performance Concrete, HPC (Neville & Aïtcin, 1998). For HPC, it is important that aggregate size is selected carefully. The reason to why the smaller fractions are beneficial, is due to two parameters. Firstly, the differential stresses at the aggregatecement paste interface, will likely cause microcracks, and this can be prevented by smaller fractions. Secondly, due to the comminution of rocks, large flaws are also reduced, thus resulting that smaller aggregates are stronger than larger ones (Neville & Aïtcin, 1998). Angular aggregates do also have favorable benefits over round aggregates, as angular aggregates possess higher compressive strength, due to higher interlocking action between the angular aggregates (Nitka & Tejchman, 2020). Due to the recommendation of maximum 10-14 mm (Neville & Aïtcin, 1998), a 25% reduction of 8-16 mm to 0-8 mm fractions was chosen, instead of the ratio between the original 50-50 distribution.

2.3.3 Concrete mixing and curing

Small changes in the composition of the concrete mixture can have significant differences in workability and strength properties. Therefore, trial mixtures are used, and the mixture is adjusted according to desired properties (Maage, 2015, p. 165).

The standard curing of concrete is water storage at 20°C (Heidelberg Materials). Higher temperatures, above 40°C, result in rapid hydration and thus rapid strength development and vice versa. High curing temperatures, on the other hand, can lead to lower final strength and may cause cracking (Maage, 2015, pp. 323-324).

2.4 Theory related to test procedure.

To determine the properties of concrete in both fresh and hardened states, the group has utilized various theories associated with the testing procedure. This chapter will describe the theory behind the testing procedure we used.

2.4.1 Water content in the aggregate

Water content in aggregate is checked to measure the total free water present in a sample of aggregate. The water can be from the surface of the aggregate and from water available in the pores of the aggregate particles (Pavement Interactive, n.d.).

2.4.2 Particle size distribution in the aggregate

The particle size distribution is a measure of the weight percentage of different particle size in granular and aggregate materials. Particle size distribution is important in determining the technical properties of concrete and is expressed in the form of a sieve curve (Thue, 2019).

2.4.3 Specific heat capacity

Specific heat capacity, c, indicates the amount of energy required to heat up 1 kg of material by 1 K. It also indicates in the same way how much heat is released when the material is cooled. Specific heat capacity is expressed in J/(kgK) (CBI Norge, n.d.).

2.4.4 Isothermal Conduction Calorimetry

With the use of isothermal conduction calorimeter, the heat of hydration of cementitious materials is directly measured by monitoring the heat flow from the specimen when both the specimen, and the surrounding environment are at approximately isothermal conditions. Isothermal calorimetry is a good way to follow and document all stages of the hydration process (Wadsö, 2005):

- I. Rapid initial process
- II. Dormant Period
- III. Acceleration period
- IV. Retardation period
- V. Long term reactions



Figure 10: The hydration process (Wadsö, 2005)

2.4.5 Initial and final setting time – VICAT

The transition where the mortar changes from a liquid/plastic material to a solid substance is called setting time. After setting, the mass becomes stiff, while the strength development has not yet properly started. The setting time of concrete is determined according to *NS-EN* 480-2 as the age of concrete at which the penetration resistance reaches 3.5 MPa from a piston, however it can also be determined from the heat evolution curve (Meyer, 2021).

2.4.6 Workability

In concrete terminology, the term workability is divided into three branches: stability, mobility, and compressibility. What they have in common is that they qualitatively and partly quantitatively describe the behavior of fresh concrete (Maage, 2015, p. 181).



Figure 11: Workability (Maage, 2015, p. 181)

A commonly used method for classifying the workability of concrete is through the use of slump tests. The application range of the slump test method extends from very stiff to very fluid concrete.

Class	Slump tested in accordance with EN 12350-2 mm
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5 ^a	≥ 220
a See Note 1 to 5.4.1.	

Table 3 - Slump classes

Table 4: Slump classes (Standard Norge, 2004)

Table 3 Slump classes from NS-EN 206:2013+A2+NA is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See www.standard.no

When the slump is higher than 250 mm, further differences give insignificant variations in the workability properties of the concrete.

For concrete with a slump higher than 250 mm, it is natural to use spread measurements (Maage, 2015, p. 187). With the help of the spread measurement, the consistency class of the concrete can be classified.

Class	Slump-flow a tested in accordance with EN 12350-8 mm
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850
^a The classification is not applicable to concrete with <i>D</i> _{max} exceeding 40 mm.	

Table	6 —	Slum	p-flow	classes
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Table 6 Slump-flow classes from NS-EN 206:2013+A2+NA is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See www.standard.no

It is also natural to carry out a flow diameter test to classify flow class. This is done according to test method *NS-EN 12350-5*.

Class	Flow diameter tested in accordance with EN 12350-5 mm
F1a	≤ 340
F2	350 to 410
F3	420 to 480
F4	490 to 550
F5	560 to 620
F6 ^a	≥ 630
a See Note	e 1 to 5.4.1.

Table 5 — Flow classes

Table 6: Flow classes (Standard Norge, 2013, p. 27)

Table 5 Flow classes from NS-EN 206:2013+A2+NA is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See www.standard.no

Table 5: Slump-flow classes (Standard Norge, 2013, p. 28)

2.4.7 Air content

Concrete is a porous material that contains 120-180 l/m³ of pores in the concrete. A large portion of these pores, especially on the surface, become filled with water when the concrete is exposed to free water for short or long intervals. When the water in these pores freezes, the ice expands, which can damage the concrete (Maage, 2015, p. 227). Today, the amount of air content in the concrete is controlled by a standard procedure, explained in chapter 4.2.7 Air content.

2.4.8 Density

Density, or mass density, is expressed in kg/m^3 and is the ratio between the mass of a given sample of concrete and its volume.

2.4.9 Compressive strength

Shape of Test Specimen	Size in mm	Modification Factor
1	100 x 100 x 100	0.8
Cube	150 x 150 x 150	0.8
	200 x 200 x 200	0.83
	150Ф x 300	1.0
Cylinder	100Ф x 200	0.97
- 12.	200Φ x 500	1.05
Principal Principal	150 x 150 x 450	1.05
Square Prism	200 x 200 x 600	1.05

Table 7: Modification factors on conversion of strength of concrete specimens (Building Research Institute, n.d.)

Compressive strength is defined as the average value of the maximum load of several standardized test specimens that are loaded to failure. The maximum load is converted to nominal stress (Maage, 2015, p. 195).

EN 206 /4/ defines the compressive strength of concrete in strength classes with the

designation B and a two-digit number, for example, B25, which represents the characteristic strength measure on cylinders after standard curing for 28 days (Maage, 2015, p. 195). This means that the concrete is assigned a strength class depending on the requirements for the characteristic cylinder strength, f_{ck}, even if the characteristic cube strength f_{ck,cube}, is higher. Modification factors shown in Table 7 can be used when testing cube strength to present the characteristic cylinder strength.



Figure 12: Compression testing machine (EPOXY TILE FLOORING, 2021)

2.4.10 Chloride intrusion

When enough chlorides encounter the reinforcing steel, the passivating oxide layer is destroyed, and corrosion may occur even if the pH value is high. This type of corrosion often has a faster progression than when the process is initiated by carbonation (Maage, 2015, p. 42). Corrosion resulting from chloride ingress is considered "more dangerous" than carbonation, as the progression occurs in more delimited areas on the steel surface where the oxide layer is destroyed. This leads to a faster deterioration of the steel, which can be compared to "cutting" the reinforcement, called "pitting" (Maage, 2015, p. 224).

The limit value for a sufficient amount of chlorides to initate corrosion is not a defined range, but is determined by factors such as the pH level, pore structure, porosity, moisture, etc. of the concrete (Maage, 2015, p. 221). Both free and bound chlorides are present in concrete. The free chlorides are dissolved in the pore water, while some will be chemically or physically bound to reaction products. Only the free chlorides will create problems with regard to corrosion. The ratio of free to bound chlorides is not significantly dependent on the mass ratio or moisture level, but rather on the type of cement, the amount of SF, and the pH level in the concrete.

The cathodic process, the "engine" of corrosion (Maage, 2015, p. 223):

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$$

Anode process, steel corrodes (Maage, 2015, p. 223):

$$Fe \longrightarrow Fe^{++} + 2e^{-}$$

The corrosion process occurs as follow:

- 1. During the initiation process, there is no corrosion occurs, and there are no signs of degradation.
- 2. After the initiation process, it is unpredictable when the corrosion damage is visible.

The anode process as described chemically above, is a reaction on the steel where the iron disintegrates. The electrons travel from one place of the steel to another place, where it is enough O and H_2O to start the cathode process. The bigger the cathode to anode ratio, the faster corrosion process (Maage, 2015, p. 223).

Corrosion process, or "rust" (Maage, 2015, p. 224):

$$Fe^{++} + 2OH^{-} \longrightarrow Fe(OH)_2$$

2.4.11 Carbonation

In principle, concrete is a very alkaline construction material with a pH level of around 13,5 - 14,0 (Maage, 2015, p. 219). This is due to the reaction product Ca(OH)₂, which forms during the hardening process of concrete, as well as small amounts of alkaline compounds such as Na₂O and K₂O. The combination of these components results in ion formation in the pore water, and an oxide layer forms on the surface of the reinforcing steel – corrosion cannot occur (Maage, 2015, p. 219).

When CO₂ penetrates the concrete, and reacts chemically with the mentioned components, the carbonation process occurs (Maage, 2015, p. 219):

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

In carbonated concrete, the pH value will be reduced to approximately 8.3, and the reinforcing steel is no longer protected by the oxide film. This process depends on relative humidity and completely stops at below approximately 50% humidity, as there is not enough water content in the pores of the concrete for the chemical reaction to occur (Maage, 2015, p. 219).

2.5 Durability and reinforcement

⁽¹⁾ Durability describes the ability of a structure to achieve its intended service life and meet the requirements for usability, strength, and stability, without significant reduction of its usefulness or the need for extensive unforeseen maintenance (Standard Norge, 2004, p. 45).

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⁽¹⁻²⁾ To achieve the design service life, consideration should be given to design, material selection, construction details, execution, quality control, inspection, and documentation during the design phase (Standard Norge, 2004, p. 47)

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Concrete structures are usually durable and will typically serve their function for a longer period than deigned for, provided they are properly designed and constructed. However, various forms of deterioration have been observed. The causes of deterioration are relatively well known (Maage, 2015, p. 217).

Looking at the different types of damage to concrete structures both in Norway and in most other countries today, it is quickly apparent that the damage is largely related to reinforcement corrosion. To prevent corrosion from starting, the concrete cover is crucial (Maage, 2015, pp. 217-226).

2.5.1 Concrete cover



⁽¹⁻²⁾ To achieve the intended service life of a concrete structure, measures must be taken to protect the various components of the structure against the relevant environmental factors (Standard Norge, 2004, p. 47).

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Figure 13: Cross-section of reinforced column (Anre, 2020)

⁽¹⁾ The concrete cover is the distance between the surface of the outermost rebars, and the nearest surface of the concrete (Standard Norge, 2004, p. 47).

⁽²⁾ When designing concrete structures according to *NS-EN 1992-1-1*, the nominal cover, C_{nom} , is defined as a minimum cover, C_{min} , plus a deviation ΔC_{dev} to be taken into account in the design (Standard Norge, 2004, p. 47).

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 $^{(1-2)}$ The minimum concrete cover, C_{min} , is intended to ensure safe transfer of forces through adhesion, protection of steel against corrosion, and satisfactory fire resistance (Standard Norge, 2004, p. 48).

Chapter 4 - 4.4.1.2 Minste overdekning Cmin (1) and (2) from NS-EN 1992-1-1:2004+A1:2014+NA:2021 is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See <u>www.standard.no</u>

⁽¹⁾ To obtain the nominal cover, an addition to the minimum cover is made by increasing the minimum cover by the absolute value of the allowed negative deviation, ΔC_{dev}

(Standard Norge, 2004, p. 51).

Chapter 4 - 4.4.1.3 Tillatte avvik, hensyn ved prosjekteringen (1) from NS-EN 1992-1-1:2004+A1:2014+NA:2021 is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See <u>www.standard.no</u>

⁽²⁾ Nominal cover for reinforcement (Standard Norge, 2004, p. 47):

 $C_{nom} = C_{min} + \Delta C_{dev}$

Where:

C_{min} - Minimum cover, mm

 $\Delta C_{dev}~$ - Allowable deviation, mm

C_{nom} - Nominal cover, mm

Chapter 4 - 4.4.1.1 Generelt (1) and (2) from NS-EN 1992-1-1:2004+A1:2014+NA:2021 is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See <u>www.standard.no</u>

2.5.2 Minimum reinforcement

⁽³⁾ Minimum reinforcement area, As, min, is specified to prevent brittle failure modes, large cracks, and to absorb forces that arise from imposed actions (Standard Norge, 2004, p. 151).

Chapter 9 - 9.1 Generelt (3) from NS-EN 1992-1-1:2004+A1:2014+NA:2021 is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See <u>www.standard.no</u>

⁽¹⁾ When reinforcing concrete in building structures, the cross-sectional (Standard Norge, 2004, p. 151):

As,
$$min = 0.26 * \frac{f_{ctm}}{fyk} * b_t * d \ge 0.0013 * b_t * d$$

Where:

f_{ctm} - Mean value of concrete's axial tensile strength

fyk - Characteristic yield strength of reinforcement

bt - Mean width of tension zone

d - Effective thickness of the cross-section, distance from the centerline of the tensile

reinforcement to the compression edge.

Chapter 9 - 9.2.1.1 Minste og største armeringsareal (1) from NS-EN 1992-1-1:2004+A1:2014+NA:2021 is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See www.standard.no

2.6 BIM, Building Information Modeling

Building Information Modeling, BIM, is a digital process used in the construction industry and engineering. A BIM model is an accurate and detailed model of a building or infrastructure. BIM models can contain all relevant information for a construction project, including dimensions, materials, functions, and location. BIM models can also include information about energy consumption, costs, construction time, operation, and maintenance (Autodesk, n.d.).

2.6.1 Users of BIM

All professional groups involved in a construction project can use BIM. The typical users are architects, engineers, contractors, and building owners. BIM makes it possible to streamline collaboration and can contribute to a more accurate project and a better end product. Architects design, engineers calculate, interior designers visualize spaces and furnishings, contractors perform quantity calculations, plan logistics and execute the project as planned while building owners use BIM to have oversight and control throughout the construction phase (Nordic BIM Group, n.d.).

2.6.2 BIM Standard

NS-EN ISO 19650 is an international standard and provides a description of the principles for information management using BIM. It is a framework administration and information exchange, including version control and organization, for all stakeholders involved in a construction project (Standard Norge, 2022).

2.6.3 Revit

Revit is a BIM software used by architects and engineers to create high-quality buildings and infrastructure. Revit has several different applications, but it can be used to model shapes, structures, and systems in 3D with parametric accuracy, precision, and ease (Autodesk, n.d.).

2.6.4 Benefits

Some benefits of using BIM models in the construction industry include (McKenna Group, n.d.):

- Better communication and teamwork.
- Visualization of the result in the design phase.
- Conflicts between disciplines are detected more efficiently and easily.
- Can minimize health and safety incidents. By flagging high-risk areas and construction phases.
- Better and more reliable budget control.
- Greener constructions, through more accurate material control.

2.7 LCA

Life Cycle Assessment, LCA, is a systematic method for assessing the environmental and resource impacts throughout the life cycle of a product or system. LCA is also used as a basis for developing Environmental Product Declarations, EPD (LCA Norge, n.d.).

LCA is divided into two main categories: "Cradle-to-Grave" and "Cradle-to-Cradle", with the latter being preferred. The LCA methodology examines all phases involved in a product, from raw material extraction, transport, usage phase, to disposal or recycling (LCA Norge, n.d.).

An EPD describes the environmental impact of a product or system and is documented in a



Figure 14: The product life cycle stages (Life cycle assessment, 2020)

concise report. EPDs are intended to provide a better basis for assessing environmental impacts, promoting environmental development, and are an important tool for innovative product development. They should be publicly available, approved by a third party, comparable and additive for use in larger projects (LCA Norge, n.d.).

2.7.1 Users of LCA

LCA can be used in the construction industry to account for the environmental impact of different design choices or technical alternatives, and to compare the impact from these. This is done to find the most environmentally friendly solutions during a project or to document any environmental impacts upon delivery of the final product (Multiconsult, n.d.).

2.7.2 LCA Standard

The framework and standard used to conduct a complete LCA is *NS-EN ISO 14040*, and the methodology for the analysis itself is mainly divided into 4 components:

- Inventory calculation of emissions
- Classification categorization of emissions
- Characterization calculation of environmental impacts
- Improvement analysis of how the product life cycle can be improved/optimized (LCA Norge, n.d.).

The European standard for the development of EPDs for buildings and construction, *NS*-*EN 15804*, defines how a company should produce environmental declarations. The standard provides clear guidelines on how companies in the construction industry should perform LCA in EPDs. The standard ensures that all product groups use the same LCA methods to compare EPDs (LCA Norge, n.d.).

Product Category Rules, PCR, are developed as an addition to *NS-EN 15804* and contain additional rules and conditions for specific product categories. The main principle of a PCR is to determine which processes and materials the analysis should cover, and what should be defined as the declared unit for the product. This is done so that manufacturers must disclose the content of substances with significant environmental impact in relevant products - to make it easier to compare the environmental footprints of several products within the same category (LCA Norge, n.d.).

2.7.3 SimaPro

SimaPro is an innovative software tool used to perform LCA for products and services. As one of the leading LCA software solutions in the world, SimaPro is used by companies, consultants, and universities in over 80 countries (SimaPro, n.d.). The program has a vast library of data and science-based information necessary to collect, analyze, and monitor sustainability data for products and services. This makes it easy to model life cycles in a systematic way while being able to edit and customize the various products that are already in the database. The software includes a wide range of features that help users to identify and estimate the environmental impact of a product from raw material extraction to waste management. This makes it a useful tool in the construction and engineering industry as it can help businesses understand and improve their sustainable development (SimaPro, n.d.).

2.7.4 Benefits

When using LCA in the early stages of concept development for systems or products, it allows for an assessment of environmental impacts of various alternatives. This provides a systematic way to document and identify the most environmentally friendly and costeffective solutions for the given concept. Below, the principle of a LCA is illustrated.



Figure 15: Structure principle of LCA (BNP Media, 2021)

2.7.5 GWP – Global Warming potential

When conducting the LCA study in SimaPro, the value for GWP100 is used. This refers to the accumulated warming effect in relation to CO₂-emissions over a period of 100 years. GWP is usually divided into 4 different indicators:

GWP Total: the sum of fossil, biogenic, and land transformation.

GWP Fossil: The GWP fossil indicator considers GWP for greenhouse gas emissions and sequestration across all media resulting from the oxidation or reduction of fossil fuels or

fossil carbon-containing substances. It also includes sequestration or emissions of greenhouse gases from inorganic materials, such as carbonation of cement.

GWP Biogenic: In brief, this refers to the CO_2 stored in the material/product, indicating the amount of CO_2 absorbed from the atmosphere during the growth of biomass and biogenic emissions to air through oxidation or decomposition of the biomass, for example, burning of biomass.

GWP Land transformation: This is the indicator for greenhouse gas emissions and sequestrations CO₂, carbon monoxide (CO), carbon tetrahydride (CH₄) that arise from changes in specified carbon stocks as a result of land use and land use change.

(LCA, n.d.)

3 Framework

The following manuals and standards that has been utilized to produce this thesis:

Standards	Description
HB R210 (Vegdirektoratet, 2014)	Håndbok R210 Laboratorieundersøkelser consists of method descriptions for laboratory analyses carried out in the Norwegian Public Roads Administration (Statens Vegvesen). HB R210 is based on current standards.
NS-EN 206 (Standard Norge, 2013)	NS-EN 206 specifies requirements for the composition of concrete and rules for verifying the expected properties.
NS-EN 1992-1-1, EC 2 (Standard Norge, 2004)	Eurocode 2 provides the basis for designing concrete structures, as well as requirements for capacity, serviceability, durability, and fire resistance.
NS-EN ISO 14040 (Standard Norge, 2006)	NS-EN ISO 14040 describes the principles and framework for life cycle assessment (LCA), its purpose, and scope.
NS-EN 12350 (Standard Norge, 2019)	Testing the properties of fresh concrete
ASTM C 1679 – 09 (Standard Norge, 2022)	Measuring Hydration Kinetics of Hydraulic Cementitious Mixtures Using Isothermal Calorimetry

NS-EN 196-3:2016 (Standard Norge, 2016)	Methods of testing cement - Part 3: Determination of setting times and
	soundness
NT Build 492 (Nordtest, 1999)	Concrete, mortar, and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments

Table 8: Utilized standards

4 Method

To make results that are comparable and reproducible, the group has used standardized tests and methods that are based on official international standards. These will depict the quality and properties of the GPC recipe developed by the group. In this chapter, the methods and procedures used will be described and pictures of the actual testing procedures will be included. The flow chart below illustrates the process of developing the final recipe, and extracting of the results:

Flow chart of recipe development







Figure 16: Flow chart of the GPC development

4.1 Development of recipe

There are far and few between available standards regarding geopolymer concrete recipes. The counselor of this group had a premade recipe, mixed between two existing recipes, that could be tested with different molarities of the alkali solutions, as well as workability of the mix designs, and then finally strength.

Over a period of about one month the group worked on developing a geopolymer recipe. This process resulted into 11 different recipes the group used for further experiments. The group used the calorimetric test results to eliminate 8 of the 11 recipes. Out of these remaining 3 recipes, it was clear to the group that the concrete recipe with the highest early compressive strength and best workability was the one the project will focus on, GP5.2.

GP5.2, L/GB = 0,55				
Material	Recipe weight	Actual weight, batch 1	Actual weight, Batch 2	$\frac{kg}{m^3}$
FA	5,472kg	5,472 <i>kg</i>	5,472 <i>kg</i>	243,2kg
GGBFS	3,648kg	3,646kg	3,648kg	162,1 <i>kg</i>
Na ₂ SiO ₃	2,736kg	2,736kg	2,736kg	121,6 <i>kg</i>
КОН	1,824 <i>kg</i>	1,824 <i>kg</i>	1,824 <i>kg</i>	81,1 <i>kg</i>
Free water	0,3045 <i>kg</i>	0,3045 <i>kg</i>	0,3045 <i>kg</i>	13,5 <i>kg</i>
SP	0,177 <i>kg</i>	0,177 <i>kg</i>	0,177 <i>kg</i>	7,9kg
Aggregate 0/8	21,703 <i>kg</i>	21,702 <i>kg</i>	21,702 <i>kg</i>	964,5 <i>kg</i>
Aggregate 8/16	17,001 <i>kg</i>	17,002 <i>kg</i>	17,002 <i>kg</i>	755,7 <i>kg</i>
L/GB ratio	12	1,6 + 81,1 + 13,5 243,2 + 162,1	$\frac{6+7,9[kg]}{1[kg]} = 0,5$	55

Table 9: Recipe and actual weight of GP5.2

4.1.2 Aggregate size

The group eliminated the fraction of 16-22 mm and settled for 0-8 mm and 8-16 mm, as stated in the theory, 2.3.2 Aggregate size. As one if the standard fractions is 8-16 mm, the group chose this instead of creating a fraction series of its own. The 25% reduction of 8-16 mm to 0-8 mm was also chosen, to come closer to the suggested aggregate size of 10-14 mm.

4.1.3 Concrete mixing and curing

During the production of concrete, the group chose to follow the procedure described in *HB R210 411, "Produsering av betong i laboratorium"*. A forced mixer of type (ZK 50 HE) was used, and the group chose to divide the desired mixture into two batches. These batches were mixed on the same day, and deviations are assumed to be small. After mixing, the batch temperature was measured, and the following tests, 4.2 Test procedures, and casting of test specimens were carried out.



Figure 17: Concrete compulsory mixer of the type ZK 50 HE (Pemat)

Casting of test pieces was carried out according to *HB R210 416*, "*Støping av Prøvestykker*", with a small deviation. As stated earlier, the optimal curing conditions of GPC is between 40-100°C for 20 hours. The group therefore chose to deviate from storing with plastic for 16 hours and instead subject the fresh concrete to 80°C and 20 hours, and then in ambient conditions at 20°C in a strict temperature-controlled room. When casting the desired GP5.2 mix, a total of 4 cubes were cast for carbonation testing, 4 cylinders for chloride ingress testing, and 12 cubes for compressive strength testing at 1, 7, and 28 days, with half of these cured in an oven and the remainder at room temperature, 20°C. After 24 hours, the cubes were demolded, and the samples were sealed in an airtight container.

4.2 Test procedures

The following tests are chosen to determine the behavior of the GPC in fresh and cured stage. It is to be stated that there is limited time available to perform all the tests necessary to establish a definite proposition of the performance of the final concrete product.

4.2.1 Water content in the aggregate

When determinate the water content in the aggregates, the group follows *HB R210, 121* "*Vanninnhold i tilslag*".

This is done by measuring a bowl of moist aggregate to be tested after a certain minimum amount as shown in, Table 10 has been weighed.

Upper grain size (D) (mm)	Minimum sample quantity (kg)
< 1	0,2
4	0,8
8	1,6
16	3,2
22	4,4

Table 10: Minimum sample quantity of the upper grain size

The moist sample is weighed and placed in a drying oven until a constant mass is obtained. After the sample is dry, the mass is then measured again.

Formula for moisture content:

$$w = \frac{(M_1 - M_2)}{(M_2 - M_3)} * 100$$

Where:

- w water content in %
- $M_1 \qquad \text{-mass of moist sample in grams + bowl} \\$
- $M_2 \qquad \text{-mass of dry sample in grams} + bowl$
- M_3 mass of bowl in grams

4.2.2 Particle size distribution of aggregates

When determining the particle size distribution of aggregates, the group followed the method in *HB R210, 131 "Sikteanalyse (tørrsikting av vasket materiale)"* by Statens Vegvesen.

This is done by measuring a quantity of aggregate as shown in Table 11.

Upper grain size (D) (mm)	Sample quantity (kg)
90	80
63	40
45	20
32	10
22	5

16	2,6
11	1,4
8	0,6
≤4	0,2

Table 11: Measured quantity of aggregate

The aggregate is sieved through sieves with square openings for 10 minutes. The sieves are weighed before and after the test.

The results are recorded by calculating the residue for each sieve test, $R_1, R_2, ...+..., R_n$, based on the total sample amount (M₁), and then summing them up.

The percentage value for each particle size is obtained using the following formula and applies to all aggregate down to 0.063 mm:

$$X_i = \frac{R_i}{M_1} * 100$$

Where:

 R_i - mass in grams of each fraction

 M_1 - the total dry mass of the sample

Particle size less than 0.063 mm (fine aggregates) is determined by the following formula:

$$f = \frac{(M_1 - M_2) + P}{M_1} * 100$$

Where:

M₁ - the total dry mass of the sample

 M_2 - particle size greater than 0.063 mm after washing

P - sieved material left in the bottom pan

4.2.3 TAM calorimetric test

The behavior of the matrix, mainly the setting time and curing time, and the level of hydration, is determined by a calorimetric test. The objective of the calorimetry machine is to level out the temperature of the heat emitted by samples, and calculate the energy produced. The samples are matched to an individual mass of reference, m_{ref} , with a fixed specific heat capacity, c. This is then recorded at what time the energy is released and the amount of energy (Wadsö, 2005).



Figure 18: TAM apparatus

When executing the calorimetric test, the group calculated the precise mass of each test specimen using the formula for specific heat capacity.

Formula for specific heat capacity is (The Engineering Toolbox, n.d.):

$$c = \frac{Q}{m * \Delta \mathrm{T}}$$

Where:

- c specific heat capacity, J/(kgK)
- m weight of mass, kg
- ΔT rate of temperature change, K

Q - energy, J

The following values for heat capacity, provided by one of the counsellors, were used to calculate the mass of reference for the ampoules:

Heat Capacity	Value(J/Kg*K)
C _{slag}	1,05
C _{FA}	0,72
Cpw	4,18
C _{Na2SiO3}	0,92
C _{NaOH}	0,7
Скон	1,174

Table 12: Values of heat capacity

The group then measured the water for the reference ampules, and mixed the cement paste for the geopolymer in the sample ampules, sealed them and started the TAM test. The mass including the ampules were calculated to be around 6 g total of total mass each to simplify the test routine.

The TAM process included a total of 11 different geopolymer modifications and was processing information for 72 hours. The group then got the results from the computer connected to the chamber, in diagram form. The diagrams illustrated heat production over time.
As the figure below shows, **P** reflects the **rate** of the process, **Q** reflects the **extent** of the process.



Figure 19: Rate vs. extent of the process (Wadsö, 2005)

4.2.4 Initial and final setting time of Cement paste, VICAT

With the use of the automatic Vicat machine, "Vicatronic Automatic Vicat Recording Apparatus", the initial and final setting time of the geopolymer paste gets determinate.



Figure 20: Vicatronic Automatic Vicat Recording Apparatus (MATEST, n.d.)

By following the test procedure described in *NS-EN 196-3*, the requirement for the room is at $(20^{\circ}C \pm 2)$, and not less than 90% relative humidity. The probe was sat to free fall, and the following parameters was sat during the test (MATEST, n.d.):

- Interval time: 5 min
- Total time: 420 min
- Calibration: 0 mm and 40 mm

4.2.5 Slump test

Following the procedure described in *HB R210, 412 Konsistens; synkmål*, the group determined the consistency of the fresh geopolymer concrete. The slump test measures the distance between the top of the slump cone and the highest point of the concrete after the cone has been lifted and moved aside, as shown in Figure 21.

The base is moisturized, and the cone is filled with three approximately equally thick layers while held against the base. Each layer is compacted with 25 impacts of a steel rod before the next layer is filled. After the third layer is compacted, the concrete is refilled so that it is level with the surface of the cone.



The group has performed the slump test, and the measurements were derived. The slump test is shown in Figure 22 below.



Figure 22: Slump flow in the creation

4.2.6 Slump flow test

Simultaneously as conducting the slump test, the group also measured the spread of the geopolymer mixture. This is done according to the procedure described in *NS-EN 12350-8: Testing fresh concrete, Part 8: Self-compacting concrete – Slump-flow test.* The GPC developed by the group is classified as self-compacting concrete, SCC, due to the addition of superplasticizer.



Figure 23: Flow spread (Standard Norge, 2019)

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The slump-flow is the mean of d_1 and d_2 , expressed to the nearest 10 mm, given by the formula (Standard Norge, 2019):

$$SF = \frac{d_1 + d_2}{2}$$

Where:

SF - is the slump-flow; mm

d₁ - is the largest diameter of flow spread; mm

 d_2 - is the flow spread at 90° to d_1 ; mm

Chapter 8 Prøvingsresultat formel og tekst from NS-EN 12350-5:2019 is reproduced by B23B02 in the thesis "Geopolymer Concrete: A future-oriented concrete" under license from Standard Online AS May 2023. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. See www.standard.no

4.2.7 Air content

When determining the air content in the GPC, method *415 "Luftinnhold, trykkmetoden"*, described in *HB R210* by Statens Vegvesen is followed. This is carried out using a calibrated air meter shown in Figure 24.



Figure 24: Air content measurement tool, controlling air content of fresh concrete (Vegdirektoratet, 2014)

During the procedure, three layers of concrete are added to the container, with each layer being worked on with 25 impacts from a steel rod. Excess material is removed from the container, and when the top part is assembled, ball valves are opened. Water is added to one of the ball valves until it flows out of the opposing valve, free from air bubbles. The gauge is held slightly inclined to allow air under the lid to escape, and water is added as needed.

The adjustment valve is closed before the pressure is pumped up and the gauge is adjusted to zero. The ball valves are then closed, and the air content of the GPC is read when the gauge has stabilized. The air content is expressed in percentage with one decimal (Vegdirektoratet, 2014).

4.2.8 Density

In test method *HB 210, 422 Densitet*, the density of hardened concrete is determined after water immersion. Due to ambient curing and heat curing of the geopolymer concrete, the group has chosen to determine the dry density by measuring the mass and volume. Density, ρ , is defined as the ratio of the mass of a given concrete sample to its volume and is expressed according to the Statens Vegvesen (Vegdirektoratet, 2014):

$$\rho = \frac{m1}{V}$$
 , rounded to the nearest 10kg/m³

ho - density, (kg/m³) m1 - weight, (kg) V - volume, (m³)

4.2.9 Compressive strength test

Test method 1, from 14.631 in HB-R210 Laboratorieundersøkelser, describes the procedure the group conducts for compressive strength testing of cast specimens. The purpose of this test method is to determine the compressive strength (f_c) of the relevant test specimens.

The following guidelines and standards are adhered to during the execution of compressive strength testing:

• NS-EN 12390-3: Testing hardened concrete - Part 3: Compressive strength of test specimens.

• NS-EN 12390-1: Testing hardened concrete - Part 1: Shape, dimensions, and other requirements for test specimens and molds.

Compressive strength describes the concrete's ability to resist stresses that lead to cracking and/or deformation.

In the testing procedure, the relevant test specimens are removed from the water bath/molding container at least half an hour prior to testing and dried of free surface water. Subsequently, the dry density and dimensions of the test specimens are measured using a sliding caliper.

It is important to verify the angle between the side edges of the pressure surface using a square. The compression testing is performed while the specimens are surface-moist and are placed centrally in the compression testing apparatus.

The specimen is continuously subjected to centrally applied load with a pressure increase of $0.6\pm0.2 \frac{MPa}{s}$, according to *NS-EN 3668*. The compressive strength per specimen is then recorded. This procedure is repeated after 1, 7, and 28 days to document the compressive strength development of the relevant concrete.

For cast test specimens, the compressive surface area is calculated based on the nominal dimensions of the mold if the measured dimensions of the test specimen do not deviate by more than \pm 1.0%. The compressive strength is reported in MPa to one decimal place.

The compressive strength (f_c) of concrete is expressed in MPa, to one decimal place and calculated using the formula (Vegdirektoratet, 2014):

$$f_c = \frac{F}{a}$$

Where:

a - the pressure surface of the sample, mm²

F - applied centric force, N

4.2.10 Rapid Chloride permeability test



Figure 25: Setup of the actual test, RCPT

Figure 26: Setup of the test, RCPT (Nordtest, 1999)

According to *NT Build 492, Rapid Chloride permeability test (RCPT)* is conducted to test the resistance of chloride penetration, thus stating a life expectancy of a concrete sample. The concrete sample is either casted in a cylindrical shape or core drilled with a diameter of 100 mm, and at least 160 mm of thickness if casted and 100 mm if drilled. The cylinder is then cut to 50 mm thickness and epoxy is applied on the side walls of the cylinder. This is to allow the liquids to enter only at the ends of the cylinder. A rubber sleeve is then mounted in the cylinder, so the edge is flush with the surface of the sample.

Catholyte and anolyte:

- The Catholyte consists of 10% sodium chloride (NaCl) solution (100 g NaCl in 900 g distilled water).
- The Anolyte consists of 0.3 N NaOH solution (12 g NaOH in 1 l distilled water), Appendix 30.
 The solutions are then stored in set temperature at 20-25°C.

The cathode is placed on a plastic support inside a plastic box. The sample with the sleeve, is then submerged in the catholyte and placed on the 3D-printed plastic support. The anolyte is then poured inside the rubber sleeve, with a cylindrical casing in PVC. The

cathode and anode are then hooked up to a DC voltage, with a constant 10 V and a current

of 0.22 Ah for 24 hours as seen in the table below.

Initial current I _{30V} (with 30 V) (mA)	Applied voltage U (after adjustment) (V)	Possible new initial current I ₀ (mA)	Test duration <i>t</i> (hour)
<i>l</i> ₀ < 5	60	<i>I</i> ₀ < 10	96
5 ≤ <i>l</i> ₀ < 10	60	10 ≤ <i>I</i> ₀ < 20	48
10 ≤ <i>I</i> ₀ < 15	60	$20 \le I_0 < 30$	24
15 ≤ <i>I</i> ₀ < 20	50	25 ≤ <i>I</i> ₀ < 35	24
$20 \le I_0 < 30$	40	25 ≤ <i>I</i> ₀ < 40	24
$30 \le I_0 < 40$	35	35 ≤ <i>I</i> ₀ < 50	24
$40 \le I_0 < 60$	30	$40 \le I_0 < 60$	24
$60 \le I_0 < 90$	25	50 ≤ <i>I</i> ₀ < 75	24
90 ≤ <i>l</i> ₀ < 120	20	60 ≤ <i>I</i> ₀ < 80	24
120 ≤ <i>I</i> ₀ < 180	15	60 ≤ <i>I</i> ₀ < 90	24
$180 \le I_0 < 360$	10	60 ≤ <i>I</i> ₀ < 120	24
<i>I</i> ₀ ≥ 360	10	<i>I</i> ₀ ≥ 120	6

Table 1. Test voltage and duration for concrete specimen with normal binder content.

Table 13: Test voltage and duration ((Nordtest, 1999)

The specimens are then subjected to two liquids, the anolyte and the catholyte, namely NaCl and NaOH over the period of 24 hours. After the 24 hours period, the group cut, cleans and surface drying the sample, and wait 15 minutes before the silver nitrate is sprayed on to the fresh center cut of the cylinder. The silver nitrate (AgNO₃) will leave a bright line of white color in the geopolymer, that specifies where the chloride has penetrated the sample. This will state the level of penetration, and at what level the concrete cover should be, to sufficiently protect metallic reinforcements. The figure below shows the procedure of how to measure the chloride penetration. The group measures the depths from X_{d1} to X_{d7} .



Figure 27: Illustration of measurement of chloride penetration depths (Nordtest, 1999)

The following picture shows the specimen used in the test starting to show the white line that indicated the chloride penetration depth:



Figure 28: Chloride penetration depth starts to get visible after using the AgNO₃

The non-steady-state migration coefficient, D_{nssm} then gets determined from following formula:

$$D_{nssm} = 0.0239 * \frac{(273+T)*L}{(U-2)*t} * \left(x_d - 0.0238 * \sqrt{\frac{(273+T)\cdot L \cdot x_d}{U-2}} \right)$$

Where:

 $D_{nssm}~$ - Non-steady-state-migration coefficient, $*10^{\text{-}12}~m^2/s$

- U Absolute value of the external potential applied between the two electrodes, V
- T Average value of the initial and final temperatures in the anolyte, ^oC
- L Thickness of specimen, mm
- x_d Average value of penetration depths, mm
- t Test duration, hours

As there still are no acceptance criteria for the chloride diffusion coefficient, it has been developed a suggested set of values as a guideline on the chloride migration coefficient, D_{nssm}, measured by the RCM test. These values are based on Tang and Nilsson's development in 1992, which was standardized by NORD's NT Build 492 in 1999. The following values are then a suggestion based on the two latter developments, developed in 2013 (Dhanya, Santhanam, Pillai, & Gettu, 2014, p. 7).

Category	Wenner Resistivity (k Ω cm)	Total charge passed (Coulombs)	Non-steady state migration coefficient x 10 ⁻¹² (m ² /s)
Excellent	> 50	<1000	<8
Good	10-50	1000-2000	8-16
Moderate	10-50	2000-4000	16-24
Poor	<10	>4000	>24

Table 14: Chloride resistance classification criteria for concrete (Dhanya, Santhanam, Pillai, & Gettu, 2014, p. 13)

4.2.11 The carbonation depth

Before testing of carbonation depth, or determining the carbonation front, the concrete specimen is intended to be stored in a concentrated CO_2 -level using the *Sanyo Model MCO-17AIC Laboratory Incubator*. The storage period in CO_2 was set at 14 days, with a CO_2 -level of approximately 5% at a temperature of 30°C. This is done to accelerate the carbonation of the concrete specimen to obtain a usable result.

Due to a leakage in the mentioned incubator, time was running out and the group decided on a backup solution: to calculate the amount of dry ice, CO_2 in solid form, that could replace manually controlled CO_2 -level supplied through the ventilation using the ideal gas law and store the specimens in a new incubator without ventilation, the *Votsch VCL 4003*.

New parameters for storing the concrete specimen are: 14 days, approximately 5% CO₂-level, 20% humidity, and a temperature of 20°C.

Calculation of the amount of CO₂-equivalent to 5% in the new incubator without a CO₂gas supply vent using the ideal gas law:

$$pV = nRT$$

Where:

p - pressure, 101 kPa

V - Volume, liter/m³

n - amount of substance, mol

R - gas constant, R=0.082058 (L*atm)/(K*mol)

T - temperature, K

Once the 14 days of carbonation was complete, the specimens were removed from the equipment. After splitting the cubes, it subjected to a pH indicator, phenolphthalein. The pH indicator consisted of 1% of phenolphthalein ($C_{20}H_{14}O_4$), in water. Then the indicator was sprayed on the split surface of the specimen – generating a bright purple colored area to draw a line between carbonated and non-carbonated GPC. Then the group measured the depth in following method (Atiş, 2003):



Figure 30: Accelerated Carbonation Measuring Principle, (Atiş, 2003)



Figure 29: The carbonated surface

Carbonation depth D is calculated by:

$$D = \frac{A1 + A2 + B1 + B2 + C1 + C2}{6}$$

Where:

D - the average of the 6 measured zones.

There are very few standardized tests that deal with accelerated carbonation testing and how results should be documented. Therefore, the group chooses to compare results from their own conducted test to documented test results in (Atiş, 2003), focusing on CEM-II/A-S 42.5N due to its similarities with the self-developed geopolymer recipe (Atiş, 2003).

5 Results

When reviewing the properties of GP5.2, the group primarily focus on the oven-hardened batch, due to the significant difference in hardened properties based on literature study. The results are discussed in the following subsections.

5.1 Geopolymer

The group has been developing in total 11 recipes, although, it was one recipe that was used for the rest of the research, Table 9. This recipe has been tested on different aspects, both fresh and cured state. The durability has also been tested with chloride and carbonation tests. The table below, Table 15, shows the results of the recipe the group chose. The GP5.2 was made in two batches, 22.03.23.

GP5.2 results (cured in oven, 80°C, 20 hours)					
	Fresh properties				
Test procedure	Value	Appendix/table number			
L/GB ratio	0,55				
Slump	260 <i>mm</i>				
Flow	555 <i>mm</i>				
Temperature	34,3°C				
ТАМ	Appendix 20-24				
Vicat	Initial setting time: 2h Final setting time: 3h	Appendix 16			

Air content	2,9%		
Aggregate size	0-8mm and 8-16mm	Theory chapter 2.3.2 aggregate size	
Aggregate	Sand = 0,25%	Appendix 29	
watercontent	Gravel = 0%		
Aggregate grain	Gravel fraction:	Sieve curves are presented in:	
grading	<8mm = 6%	Appendix 28 for gravel	
	<10mm = 18%	Appendix 27 for sand	
	<12,5mm = 26%		
	<16mm = 33%		
	<20mm = 16%		
	<25mm = 0%		
	<25mm = 0%		
	Sand fraction:		
	<0,125mm = 5%		
	<0,25mm = 12%		
	<0,5mm = 25%		
	<1mm = 23%		
	<2mm = 15%		
	<4mm = 8%		
	<8mm = 8%		
	>8mm = 3%		

Table 15: GP5.2 results

When investigating the fresh properties of the geopolymer concrete, the group used standardized test methods based on those used for traditional concrete. This approach may result in unknown discrepancies, as there are no standardized methods for testing geopolymer concrete at this moment. However, it is assumed that any discrepancies are not significant. By solely examining the mass ratio of GP5.2, its properties correspond to those of a concrete classified as B30, M60 (Maage, 2015, p. 156). The characteristic strength of this concrete is 30 MPa, which is significantly lower than the strength achieved by GP5.2.

The workability properties are crucial when investigating the fresh properties of concrete, including its ability to flow and fill forms and molds. In the testing of GP5.2, the slump test result is S5, as shown in Table 4, and the flow test results in SF1, as shown in Table 5. These results indicate that GP5.2 achieves good workability properties.

As seen from the Vicat test results in Appendix 16, the initial setting time of GP5.2 is 2 hours, and the final setting time is 3 hours. This is due to the high temperature of GP5.2 during casting. When curing GP5.2 in an oven, there is a significant difference in the development of early high strength compared to GP5.2 cured in ambient environment.

When evaluating Isothermal Calorimetry results, the group examine the relationship between the rate (P) and extent (Q) of the process. During the first round of TAM testing, the group selected GP1.2 based on the best result with the highest Q-value and a simultaneously high but delayed P-value, as referred to in 4.2.3 TAM calorimetric test, shown in Appendix 5. Through a modified recipe based on GP1.2, to achieve higher early strength, the group settled with recipe GP5.2 – with a lower L/GB ratio and included SP, which satisfies the desired properties, Appendix 8.

In regular concrete, the air content without L-material is typically around 2%. However, it is common practice to increase the air content to $5 \pm 1.5\%$ to protect the concrete from degradation due to frost exposure (Maage, 2015, p. 111). Based on this, the group concluded that GP5.2 with an air content of 2.4% satisfies the typical air content, but air-entraining agents may be necessary to increase the frost resistance of the concrete.

When developing geopolymer, hardened properties are also an important factor that affects their applications, and the results of tests on these properties will be discussed in the next section.

Hardened properties, (Cured in oven 80°C, 20hrs)					
Cube specification	Dry Density	Value			
1 day, cube 1 23.03.23	2365,3 $\frac{kg}{m^3}$	81,4 $\frac{N}{mm^2}$			
1 day, cube 2 23.03.23	2393,1 $\frac{kg}{m^3}$	84,5 $\frac{N}{mm^2}$			
7 days, cube 1 29.03.23	2371,0 $\frac{kg}{m^3}$	91,3 $\frac{N}{mm^2}$			
7 days, cube 2 29.03.23	2388,2 $\frac{kg}{m^3}$	88,3 $\frac{N}{mm^2}$			
28 days, cube 1 19.04.23	2325,6 $\frac{kg}{m^3}$	90,2 $\frac{N}{mm^2}$			
28 days, cube 2 19.04.23	2382,4 $\frac{kg}{m^3}$	90,3 $\frac{N}{mm^2}$			
Rapid Chloride Migration Test	D _{nssm} , non-steady-state m	igration coefficient	Appendix number		
Cylinder 1, 100mm diameter, 50,6mm height	15,39 * 10 ⁻	$\frac{m^2}{s}$	30		

Rapid Carbonation Test	Dry Density	Carbonation depth	Appendix number
28 days, cube 1 (CO ₂)	2375,3 $\frac{kg}{m^3}$	2,946mm	31
28 days, cube 2 (CO ₂)	2376,5 $\frac{kg}{m^3}$	4,833mm	31

Table 16: Hardened properties

As shown in Figure 31 and Table 16, the early strength of GP5.2, when cured in an oven, is relatively high, but the strength development is very stagnant. As seen in Appendix 26, the strength of GP5.2 concrete after 1 day cured in ambient environment was at the lowest, 12.9 MPa, while the GP5.2 concrete cured in an oven was at the lowest, 81.4 MPa. This is because the hydration rate strongly depends on the temperature level, 2.3.3 Concrete mixing and curing, and the change in particle size distribution of FA at elevated temperatures, 2.2.2 Geopolymer as a binder.

The rate of hardening compared of GP5.2 compared to CEM – II/A-S 42.5R (Cemmac, n.d.):



Figure 31: Hardening process of GP5.2 and CEMII/A-S 42.5 R

The ability of GP5.2 to resist chloride penetration is shown as a D_{nssm} value, calculated to be 15.39 * 10⁻¹² m²/s, Appendix 30, and its average chloride penetration depth of x_d of 12.4 mm. This is rated as a "good" result which indicates that GP5.2 may be a suitable concrete for demanding exposure classes, Table 14. This is highly desirable as the "Modellageret", which the module wall mentioned in, 5.2, was intended for – are exposed to airborne chlorides from seawater in Glomma.

During the carbonation depth test on GP5.2, carbonation depths were measured on 2 specimens. One of the specimens achieved a calculated depth (D) of 2.95 mm, while the other achieved a depth of 4.83 mm, Appendix 31 and Figure 29. By comparing these results from, Table 17, below, the group can conclude that GP5.2's worst results for carbonation resistance is better than mix designs M0-M4 (Atiş, 2003), RH=65%, 20°C, based on the fact that the test was carried out under ideal conditions. Comparison was also made against the same mix design, but at RH=100%. Here, GP5.2 performs better than M0-M3 at its worst result, but only worse than M4 with its best result. This suggests that higher RH results in better resistance to carbonation penetration.

Table 5. Accelerated carbonation depth (mm) of concrete cured at 100% RH with 20 $^\circ\mathrm{C}$

Table 4. Accelerated carbonation depth (mm) of concrete cured at 65% RH with 20 $^\circ\text{C}$

lix Name	3 days	7 days	28 days	3 months	Mix name	3 days	7 days	28 days
M0	9.10	7.40	4.50	3.30	MO	9.60	8.50	6.50
M1	13.30	10.90	6.50	4.60	M1	14.10	12.80	10.40
M2	13.80	11.70	7.30	5.00	M2	14.90	13.40	11.30
M3	8.70	8.40	3.20	1.80	M3	10.30	9.80	6.30
M4	9.60	7.50	2.10	1.60	M4	9.80	9.30	5.70

Table 17: Accelerated carbonation depth (mm) of comparable concrete (Atis, 2003)

It was noted that the geopolymer concrete had a strong green color upon demolding of the ambient environment – cured samples. The concrete appeared to be somewhat darker than traditional concrete some days after demolding, and there was a significant difference in how easily the concrete released from the plastic and steel molds. Based on the observation in Figure 32 and Figure 33, a substantial amount of concrete remained firmly adhered to the steel mold. This can indicate that the adhesion properties of the GPC to steel is positively affected.



Figure 32: Photo of standard steel molding, showing how the GPC sticks to the steel



Figure 33: Photo of plastic molding used for the chloride migration test cylinders



Figure 34: Failure mode of GP5.2



Figure 35: Photo after demolding GP5.2 recipe

5.2 Potential use of Geopolymer concrete, BIM review

The purpose of this chapter is to discuss the potential uses for the GPC that the group has identified.

Table 16 presents the compressive strength result of GP5.2 cured in oven, 1 day after mixing, that indicated 81.4 MPa and 84.5 MPa. When examining the setting process of GP5.2 from Appendix 16, which describes the initial and final setting time, it can be concluded that the concrete cures relatively quickly. Using these two parameters, the group has considered that the geopolymer recipe could be suitable to produce precasted elements.

In this context, the group has a proposal of a potential non-structural outer wall that is meant for FMV-Vest's "Modellageret". The group's proposal is that a reinforced

demountable module wall can be used, due to the uncertain future of the building after the next 10 years – caused by a new regulatory plan. The concept behind the module wall is that after it has served its original purpose, it can be reused for a completely different purpose *or* as a new wall in a new building



Figure 36: "Modellageret" today

- to reduce the CO₂-emission regarding the rehabilitation of the "Modellageret".

After considering the original intended purpose of the module wall, the group has discussed various ways the wall could be reused for. Initially, the group has evaluated various possibilities where landscape architects potentially could reuse the wall for flower beds, separation functions in the landscape or other detail features. The idea is that the



Figure 37: Realistic impression image of the module wall

module shouldn't be demolished, but rather used in their original form or adaptation. The main objective for the reuse is to have an aesthetically pleasing appearance, where the mechanical properties are less relevant.

Through recommended further research and development of the module wall, the group sees opportunities for such reusable elements. This would mean that the wall's lifespan should be increased from the current requirement of 50 years for precasted elements (Arkin, 2023).

To achieve this goal, the focus should be on durability. As mentioned in theoretical 2.5 Durability and reinforcement, the cover thickness is crucial for reinforcement corrosion, which is again the most common damage mechanism for concrete structures.

The concrete cover and reinforcement must therefore be calculated and justified according to the intended purpose of the module wall.



Figure 38: Ratio between Concrete cover and W/C (Maage, 2015, p. 220)

After evaluating the condition of the wall, it can be repurposed in another location where the demands are equal or lower. As the module wall in this case is a non-load-bearing exterior wall that will be exposed to airborne chlorides and located near the coast, the group assume that the concrete cover in the construction could be dimensioned according

to exposure class XS1. According to *NS-EN* 1992-1-1, this entails a covering of 50 mm. Since the wall is non-load-bearing, we would recommend minimum reinforcement, like described in *NS-EN* 1992-1-1, to minimize cracking and prevent brittle failure, 2.5.2 Minimum reinforcement. Due to the lack of standards in geopolymer concrete, the calculation of reinforcement and the concrete cover is difficult and recommended for further





work. The dimensions (length x height x thickness) are something that must be specified in an order regarding the primary purpose of the wall. Our proposal for the module wall that

will be used in "Modellageret", is a thickness of minimum 200 mm due to the concrete cover. The length and the height must be specified *after* architectural measurements of "Modellageret", and before the rehabilitation is initiated. See Figure 39 for a proposed cross-section of the module wall.

Figure 40 is an exclusively *proposal* drawing for the reinforced demountable module wall. This reinforcement placement is based on an image of a precast wall made by Heidelberg Materials Prefab Norge, Appendix 35. Figure 40 shows the proposal of the design of the reinforcement placement, but the placement must be designed according to the intended purpose of the wall, the anchoring and the forces that will be inflicted on the wall.



Figure 40: Reinforcement conceptual drawing

During the design of such an element, considerations must be given to anchoring and its structural design, dimension, production, transportation, installation, building physics like isolation, and more. The group has considered that the module wall could be anchored with a bolted solution, but this is a proposal for further work. Factors that are mentioned above must be considered when dimensioning a prefabricated wall, so this is just a *concept*, and the points above are recommended for further development and research. Finally, an existing IFC file, Figure 41, has been modified to show the concept of the module wall integrated into "Modellageret".



Figure 41: "Modellageret" with one wall replaced with GPC module wall

5.3 LCA Study

Due to the group's desire to reduce CO_2 -emissions from the construction industry, the group conducted an LCA study of a self-developed geopolymer concrete and compared it to a concrete type with similar mass ratio. The task was to conduct an LCA study on the processes and data included in A1 and A3:

A1: Extraction of raw materials

A3: Product

This essentially involves the entire production process of a product, and this is precisely where the group wanted to reduce the environmental impact. Phase A2 transport was not considered as the location of raw material production varies greatly. Transport is a major environmental impact, which would give a false impression of both GP5.2 and CEM-II based on extraction of raw materials and production (Statistisk sentralbyrå, 2019).

The group decided to compare GP5.2 to a traditional concrete mix: CEM-II/A-S 42.5N based on its relatively similar mass ratio and the content of GGBFS. Table 18 below describes the cement-slag combination, and Table 19 represents the recipe that we compared against:

	Constituents in standard composition of the tested cements, m%				
Cement types	Main				
	Clinkers	GGBS	Fly ash	Gypsum	
CEM I 42,5 N	95-100	0	0	5	
CEM II/A-S 42,5 N	<mark>85</mark> –94	<mark>15</mark> (6–20)	0	5	
CEM II/B-S 42,5 R	65–79	20 (21-35)	0	5	
CEM III/A 32,5 N	35-64	60 (36-65)	0	5	
CEM III/B 32,5 N-S	20-34	75 (66-80)	0	5	
CEM V/A (S-V) 32,5 N	40-64	30 (18-30)	30 (18-30)	5	

TABLE 4: Standard composition of the tested cements according to EN 197-1:2000, m%.

Table 18: Cement-slag ratio of the compared recipe (Kopecskó & Balázs, 2017)

	w/c	= 0.35	w/c :	= 0.45	w/c =	= 0.55
Mixture	NAE	AE	NAE	AE	NAE	AE
	(kg/m ³)					
Cement	440	440	440	440	440	440
water $(w/c = 0.35)$	154	154	198	198	242	242
River sand 0-1 mm (25 m%)	451	451	425	424	408	396
River sand 0–4 mm (20 m%)	361	361	340	339	327	317
River gravel 4–8 mm (55 m%)	993	993	934	932	898	871
Superplasticizer (1.15 m%)	5.06	5.06	1.76	1.76	0	0
AE (0.35 m%)	_	1.54	_	1.54	_	1.54
Sum	2404.06	2405.60	2338.76	2336.30	2315.00	2267.54

Table 19: The recipe used for the LCA study (Kopecskó & Balázs, 2017)

This LCA study is a simplified approach to the GP5.2 recipe that the group has developed, Table 9, and the database from SimaPro has been used as a reference in the analysis. The processes that are excluded from the database of SimaPro are selected after reviewing EPDs and web sourced information. The used energy consumption properties can be found in the table below.

Materials	Energy used in production	Sources
CEM II/A-S 42,5 N with 15% Ground Granulated Blast- Furnace Slag	0,85 kWh for cement and 0,00705 kWh slag for a total of 1kg mixed CEM II/A-S	(Cyr & Patapy, 2016, p. 5) (The International EPD System, 2019, p. 10)
GGBS	0,047 kWh/kg	(The International EPD System, 2019, p. 10)
Sodium Silicate solid	1,5 kWh/kg	(Ramagiri, Chintha, Bandlamudi, Maeijer, & Kar, 2021)
Potassium hydroxide	4,81 kWh/kg	(Jiang, et al., 2021)

Sika Viscocrete	4,54 kWh/kg	(European Federation of Concrete Admixtures Associations , 2021)
FA	0 kWh/kg	Waste product
Water	0 kWh/kg	
Aggregate 0-8	0,00226 kWh/kg and 0,0836 MJ/kgn (Diesel)	(Statens vegvesen, 2009)
Aggregate 0-16	0,00226 kWh/kg and 0,0836 MJ/kg (Diesel)	(Statens vegvesen, 2009)
Electricity from Mixing	62,4 kWh/m3	Info from Heidelberg Materials
Electricity from heat chamber (80°C)	15,55 kWh/m3	Heat chamber, Østfold university College
Energy of Diesel when mixing	152,3 MJ/kg	Info from Heidelberg Materials

Table 20: Key values used in the LCA study

CEM-II /A-S 42.5N Concrete:



Figure 42: CEM-II /A-S 42.5N Concrete life cycle network

As the LCA chain in Figure 42, shows, the production of OPC itself constitutes the majority of the CO₂-emissions generated during the production of traditional concrete – a whopping 92.6% of the climate impact is accounted for in this category. The group anticipated that the environmental impact from OPC would be high, and it is precisely this category that is desired to reduce. As demonstrated in Appendix 33, the production of 1 m³ of OPC alone accounts for 386 kg CO₂-equivalents, exclusively from GWP100 Fossil.

GP5.2 – geopolymer concrete:



Figure 43: GP5.2 life cycle network

When conducting an LCA on the self-developed GP5.2, it was found that the production of the binders, Sodium Silicate and Potassium Hydroxide, accounts for 72.9% of the climate impact of 1 m³ of produced geopolymer. This is due to the high energy demand required to manufacture these chemical components.

Comparison

When directly comparing the production of GP5.2 and CEM-II/A-S 42,5N, the group focuses on two categories, with a primary emphasis on CO₂-emissions. CO₂-equivalents and MJ energy consumption.



Figure 44: Energy Consumption

As clearly shown in Figure 44 and Figure 45, there is imbalance in the comparison of CO_2 equivalents and MJ energy consumption in the production of 1 m³ of GP5.2 and CEM-II/A-S 42.5N.

The LCA study reveals that the production of GP5.2 is considerably more energy-intense, consuming 5349.401 MJ, compared to the production of CEM-II /A-S 42.5N, which uses 4742.359 MJ, with the difference amounting to 12.8% more than CEM-II/A-S 42.5N based on the values calculated in Appendix 32.

However, there is a significant difference in the amount of CO₂-equivalents between the production of GP5.2 and CEM-II/A-S 42.5N.

As shown in Figure 45, the GWP100 total level of GP5.2 is calculated to be approximately 56% of the production of CEM-II/A-S 42.5N. This represents a reduction of 44%, which is a significant difference if the production quantity is scaled up. The total amount of CO₂-equivalents in the production of CEM-II/A-S 42.5N is 386.811 kg/m³ compared to GP5.2s considerably lower total amount of 216.890 kg/m³.



When producing these types of concrete, the goal of reducing the CO_2 -level with GP5.2 has been achieved. However, there is a very high energy consumption in the production of the chemically composed alkaline activators that replace water in traditional concrete.

5.4 Sources of error and discussion

Test methods and results

- The purpose of the thesis is to compare traditional concrete and GPC, and methods are based on traditional standards, and not GPC specific. It is therefore based on the fact that the available standards on GPC are scarce.
- Due to the change of carbonation cabinet and uncertainties regarding the CO₂concentration calculated based on the ideal gas law, the group cannot legitimize the rate of carbonation from this test. The group acknowledges that the ideal gas law represents an idealized model and may not accurately reflect the behaviour of realworld gases. Nevertheless, it is reasonable to deduce that the rapid carbonation test yields genuine results, given that the chamber is sealed hermetically, and the ideal gas law equation has been computed accurately.
- Comparison of properties between GPC and traditional concrete is based solely on literature and standards. This demands extensive testing and empirical research to develop characteristic attributes. Despite the lack of time and the extent of the testing conducted in this thesis, the mentioned results could be an indication.
- Human factors are inevitable and should always be considered.

Potential use of Geopolymer concrete, BIM review

- The reinforcement and the anchoring of the module wall was not dimensioned nor designed, since the available standards on GPC are scarce. Due to the fact that this thesis was restricted to examining GPC properties, it was deemed prudent to recommend a separate problem statement dedicated to dimensioning.

LCA study

- The group has based the LCA study on the limited software library provided by SimaPro. This can lead to positive or negative fluctuations on the results.
- The energy consumption is another aspect that is considerably variable, and based upon web sourced information. Throughout the LCA study, the group noticed that the alkali solutions had a significantly high energy consumption due to electrolysis. Based on the theory gathered regarding GPC, it was surprising that the energy consumption was rated at such levels.

6 Conclusion

The thesis started with the following problem statement:

The purpose of this thesis is to investigate the durability and properties of a self-developed geopolymer concrete, as well as comparing the CO_2 -emissions from the production phase versus traditional concrete – with the goal of promoting emission awareness in the construction and engineering industry using BIM and LCA.

In conclusion, the self-developed GPC indicated good fresh and hardened properties through testing procedures. The results contribute to conclude that the durability properties are at least as good as traditional concrete, even surpassing on some attributes – given the optimal curing temperature. Through the rapid carbonation and chloride migration test, and with the correct rebar cover, the GPC would overcome the dimensioning lifespan of 50 years. Through both the attribute testing and BIM review, the group additionally concluded that the self-developed concrete is suitable to be utilized as a reusable and detachable module wall.

The LCA study justified the goal of decreasing CO₂-emissions in the production phase of GPC, compared to traditional concrete by almost fifty percent, thus higher energy consumption. By utilizing BIM and incorporation of LCA results, the project owner can differentiate between several construction materials, helping to decide which – based upon emissions. "Modellageret" is such a project that could benefit of this.

All things considered; GPC demonstrates exquisite properties regarding especially hardened properties, promising to excel traditional concrete while significantly reducing CO₂-emissions, making it an ideal choice for future oriented constructions.

7. Suggestions for further work

During this thesis we discovered several challenges and uncertainties regarding development of the product. The following problem statements could be interesting to review to optimize the potential of the future oriented GPC.

Geopolymer concrete

- It is highly needed to research on standardizing properties on GPC, as it would be interesting to develop a comprehensive comparison to traditional concrete.
- It's recommended to research available binders due to the uncertainties regarding use of FA from coal powerplants assumingly shutting down in the future. Could a transition to ash from volcanoes, mine tailing, rice husk ash, or other binders prove to have similar or better properties than FA?
- When examining the extremal points regarding the carbonation and chloride resistance, it was observed that they could be in relation to the aggregates.
 Consequently, it would be interesting to test other and different aggregate sizes.
 Would this differ due to usage of SF, as it could decrease the interfacial transition zone?

Potential use of Geopolymer concrete, BIM review

- The dimensioning and designing of GPC constructions in Europe as we speak, is
 practically not feasible, due to the lack of standards. This challenge the use of GPC
 in actual projects, as the group experienced this exact problem, when trying to
 calculate the minimum reinforcement because this is exclusively related to
 traditional concrete.
- To promote reusability, it is essential to extend the lifespan of concrete structures. Furthermore, in order to achieve the goal of reusability, it is worthy to explore various anchoring options and reinforcement placements for precast concrete elements. Hence bolted anchorage has been suggested as a means of making the concrete elements dismountable, a prerequisite for its complete reusability. The design of these aforementioned options would generate a highly interesting research problem.

LCA study

- After the LCA study, it was noticed that the alkali solutions had a significantly high energy consumption due to electrolysis. Is it possible to substitute the present alkaline solutions with a less energy intense product, or decrease the L/GB ratio to reduce amount of alkaline solutions, with similar or better properties?
- Based on the experience from utilizing the LCA software, it would be appreciated to have optional extensive and comprehensive details, that could further improve the credibility of the results from the LCA study. To gain these details, it would be interesting and advisable to increase the database to accommodate new users of the software. Lastly, this is to empower the message on environmentally consciousness.
8 Reference

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9 Appendix

Appendix 1: 14.02 23 – First recipe of the recipe development; GP1.1, GP1.2, GP2.1, GP2.2, GP3.1, GP3.2, GP4.1 and GP4.2

			Series 14	/2/2023			
	GP	1.1			G	6P1.2	
60FA/40GGBFS	Recipe [g]	L/B	Measured [g]	67FA/33GGBFS	Recipe [g]	L/B	Measured [g]
Fly ash	10,0	0,40	10,00	Fly ash	10,0	0,40	10,00
Slag	6,8		6,80	Slag	6,8		6,80
Na ₂ SiO ₃	4,1		4,10	Na ₂ SiO ₃	4,1		4,10
NaOH	2,7		2,70	кон	2,7		2,70
Extra water	1,7	0,50	1,70	Extra water	1,7	0,50	1,70
SUM	23,6		23,6	SUM	23,6		23,6
	mol/liter				mol/liter		
Molarity NaOH	14			Molarity KOH	14		
			Series 14	/2/2023			r
	GP	2.1			G	iP2.2	
60FA/40SI	Recipe [g]	L/B	Faktisk oppmålt [g]	67FA/33SI	Recipe [g]	L/B	Faktisk oppmålt [g]
Fly ash	16.8	0.40	16.79	Fly ash	16.8	0.40	16.80
Slag	8,4	,	8,40	Slag	8,4	,	8,40
- C	,				,		,
Na ₂ SiO ₃	6,0		6,00	Na ₂ SiO ₃	6,0		6,00
NaOH	4,0		4,00	кон	4,0		4,00
	,		,		,		,
Extra water			0,00	Extra water			0,00
SUM	35,2		35,2	SUM	35,2		35,2
	mol/liter				mol/liter		
Molarity NaOH	14			Molarity KOH	14		
			Series 1/1	2/2023			
	GP	3 1	Jenes 14/	272023	6	D3 2	
60FA/40SI	Recine [g]	1/B	Measured [g]	67FA/33SI	Recine [g]	1 J.2	Measured [g]
Fly ash	10.0	0.40	10.00	Fly ash	10.0	0.40	10.00
Slag	6.8	0,10	6.80	Slag	6.8	0,10	6.80
	- / -				-,-		-,
Na ₂ SiO ₂	4.1		4.10	Na ₂ SiO ₂	4.1		4.10
NaOH	2.7		2.70	кон	2.7		2.70
					-,.		
Extra water	1,7	0,50	1,70	Extra water	1,7	0,50	1,70
SUM	25,3		25,3	SUM	25,3		25,3
	mol/liter				mol/liter		
Molarity NaOH	10			Molarity KOH	10		
			Series 14	2/2023			
	GP ⁴	4.1	Manager and I al	6754/2251	G Desire [s]	1P4.Z	No sourced [-]
60FA/40SI	Kecipe [g]	L/B	Ivieasured [g]	67FA/3351	Kecipe [g]	L/B	Ivieasured [g]
Fly ash	16,8	0,40	16,79	Fly ash	10,8	0,40	16,80
Sidg	0,4		0,40	Siag	0,4		0,40
Na SiO	6.0		6.00	Na SiO	6.0		6.00
	4.0		4.00		4.0		0,00
NaUn	4,0		4,00	KOH	4,0		4,00
Extra water			0.00	Extra water			0.00
SUM	35.2		35.2	SUM	35.2		35.2
	mol/liter		55,2		mol/liter		00,2
Molarity NaOH	10			Molarity KOH	10		
	10				10		

	GP1.	1	GP	1.2	GP2	.1	GP2	.2
Recipe (R)/ actual (A)	R	A	R	A	R	A	R	A
m _{FA}	2,37 <i>g</i>	N/M	2,37g	N/M	2,864 <i>g</i>	N/M	2,864 <i>g</i>	N/M
m _{GGBFS}	1,613 <i>g</i>	N/M	1,613 <i>g</i>	N/M	1,432 <i>g</i>	N/M	1,432 <i>g</i>	N/M
m _{Na2} SiO3	0,972 <i>g</i>	N/M	0,972 <i>g</i>	N/M	1,023 <i>g</i>	N/M	-	N/M
т _{NaOH}	0,640 <i>g</i>	N/M	-	-	0,640 <i>g</i>	N/M	-	N/M
т _{кон}	-	-	0,640 <i>g</i>	N/M	-	-	0,640 <i>g</i>	-
m _{H20}	0,403 <i>g</i>	N/M	0,403 <i>g</i>	N/M	-	N/M	-	N/M
	GP3.	1	GP:	3.2	GP4	.1	GP4	.2
Recipe(R)/ actual(A)	R	А	R	А	R	А	R	А
m _{FA}	2,37 <i>g</i>	N/M	2,37g	N/M	2,8644 <i>g</i>	N/M	2,8644 <i>g</i>	N/M
m _{GGBFS}	1,613 <i>g</i>	N/M	1,613 <i>g</i>	N/M	1,4322 <i>g</i>	N/M	1,4322 <i>g</i>	N/M
m _{Na2} SiO3	0,972 <i>g</i>	N/M	0,972 <i>g</i>	N/M	1,023 <i>g</i>	N/M	1,023 <i>g</i>	N/M
т _{NaOH}	0,640 <i>g</i>	N/M	-	-	0,640 <i>g</i>	N/M	-	-
т _{кон}	-	-	0,640 <i>g</i>	N/M	-	-	0,640 <i>g</i>	N/M
m _{H20}	0,403 <i>g</i>	N/M	0,403 <i>g</i>	N/M	-	-	-	-

Appendix 2: 16.02.23 – Projected recipe mass to TAM-test, (Not measured = N/M)

Appendix 3: 16.02.23 – Total mass in ampoules

	GP1.1	GP1.2	GP2.1	GP2.2	GP3.1	GP3.2	GP4.1	GP4.2
Ampoule nr.	A1	A2	A3	A4	A5	A6	A7	A8
<i>m_{Ampoules}</i>	6,120 <i>g</i>	6,398 <i>g</i>	5,990 <i>g</i>	6,492 <i>g</i>	6,066 <i>g</i>	6,058 <i>g</i>	6,410 <i>g</i>	6,419 <i>g</i>

Appendix 4: 16.02.23 – Mass of reference – water, mref and measured mass

	m _{ref} (water)	Measured mass
GP1.1 – Ampoule B1	1,538 <i>g</i>	1,538 <i>g</i>
GP1.2 – Ampoule B2	1,610 <i>g</i>	1,611 <i>g</i>
GP2.1 – Ampoule B3	1,193 <i>g</i>	1,190 <i>g</i>
GP2.2 – Ampoule B4	1,270 <i>g</i>	1,270 <i>g</i>
GP3.1 – Ampoule B5	1,538 <i>g</i>	1,539 <i>g</i>
GP3.2 – Ampoule B6	1,610 <i>g</i>	1,602 <i>g</i>
GP4.1 – Ampoule B7	1,193 <i>g</i>	1,190 <i>g</i>
GP4.2 – Ampoule B8	1,270 <i>g</i>	1,275 <i>g</i>

Appendix 5: 21.02.23 – Initial TAM-test, GP1.1-GP4.2



Appendix 6: 22.02.23 - Flow of mortar, 15 hits/15 seconds

Recipe	Values from cross measuring	Final flow
GP1.1	$\frac{21cm + 22,5cm}{2}$	21,75 <i>cm</i>
GP1.2	$\frac{22,3cm+22,5cm}{2}$	22,4cm
GP3.1	$\frac{21cm + 22,5cm}{2}$	22,5 <i>cm</i>

CERTIFICATE

TEST NUMBER : 01	DATE OF TEST : 24/02/2023
KIND OF TEST : EN196-3:2005	SPECIMEN TIME : 13:42:00
POINTS MOVE [mm]	START DELAY[m]:
30 4.00	1ST PEN TIME : 13:55:00
24 5.25	SPECIMEN TYPE : C2
18 5.25	WATER CONT.[%]: 50.0
12 5.25	TEMPERATUR[øC]: 22.7
2 5.25	HUMIDITY[%] : 24.2
OPERATOR CODE : CJ	FALL TYPE : FREE
CUSTOMER CODE : GP11	TIME TYPE : FIXED

FINAL SETTING : NO TIME [m] : 5



Appendix 8: 24.02.23 – Creation of GP5.2, modification of GP1.2

GP5.2	Amount, mass
FA	270 <i>g</i>
GGBFS	180 <i>g</i>
Na ₂ SiO ₃	135,7 <i>g</i>
KOH (14M)	89,3 <i>g</i>
Sand	1350 <i>g</i>
H ₂ O	10g
SP viscocrete, Sika® (2% of total binder)	9 <i>g</i>

Appendix 9: 24.02.23 – Flow of mortar, 15 hits/15 seconds

	Flow	Slump
GP5.2	140 <i>mm</i>	33 <i>mm</i>

Appendix 10: 24.02.23 – Compressive strength, 1 day, 50 mm x 50 mm x 50 mm cubes, mortar

Recipe	Applied force	Force per surface area
GP1.1	10,9 <i>kN</i>	$4,36 \ \frac{N}{mm^2}$
GP1.2	29,2kN	11,68 $\frac{N}{mm^2}$
GP3.1	12,2 <i>kN</i>	$4,88 \frac{N}{mm^2}$

	GP5.2 – 4 day test, compressive strength					
Nr.	Density, dry	Applied force	Force per surface area			
1	$2357,6\frac{kg}{m^3}$	107,8 <i>kN</i>	$43,04 \ \frac{N}{mm^2}$			
2	2354,6 $\frac{kg}{m^3}$	76,9kN	$30,76 \ \frac{N}{mm^2}$			
3	2348,8 $\frac{kg}{m^3}$	99,8kN	$39,92 \ \frac{N}{mm^2}$			

Appendix 11: 28.02.23 – Compressive strength, 4 day, 50 mm x 50 mm x 50 mm cubes, mortar

Cube nr. 2 was not placed in center of compressive area, resulting a non-perpendicular application of force. This then likely led to lower compressive strength.

Appendix 12: 28.02.23 – Compressive strength, 1 day, 50 mm x 50 mm x 50 mm cubes, mortar

	Compressive strength, 5 days					
Nr.	Recipe	Density	Force per surface area			
2	GP1.1	2236,8 $\frac{kg}{m^3}$	$27,6 \ \frac{N}{mm^2}$			
3	GP1.1	2226,4 $\frac{kg}{m^3}$	$28,08 \ \frac{N}{mm^2}$			
2	GP1.2	2199,2 $\frac{kg}{m^3}$	$26,08 \ \frac{N}{mm^2}$			
3	GP1.2	2230,4 $\frac{kg}{m^3}$	$31,64 \ \frac{N}{mm^2}$			
2	GP3.1	2188,8 $\frac{kg}{m^3}$	$20,44 \ \frac{N}{mm^2}$			
3	GP3.1	2226,4 $\frac{kg}{m^3}$	$22,68 \ \frac{N}{mm^2}$			

Appendix 13: 28.03.25 – Creating mix for mortar flow test and 50 mm x 50 mm cubes

	GP1.2-0,45	GP1.2-0,50
FA	270g	270 <i>g</i>
GGBFS	180g	5,974 <i>g</i>
Na ₂ SiO ₃	108,56 <i>g</i>	108,56 <i>g</i>
КОН	71,44 <i>g</i>	71,44 <i>g</i>
H ₂ O	45g	22,5 <i>g</i>
Sand	1350g	1350g
SP - flube	-	9 <i>g</i>

Appendix 14: 28.02.23 – Flow of mortar, 15 hits/15 seconds

Recipe	Values from cross measuring	Final flow
GP1.2-0,45	$\frac{14,5cm + 14,5cm}{2}$	14,5 <i>cm</i>
GP1.2-0,50	$\frac{11,1cm + 11,5cm}{2}$	11,3 <i>cm</i>

Appendix 15: 01.03.23 – Creating GP5.2 paste mix for Vicat test

GP5.2 paste mix				
FA	270,0 <i>g</i>			
GGBFS	180,0 <i>g</i>			
Na ₂ SiO ₃	135,7 <i>g</i>			
КОН	89,3 <i>g</i>			
H ₂ O	10,0 <i>g</i>			
SP - viscocrete	9,0 <i>g</i>			

CERTIFICATE

TEST NUMBER : 02 DATE OF TEST : 01/03/2023 KIND OF TEST : EN196-3:2005 SPECIMEN TIME : 15:14:00 POINTS MOVE [mm] START DELAY[m]: ---30 4.00 1ST PEN TIME : 15:40:00 24 5.25 SPECIMEN TYPE : C2 18 5.25 WATER CONT.[%]: 52.0 12 5.25 TEMPERATUR[øC]: 23.3 2 5.25 HUMIDITY[%] : 22.1 OPERATOR CODE : CJ FALL TYPE : FREE CUSTOMER CODE : GP52 TIME TYPE : FIXED

FINAL SETTING : NO TIME [m] : 5



Appendix 17: 01.03.23 – Projected mass to TAM-test

	GP5.2		GP1.2-0,45		GP1.2-0,50	
Recipe	R	А	R	А	R	А
(R)/ actual						
(A)						
m _{FA}	2,334 <i>g</i>	2,330 <i>g</i>	2,449 <i>g</i>	2,450 <i>g</i>	2,400 <i>g</i>	2,400 <i>g</i>
m _{GGBFS}	1,556 <i>g</i>	1,560 <i>g</i>	1,633 <i>g</i>	1,630 <i>g</i>	1,600 <i>g</i>	1,600 <i>g</i>
m _{Na2SiO3}	1,173 <i>g</i>	1,178 <i>g</i>	0,985 <i>g</i>	0,986 <i>g</i>	1,965 <i>g</i>	0,965 <i>g</i>
m _{NaOH}	-	-	-	-	-	-
m _{KOH}	0,772 <i>g</i>	0,790 <i>g</i>	0,648 <i>g</i>	0,650 <i>g</i>	0,635 <i>g</i>	0,629 <i>g</i>
m_{H_2O}	0,086 <i>g</i>	0,085 <i>g</i>	0,204 <i>g</i>	0,208 <i>g</i>	0,400 <i>g</i>	0,400 <i>g</i>
m _{SP visco}	0,076 <i>g</i>	0,073 <i>g</i>	-	-	-	-
m _{SP flube}	-	-	0,082 <i>g</i>	0,083 <i>g</i>	-	-

Appendix 18: 01.03.23 – Total mass in ampoules

	GP5.2	GP1.2-0,45	GP1.2-0,50
Ampoule nr.	A1	A4	A5
m _{ampoules}	5,314	5,974 <i>g</i>	6,021 <i>g</i>

	Compressive strength test, beams 40mmx40mm						
Recipe	Nr	Date of mixing	Curing age	Density	МРа		
GP1.1		23.02.23	7	2282,7 kg/m ³	31,3		
GP1.2		23.02.23	7	2275,5 kg/m ³	31,6		
GP3.1		23.02.23	7	2271,6 kg/m ³	21,0		
GP5.2		24.02.23	7	2289,3 kg/m ³	44,9		
GP1.2-0,5	1	28.02.23	1	2320,0 kg/m ³	18,6		
GP1.2-0,5	2	28.02.23	1	2266,7 kg/m ³	42,1		
GP1.2-0.5		28.02.23	7	2327,7 kg/m ³	19,4		
GP1.2-0,45	1	28.02.23	1	1955,4 kg/m ³	9,9		
GP1.2-0,45	2	28.02.23	1	1966,8 kg/m ³	9,3		
GP1.2-0,45		28.02.23	7	2029,7 kg/m ³	18,3		

Appendix 19: 01.03.23 – Compressive strength of recipes before finally landing on GP5.2



Appendix 21: 01.03.23 - TAM results of all recipes in comparison, normalized heat flow and normalized heat



Appendix 22: 01.03.23 – TAM results of recipes in comparison, normalized heat flow



Appendix 23: 01.03.23 – TAM results of recipes in comparison, normalized heat flow



Appendix 24: 01.03.23 – TAM results of recipes in comparison, normalized heat flow



Appendix 25: 01.03.23 – Compressive strength results of recipes in comparison



Appendix 26: 22.03.23 – Compressive strength of GP5.2, air cured

Compressive strength date	Curing age	Number	Strength	Notes
23.03.23	1	1	12,9 $\frac{N}{mm^2}$	Not centered
23.03.23	1	2	13,9 $\frac{N}{mm^2}$	Flaked off on one side, 6mm
29.03.23	7	1	$34,4 \ \frac{N}{mm^2}$	Flaked off on one side, 2mm
29.03.23	7	2	$38,8 \ \frac{N}{mm^2}$	
19.04.23	28	1	54,5 $\frac{N}{mm^2}$	Moist on the bottom
19.04.23	28	2	54,7 $\frac{N}{mm^2}$	

Appendix 27: 22.03.23 – Sieving of aggregates, 0-8 mm

Weight sand [g]	1000				
Fraksjoner 🛛 🛩	Weight empty sieve [g] 🛩	Weight sand [g] <mark>~</mark>	Measured sand [g]	Ratio sand/empty -	Total 🛛 🛁
<0,125mm	1356	1406	50	5 %	5 %
<0,25mm	646	762	116	12 %	17 %
<0,5mm	590	842	252	25 %	42 %
<1mm	652	884	232	23 %	65 %
<2mm	732	878	146	15 %	80 %
<4mm	840	924	84	8 %	89 %
<8mm	974	1056	82	8 %	97 %
>8mm	954	986	32	3 %	100 %
Sum after sieving			994	100 %	



Total

Appendix 28: 22.03.23 – Sieving of aggregates, 8-16 mm

Weight grave	[g] 3005				
Fraksjoner	✓ Weight empty sieve [g]	Weight sand [g] 🛛 🛩	Measured sand [g]	Ratio sand/empty 🖌	Total 🗸
<8mm	1375,8	1551,5	175,7	6 %	6 %
<10mm	954,7	1498,1	543,4	18 %	24 %
<12,5	1060,9	1852,4	791,5	26 %	50 %
<16	1075,7	2074,1	998,4	33 %	84 %
<20mm	1368,2	1861,8	493,6	16 %	100 %
<25mm	1367	1367	0	0 %	100 %
>25mm	1257,9	1257,9	0	0 %	100 %
Sum after siev	ving		3002,6	100 %	



Total

Appendix 29: 22.03.23 – Water content in aggregates

0-8 mm aggregate water content:

$$w = \frac{(M_1 - M_2)}{(M_2 - M_3)} * 100 = \frac{1900 - 1896}{1900 - 300} * 100 = 0,25\%$$

8-16 mm aggregate water content:

$$w = \frac{(M_1 - M_2)}{(M_2 - M_3)} * 100 = \frac{3500 - 3500}{3500 - 300} * 100 = 0\%$$

Appendix 30: The test started 19.04.2023 and had a duration of 24 hours before measuring the values shown below 20.04.2023

Chloride penetration

Preset conditions	
10 V	
24Hours	
225mA	

Measured values		<u>CatholyteºC</u>	<u>AnolyteºC</u>	Voltage
	Start	15,2	24,5	225mA, 10V
	Finish	18,2	19,3	217mA, 10,6V

Results of measured depths in GP5.2 in mm.

Xd6	Xd4	Xd2	Xd1	Xd3	Xd5	Xd7	
	14	14,5	17,9	10	10	9,5	11

Illustration of the chloride penetration depths in the measurement zone (mm)



Non-steady-state-migration coefficient:

$$D_{nssm} = 0.0239 * \frac{(273+T)*L}{(U-2)*t} * \left(x_d - 0.0238 * \sqrt{\frac{(273+T)\cdot L \cdot x_d}{U-2}} \right)$$

Where:

 $D_{nssm}~$ - Non-steady-state-migration coefficient, $*10^{-12}~m^2/s$

U - Absolute value of the external potential applied between the two electrodes. V =10,6V

T - Average value of the initial and final temperatures in the anolyte, °C. T=21,9°C

L - Thickness of specimen, mm. L=50,6 mm

- x_d Average value of penetration depths, mm. x_d=12,4 mm
- t Test duration, hours. t=24h

$$D_{nssm} = 0.0239 * \frac{(273+21,9)*50,6}{(10,6-2)*24} * \left(12,4-0,0238 * \sqrt{\frac{(273+21,9)\cdot50,6\cdot12,4}{10,6-2}}\right)$$
$$D_{nssm} = 15,39 * 10^{-12} \frac{m^2}{s}$$

Non-steady migration coefficient (D_{nssm}) of the studied concrete mixtures, water to cement ratio of 0,55:

Results of carbonation age:

The following formula is a formula based on *intuition* and is a *proposal* on how to determine the age of a concrete sample, from a Rapid Carbonation test (Duran Atiş, 2003), based on:

- Carbon-concentration in air, 421PPM
- Carbon-concentration in chamber, 50000PPM
- Duration of test procedure, 14 days
- 1 year = 365 days

$$\frac{50000PPM}{421PPM} \times \frac{14 \ days}{365 \frac{days}{year}} = 4,56 years$$



Illustration of measurement zones, when measuring chloride depths.

Measurements: 2 cubes, cured in oven.

Cube #1	Cube #2
A1: 1,5mm	A1: 3,37mm
A2: 0mm	A2: 4,03mm
B1: 7,26mm	B1: 7,48mm

B2: 3,67mm	B2: 6,5mm
C1: 1,49mm	C1: 2,61mm
C2: 4,06mm	C2: 4,62mm
D: 2,946mm	D: 4,83mm

Appendix 32: Energy consumption in the production process

Impact category	Unit	LCA, CEM II/A-S 42,5 N Concrete	Lifecycle of 1m3 Geopolymer
Non renewable, fossil	MJ	2,61E3	3,01E3
Non-renewable, nuclear	MJ	210	564
Non-renewable, biomass	MJ	0,259	0,401
Renewable, biomass	MJ	47,1	97
Renewable, wind, solar, geothe	MJ	85	118
Renewable, water	MJ	1,79E3	1,56E3

Appendix 33: CO2-equivalent

Se	Impact category	Unit	LCA, CEM II/A-S 42,5 N Concrete	Lifecycle of 1m3 Geopolymer
	GWP100 - fossil	kg CO2-eq	386	216
	GWP100 - biogenic	kg CO2-eq	0,593	0,599
	GWP100 - land transformation	kg CO2-eq	0,218	0,291

Appendix 34: The materials of each recipe used for the LCA comparison

No	Process /	Project	Unit	LCA, CEM II/A-S 42,5 N Concrete	Lifecycle of 1m3 Geopolymer Concrete
1	Cement, blast furnace slag 6-20% {RoW}] cement production, blast fu	Concrete with CEM II/A-S 42,5 №	kg	440	x
2	Diesel, burned in building machine {GLO} processing Cut-off, S	Ecoinvent 3 - allocation, cut-off	MJ	289	296
3	Electricity, medium voltage {NO} electricity voltage transformation fr	Ecoinvent 3 - allocation, cut-off	GJ	1,7	1,41
4	Flygeaske GP5.2	GP5.2 LCA analysis	kg	x	243
5	Gravel, crushed {RoW} production Cut-off, S, GP5.2	GP5.2 LCA analysis	kg	x	756
6	Ground granulated blast furnace slag {RoW} production Cut-off, S, (GP5.2 LCA analysis	kg	x	162
7	Plasticiser, for concrete, based on sulfonated melamine formaldehyde	GP5.2 LCA analysis	kg	x	7,87
8	Potassium hydroxide {RER} production Cut-off, S, GP5.2	GP5.2 LCA analysis	kg	x	41,8
9	Sand {RoW}] gravel and quarry operation Cut-off, S, GP5.2	GP5.2 LCA analysis	kg	x	965
10	Sand {RoW} sand quarry operation, extraction from river bed Cut-of	Concrete with CEM II/A-S 42,5 №	ton	1,63	x
11	Sodium silicate, solid {RER} sodium silicate production, furnace proce	GP5.2 LCA analysis	kg	x	43,9
12	Transport, freight, lorry 16-32 metric ton, EURO4 {RER} transport, freig	Ecoinvent 3 - allocation, cut-off	tkm	116	x
13	Transport, freight, lorry 16-32 metric ton, EURO4 {RER} transport, freig	GP5.2 LCA analysis	tkm	x	117
14	Waste concrete {Europe without Switzerland} treatment of waste con	Concrete with CEM II/A-S 42,5 №	ton	2,31	x
15	Waste concrete {Europe without Switzerland} treatment of waste con	GP5.2 LCA analysis	ton	x	2,35
16	Waste scenario for landfill, GP5.2	GP5.2 LCA analysis	ton	x	2,35
17	Waste scenario landfill	Concrete with CEM II/A-S 42,5 N	ton	2,32	x
18	Water, completely softened {RER} market for water, completely soften	Concrete with CEM II/A-S 42,5 №	kg	242	x
19	Water, completely softened {RER} market for water, completely soften	GP5.2 LCA analysis	kg	x	91,2
20	Water, completely softened {RoW} market for water, completely softe	GP5.2 LCA analysis	kg	x	39,3

Appendix 35: Live photo of reinforment of an actual solid module wall

