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Abstract

The construction industry is one of the main sources of pollution in the world with concrete and cement production accounting for at least 8% of the global greenhouse gas emissions. The recent increase in demand for environmentally friendly materials and buildings has resulted in the development of new concretes with a reduced environmental footprint. Common practice is to replace part of the cement binder with supplementary cementitious materials which have pozzolanic properties of which fly ash, blast furnace slag and silica fume are the most common. Through the replacement of cement in the binder the concrete is able to directly reduce its total environmental impact.

The rise of environmentally friendly solutions has led to an increase of eco labeling, comparative assertions, and misleading claims regarding their performance. In order to ensure that such claims are accurate different assessment methodologies applicable for the European continental environment have been developed such as CML 2.1, Eco Indicator 99, ReCiPe 2016 among others. These methods all adhere to the ISO 14040 series of standards and by extension the CEN/TC 350 series (EN 15804 and EN 15978). The standards allow for comparison and transparency on how buildings and building materials are evaluated by providing core rules and regulations which have to be followed in order to gain a credible certification. The specifications provided for Environmental Product Declarations and building Life Cycle Assessments require the inclusion of mandatory environmental indicators in the form of global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential, ozone depletion potential, adiabatic depletion potential of minerals and fossil fuels. These standardized indicators are based on scientifically backed and agreed upon calculation methods, this means that products, services, and buildings that have undergone an environmental evaluation in accordance with ISO/EN have a transparency, quality, reliability, and third-party verification guarantee. Further optional details and indicators can be included as needed through the use of one of the afore mentioned impact assessment methodologies.

A basic high fly ash content concrete was developed (50% fly ash) to be incorporated as part of a multi-story concrete parking garage in order to quantify how effective it is in reducing the environmental footprint of the building as a whole. The results indicated a total of 15,28% reduction in the parking garage's greenhouse gas emissions. However, when considering the buildings energy usage throughout its 60-year design service life the reduction due to the environmentally friendly concrete alone was not enough to achieve a significant result. The use of supplementary cementitious materials such as fly ash prove effective at lowering the environmental footprint of concrete buildings but should be paired with other measures such as additional "green" materials and clean sources of energy to supply the building and processes such as transportation of materials and machinery needed for the construction.

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1. Introduction

1.1. Background

This thesis investigates the different tools, frameworks and calculation methods which can be used to aid the quantification of the environmental impacts of concrete. The construction sector has had an increasing interest in reducing its emissions and stress on the environment, the development of environmentally friendly concrete aids the expansion of a constantly increasing inventory of “green” building materials. There are many different ways to interpret and define how a material impacts the environment, this large array of terminology, methods and definitions creates a standardization problem where individual studies and data sets are impossible to compare due to the use of completely different approaches and strategies. Throughout the last decades increasing amounts of resources and efforts have been made especially within the European union to standardize, provide guidelines and methodologies through the development of the CEN/TC 350 standards which are meant to act as the backbone of environmental impact assessment.

Sustainability and environmentally friendly solutions have become mainstream across the industry however this has led to a more superficial perspective. Often times the holistic focus is lost in favor of satisfying market demand with buzzwords and ecolabels. This highlights the need for more rigorous and in-depth assessment of environmental solutions in order to really quantify and prove their effectiveness at a larger scale.

1.2. Objective and scope

The goals of this thesis are to:

(I) Provide an overview and description of the current methodologies and strategies used for the environmental assessment of concrete (also applicable to most buildings, products, materials, and processes).

(II) Assess the viability of experimental high fly ash content concrete (50% fly ash) compared to the current standard of fly ash concrete (35% fly ash). The scope of the assessment is focused on the concrete’s ability to reduce environmental impacts in comparison to the entire building system. The basic strength properties of the concrete are also assessed in order to ensure its viability as a building material.

2. Environmental concrete

2.1. Concretes effect on the environment

Concrete is the most commonly used material in the construction industry due to its high compressive strength, fire, and water resistance, excellent durability, and the ability to be molded into any desired shape and size. This versatility paired with a relatively low cost makes concrete difficult to replace with alternative materials at a large scale. [1]

Concrete is a composite material composed of 3 main ingredients: cement, aggregates, and water. Cement is responsible for around 90% of the total greenhouse gas emissions associated with concrete production. One ton of regular Portland cement produced in Norway is estimated to result in greenhouse gas emissions equivalent to 750 kg of CO_2. The remaining emissions come mainly from the processing and crushing of rocks in order to transform them into the correct size aggregates as well as the transportation of materials using trucks and boats. The environmental impact associated with concrete and cement production has been a topic of discussion since the 1980s. [2] The concrete industry has actively been working on reducing its environmental impact through the development of new and alternative methods and technologies such as carbon capture, recycling and reusing of materials and research into more environmentally friendly replacements. [3] [4]

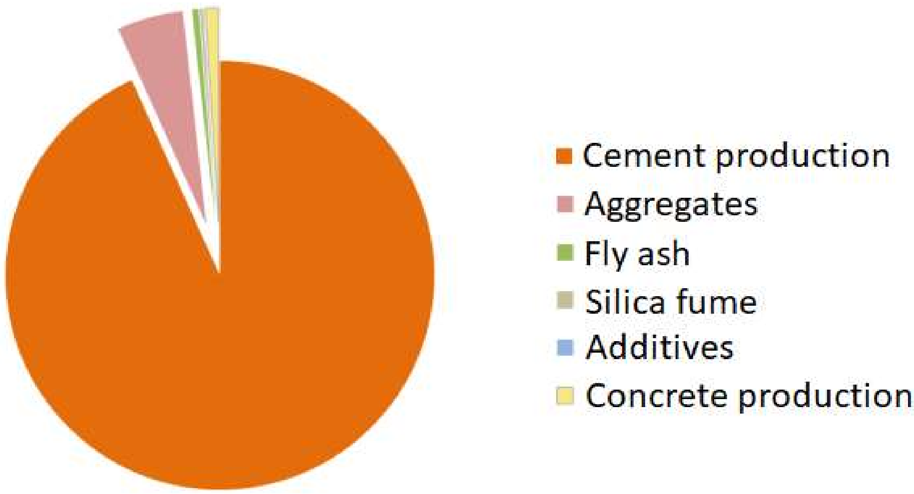


Figure 2-1: Greenhouse gas emissions for typical concrete used in the construction industry. This example refers to B30 M60 concrete produced by NorBetong at Sjursøya in Oslo [2]

Environmental concrete is a collective term used for concrete that has in some shape or form been modified to reduce its carbon footprint. There are multiple methods to achieve reduced emissions, however one of the most common is the use of supplementary cementitious materials (SCMs). SCMs are materials that have very similar binding properties as those of cement, but much lower greenhouse gas emissions associated with their production. Through the use of SCMs it is possible to decrease the amount of cement required, consequently reducing the carbon footprint of the concrete. [5]

2.2. Portland cement

2.2.1. Production and properties of Portland cement

Limestone is the main raw material that is used in the production of Portland cement. The limestone is first extracted from mines and quarries and thereafter ground together with smaller amounts of bauxite, iron oxide, quarts, and gypsum among others. The mixture is then transformed into tiny particles called raw meal through undergoing a grinding process using raw mills. After the grinding process the raw meal is passed onto cyclone preheaters where its temperature is raised to about 1000 °C. Once the preheating process is complete the raw meal is further heated up to 1450 °C in a rotary kiln, the resulting combustion gas that is produced can reach temperature of up to 2000 °C. Throughout the grinding and heating process the main component of limestone, calcium carbonate ($CaCO_3$) is converted into calcium oxide (CaO) and carbon dioxide (CO_2) through a process called calcination. [6]

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

Portland cement primarily consists of clinker which is formed when calcium oxide (CaO) is sintered with the other minerals. Clinker typically appears as spherical lumps or nodules which can range between 3 to 25 millimeters in size. Clinker is then ground and mixed with small amounts of gypsum and potentially other minerals in a cement mill. The ratio of additional gypsum and minerals is often used to change the properties of the cement. Once the cement has finished production, it is then stored in large silos before being packed and shipped to factories, stores, and other consumers. The large amounts of greenhouse gas emissions released during the production of cement are due to the calcination of calcium carbonate ($CaCO_3$) which releases large amounts of carbon dioxide (CO_2) as well as the fossil fuels burned in order to heat up and power the rotary kiln, raw mills, and cement mills. [6]

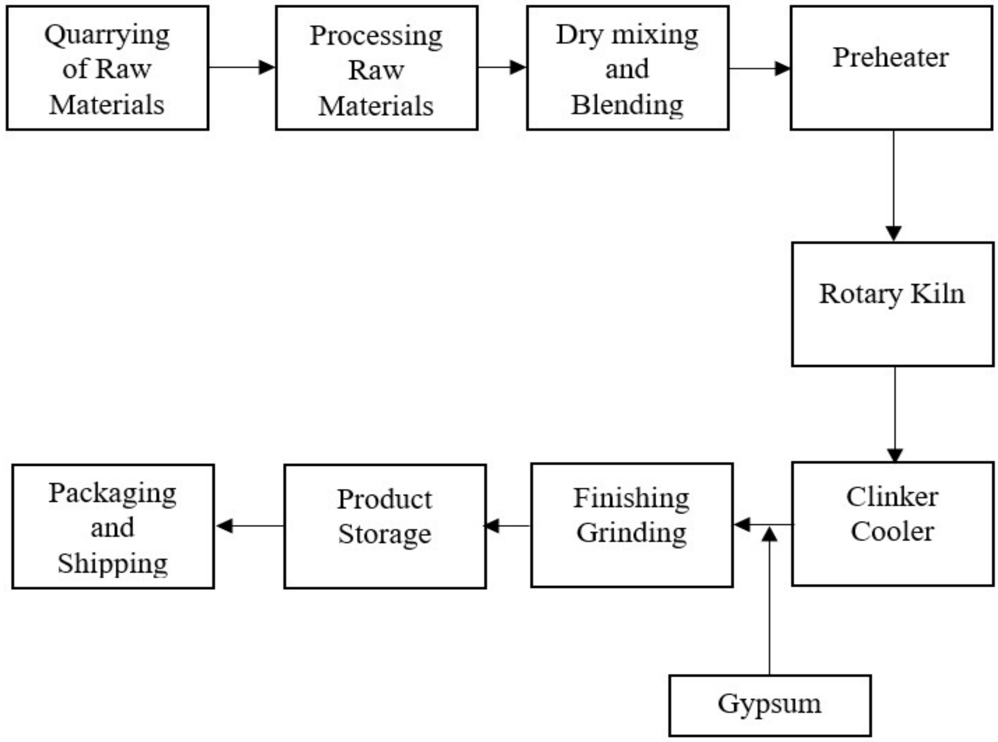


Figure 2-2: Flowchart of cement production

Portland cement has four primary minerals which all contribute to determining the properties of the cement. The properties vary depending on the distribution of these four minerals. [7]

Name	Empirical formula	Symbol	Percent of total weight
Tricalcium silicate	$3CaO \cdot SiO_2$	C_3S	$50-60$ %
Dicalcium silicate	$2CaO \cdot SiO_2$	C_2S	$18-22$ %
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A	$5-10$ %
Tetracalcium aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF	$6-10$ %

Table 2-1: Main minerals found in clinker

The density and fineness of cement is measured through a standardized method outlined in NS-EN 196-6 using a Blain apparatus. The test is performed by forcing air through a tube containing a certain amount of cement powder and recording the resistance to airflow in order to determine the density. [8] Regular Portland cement typically has a fineness (Blaine) within the 300-500 $\frac{m_2}{kg}$ range. [9] Regular Portland cement is classified into the category of pure Portland cements (CEM I: 95-100% clinker content) as outlined in the standard NS-EN 197-1 which describes the requirements, conformity, and compositional criteria for ordinary cements. Pure Portland cements are defined as cements mainly consisting of clinker. [10]

Properties in fresh concrete

The combination of water and cement that serves as the binding material in concrete is called the cement paste. The proportion of water to cement is known as w/c ratio. This ratio dictates the characteristics of the concrete, including the toughness and strength of the hardened concrete and texture and workability of the fresh concrete. [11] The texture and workability of the concrete determines the ease of pouring the concrete and can be evaluated through the use of slump test, slump flow test or other methods outlined in [12]. In addition, certain additives such as superplasticizers can be used to influence the workability and slump without altering the w/c ratio of the concrete. [13]

Strength development and hydration of Portland cement

Portland cement is a hydraulic binding agent, when the cement particles come in contact with water they undergo and exothermic reaction that results in a solid reaction product. This chemical reaction is known as hydration. Due to the reaction between cement and water being exothermic, the concrete's temperature will increase during the hydration process. [14] The four main minerals found in clinker all contribute differently to the hydration process. Tricalcium silicate C_3S and dicalcium silicate C_2S react with water, as they hydrate bonds of calcium, silicone and hydroxide are formed. These bonds are referred to as calcium hydroxide (CH) and calcium silicate hydrate gel or C-S-H gel for short. The C-S-H gel is primarily responsible for the concrete's strength, durability and dimensional stability and make up approximately 70% of the fully hydrated cement paste's weight. [15]

The following chemical reactions occur during the hydration of Portland cement:

$$C_3S + H_2O \rightarrow CSH + CH + Heat$$

$$C_2S + H_2O \rightarrow CSH + CH + Heat$$

$$C_3A + H_2O \rightarrow C_3AH_6 + Heat$$

$$C_4AF + H_2O \rightarrow C_3AH_6 + CFH + Heat$$

- C_3S results in rapid strength development of the concrete as well as a high potential strength at long term. As the development is relatively fast the reaction produces around 500 $\frac{KJ}{kg}$, additionally C_3S has resistance against sulphate solutions. [16]

- C_2S contributes mostly to the concretes high long term strength capacity and is also resistant to sulphate attacks. The strength development is rather slow and subsequently produces a lower amount of heat at around 260 $\frac{KJ}{kg}$. [16]

- C_3A results in fast strength development of the concrete but contributes minimally to the long-term strength potential and is not resistant to sulphate attacks. The reaction speed between C_3A and water is very fast leading to a high release of heat at around 900$\frac{KJ}{kg}$. Typically, gypsum is added to the mixture in order to prevent the flash setting of C_3A. [16]

- C_4AF contribution to the cement properties is very little and also has a slow heat development at 300$\frac{KJ}{kg}$. [16]

The factors that influence the hydration speed of cement include its chemical composition, the fineness/Blaine and temperature during the curing process. A higher fineness exposes a larger surface area of the cement to water thus causing a faster reaction speed as well as quicker strength development in the concrete. Higher temperature during curing also contribute to a higher early strength. [17]

The formation of alkali hydroxides occurs during the cements reaction with water and raises the concretes pH level to around 14. [18] The high levels of calcium hydroxide makes the concrete mixture very basic, and the high pH creates a protective oxide layer that shields the steel reinforcement from corrosion. [19] Throughout the induction period, an increase of OH^- ions and Ca^{2+} ions can be observed. [18] These ions slow the hydration process until sufficient saturation of calcium has occurred. However, after a few hours the hydration process speeds up again creating chemical network that leads to the hardening of the concrete. At this stage the binder within the concrete becomes stable and the concrete is able to support itself although its full-strength potential has not yet been achieved. To ensure further strength and durability development, appropriate curing techniques should be used after the concrete has set. [20]

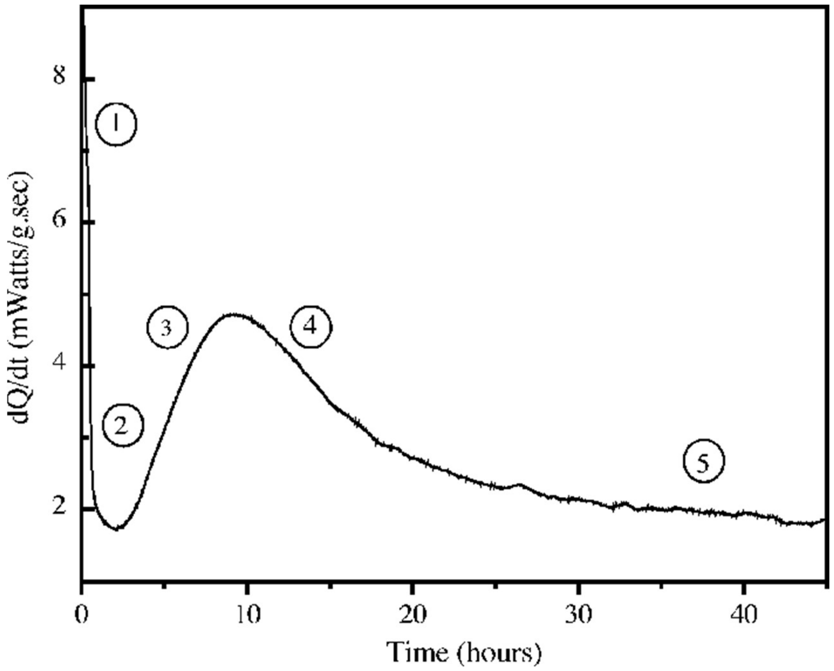


Figure 2-3: Temperature development in concrete during early stages of curing [21]

Stage 1, shown in Figure 2-3: Temperature development in concrete during early stages of curing is defined as the time right after the cement comes into contact with water. As the hydration reaction initiates the temperature in the concrete will be high. During stage 2 the temperature will rapidly fall off before reaching the start of stage 3.

The hydration of the cement then accelerates during stage 3 and C-S-H-gel begins to form, subsequently causing the temperature to rise all throughout stage 3. Stage 3 is typically reached after 2 to 5 hours depending on the curing conditions and chemical composition of the Portland cement. The hydration rate is also affected by the external and internal temperature, lower temperatures result in reduced a hydration rate meanwhile higher temperatures result in quicker hydration. Additionally, if the temperature exceeds 30°C, it can have a reverse effect and slow down the hydration rate.

In stage 4 cement particles are covered in an increasingly thick layer of hydration products. This reduces the amount of available cement particles that can react with water and form C-S-H-gel thus decreasing the hydration rate and temperature of the concrete as a whole. During stage 5 most of the cement particles are covered in hydration products and the hydration rate slows down even further, the temperature also decreases eventually reaching ambient temperature. However, even after stage 5 the concrete continues to harden and gain strength as the internal structure continues to densify and hydrate to some extent. [21]

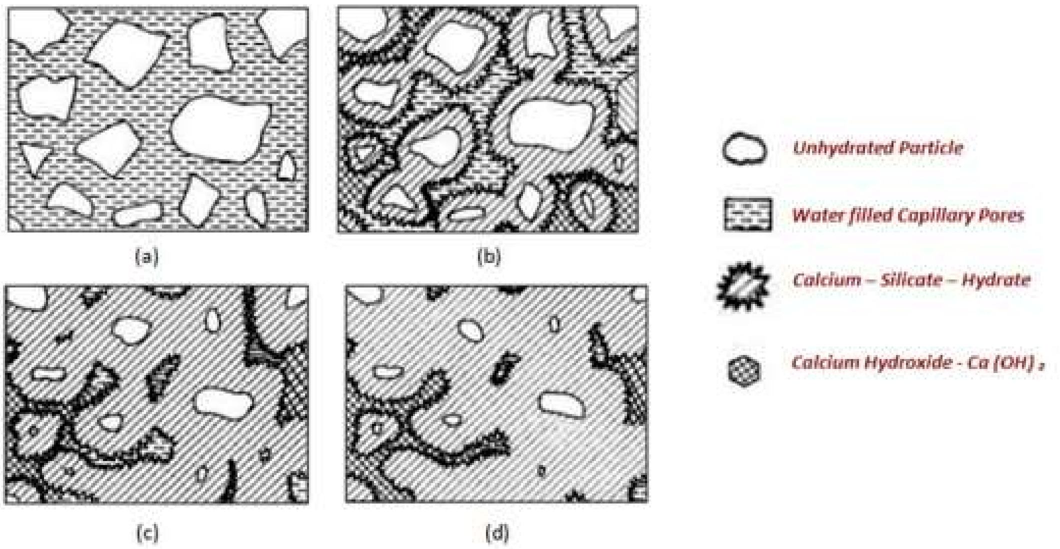


Figure 2-4: Development of microstructure during hydration. (a) Initial mix (b) 7 days (c) 28 days (d) 90 days [22]

The degree of hydration (α) for a given concrete can be calculated by considering that α is directly proportional with the amount of water that has been chemically bound during the hydration process. To determine the amount of chemically bound water the cement paste is dried at 105°C and subsequently burned at 1000°C then the loss of water is divided by the weight of the sample after burning. [23]

$$\alpha = \frac{W_n}{W_n(\infty)} = \frac{W_n}{0.23} < 1.0$$

Where,

α is the degree of hydration
W_n is the amount of chemically bound water
$W_n(\infty)$ is the theoretical 100% hydration of the cement, taken as $\frac{0.23\ g}{g\ cement}$

2.3. Low-carbon concrete

The increasing importance and focus on environmentally friendly solutions and alternatives withing the construction industry has raised concerns surrounding the environmental effect that the concrete used in building projects has on the total emissions. One way to quantify this is through the use of low-carbon concrete, however the term has not yet been explicitly defined leaving room for interpretations on what exactly classifies as low-carbon concrete. Guidelines have been given by the Norwegian Concrete Association (Norsk Betogforening) in a document referred to as NB *Publication number 37.*

The above-mentioned publication defines low-carbon concrete as concrete for which climate impact reducing measures have been taken and complies with the requirements of predefined classifications. Additionally, the requirements set in NS-EN 206+NA have to be followed. There are three main classifications of low-carbon concrete outlined in *Publication number 37:*

- **Low-carbon B** – Can usually be achieved through ordinary recipe-based measures
- **Low-carbon A** – Can usually be achieved through special recipe-based measures

- **Low-carbon Plus and low-carbon Extreme** – Requires the use of special binder compositions that are not expected to be widely available or approved for use in all durability classes

The different low-carbon classes set specific requirements for the concrete's strength as well as total greenhouse gas emissions produced by the concrete. These emissions are measured per cubic meter of concrete, all processes related to the production of the concrete are included and the GWP value taken from parts A1-A3 in the concretes EPD is used as starting point.

Strength and carbon classification	B20	B25	B30	B35	B45	B55	B65
Maximum greenhouse gas emissions [kg CO_2 equivalence per m^3 concrete]							
Industry standard	240	260	280	330	360	370	380
Low-carbon B	190	210	230	280	290	300	310
Low-carbon A	170	180	200	210	220	230	240
Low-carbon Plus			150	160	170	180	190
Low-carbon Extreme			110	120	130	140	150

Table 2-2: Low-carbon concrete classes with their associated allowable greenhouse gas emissions [2]

When choosing a low-carbon class for a given building project, the projects conditions and requirements must be taken into consideration. Requirements such as durability, exposure class and strength class and conditions such as availability of binders, quality of the aggregates, transportation distances, competence of the laborers, etc. [2]

2.4. Pozzolanic reactions

A pozzolan is a siliceous or siliceous and aluminous material, pozzolanic materials are often added to regular Portland cement as a partial replacement of the cement. When pozzolans are combined with water and calcium hydroxide, they produce a substance with similar binding properties to cement. Although pozzolans do not have hydraulic binding properties on their own, they react with calcium hydroxide during the hydration of Portland cement to form similar products. Naturally the size and purity of the pozzolan particles affects the speed and extent of these reactions, which are known as pozzolanic reactions. The pozzolanic reaction which occurs during cement hydration is shown below: [24]

$$2SiO_2 + 3Ca(OH)_2 \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O$$

$$2S + 3Ca(OH)_2 \rightarrow C_3S_2H_3$$

$$Silica + Calcium\ hydroxide \rightarrow C - S - H$$

2.5. Mineral admixtures

Mineral admixtures are finely divided materials which are added to the concrete. The admixtures are incorporated into the binder in order to cut costs, lower total cement use or obtain desirable engineering properties. The European standard NS-EN 206 clause 5.1.6 classifies mineral admixtures into two categories: [25]

- Type I: Inert mineral admixtures

- Filler (Particle diameter < 0.063 mm)
- Pigments in accordance with NS-EN 12878

- Type II: Pozzolanic or latent hydraulic mineral admixtures
  - Fly ash and silica fume (pozzolanic admixtures)
  - Ground blast furnace slag (latent hydraulic admixtures)

Due to the necessity of calcium hydroxide for pozzolanic reactions (type II admixtures) to occur, the binder needs to include a certain amount of Portland cement such that calcium hydroxide can be formed through the hydration process.

2.5.1. Fly ash

Fly ash is the most widely used pozzolanic mineral admixture in concrete. It is a byproduct of the exhaust gases emitted from coal powered powerplants. Coal powerplants are among the most polluting but due to their low cost and ease of use many countries around the world still depend on them to meet their energy needs. [26] As a result, the annual production of fly ash is quite significant at an estimated 500 million tons produced every year. [27]

Fly ash is considered as a highly versatile mineral admixture which is valued for its ability to improve the strength, durability, and workability of concrete. It can be used in wide range of concrete applications such as the production of precast concrete, ready-mix concrete, and paving. One of the major advantages of using fly ash is the reduction of clinker needed in concrete. Clinker is a key component of cement that is produced through heating limestone and other materials to extremely high temperature in a kiln. As previously mentioned, the production of clinker is associated with large amounts of the greenhouse gas emissions and plays a big part in the carbon footprint of the concrete industry. The use of fly ash as a clinker replacement effectively helps reduce the environmental impact of concrete production. However, it is important to consider that fly ash is a byproduct and not a product specifically produced for the concrete industry, its properties and quality can therefore vary based on a wide range of factors. These factors can be things such as the characteristics of the coal burned at the powerplants, how the fly ash is separated from the exhaust gases, peak temperatures, and heat development. It is therefore important to ensure that the fly ash used in concrete meets the necessary standards and requirements. [28]

The requirements for fly ash and other mineral admixture are outlined in the European standard NS-EN 450-1:2012. The CEN and ASTM standards set requirements for the mineral admixtures' chemical properties, physical properties and the maximum allowable amount that can be using. [29] There are two main classes of fly ash in the ASTM standard which are outlined below: [30]

- Class F
  - Contains less than 10% calcium oxide
  - Used in applications where high strength is required
- Class C
  - Contains 10-30% calcium oxide
  - Used in applications where low heat development and increased workability is desired

Oxide	Percentage (wt %)	
	Class F fly ash	Class C fly ash
SiO_2	62.29	48.2
Al_2O_3	15.94	18.4
Fe_2O_3	6.24	3.7
CaO	7.92	19.6
MgO	1.57	1.1
SO_3	-	1.7
$f - CaO$	-	5.2

Table 2-3: Chemical composition of class F and class C fly ash [31]

Fly ash particle are spherical in shape and have a high degree of fineness, the particle diameters typically range between 1-100 µm. Due to its fineness, the total surface area of fly ash per kilogram is approximately 250-600 m^2 and as a result allows the particles to easily react with calcium hydroxide. Fly ash can alternatively be ground down before being used as an admixture in concrete. However, the grinding process will change the spherical shape of the fly ash particles. [32]

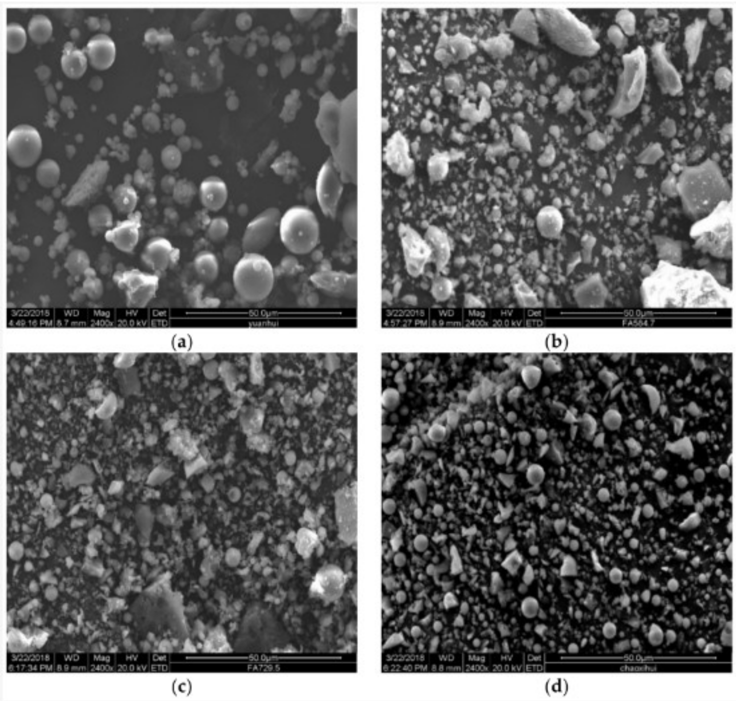


Figure 2-5: SEM images of different fly ash. (a) Raw fly ash. (b) 1h of grinding in ball mill. (c) 2h of grinding in ball mill. (d) Grinding in vertical mill. [33]

Concrete that includes fly ash will appear darker in color compared to concrete made solely with Portland cement. Fly as also has a lower density of approximately 2300 $\frac{kg}{m^3}$, in contrast to Portland cement which has a density of approximately 3000$\frac{kg}{m^3}$. As a result, Portland-fly ash concrete can potentially have lower total density than pure Portland concrete but given that the binder component only represents a small fraction of the overall weight of the concrete, this weight difference is unlikely to be substantial. [32]

NE-EN 197-1:2011 outlines the categorization of fly ash containing cements, which most commonly are a blend of fly ash and Portland cement in different proportions. The standard distinguishes between two types of fly ash: siliceous and calcareous, which each exhibit distinct chemical properties that can influence their performance in concrete. The main difference in chemical composition is that siliceous fly ash contains high levels of SiO_2 and calcareous fly ash contains higher levels of CaO. Siliceous fly ash is currently the most widely used type in Norway. [10]

The four main classifications of Portland-pozzolan cements with fly ash are, in accordance with the standard:

Classification	Fly ash content (%)	Type
CEM II/A-V	6-20	Siliceous
CEM II/B-V	21-35	Siliceous
CEM II/A-W	6-20	Calcareous
CEM II/B-W	21-35	Calcareous

Table 2-4: Classifications of different Portland-pozzolan cements with fly ash. [10]

Properties in fresh concrete

Incorporating fly ash into concrete can decrease the amount of water needed to create the mixture compared to using pure Portland cements. This reduction in water content does not adversely impact the workability or compatibility of the fresh concrete. The percentage of water content reduction can range from 5% to 15% with higher ratios of water to cement leading to more significant reductions in water content. However, exceeding a 20% fly ash content in the binder will not provide any additional reduction in water content needed. Fly ash and superplasticizers function similarly in decreasing the necessary water content. Hence when used together with superplasticizers, the water reducing benefits of fly ash may not be as pronounced. [32]

Strength development and hydration

During the hydration process of fly ash, C-S-H products are produced similarly to those produced from Portland cement. However, the fly ash particles react slower than the cement particles, this is due to the glass in fly ash first starts to break down when the pore water exceeds a pH value of 13.2. In order to reach such a high pH value some of the Portland cement has to react before the fly ash reaction is initiated. At temperatures about 20°C and higher, the reaction rate of both the fly ash and cement increases but the change in the rate of acceleration is much more significant for fly ash. Fly ash particles generally retards the reaction rate of hydration as it binds to available Ca^{2+} particles from the solution and thereby making them inaccessible to react with cement particles and slowing the production of C-S-H products. Higher amounts of fly ash make this effect more pronounced.

The microstructure of the concrete is also improved through the use of fly ash. The small, spherically shaped particles are highly suitable for filling voids between the courser cement particles as well as the aggregates. This leads to better packing and compaction of the concrete resulting in increased strength. It is however important to note that strength improvements are seen for fly ash contents of up to 30%, further fly ash content can potentially lead to a reduction in overall strength. [32]

Durability

The size of large capillary pores and the presence of air in the concrete is lowered due to the dense packing and compaction of the concrete's microstructure. This results in more pores containing water, thus promoting better long-term hydration. The additional packing of the concrete also makes it more resilient against cracking throughout its service life. [32]

2.5.2. Silica fume

Silica fume is a pozzolanic mineral admixture and is a byproduct produced during the manufacturing process of silicon and ferrosilicon alloys. The raw materials used during the production are coal and quartz which are burned in a submerged arc furnace. During this process, SiO oxidizes and condenses to form silica SiO_2. The SiO_2 content in silica fume is typically around 85-99%, other trace amounts of other minerals and oxides are also present. The gray color of the silica fume is dependent on the carbon dioxide content. When the smelting furnace reaches sufficiently high temperatures, a large portion of the carbon will be burned resulting in near carbon free silica fume. A determining parameter in the purity of the silica fume is the amount of silicone content in the ferrosilicon alloys being produced. A higher silicone content results in a higher amount silica in the silica fume. [34]

The silica particles are spherical in shape and have a very high degree of fineness. The diameter of the particles is typically in the 0.03-0.3 µm. [35] Due to the extreme fineness of the particles, the standard Blaine method cannot be used. Instead, the fineness of the silica particles is measured though the method known as nitrogen adsorption which can be used to indicate a fineness of up to 20,000 $\frac{m^2}{kg}$. Silica has a much greater fineness compared to other mineral admixtures such as fly ash and granulated blast furnace slag resulting in an increased reaction rate with the calcium hydroxide from the hydration of Portland cement. [34]

The as-produced density of silica fume ranges between 130-430 $\frac{kg}{m^3}$, which is significantly lower than that of Portland cement which lays within the 3000 $\frac{kg}{m^3}$ range. The low density and high fineness of the silica fume particles makes it difficult and expensive to handle. To combat these challenges two different alternatives have been developed, namely densified or compacted pellets and slurried silica fume each with a density of 200-600$\frac{kg}{m^3}$ and 1300-1400 $\frac{kg}{m^3}$ respectively. These alternative forms of silica fume can potentially result in slightly different properties when used in concrete. [34]

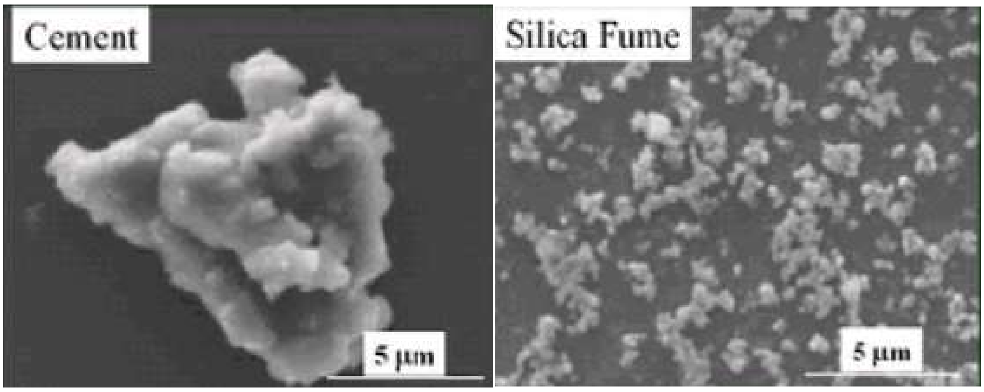


Figure 2-6: The difference in fineness between cement and silica fume. [36]

The maximum limit that is set by NS-EN 206 is 11% added silica fume content for concrete. Therefore, the ability to reduce the carbon footprint of the concrete by only using silica fume as an admixture is limited. However, the K-factor associated with silica fume is typically higher than other admixtures and as a result this will reduce the amount of Portland cement in the effective binder to a greater degree. [25] This reduction in Portland cement will lead to a positive environmental effect. Portland-silica cements are classified in NE-EN 197-1:2011: [10]

- CEM II/A-D 6-10% silica fume content, 0-5% additional constituents

The even distribution of the silica fume in the concrete is important to consider when using it as an additive, especially when it comes in pellet form. To achieve this, it may be necessary to extend the mixing time of the concrete. Additionally, the order of the materials added to the mixer can also impact how evenly the silica fume is spread throughout the concrete. To attain optimal coverage of the aggregate surface the silica dust should make up around 10% of the effective binder. [37]

Properties in fresh concrete

The presence of silica fume in a concrete mixture can increase the total surface area of the particles within leading to a higher water demand. In order to maintain the desired level of workability of the fresh concrete while still keeping the w/c ratio low, superplasticizers can be used. The use of silica fume will also improve the effectiveness of the superplasticizers further increasing the workability or alternatively less superplasticizer can be used for the same effect. [32]

Silica-Portland cements often require a higher slump due to the highly cohesive and dense microstructure. Typically, a slump value of around 25-50 mm higher is required to achieve the same degree of compaction. If the water content in the concrete mixture is too low the concrete may become stiff and too cumbersome to work with. It is therefore recommended that a water content of 150 kg per cubic meter of concrete is used in order to prevent an overly stiff mixture. [32]

The inherent density of Portland-silica concretes can result in very low air content, thus requiring the need for air entraining admixtures. Often times Portland-silica concretes will require a larger amount of air entraining admixtures compared to regular Portland concretes to achieve the same amount of air content. A certain amount of air voids within the concrete are needed to protect it from freeze-thaw damage and deicing and spalling. [32]

Strength development and hydration

throughout the hydration process of Portland-silica concrete, pozzolanic reactions occur between the silica fume particles and the calcium hydroxide produced though the hydration of the cement particles. After a sufficient amount of the cement particles have been hydrated to saturation, the silica particles begin to dissolve in the resulting solution of calcium hydroxide, forming C-S-H products on their surface. This reaction process is more pronounced in the first few days of hydration and thereafter gradually slowing down. The fast reaction speed is due to the silica fume’s high degree of fineness which provides a large surface area for the nucleation of calcium hydroxide. The rapid speed of the reactions contributes to the early strength of the concrete and can be accelerated even further through the addition of granulated blast furnace slag to the mixture. As a result of the fast reaction speed within the concrete the internal temperature also rises at a faster rate. [32]

The silica-Portland cements tight microstructure prevents new water from entering the concrete, combined with the rapid rates of hydration this can cause early water depletion in the concrete.

Compared to pure Portland cements this causes the growth of strength to stop earlier. To circumvent the rapid drying of Portland-silica concretes, special curing methods can be employed, such as wetting or letting the concrete cure while submerged in water. Silica-Portland concretes cured in such a manner result in better strength development over time. However, the late-stage strength development of pure Portland concretes and concrete containing other mineral admixtures will still surpass that of silica-Portland concretes. [38] [39]

The maximum temperature and temperature development of the concrete will have an effect on the hydration speed. Lower temperatures retard the hydration process while higher temperatures accelerate it. The Portland-silica concrete's higher temperature will aid in accelerating the already quick hydration speed. The high temperature development can also aid to combat the negative effects of external temperature fluctuations. [40]

The early strength of Portland-silica concretes is mostly caused by the dense microstructure which develops early on in the hydration process. [39] The biggest difference comparted to pure Portland cements can be seen in the first 7 days after casting, this is due to the microstructure allowing for stresses to more effectively be carried by the aggregates within the concrete. [40]

Durability

The presence of silica fume particles in the concrete result in a reduction of pore size, with the effect being most pronounced when the silica content is up to 10%. Beyond this level, further increases in silica content do not produce a significant decrease in pore size. This is because a 10% concentration of silica fume is enough to cover the aggregate surface and fill the gaps between the Portland particles. While the use of other admixtures and additives can produce this effect, the use of silica fume results in the most noticeable effect due to its high degree of fineness. [32]

Concrete containing silica fume has reduced permeability, which highlights the importance of proper curing techniques using water. In addition to this lower permeability provides better protection against chloride intrusion. Compared to pure Portland concretes, the C-S-H products in Portland-silica concretes have a lower calcium oxide to silica ratio (C/S ratio) leading to increased absorption of aluminum and alkali ions. The concrete also contains less aluminum oxide and calcium hydroxide, making it more resistant to sulfate attacks since the sulfate can be absorbed to a greater degree by the C-S-H products. [41]

The susceptibility of freeze and thaw damage is increased when using silica fume as an admixture in concrete. This is especially true when using L-class admixtures (air entraining), the combinations of larger air voids combined with a dense microstructure inhibits the movement of water within. The critical level of water saturation is also decreased due to the fine pore structure, while also impending the penetration of new water which would otherwise help prevent frost and thawing damage. Furthermore, Portland-silica concrete is also more prone to shrinkage compared to other types of concrete, with an increase in shrinkage of approximately 15%. As concrete undergoes shrinkage, stresses are generated on its surface and result in cracking. The boundary conditions of the structure can exacerbate this effect. If the concrete is restrained by other structures or reinforcement bars, the stress caused by shrinkage will be even greater causing increased cracking. [42] [41]

Bleeding is a phenomenon where water moves up to the surface of the concrete mixture causing segregation and weak planes between cement particles. The addition of silica fume can reduce the bleeding by absorbing some of the free water in the mix, making the mixture more homogeneous and resulting in fewer areas of weak planes and segregation. As previously mentioned, the silica fume results in finer capillary pores which limit the movement of water through the concrete by capillary action, which also contributes to reduced bleeding. A lower amount of bleeding ultimately results in a surface that is less susceptible to abrasion damage. [43]

2.5.3. Slag

Blast furnace slag is a byproduct of the iron making process and is produced when iron ore is smelted in a blast furnace to produce pig iron. The production of steel and iron is essential around the world, the resulting byproduct (slag) is therefore unavoidable. Around 300kg of slag is produced for every ton of pig iron. The slag is composed of a combination of silicates, aluminosilicates, and oxides. The composition of the slag is dependent on a variety of factors such as the type of iron ore being smelted, the temperature of the furnace and the cooling method use to solidify the molten slag. In order for the slag to be suitable as a cement replacement it needs to be quenched to avoid crystallization. [44]

The most common compounds found in blast furnace slag include:

- Calcium oxide (CaO): 38-50%
- Silicon dioxide (SiO_2): 27-39%
- Aluminum oxide (Al_2O_3): 8-20%
- Magnesium oxide (MgO): <10%

Blast furnace slag my also contains other minerals and elements in small amounts such as phosphorus, sulfur, and heavy metals. Although these are not present in large quantities, they can still be a cause of concern regarding health risks and environmental damage.

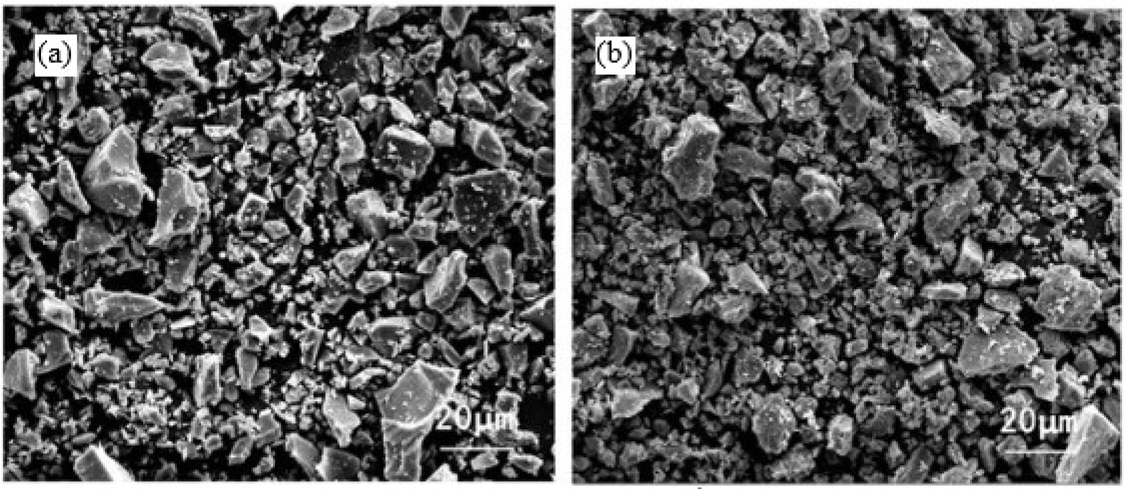


Figure 2-7: SEM images of (a) blast furnace slag. (b) cement clinker. [45]

The shape of the slag particles is sharp edged, unlike the spherical shape of fly ash particles. Slag usually appears light gray in color, which contributes to the bright appearance of slag-based concrete in comparison to pure Portland concretes. Moreover, the density of slag is slightly lower than that of conventional Portland cement, which has an average density of about 3000 $\frac{kg}{m^3}$ while slag has a density of around 2900-2950 $\frac{kg}{m^3}$. [32]

There are several ways in which slag can be incorporated as a binding material in concrete, either by itself as a raw material in the conventional production of clinker or by combining it with other binders. The most commonly used method is to blend the slag with the cement. This is done by finely grounding the slag to an appropriate level of fineness and then dry mixing it with Portland cement. The ratio of slag to Portland cement can be adjusted to accommodate the requirements of both consumers and manufacturers however the quantity of slag is a key factor in the classification of the cement.

The different classifications of slag cements are in accordance with NS-EN 197-1:2011: [10]

- CEM III/A: 36-65% slag
- CEM II/A-S: 6-20% slag
- CEM III/B: 81-95% slag
- CEM II/B-S: 21-35% slag
- CEM III/C: 81-95% slag

Properties in fresh concrete

Slag generally has a higher level of fineness compared to regular Portland cement, usually exceeding 350 $\frac{m^2}{kg}$. Due to its high fineness, slag can accelerate the reaction rate during the initial stages of curing. Furthermore, the fine slag particles contribute to increasing the density of fresh concrete by evenly distributing slag and Portland particles in the cement paste, resulting in a more compact structure. The denser structure of the fresh concrete enhances its cohesiveness and workability. This higher degree of cohesion counteracts separation of the cement and aggregates in the fresh concrete, slag concretes are therefore highly resistant to bleeding as opposed to regular concrete. [32]

Compered to Portland cements, slag cements exhibit slower heat development and lower peak temperature, which can lead to a delayed setting time. The increase in setting time can vary depending on the percentage of slag content but will typically range from 30-60 minutes or more. Slag cements are also more sensitive to adjustments in water content compared to pure Portland cement. However, reduction in the w/c ratio can still result in equivalent workability for fresh concrete. [46]

Strength development and hydration

When water is added to Portland-slag cement, the Portland cement particles are the first to hydrate, while the slag splits off small amounts of calcium and aluminum ions. For the slag to hydrate hydroxyl ions are need, these ions come from the cement particles and help break down the glass material in the slag making it available to react with alkali hydroxides. Once the slag has reacted with the alkali hydroxides it then reacts with the calcium hydroxide released by the Portland cement particles, forming C-S-H products. By reaction with any alkalis present in the aggregate and Portland cement, the reaction products of the slag prevent these alkalis from being available to react with the silica particles present in the concrete. This, in turn, reduces the likelihood of harmful alkali-silica reactions which can lead to cracks and damage in the concrete. Additionally, this process allows for greater flexibility when selecting Portland cement and aggregates with higher levels of alkalis. Typically, finer Portland cements have better long-term strength development when combined with slag due to the higher amounts of alkalis and C_3A content. [43]

It is important to note that the strength development of slag containing concrete differs from that of pure Portland concrete. Slag concrete develops strength at a slower rate depending on om the amount of slag used. Generally, good strength development is observed in the midterm when the slag content is around 50% of the effective binder. The best long term strength development occurred at slag contents of 50-75%. The typical tradeoff with slag concretes compared to pure Portland concretes is a slower strength development for better long-term strength. [32]

Durability

Due to the dense nature of slag concretes the permeability is significantly reduced when compared to pure Portland concretes. The permeability difference between the two can even approach a factor of 100. The reduced permeability aids in increased durability and results in smaller capillary pores which protect the concrete from salt intrusion. [32]

2.6. K-value for mineral admixtures

The k-value is a value used in the calculation of the concretes mass ratio; this method is known as the k-value method. The k-value is used to quantify the efficiency of the mineral admixtures used, due to their physical and chemical properties they are often used as a partial replacement of the cement. A k-value above 1.0 indicates that the added admixtures are more beneficial than cement whereas values bellow 1.0 indicate that the material is less beneficial. The mass ratio of a given concrete is determined through the following formula: [47]

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

Where,

m is the mass ratio of water to binder
v is the total free water content
c is the cement content
k k-value for a given admixture, such as fly ash
p is the amount of mineral admixtures

Addition criteria regarding the ratio of admixtures to binder are given in NS-EN 206: [25]

- For fly Ash: $\frac{p}{c} \leq 0,35$
- For silica fume: $\frac{p}{c} \leq 0,11$
- For slag: $\frac{p}{c} \leq 0,80$
- For slag combined with mixed fly ash in the cement: $\frac{p}{c} \leq 0,60$

The guidelines regarding what k-value should be selected are found in NS-EN 206. The durability and classification of the concrete dictates which value should be used.

Fly ash

<table>
<tr><th rowspan="2">Sementtype</th><th colspan="6">Bestandighetsklasse a, b, c</th></tr>
<tr><th>M90</th><th>M60</th><th>M45</th><th>MF45</th><th>M40</th><th>MF40</th></tr>
<tr><td>CEM I</td><td rowspan="3">1,0</td><td rowspan="3">0,4</td><td rowspan="3">0,7</td><td rowspan="2">0,7</td><td rowspan="3">0,7</td><td rowspan="2">0,7</td></tr>
<tr><td>CEM II/A-V, CEM II/A-S d,
CEM II/A-L d, CEM II/A-LL d
CEM II/A-D d, CEM II/A-M e, d</td></tr>
<tr><td>CEM II/B-V, CEM II/B-S d, CEM II/B-M e, d</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>Øvrige sementer</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

a Innblanding av flygeaske kan medregnes ved beregning av masseforhold og minste effektive bindemiddelmengde i henhold til kravene i tabell NA.12.
b "-" i tabellen betyr at Norsk Standard ikke gir regler for dette i denne kombinasjonen av sementtype og bestandighetsklasse. Det henvises også til NA.5.3.2(902).
c Verdiene gjelder for sement med en styrkeklasse på minst 42,5. For lavere styrkeklasser reduseres verdiene med 0,1.
d For andre bestandighetsklasser enn M90 benyttes *k*-verdien for mengden tilsatt flygeaske inntil andel Portlandsementklinker (K) er redusert til 50 % av bindemiddelmengden.
e Regelen omfatter sementtypene CEM II/A-M og CEM II/B-M som kun er basert på hovedkomponentene klinker (K), flygeaske (V), slagg (S) og kalksteinfiller (L og LL).

Figure 2-8: Recommended k-value for fly ash [25]

Silica fume

Sementtype	Bestandighetsklasse a, b					
	M90	M60	M45	MF45	M40	MF40
Sementer som det er gitt regler for i NA.5.3.2, tabell NA.12	1,0	1,0	2,0	2,0	2,0	2,0
Øvrige sementer	-	-	-	-	-	-

a Innblanding av silikastøv kan medregnes ved beregning av masseforhold og minste effektive bindemiddelmengde i henhold til kravene i tabell NA.12.
b "-" i tabellen betyr at Norsk Standard ikke gir regler for dette i denne kombinasjonen av sementtype og bestandighetsklasse. Det henvises også til NA.5.3.2(902).

Figure 2-9: Recommended k-value for silica fume [25]

Slag

<table>
<tr><th rowspan="2">Sementtype</th><th colspan="6">Bestandighetsklasse a, b, c, d</th></tr>
<tr><th>M90</th><th>M60</th><th>M45</th><th>MF45</th><th>M40</th><th>MF40</th></tr>
<tr><td>CEM I</td><td rowspan="4">1,0</td><td rowspan="4">0,5</td><td rowspan="4">0,8</td><td rowspan="2">0,8</td><td rowspan="4">0,8</td><td rowspan="2">0,8</td></tr>
<tr><td>CEM II/A-V, CEM II/A-S, CEM II/A-L e,
CEM II/A-LL e, CEM II/A-D e, CEM II/A-M e, f</td></tr>
<tr><td>CEM II/B-V, CEM II/B-S, CEM II/B-M e, f</td><td rowspan="3">-</td><td rowspan="3">-</td></tr>
<tr><td>CEM III/A, CEM III/B</td></tr>
<tr><td>Øvrige sementer</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

a Innblanding av slagg kan medregnes ved beregning av masseforhold og minste effektive bindemiddelmengde i henhold til kravene i tabell NA.12.
b "-" i tabellen betyr at Norsk Standard ikke gir regler for dette i denne kombinasjonen av sementtype og bestandighetsklasse. Det henvises også til NA.5.3.2(902).
c Verdiene gjelder for sement med en styrkeklasse på minst CEM 42,5. For lavere styrkeklasser reduseres verdiene med 0,1.
d Angitt *k*-verdi brukes for hele den tilsatte mengden slagg (ut over eventuelt innhold i sementen) inntil beregningsmessig grense for totalt slagginnhold er nådd, se under.
e *k*-verdien kan brukes for en mengde tilsatt slagg inntil andel Portlandsementklinker (K) er redusert til 40 % av bindemiddelmengden.
f Regelen omfatter sementtypene CEM II/A-M og CEM II/B-M som kun er basert på hovedkomponentene klinker (K), flygeaske (V), slagg (S) og kalksteinfiller (L og LL).

Figure 2-10:Recommended k-value for slag [25]

2.7. Other forms of environmentally friendly concrete

Recycled concrete

When old concrete buildings are demolished, the concrete debris can be recycled and used as natural aggregate when creating new concrete and structures. The concrete is crushed, cleaned, and sorted in order to separate the aggregates from the fines. The main advantages of reusing old concrete as aggregates is that new aggregates don't need to be extract from a quarry and processed, this in turn reduces the environmental impact of new concrete that uses recycled concrete aggregates. The recycled aggregates can also serve a backfilling material for the foundation of new structures. [48] [49]

Alternative fuels

During cement production large amounts of fuel and energy are used to heat and smelt the raw materials into clinker. As coal is the most common energy source in the world, replacing it with a more environmentally friendly fuel such as biofuel, waste, or electricity from renewable sources such as solar, wind or hydro power can lower the total environmental impact associated with clinker production. [50]

Carbon capture

Carbon capture is the process of capturing the CO_2 emissions generated during clinker production and storing them so that they aren't released into the atmosphere. There are several types of carbon capture technology however it is still in the early stages of development and can be expensive to implement. One method is to use solvents and absorbents to directly capture the exhaust gases and then compress them. Another method is to burn the fuel with pure oxygen which results in a concentrated stream of CO_2 which is easier to capture. Once the carbon has been captured and compressed in can be stored in deep geological formations such as depleted oil and gas wells or deep unmineable coal seams. [51]

3. Methods for assessment of environmental impact

3.1. EPDs

Environmental product declarations (EPDs) are reports that provide detailed and thorough information about a products environmental impact throughout its lifecycle. These reports follow strict guidelines, including the ISO 14040 series of standards in order to ensure consistency and accuracy across different types of products and industries. EPDs typically include information on a product's energy and resource use, greenhouse gas emissions, water consumption and other environmental impacts. [52]

One of the key benefits of EPDs is that they provide a standardized way of comparing the environmental impact of different products within the same category. For example, if a building contractor is looking for building materials with the lowest environmental impact, they can directly compare the EPDs of each product and make an informed decision. [52]

When creating EPDs for building materials a process called life cycle assessment (LCA) is used. This process involves evaluating the environmental impact of a product from cradle to grave, cradle to gate to gate to cradle. The LCA process includes multiple stages such as raw material extractions, transportation, manufacturing, and distribution. Throughout each stage the data on energy and resource use, emissions and waste generation by the product is collected. [52]

The Norwegian standard NS-EN 15804+A2 which is based on the international ISO 14025 is used for the development of EPDs (in Norway). The standard defines the principles and procedures for developing Type III environmental declarations. The different types of labels/declarations are: [53]

- Type III: Type III declarations are based on LCAs and generally provide detailed information about a service or product's environmental impact across its entire life cycle. These types of declarations are third-party verified, and the information is presented in standardized format. This allows proper comparison between products or services. [54]
- Type II: Type II declarations are self-declared environmental claims made by the manufacturers of a certain product. However, they are still based on standardized criteria and eco labels. The intention of these types of declaration is to provide consumers with information regarding the environmental attributes of a service or product but the reliability of the claims may vary due to them not being independently verified. [55]
- Type I: Type I labels are labels that are given to services or products that have met predetermined environmental criteria. They are based on a comprehensive evaluation of the product or service's impact on the environment throughout its life cycle. [54]

The main distinguishing factor between type III and type I declarations is that they serve different purposes and proved differing levels of detail about a product's environmental impact. Type I labels are most often used in order to easily identify more environmentally friendly or preferable products. Type III declaration, like EDPs, serve to provide a more comprehensive and detailed evaluation of a product's environmental performance.

3.2. Environmental indicators

In order to quantify and express the environmental impacts of a product, process or service certain environmental indicators are used during an LCA. These indicators are typically used to measure the potential environmental impact across a wide range of impact categories such as global warming potential, human toxicity, acidification potential, eutrophication potential, ozone deplete potential etc. It is important to note that in accordance with ISO 14044 the impact categories that are selected need to be consistent with the intended applications and goals of the LCA as well as be comprehensive such that they cover the main environmental issues relate to the structural system. Therefore, the selected indicators can vary for each individual analysis. [56] [57]

3.2.1. Global warming potential

Global warming potential (GWP) is used to measure how different greenhouse gases impact the earth's environment. It is a metric used to compare gases such as carbon dioxide, methane, and nitrous oxide. The GWP of a gas is defined as the relative warming effect compared to that of carbon dioxide over a specific time frame. Typically, a time period of 100 years is used but can vary depending on the specific application. [58]

The particular value for the GWP of different greenhouse gases is found using characterization factors. Characterization factors are derived from scientific models that estimate how various stressors might affect the impact categories such as climate change. For example, if the amount of nitrous oxide emissions from a factory is known, a characterization factor can be applied in order to estimate how much these emissions translate to carbon dioxide equivalents. The factors can however differ depending on circumstances such as geography, time and specific method used for LCA analysis. [59] The Intergovernmental Panel on Climate Change (IPCC) provides characterization factors (essentially the GWP value) for different greenhouse gases. These values are based on scientific literature and provide a standardized methodology of calculating the relative warming effect of the different greenhouse gases.

The GWP values are based on their respective radiative forcing, which accounts for factors such as their atmospheric lifetime and their ability to absorb and emit radiation. The GWP of a given emission is the ratio of heat radiation absorption resulting from the instantaneous release of that specific greenhouse gas and an equal emission from carbon dioxide integrated over a given period: [60]

$$GWP_i = \frac{\int_0^T a_i c_i(t)dt}{\int_0^T a_{CO_2} c_{CO_2}(t)dt}$$

$$Greenhouse\ effect = \sum_i GWP_i * m_i$$

Where,

a_i is the heat radiation absorption per unit concentration increase of a greenhouse gas *i*.
$c_i(t)$ is the concentration of greenhouse gas *i* at time *t* after release.
T is the time period in years over which the integration was made.
m_i is the total amount of gas *i* emitted into the atmosphere.

Gas	Chemical formula	Lifetime (years)	Global warming potential (Time horizon)		
			20 years	100 years	500 years
Carbon dioxide	CO_2	variable	1	1	1
Methane	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-134a (hydrofluorocarbon)	CH_2FCF_3	14.6	3400	1300	420
HFC-23 (hydrofluorocarbon)	CHF_3	264	9100	11700	9800
Sulfur hexafluoride	SF_6	3200	16300	23900	34900

Table 3-1: GWP values for different greenhouse gases provided by the IPCC [60]

However, it is important to note that the values provided by the IPCC are not absolute but rather relative values that are used for general comparison. These values are based on a range of uncertainties and assumptions and can vary depending on the selected time period and other factors considered in the assessment.

3.2.2. Acidification potential

When assessing the potential impact of a product or process, acidification is an important category to consider as it can result in acid rain which can cause harm to wildlife, plants, and aquatic ecosystems. The assessment typically involves analyzing the emissions of acidifying substances, including nitrogen oxides, nitrogen monoxide and sulfur dioxide throughout the products or process' life cycle. [61]

Similarly, to the method used for calculation of GWP, the acidification potential of different substances is measured using $H^{+}equvalents$, a characterization factor is used in order to quantify their acidification compared to sulfur dioxide. In practice this means that the acidification potential (AP) of a substance is defined as the ratio between the number of $H^{+}equvalents$ for that given substance to the $H^{+}equvalents$ of Sulfur dioxide. [59]

$$AP_i = \frac{v_i / M_i}{v_{SO_2} / M_{SO_2}}$$

$$acidification = \sum_i AP_i * m_i$$

Where,

v_i is the potential $H^{+}equvalents$ of a substance *i*.
M_i is the mass of substance *i*.
m_i is the total amount of gas *i* emitted into the atmosphere.

The three most common emissions that contribute to acidification are presented:

Acidifying emissions	Chemical formula	AP	Unit	Common sources
Sulfur dioxide	SO_2	1	$\frac{kg\ SO_2eq}{kg}$	Combustion of heavy fuels
Ammonia	NH_3	1.88	$\frac{kg\ SO_2eq}{kg}$	Industry and agriculture
Nitrogen oxides	NO_x	0.7	$\frac{kg\ SO_2eq}{kg}$	Biomass, combustion of fuels

Table 3-2: Common emissions that contribute to acidification and their respective characterization factors [59]

3.2.3. Photochemical ozone creation potential

Photochemical ozone creation potential (POCP) is used to measure the potential of volatile organic compounds (VOC) to generate ozone (O_3) through a sunlight-initiated oxidation in the presence of nitrogen oxides. VOCs have a large magnitude of emission sources such as vehicles, factories, and other industrial processes. [61]

Limiting emissions of VOCs and NOx is a strategy that can be employed in order to reduce ozone levels during photochemical pollution. However, the effectiveness of these measures varies depending on the ambient conditions. Cases of a high nitrogen oxides to VOCs ratio is deemed to be more beneficial than a low ratio meaning that reducing the emissions of VOC rather than NOx is more effective at lowering ozone levels. Developing an index to indicate the relative impact of various VOCs on ozone formation is complex and challenging. One established approach is to use atmospheric boundary layer models with detailed chemical mechanisms that include all factors that affect ozone production from a specific VOC. These models quantify ground level ozone formation under conditions that simulate the real atmospheric boundary layer. This has led to the development of reactivity or ozone formation potential (OFP) scales, the POCP scale being one of the most widely known and utilized. Derwent and co. developed the POCP scale to represent the ozone formation in north-western Europe and is based on a boundary layer section of air over a period of multiple days. The air is idealized to travel in a straight-line trajectory which is set to originate over Austria and stops in the UK, this is all done using a photochemical trajectory model PTM. [62]

In order to determine the POCP of a specific VOC, the impact of a slight increase in its emission is measured by comparing the calculated amount of ozone formed to that resulting from an identical increase in the emission (based on mass) of a reference VOC. The reference VOC most commonly used is ethene. Therefore, the POCP of a VOC_i is defined as follows: [62]

$$POCP_i = \frac{O_3(VOC_i) - O_3(base)}{O_3(ethene) - O_3(base)}$$

$$Oxidant\ formation = \sum_i POCP_i * m_i$$

Where,

$O_3(base)$	is the simulated ozone level in the base case.
$O_3(VOC_i)$	is the simulated ozone level when the emissions of VOC_i are incrementally increased.

$O_3(ethene)$ is the simulated ozone level when the emissions of ethene are incrementally increased.
m_i is the total amount of gas/VOC i emitted into the atmosphere.

VOC	Chemical formula	POCP (based on PTM model)
Ethene	C_2H_4	1
Propane	C_3H_8	0.183
Pentane	C_5H_{12}	0.366
2,3-dimethylbutane	C_6H_{14}	0.542
Propene	C_3H_6	1.054
Butan-1-ol	C_4H_9OH	0.539
Formaldehyde	CH_2O	0.471
Propanal	C_3H_6O	0.612
Acetone	C_3H_6O	0.075
Butan-2-one	C_4H_8O	35.3
Pentan-2-one	$C_5H_{10}O$	50.4

Table 3-3: POCP of VOCs [59]

3.2.4. Abiotic depletion potential

Abiotic depletion potential (ADP) is an environmental assessment indicator commonly used to measure the depletion of nonrenewable natural resources. ADP can be subdivided into two main categories, namely fossil fuel depletion potential (ADPE) and mineral depletion potential (ADPM). ADPE is used for resources such as coal, oil and natural gas and considers the total availability and concentration of fossil carbon in the earth's crust. ADPM is applicable to non-fuel minerals and metals such as industrial minerals (bauxite, gypsum, mineral sands etc.), copper, iron, and aluminum. [61]

ADPM is found as the ratio of percent total extracted resource to the reference resource, antimony. [59]

$$ADPM_i = \frac{DR_i / (R_i)^2}{DR_{ref} / (R_{ref})^2}$$

$$Total\ abiotic\ depletion = \sum_i ADP_i * m_i$$

Where,

m_i is the quantity of resource extracted in kg.
R_i is the total reserve of a resource in kg.
DR_i is the extraction rate of resource i in kg per year.

The same method is used for fossil fuel depletion (ADPE) however fossil fuel extraction is quantified as the fuel's energy in MJ.

3.2.5. Eutrophication potential

Eutrophication potential (EP) is an indicator used to quantify the release of nutrients into the surrounding environment. The discharge of nutrients such as phosphorus and nitrogen into soil or freshwater bodies leads to freshwater eutrophication. This in turn has various environmental impacts. Freshwater eutrophication results in a sequence of ecological impacts, starting with increased nutrient emissions into freshwater, leading to greater nutrient uptake by autotrophic organisms like cyanobacteria and algae as well as heterotrophic species such as fish and invertebrates. Ultimately, this results in a relative loss of species and Eco diversity. This shift in diversity is often observed by rapid algal growth and leads to a lack of oxygen negatively affecting the fauna and flora of a freshwater body. The large increase of organic materials naturally increases the oxygen deficit which is created through the decomposition process of said organic matter. Therefore, a substance's EP is essentially its potential to contribute to biomass growth which results in the consumption of oxygen. Phosphate is the most common reference nutrient used to quantify the EP of other substances. EP is therefore expressed as phosphate equivalents (PO_4^{3-}). [61]

$$EP_i = \frac{v_i / M_i}{v_{PO_4^{3-}} / M_{PO_4^{3-}}}$$

$$Eutrophication = \sum_i EP_i * m_i$$

Where,

v_i is the potential biomass created by substance *i.*
M_i is the emitted quantity of substance *i.*
m_i is the total amount of units of substance *i* emitted.

Substance	**Chemical formula**	**EP ($\frac{kg\ PO_4^{3-}}{kg}$)**
Phosphate	PO_4	1.00
Phosphorus	P	3.06
Nitrate	NO_3	0.42
Ammonia	NH_3	0.33
Nitrogen oxides	NO_x	0.13

Table 3-4: EP of common substances

3.2.6. Ozone depletion potential

Ozone depletion potential (ODP) is an environmental indicator that was developed in order to evaluate the potential of long-lived gases, which often have a multiyear atmospheric lifetime, to impact the stratospheric ozone. The stratospheric ozone is of particular interest due to roughly 90% of the total ozone being contained in this layer, with the remaining ozone being in the troposphere. The ODP concept employs the reduction in total column ozone because the entirety of the ozone found in all layers contributes to protecting humans and the biosphere against elevated levels of ultraviolet radiation. [61]

As with most environmental indicators the method of calculating the ODP of a specific substance is through comparing it to a given reference substance. The selected substance's effectiveness at depleting ozone is typically compared to that of trichlorofluoromethane (CFC-11). CFC-11 is a chlorofluorocarbon which was commonly used in refrigeration, air conditioning and aerosol products before being phased out by the Montreal protocol in 1987 due to is highly destructive impact on the ozone layer. CFC-11 therefore has a reference ODP value of 1.0. [59]

$$ODP_i = \frac{\Delta[O_3]_i}{\Delta[O_3]_{cfc-11}}$$

$$Total\ ozone\ depletion = \sum_i ODP_i * m_i$$

Where,

$\Delta[O_3]_i$ is the change in the ozone column due to annual emissions of substance i.
m_i is the amount of emissions in kg.

3.2.7. Summary

Environmental indicators are used within an LCA to quantify the different impacts that a product or service can have on environment. It is however important to note that there is no "correct" amount of indicators that have to be included. The indicators outlined in the section above are only the mandatory indicators as defined by NS-EN 15804/NS-EN 15978 and aren't necessarily always included in every LCA (depending on which standard is followed if at all). Which indicators and impact categories are included is entirely up to the scope and goals of the LCA being conducted and are therefore selected on a case-by-case basis.

Indicator	Abbreviation	Unit
Global Warming Potential	GWP	kg CO_2 eq.
Depletion potential of ozone layer	ODP	kg $CFC-11$ eq.
Acidification potential of land and water	AP	kg SO_{2-} eq.
Eutrophication potential	EP	kg PO_4^{3-} eq.
Formation potential of ozone photochemical oxidants	POCP	kg C_2H_4 eq.
Abiotic resource depletion potential of minerals	$ADP_{minerals}$	kg Sb eq.
Abiotic resource depletion potential of fossil fuels	$ADP_{fossil\ fuels}$	MJ, net calorific value

Table 3-5: Necessary indicators describing environmental impacts according to NS-EN 15804/NS-EN 15978.

3.3. General LCA framework

The framework on how to conduct an LCA can depend on the scope of the project, use applications, importance and most importantly budget. The highest quality assurance comes from following the guidelines provided by the ISO 14040 standard and CEN/TC 350 standards. The main steps involved in an LCA as outlined in ISO 14040 can be broken down into: [63]

- Definition of the scope and goals of the project
- Inventory analysis
- Impact analysis
- Interpretation of results

The figure bellow demonstrates the flow of the analysis. The two-way arrows indicate that the entire process is iterative and interactive in nature. For example, when you have gotten to the impact assessment stage, it may become apparent that specific data or information critical to the LCA is missing or misrepresented. This means that there is a need to circle back to the inventory collection/analysis phase in order to correct this oversight/error and repeat the impact assessment. Another case may be the discovery of errors or insufficient data during the interpretation of the results. If the results are unclear or don’t fulfill the set requirements, then the scope and goals of the study need to be revised and edited. [64]

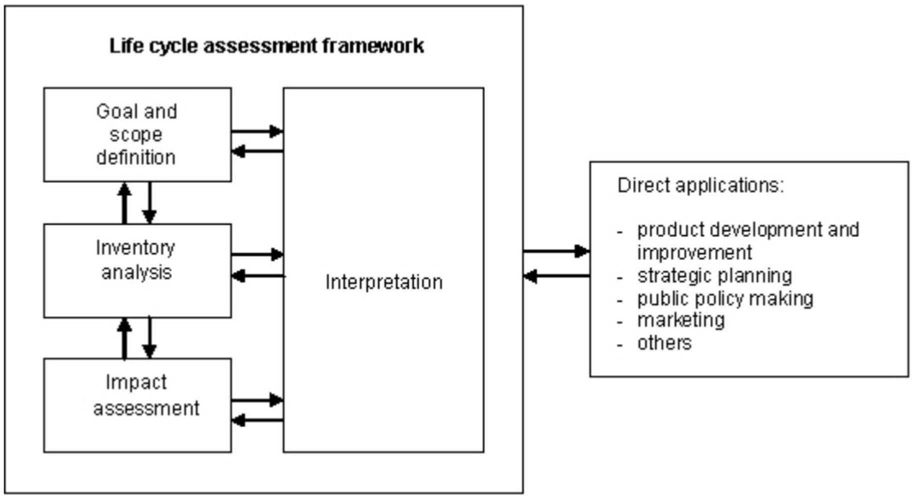


Figure 3-1:LCA framework as described in ISO 14040 [63]

3.3.1. Goal and scope definition

A critical aspect in the initial phase of the LCA is determining the scope and goals of the study. This step plays a crucial role in guiding the decision-making process throughout the subsequent stages of the study. To ensure that the study’s purpose, intended use of results, and scope are clearly defined, it is advisable to allocate ample time to this phase. Doing so can ultimately save time during the later stages.

Defining the goal of the study

According to the ISO 14040 standard, when defining the goal of an LCA study, it is important to consider several factors: [63]

- What is the reason for carrying out the study and its application
- Who is the intended audience (to who the results are intended to be communicated)
- Whether the results are intended to be used as a comparative analysis and if it is going to be disclosed to the public (comparative assertion)

The definition of the goal for an LCA study should be a collaborative effort between the party requesting the study and the study team. Their reasons for conducting the study as well as where they're going to be applied and the audience for the results should be clearly understood and documented to establish the scope of the study. [65] [66]

The purpose and intended applications of the study may vary, such as conducting an LCA for a product for the first time to identify where the primary environmental impacts occur. Questions that may arise during this process include identifying the dominant environmental impacts of the product or services and determining which stages of the product or services' life cycle have the most significant contribution to its overall impact. Additionally, the study may seek to identify opportunities to improve the products or services environmental performance. [65] [66]

The intended audience for the study results may differ as well, ranging from internal use for product development to external communication to customers or consumers. It is important to clarify the intended audience to determine the appropriate level of detail and transparency required in the study, as well as the appropriate format for communicating the results. [65] [66]

A comparative assertion refers to a certain product which claims its environmental performance is equal to or better than rivaling products. Due to the potential impact and severity of such a claim, there are specific rules and guidelines that must be followed for this type of LCA to be considered valid. These rules typically include specific reporting requirements, such as the need to provide transparent and accurate information on the methods that were used to conduct the LCA, the data sources used, and the assumptions made. In addition, to ensure the credibility of the results, a critical review of the study should be conducted by a review panel. Review panels typically consist of independent experts and representatives from relevant stakeholder groups such as industry associations, NGOs, and government agencies. The panel's role is to review the LCA study's methodology, data, and assumptions as well as to assess the validity and reliability of the results. [65]

Defining the scope of the study

When determining the scope of the study, it is important to ensure that the goal can be achieved within the defined limitations. The scope should provide a detailed and comprehensive description of the study, taking into account the following aspects:

- The product system
- The functional unit, reference flow and what functions the product system has
- System boundaries
- Allocation procedures
- The methodology for environmental impact assessment
- Types of impacts to be considered and interpretation to be performed
- Data and data quality requirements
- Limitations and assumptions
- Critical review considerations
- Format of the final report as required by the study

It is important to note that due to the iterative nature of an LCA various aspects outlined above may need to be modified throughout the process such that they meet the goals of the study. [65]

Function, functional unit, and reference flow

Defining the functional unit is a crucial element of the LCA study as it expresses the product system's delivered function. The functional unit is a quantitative measure on the studied systems function and is used as a reference to which the inputs and outputs of the product system are related. This enables the comparison of two different product systems. For instance, in the case of concrete, the functional unit may be defied as per cubic meter poured or per ton of concrete used. This definition enables a comparison of the environmental impact of two different types of concrete with the same functional unit even if they have different technical properties concerning composition, durability, maintenance etc. The reference flow refers to the physical flow of energy or materials required to fulfil the functional unit. In the case of concrete, the reference flow could be the amount of cement required to create one cubic meter of concrete. This again varies depending on the technical specifications of the concrete. [65] [66]

Product system and system boundaries

The boundaries of the system specify the unit processes encompassed by the product system, as well as the inputs and outputs that are considered. The decision regarding which processes to incorporate into the system is reliant on the study's objectives and how the results are intended to be used. [67]

Initially a flowchart of the product system should be developed to help in defining the system boundaries. This flowchart shows which processes should be included in the system and how they are connected. The flow chart serves as a basis for the inventory analysis phase of the LCA, where data is collected for each process in the chart. [67]

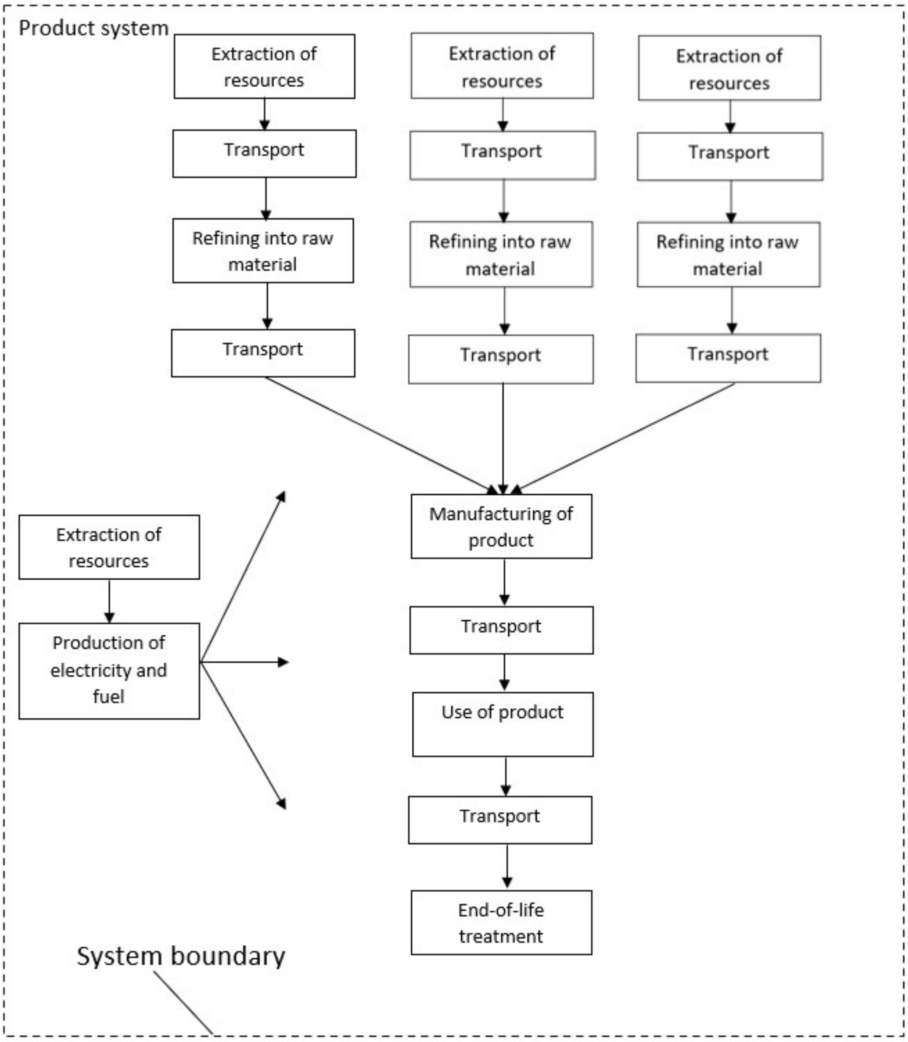


Figure 3-2: Example of a flowchart for a given product system

Given that most technical activities are interrelated, it is crucial to define which activities, inputs, and outputs to include and exclude. This helps to limit the scope of the study and focus on the most critical/important aspects. Excluding parts of a system or inputs and outputs is called "cut offs". However, the exclusion of life cycle stages must always be justified and based on the goal of the study. For example, in an LCA of a product, the construction and building of the production facility and machinery may be excluded because their impact is assumed to be so small in relation to the overall result. Even though the environmental impact of constructing the production factory may be large on its own, it is important to put it into context when regarding a singular product. A factory has the capability to manufacture thousands or millions of a single type of product and therefore contributes every little to each individual product's environmental footprint. [65] [66]

To define the inputs and outputs for an environmental system (elementary flows) it is necessary to determine which should be included in the life cycle of a product. The life cycle begins with the extraction of resources from the environment and continues with the various production and transportation processes that generate emissions into the environment. Waste is also generated which needs to be managed. Ultimately, the life cycle of a product ends with some form of end-of-life treatment, such as landfill leakage or emissions from waste incineration. [65] [66]

The selection of inputs and outputs that come from or go into the environmental system is determined by the environmental impact assessment and the specific environmental impacts that need to be evaluated in the LCA. Geographical and time-related factors may also need to be considered, such as regional ecosystem sensitivity to environmental impacts or varying atmospheric pollutant lifespans. [65] [66]

Allocation

To allocate means to divide inputs and outputs among the products being studied, which is required when a process produces multiple products. In such cases, the materials and energy inputs and environmental releases must be allocated to each of the different products generated by the process. The guidelines for allocation should be established during the goal and scope definition phase and should be consistently applied throughout the study. [65] [66]

Data quality

The accuracy and credibility of the LCA study results depend on the quality of the underlying data, specifically the data describing the processes which are included in different parts of the product system. Hence, it is crucial to establish data quality criteria, i.e., the level of data quality necessary to achieve the study's objective. This involves setting the data collection quality level for the upcoming inventory phase of the study. It is essential to determine which data should be collected, as well as how and where the data should be obtained. [65] [66]

ISO 14044 puts forth the following quality requirements that should be considered during the definition of scope phase:

- Time coverage, meaning what period of time should the data represent
- Geographical coverage, meaning what region should the data represent (different parts of a product are often sourced from different parts of the world)
- Technology coverage, meaning what level of technology should be included (specific technology, best available or industry average etc.)
- The precision and representativeness of the data
- Consistency and reproducibility of the study
- Sources of the data
- Uncertainty regarding the data (variance, standard deviation, model uncertainty as well as how knowledge gaps should be handled)

3.3.2. Inventory analysis

Life cycle inventory (LCI) is a crucial component of the LCA process, it involves collecting, quantifying, and analyzing data on the inputs and outputs associated with the life cycle stages of a product. Thereafter the product is analyzed and interpreted.

There are two main parts involved in the LCI:

- **Collection of data** for each of the processes that have been included in the defined product system. Verifications and validation of the data that has been collected should also be performed to ensure all requirements are met.
- **Aggregation into inventory result.** This process involves combining the inputs from each unit process to obtain the overall outcome for the product system. The resulting inventory outcome presents information on the resources and emissions such as those

released into the air, water, or soil (selection of indicators differs on a case-by-case basis).

Collection and validation of data

The quality of the data utilized for the LCA plays a pivotal role in the usefulness of the results, particularly in terms of its relevance, accuracy, and representativeness. Typically, data collection is the most time-intensive phase of the LCA. Hence, careful planning of data collection in accordance with the quality requirements required in the "Goal and scope" phase is critical. [65] [66]

The ISO 14044 standard outlines the main parts of the data collection process:

- Preparing for data collection
- Data collection
- Validation of collected data
- Allocation

Preparing for data collection

The data collection part generally includes 3 main steps:

- ➢ Determine for which processes you need to collect data
- ➢ Determine which sources shall be used to collect data
- ➢ Set the documentation requirements and format for all data

The initial phase in preparing for data collection involves identifying the unit processes for which data is required, utilizing the primary flow chart of the product system created during the Goal and scope phase. Data collection is necessary for every component included in the process system. [65] [66]

The following step is to determine and select the appropriate data sources for the data collection. The choice of data sources is dependent on the study’s objective and pre-established initial data quality requirements. Typical sources which are used for data are:

- Internal databases such as market statistics, specifications, recipes etc.
- Specific production processes, either internal or supplier production sites
- Estimates using mathematical and statistical modelling of similar processes
- External databases such as previously published LCAs or public databases

During the preparation phase, it is necessary to establish the level of ambition for data collection and to determine which processes within the product system needs to have site-specific information from internal databases and production processes, versus generic information derived from external databases, modeling, estimations, or literature. The selection of data sources should align with the study's goal, scope, and quality requirements. Defining data documentation requirements is an essential aspect of the study, as a significant amount of information is collected during the LCA process. To ensure that information is not lost and to guarantee proper interpretation and review of the included data, it must be structured and documented. Developing or selecting a format for data documentation should be of priority. The ISO/TS 14048 format is an established format within ISO for documenting LCI data and can be utilized as a basis for defining documentation requirements and actual documentation. Such requirements may include capturing information on the data collector, process scope and data acquisition and treatment. [65] [66]

Data collection forms or questionnaires may also be required, particularly when collecting data from suppliers. Proper design of these forms is necessary to ensure proper understanding among involved parties. Clear instructions and guidance on how to use and fill in the form or questionnaire may also be helpful. [65] [66]

Data collection

Once the necessary preparation have been made, data collection for each process included in the product system can begin. Data concerning inputs and outputs such as energy usage and raw material extraction, pollution to air, water and ground and generated waste are collected for each process. The considerations and issues to be mindful of during data collection may vary depending on the chosen data sources. Typically, data for specific production processes is gathered from a variety of internal sources. This may include using resource management systems to collect information on the usage of raw materials and energy, laboratory reports to collect information on emissions to air and water, and data from waste management companies to collect information on the amount of waste produced. Collaboration and guidance from relevant personnel is often required during this process to ensure the accuracy and proper interpretation of the data. [65] [66]

Internal databases and reports can provide additional information about the studied product in the LCA, such as product performance, usage patterns, market trends and disposal. The applicability of the data must be evaluated to make sure it fits the requirements and needs of the study and steps such as processing or remodeling may need be done before it is usable in the LCA. In certain cases, it may even be required to approximate or estimate data due to absence of direct data recordings. This can be done through the use of theoretical models regarding performance or yield of a certain process or using data from a similar production process or technology. Typically, such information can be gathered through scientific literature of experts of a specific process. [65] [66]

There are many external databases and literature containing LCA-data that are available for use. However, it is important to evaluate the transparency, quality, and applicability of the data as well as other limitations and potential restrictions such as secrecy or copyright that might have to be considered before use. [65] [66]

Validation of data

The data that has been collected in the data collection phase needs to be validated in order to ensure it meets the quality requirements. This can be done by conduction mass/energy balances (comparing inputs and outputs of mass and energy with accordance to the laws of conservation) or by comparing the gathered data to data for similar processes to assess its plausibility. [65] [66]

Allocation

Allocation of inputs and outputs may be necessary when a process produces more than one product. In this case the resources, waste and emissions need to be properly divided between the multiple products.
Guidelines regarding allocation are given in the ISO 14040 standard: [63]

- If possible, allocation should be avoided by increasing the detail level in the system
- If allocation is necessary, inputs and outputs need to be partitioned in such a manner that reflects the physical relationships between products.
- If the latter is not possible allocation should be carried out by other means such as existing relationships (e.g., economic value of products)

Aggregation into the inventory result

To begin the process of aggregating data, the first step is to organize and prepare the collected information for the specific unit processes included in the final product system. This is done by linking data to each unit process and then normalizing it to the functional unit. [65] [66]

Linking data to each unit process involves identifying the reference flow for each unit process and relating the inputs and outputs data to that flow. Typically, the reference flow for each unit process is determined during the construction and finalization of the flow chart, where the intermediate product flows connect the processes. All raw materials and energy inputs and outputs of each unit process should be associated with the corresponding reference flow. This may require assigning inputs and outputs between products. [65] [66]

Normalizing the data to the functional unit means adjusting the inputs and outputs of each unit process to match the defined functional unit for the study. Essentially, this involves determining the contribution of each unit process to the functional unit. [65] [66]

After preparing the collected data, the following step is to combine the inputs and outputs for all the unit processes included in the inventory. This involves utilizing the data that has been normalized to the functional unit, where the unit processes have been scaled accordingly. The process of aggregation entails combining inputs and outputs that share the same substance and environmental impact. For instance, the total CO2 emission to air for the product system is calculated by adding up the CO2 emissions to air from all the unit processes included in the inventory. This final result of the inventory represents the total environmental impact of the product system. [65] [66]

3.3.3. Life cycle impact assessment

During the life cycle impact assessment (LCIA) the potential environmental impacts caused by the product are evaluated based on the LCI results. ISO14040 divides the LCIA into mandatory and optional elements: [63]

Mandatory

- Selection of impact categories, category indicators and characterization models
- Classifications, i.e., assigning and relating the results from the LCI to the selected indicators
- Characterization, i.e., the LCI results are calculated into results for the selected indicators

Optional

- Normalization
- Grouping such as sorting into geographic relevance, ranking or priority
- Weighting by converting impact categories into a common unit

When conducting an LCA the impact assessment is carried out by using pre-existing impact assessment methodologies that involve a predetermined set of impact categories and indicators. The methods often already encompass classification and models for characterization and weighting. Various impact assessment methods exit, with some included solely the mandatory components and other incorporating additional, optional elements such as weighting. [65] [66]

3.3.4. Interpretation of results

Interpretation plays a vital role in LCA as it aims to draw conclusions and make recommendations in line with the study's defined goals and scope. The interpretation phase involves merging the results obtained during the LCI and LCIA phases and present a comprehensive and impartial report of the study. It is worth noting that interpretation is an ongoing process that occurs iteratively alongside other phases. Therefore, it is an essential component of the LCA process, whereby each intermediate outcome from different phases of the study is continuously evaluated and analyzed.

Three main elements are outlined in the ISO 14040 standard: [63]

- Identification of significant issues or inconsistencies of the LCI and LCIA results
- Evaluation of the results by considering data quality, consistency, sensitivity, and uncertainty analysis
- Draw conclusions, communicate limitations of the study, and provide recommendations

3.4. Process Based LCA

Process based LCA is a general methodology developed by The Society of Environmental Toxicology and Chemistry (SETAC) in collaboration with the U.S Environmental Protection Agency (EPA) in 1990. This method of conducting an LCA is based on breaking down and dividing the life cycle of a product or service into individual processes such as manufacturing, transportation, disposal etc. These individual processes are analyzed and further broken down into inputs and output like energy and materials flows, air, water and soil pollution and waste generation. Process based LCAs require a high degree of detail when creating the inventory of resource inputs and environmental impacts. Regarding cement and concrete production, process based LCA models are most common as they allow for quantification of resource inputs and environmental impacts at each stage based on mass-balance calculations. [68] [69]

3.5. Economic input-output analysis-based LCA

The economic input-output analysis based LCA (EIO-LCA) has its origins in the 1930s where I-O analysis was developed by Wassily Leontief. The method was further established by a number of researchers including Walter Stahel, Robert ayres and Barry commoner. Its use in LCA and environmental assessment started in the 1970s and was improved and further developed in the following decades by researchers and organizations such as United nations Environmental Program and Organization for Economic Co-operation and Development. [70]

In order to quantify the environmental impact of a product, EIO-LCA methods examine the economic transactions between different industries. The flow of goods and services between these industries are recorded in Input-output tables and allow for the calculation of total economic activity associated with the production of a specific product. In EIO-LCA the concept of embodied energy is used. This means that the amount of energy used to create a product is estimated. This estimation is done by looking at the embodied energy associated with each economic transaction and can proved and assessment of the environmental impact of creating a product. [71] The EIO-LCA methods can prove particularly useful for evaluating the indirect environmental impacts associated with raw material extraction and transportation. Pure EIO-LCA models are mostly shied away from due to only being able to provide averages and can't distinguish between average and marginal impacts. I-O tables using non-U.S. data are also unavailable/difficult to find. [70]

	Process based LCA models	**EIO-LCA models**
Advantages	Highly detailed and process specific analysis	Includes all direct and indirect environmental effects
	Comparison of specific products	Non-limited system. Includes industries, products, services, national economy
	Allows for process improvements and analysis of weak points	Ease of sensitivity analysis
	Assessment of future product development	Public data. Easily verifiable results
Disadvantages	Subjectively set system boundary	Aggregated data
	Use of proprietary data	Difficult to assess processes
	Cannot be reproduced/ difficulty to verify if confidential data is used	Difficult to link monetary values to physical units
	Time intensive and costly	Outdated data (based on prior trends and practices)
		Non-U.S. data is often unavailable

Table 3-6: Advantages and disadvantages of both model types

3.6. Hybrid LCA

A hybrid-based LCA model incorporates the advantages of both process-based and EIO LCAs and eliminates their short comings. There are multiple ways of incorporating a hybrid-based LCA, but one common approach is to use the process-based model's strength at estimating the environmental impact of a specific process within a products life cycle such as manufacturing. The EIO-based models can then be used to estimate the upstream and downstream impacts such as the environmental impact associated with the extraction of raw materials or the disposal of the product and the waste it generates. By combining each of these models, it is possible to fill in gaps of missing data and as a result get a much more comprehensive assessment of the environmental impact. [72]

3.7. Eco Indicator 99

The Eco Indicator (EI) method of impact assessment was first developed in 1995 by the Dutch research institute and PRé consultants in the Netherlands in collaboration with other companies such as Philips Consumer electronics, NedCar, CML Leiden and multiple others. The method was later improved and refined in the form of a successor, Eco Indicator 99. EI 99 included better scientific basis for the different damage models making it more reliable as well as incorporating more environmental indicators and an improved methodology for calculating them. [73]

EI 99 is a process-based impact assessment method that uses both a midpoint and endpoint assessment approach. This approach of using midpoints which are subsequently translated in into endpoints gives a much more detailed and comprehensive assessment and transparency. When using a midpoint-endpoint method the emissions are recorded in their initial form, they are thereafter converted to midpoint categories in order to quantify their impact on the environment. The midpoint impact categories which EI99 uses are climate change (GWP), ozone layer depletion (ODP), human toxicity (cancer effect, non-cancer effects, and systemic effects), photo-oxidant formation (POCP), acidification (AP), Eutrophication (EP), ecotoxicity (aquatic and terrestrial ecotoxicity), land use, mineral and fossil fuel depletion ($ADP_{mineral}$ and $ADP_{fossil\ fuel}$) and water depletion. The environmental impacts (midpoints) are translated into endpoint damage categories though a damage analysis. EI99 has three endpoint categories: [73]

- Human health: includes impacts on human health caused by exposure to pollution and other stressors such as respiratory effects, carcinogenic effects, and nervous system effects
- Ecosystem quality: includes impacts on biodiversity, soil quality and water quality caused by pollution
- Resource depletion: includes impacts on resources such as depletion of fossil fuels, minerals and metals caused by extraction.

When all the environmental impacts have been analyzed and aggregated into each of the three endpoint categories, each of the endpoints are then weighted and normalized. This differs from other impact assessment methods as normalization and weighting is done at the midpoint level. The EI99 method is therefore simpler as weighting and normalization only has to be done to three separate categories instead of tens of midpoints. Weighting midpoint impact categories require a lot of how the mechanism of damage works and is therefore highly complicated. After the weighting and normalization process is complete, the endpoints are aggregated into a single indicator score allowing for easy direct comparison of different products and services. EI99 is primarily suited for the European climate however some impact categories such as global warming and ozone depletion are relevant on a global scale. The entire flow of the EI 99 impact assessment methodology is shown in Figure 3-3. [73]

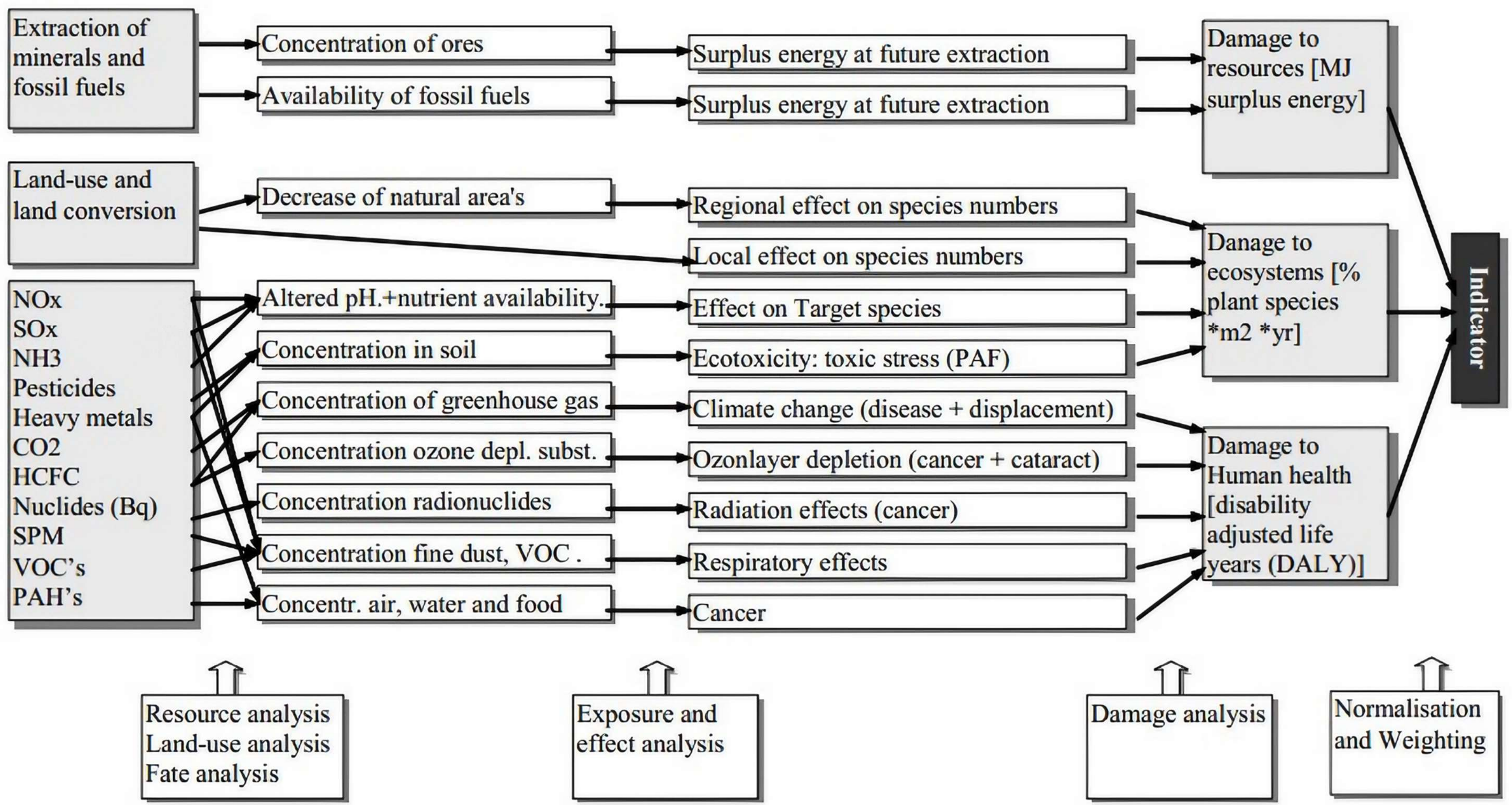


Figure 3-3: Pathways and impact categories covered by the EI99 method [73]

3.8. TRACI 2.1

The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) is a hybrid midpoint-oriented impact assessment method developed by the U.S. Environmental Protection Agency (EPA) and first released in 2008. TRACI's hybrid LCA approach means it uses a process-based approach to quantify and estimate direct environmental impacts while the IO-based approach is used to estimate upstream emissions associated with the production of inputs such as raw materials. The impact categories were defined at the midpoint level primarily because there is a higher degree of accuracy and lower uncertainty associated with modeling at this stage in the cause-effect chain. TRACI includes the following environmental impact categories: Ozone deplete, Global warming, Smog, Acidification, Eutrophication, Carcinogenics, non-carcinogenic, Respiratory effects, Eco toxicity and fossil fuel depletion. Each of these midpoints are normalized using normalization factors specifically developed for North America. TRACI 2.1 was created for the North American climate and can therefore be sub-optimal for use in Europe. [74]

3.9. CML

The CML methodology was first developed in 1992 by the institute of environmental sciences of the University of Leiden. CML uses a hybrid LCA model with a midpoint assessment approach. The method has two detail categories, a baseline, and an extended version. [75] The baseline includes 10 obligatory midpoint impact categories which are common among most LCA approaches. The obligatory categories are Depletion of abiotic resources ($ADP_{mineral}$ and $ADP_{fossil\ fuel}$), Climate change (GWP), Stratospheric ozone depletion (ODP), Human toxicity (HTP), Fresh water aquatic eco-toxicity (FAETP), Marine ecotoxicity, Terrestrial ecotoxicity, Terrestrial eco toxicity, Photo-oxidant formation (POCP), Acidification (AP) and Eutrophication (EP). Additional indicators may be added if the specific LCA study requires it. Weighting is not applied, and normalization of the indicators is based on the detail level of the LCA, for simplified LCA studies it is regarded as optional and mandatory for detailed LCA studies. The scores used for Normalization are calculated for reference scenarios: Global 1990, Europe 1995 and the Netherlands 1997. [76]

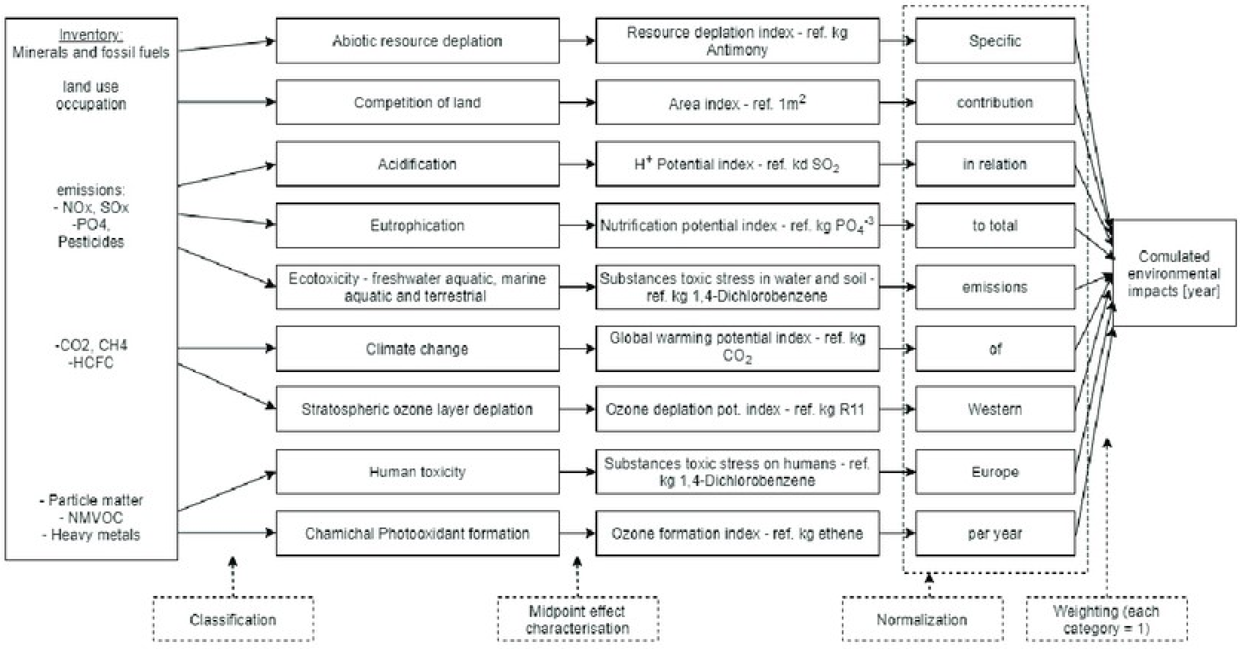


Figure 3-4: Baseline impact categories covered by CML

3.10. ReCiPe 2016

The ReCiPe 2016 methodology was developed by a group of international experts and researchers within the LCA field. The project was led by the European commission's Joint research center (JRC). The method uses a hybrid based LCA model with a midpoint-endpoint approach meaning its uses both problem oriented (midpoint) and damage oriented (endpoints) impact categories. These impact categories are given for three different perspectives which are individualist (I), hierarchist (H) and egalitarian (E). These groups are not taken as representations of archetypes of human behavior but are rather used to group assumptions, sources and magnitudes of uncertainty and value choices. The three groups are defined as follows: [77]

- Individualist perspective is based on the short-term interest, impact types that are undisputed, technological optimism as regards to human adaptation.
- Hierarchist perspective is based on the most common policy principles with regards to timeframe and issues.
- Egalitarian perspective is the most precautionary perspective, considering the longest timeframe, impact types that are not yet fully established but for which some indication is available.

The time horizon from each of the perspectives is 20,100 and 1000 years respectively. The ReCiPe method includes 18 midpoint impact assessment categories each with their respective characterization factors: Climate change, Stratospheric ozone depletion, Ionizing radiation, Ozone formation, human health, Fine particulate matter formation, Ozone formation, Terrestrial ecosystems, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Land use, Mineral resource scarcity, Fossil resource scarcity and Water use. The 18 midpoints are then aggregated into 3 endpoint damage categories: Human health, ecosystems, and Resource scarcity. The weighting of the impact categories is done through a panel approach and normalization factors based on the reference year 2010 are used in the normalization process. Each of these steps is dependent on which perspective is chosen to be used (I, H or E), the hierarchist perspective is the most commonly accepted for scientific and political purposes. [77]

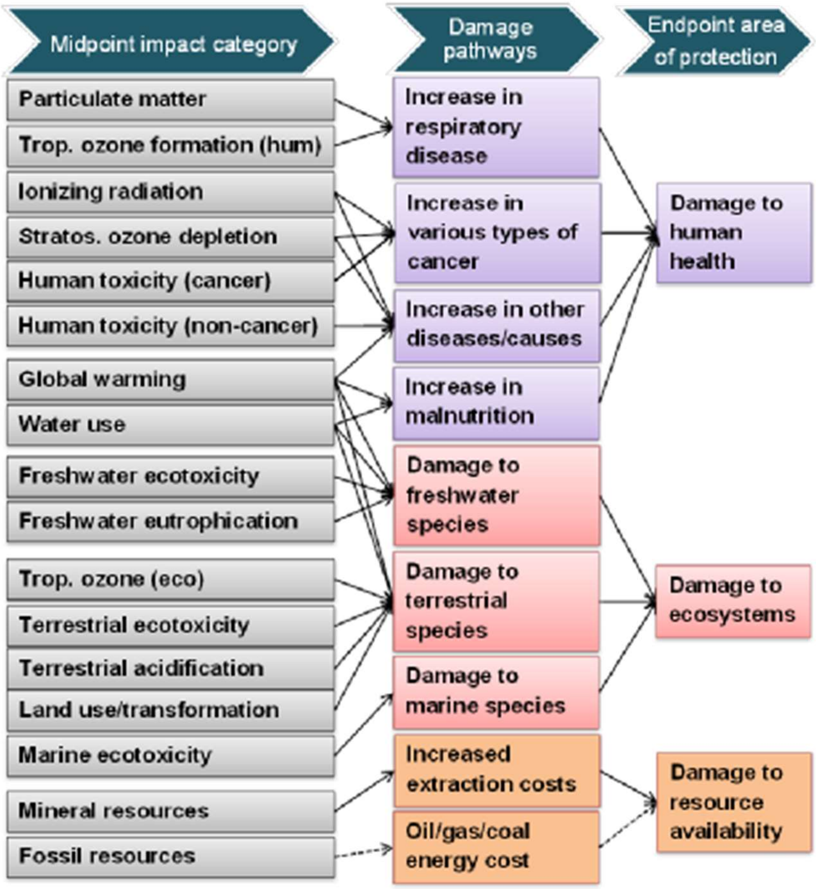


Figure 3-5: Midpoints and Endpoints covered by ReCiPe 2016 [77]

3.11. IMPACT World+

IMPACT world+ is a modern rendition of many previous older LCIA methodologies such as IMPACT 2002+, EDIP and LUCAS and is being constantly updated with the latest scientific literature regarding characterization modeling. What sets it apart is that it's designed to be a regionalized LCIA method applicable to the entire world. This is done by providing characterization factors that are continent specific allowing for more accurate assessment of any georeferenced resource use or emissions. IMPACT world+ also incorporates uncertainty calculations to account for model uncertainty and unclear/missing data for example if the location of an emission is unknown. [78]

A midpoint-endpoint approach is used similar to ReCiPe 2016 where an initial set of 30 midpoint categories are selected, these midpoints are then assessed and can potentially contribute/damage up to three endpoints (areas of protections). The three endpoints utilized in IMPACT world+ are human health, ecosystem quality and resource & eco services. The endpoints serve as a means to put each of the midpoint indicators into perspective and translate them into more comprehendible consequences of environmental damage. Normalization is done at the global level and weighting is left as optional as no weighting factors are provided. This essentially means that weighting is left up to the user to select their own factors and can therefore vary on a case-by-case basis. [78]

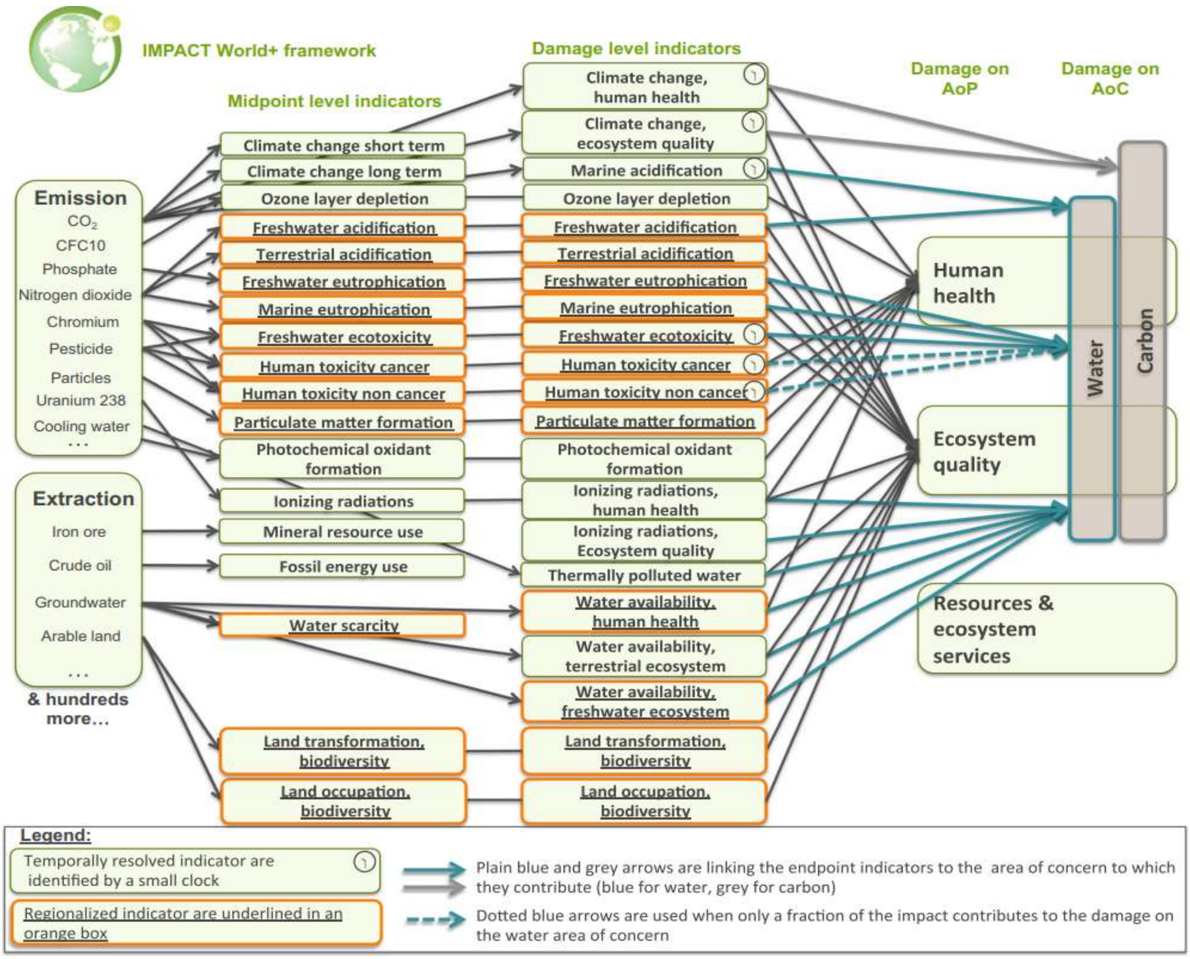


Figure 3-6: Midpoints and endpoints covered by the IMPACT world+ framework [78]

3.12. BREEAM-NOR

The Building Establishment Environmental Assessment Methodology for Norway (BREEAM-NOR) is an assessment method that evaluates the sustainability and environmental performance of buildings specifically in Norway. The original BREEAM was launched in 1990 and created by the British Research Establishment has become the most widely used method for assessing and certifying sustainable buildings with over 2.2 million buildings being certified across more than 80 different countries. The processes of certifying and assessing buildings is done through evaluating a buildings performance in a wide range of categories with each category having an individual weighting: [79]

Category	Weighting (%)
Management	12
Health and wellbeing	15
Energy	19
Transport	10
Water use	5
Materials	13,5
waste	7,5
Land use and ecology	10
Pollution	8
Innovation	10

Table 3-7: Categories evaluated in the BREEAM assessment

The final score is then calculated as:

$$Score = \frac{points\ achieved\ in\ a\ category}{maximum\ points\ achievable\ in\ category} * Weighting$$

BREEAM classification	Score in %
Outstanding	≥85
Excellent	≥70
Very good	≥55
Good	≥45
Pass	≥30
Uncertified	<30

Table 3-8: The different BREEAM classifications

The requirements and criteria are depending on the type of building being assessed, each of the main categories are also further divided into many sub sections in order to have a more in depth and comprehensive assessment. [79] It is important to note that BREEAM-NOR/BREEAM is not a LCA methodology but rather a type of certification label for buildings. BREEAMs assessment categories do however require LCAs at different levels to be performed in order to be able to quantify a buildings environmental performance. Once a building is assessed it is given a rating (score) according to how well it performs in the above listed categories.

3.13. LEED

Leadership in Energy and Environmental Design (LEED) is an alternative system for assessing the environmental performance and sustainability of buildings. It was developed in 1998 by the US Green Building Council. The evaluation categories covered by LEED are: [80]

- Sustainable sites
- Water efficiency
- Energy and atmosphere
- Materials and resources
- Indoor environmental quality
- Innovation
- Regional priority

The method is based on a scoring system similar to BREEAM where a higher score means a better environmental and sustainability performance, the scores range from Certified all the way up to Platinum. LEED is not used as commonly is Norway/Europe but is more popular in North America. The amount of LEED certified buildings is substantially lower worldwide with only around 100,000 buildings being certified. [80]

4. Method and laboratory work

4.1. Laboratory program

The goal of the practical tests conducted was to create three different concrete mixes. The first concrete mix is used as a reference sample (15%FA), the second concrete mix is used to represent current industry practices within the use of environmental concrete (35%FA) and the last mix represents experimental future environmental concrete (50%FA). The experimental concrete's strength properties will then be compared to the 15%FA and 35%FA concrete to see if it's a viable substitute of the current environmental concrete used in the industry. The scope of the practical test in this thesis is limited to the compressive strength as the main focus is on the environmental footprint. The requirements set by Norsk Betogforening for concrete used for the construction of parking garages is strength class B40 [81], therefore all the concrete mixes will be evaluated against this criterion to judge their viability. All laboratory work and testing was done in collaboration with a fellow master student, refer to [82] for a more in-depth evaluation of environmental concretes' durability and strength. Due to ongoing renovation works in the Department of mechanical, structural engineering and material science (IMBM) laboratory, the area was unavailable for use. The concrete mixer at Sandnes&Jærbetong was used instead.

4.1.1. Concrete proportioning

Cement

The cement used for all three concrete mixes is Norcem Anleggsement FA, CEM II/A-V 42,5 N. Anleggsement is commonly used for large structures such as bridges, tunnels, and other large concrete structures. The cement consists of 81% clinker, 15% fly ash + 4% filler, and has a strength class of 42,5 with a classification "N" meaning normal strength development.

Aggregates

Two types of aggregates were used in all three mixes. The aggregates are produced by Norstone in Norway, the aggregates consist of:

- Årdal 0-8 mm
- Årdal 8-16 mm

The aggregate distribution is shown in Figure 4-1.

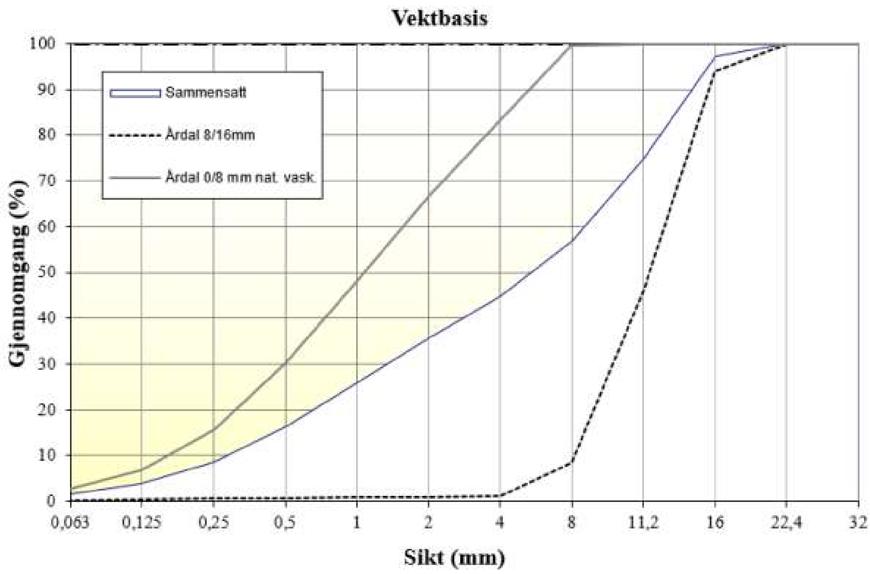


Figure 4-1: Aggregate distribution

Superplasticizer

Water reducers or superplasticizers play a crucial role in concrete mix design as they enhance the workability and flow of the concrete. Superplasticizers have the potential to improve the strength of the concrete by reducing the water requirement in the mixture. Cement particles tend to flocculate in water due to their surface charge resulting in water particles becoming entrapped and thus not being available for hydration. Superplasticizers function by altering the charge of the cement particles causing them to disperse and freeing the trapped water, which leads to better consistency and flow. The superplasticizer used for all three mixes is:

- Dynamon SX-N produced by Mapei (modified acrylic polymer)

Fly ash

The fly ash is used as a SCM where the goal is to replace part of the Portland cement in the concrete mix. As Portland cement is the biggest contributor to the release of greenhouse gas emissions in concrete, the fly ash aims to lower the total environmental footprint of concrete. In current industry practices and according to NS-EN 197-1:2011 the maximum fly ash content should not exceed 35% of the cementitious material's mass. However, this study aims to investigate the effectiveness (mechanical properties and environmental properties) of using higher amounts of fly ash than the current suggested limit. The fly ash used in all three mixes is provided by Norcem AS and has a particle density of $2300\ kg/m^3$, the composition of the fly ash falls under the certification "NS-EN 450-1, Klasse A" meaning the fly ash has:

- Minimum 50% content of SiO_2, SiO_2, Fe_2O_3
- Maximum 5% content of $SO_3, MgO,$
- Total alkali content does not exceed 1%
- Contains no more than 2% unburned carbon and ignition loss does not exceed 5%

Reference concrete recipe (15% FA)

The reference 15%FA concrete was created as a baseline scenario to represent concrete that would be used in a regular concrete structure which has not been designed to reduce its environmental footprint in any capacity. The reference concrete will also be used to compare the mechanical properties of environmental concrete in order to document its strength and viability as a replacement. This is the first most important step as environmentally friendly alternatives may be able to reduce the climate impact as whole but if it comes at the cost of the structural integrity, service life and quality of the building it may not be usable as a practical replacement in the industry. The 15%FA concrete has a $w/(c + \sum kp)$ of 0.39 and a matrix volume of 300 $\frac{L}{m^3}$ 15% FA binder content. The distribution of 0-8mm and 8-16mm aggregates was picked as approximately 50% of each as this ensure the least amounts of void space between the aggregates. The concrete is designed to cover the recommendations set by Norsk Betongforening (NB) which are a strength class of B40/45 and Durability class of M40. These recommendations are applicable for the construction of parking installations (the case study performed) and most other regular concrete structures that don't require special exposure and durability classes.

15% Fly Ash concrete recipe	Per cubic meter (kg)	Batch (kg)
Cement	376,8	13,186
Fly ash	0	0
0-8 mm aggregate	951,8	34,046
8-16 mm aggregate	949,9	33,579
Water	146,9	4,211
Dynamon SX-N (superplasticizer)	4,5	0,158

Table 4-1: Mix design for the reference 15%FA concrete

Matrix	Value
Desired matrix volume [l/m^3]	300
Obtained matrix volum [l/m3]	300
Clinker part in binder	85,0 %
Total FA- content of binder	15,0 %
Total slag content of binder	0,0 %
Volume cement paste [l/m^3]	273,0
Effectiv water content [l/m^3]	146,9
w/p	0,33
Effectiv binder [kg/m^3]	377
Totalt binder [kg/m^3]	377

Table 4-2: Matrix composition of the reference 15%FA concrete

Standard environmental concrete 35% FA recipe (35% FA)

A common way to reduce the environmental impact of cement and concrete is to reduce the greenhouse gasses released through calcination. As calcination is an unavoidable process in the production of clinker, an effective option it to include less in concrete and thus produce less total clicker. The use of FA as an effective replacement to Portland cement has been common practice. However, the current standards and industry practice set a maximum recommended

FA binder content of 35%. This concrete mix aims to act as a reference for the current design of FA based environmental concretes. Matrix volume is set to 300 $\frac{L}{m^3}$, 50-50 0-8mm and 8-16 mm aggregate distribution, $w/(c + \sum kp)$ ratio of 0.39 and 35% FA binder content.

35% Fly Ash concrete recipe		
	Per cubic meter (kg)	Batch (kg)
Cement	289,7	14,484
Fly ash	89	4,449
0-8 mm aggregate	951,8	48,637
8-16 mm aggregate	949,9	47,971
Water	137,3	5,531
Dynamon SX-N (superplasticizer)	4,5	0,227

Table 4-3: Mix design for 35% FA environmental concrete

Matrix	Value
Desired matrix volume [l/m^3]	300
Obtained matrix volum [l/m3]	300
Clinker part in binder	65,0 %
Total FA- content of binder	35,0 %
Total slag content of binder	0,0 %
Volume cement paste [l/m^3]	273,0
Effectiv water content [l/m^3]	137,3
w/p	0,30
Effectiv binder [kg/m^3]	352
Totalt binder [kg/m^3]	379

Table 4-4: Matrix composition of 35% FA environmental concrete

Experimental environmental concrete 50% FA recipe (50% FA)

The goal of this mix is to test the effects of exceeding the recommended FA binder content and see how a larger amount of SCM affect the mechanical properties as well as how big the environmental impact change is between the different mixes. The matrix volume of the mix was increased to 330 $\frac{L}{m^3}$ in order to achieve workable concrete and ensure that the concrete is able to properly mix. The $w/(c + \sum kp)$ ratio is 0.39, 50-50 0-8mm and 8-16mm aggregate distribution and 50% FA binder content.

50% Fly Ash concrete recipe		
	Per cubic meter (kg)	Batch (kg)
Cement	269	13,452
Fly ash	187	9,348
0-8 mm aggregate	909,8	46,492
8-16 mm aggregate	908	45,854
Water	132,6	5,311
Dynamon SX-N (superplasticizer)	5,5	0,274

Table 4-5: Mix design for 50% FA experimental environmental concrete

Matrix	Value
Desired matrix volume [l/m^3]	330
Obtained matrix volum [l/m3]	330
Clinker part in binder	50,2 %
Total FA- content of binder	49,9 %
Total slag content of binder	0,0 %
Volume cement paste [l/m^3]	304,2
Effectiv water content [l/m^3]	132,6
w/p	0,25
Effectiv binder [kg/m^3]	340
Totalt binder [kg/m^3]	456

Table 4-6: Matrix composition of 50% FA experimental environmental concrete

4.2. Mixing and handling process

The mixing and casting of all of the concrete and concrete specimens was done at Sandnes&Jærbetong's facilities. The 100 L concrete mixer was used for each of the concrete mixes and was inspected beforehand to check for any residual materials in order to not contaminate the current batch. The mixing procedure which was used for all three batches is as follows:

- The coarse aggregates are added (8-16 mm)
- The fine aggregates are added (0-8 mm)
- The mixer is allowed to run for a few minutes to allow for the aggregate to settle
- The cement and FA (only for batch 2 and 3) is added
- The mixer is allowed to run for a few minutes to allow for the dry mixture to mix properly
- Water is added, wet mixing continues for around 1-2 minutes
- Superplasticizer is added and mixing continues for 4 minutes

Figure 4-2: The facility used at Sandnes&Jærbetong

Once the mixing process was complete the concrete was transferred into a wheelbarrow for easier access. Immediately after a small amount of concrete was taken in order to perform a slump test to determine the concrete's flow and workability. The test was performed in accordance with NS-EN 12350-2. The slump cone was filled 1/3 at a time with each layer being compacted 20 times with a tamping rod. Once the cone is full, the top is leveled off, the weight (seen in Figure 4-2) is removed and the cone is lifted straight up with a constant speed taking around 2-5 seconds to complete the action. The concrete is allowed to settle before the distance from the top of the concrete to the top of the cone is measured.

The remaining concrete was used for the cube specimens, the casting technique used was in accordance with NS-EN 12390-1:2019 where each mold was filled in three layers and each layer was compacted using a tamping rod.

4.3. Curing methods

Two different curing conditions were chosen for this study. The first method is in accordance with NS-EN 12390-2:2019 which states that concrete cube specimens should be cured in a moist environment to ensure proper hydration and strength development. Therefore, one set of specimens is put in a water tank to cure in order to satisfy the guidelines in the standard. The second set of specimens were left to air dry without any special membrane or other methods to specifically keep them moist. This is done to compare how less favorable curing conditions affect the mechanical properties of the concrete and to potentially simulate the curing conditions present on a building site.

Due to the construction work going on in the UiS IMBM laboratory all concrete specimens had to be cast at the Sandnes&Jærbetong concrete factory. This change made availability and working hours limited. The limited time schedule meant that the specimens could not be demolded and tested after 1 day of curing and instead a compromise of 3 days for demolding and early strength testing had to be made.

4.4. Testing method

Compressive strength test

The compressive strength of all the concrete mixes was tested in order to compare how the increase in FA affects the concrete. The compressive strength test was conducted on a Toni Technik Load Frame which fulfills the requirements for testing machines set in NS-EN 12390-4:2019. The method used for testing the specimens is in accordance with NS-EN 12390-3:2021 where the concrete cube is placed in the middle of the test machine whereafter the machine loads the specimen with a constantly increasing compressive force until the specimen fails. The peak compressive load is recorded, and the compressive strength of the concrete is calculated through the following equation:

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

Where,

f_c is the compressive strength in MPa
F is the peak critical force applied
A_c is the specimen's surface area

4.5. Laboratory results

Slump

The slump for each of the three mixes is presented in Table 4-7. The reference 15% FA concrete and the 35% FA concrete both had approximately the same slump value of around 240 mm. This is expected as both mixes include the same matrix volume of 300 $\frac{L}{m^3}$ and the exact same quantity of superplasticizer. A denser consistency and increase cohesiveness was observed in the 35%FA mix due to the increased amount of fly ash. The 50%FA mix exhibited a greater slump even approaching the properties of self-compacting concrete, this was likely due to the need of an increased matrix volume of 330 $\frac{L}{m^3}$. The concrete exhibited good flow properties however the cohesiveness was increased even further compared the 35%FA concrete, this again is due to the increased amount of fly ash.

Mix	Slump (mm)
FA15	240
FA35	240
FA50	270

Table 4-7: Slumps of the different concrete mixes

Compressive strength

The compressive strength for the three different concrete mixes cured in accordance with NS-EN 12390-2:2019 (cured in a moist environment (W)) is presented in Table 4-8. The regular 15%FA mix exhibits highest early strength at the 7-day mark, this is due to the fly ash's retarding effect on the hydration resulting in slower early strength development in the 35%FA and 50%FA mixes. This trend continues until the 56-day mark where the 50%FA mix has reached the same strength levels at the reference mix. However, the 35%FA mix is still lagging behind. After 90 days the 35%FA mix has reached approximately the same strength levels as reference mix and the 50%FA mix is around 10 mPa stronger. These results are expected due to the aforementioned effect which fly ash has on the hydration process.

Compressive strength water cured (mPa)					
Specimen	**3 days**	**7 days**	**28 days**	**56 days**	**90 days**
FA15-1 (W)	-	57,89	79,68	94,29	92,75
FA15-2 (W)	-	59,67	81,67	95,88	96,56
FA15-avarage (W)	-	58,8	80,7	95,1	94,7
FA35-1 (W)	-	42,75	63,81	74,28	83,3
FA35-2 (W)	-	43,4	63,38	72,22	82,74
FA35-avarage (W)	-	43,1	63,6	73,3	93
FA50-1 (W)	-	54,85	77,76	93,39	105,7
FA50-2 (W)	-	54,85	77,68	96,63	106,8
FA50-avarage (W)	-	54,9	77,7	95,0	106,3

Table 4-8: Compressive strength of the different mixes when cured in a water tank

The compressive strength for each of the concrete mixes with no special curing measures being employed (air curing (A)) is presented in Table 4-9. The very early 3-day strength of the 35%FA mix is surprisingly high compared to the reference and 50%FA mix. The strength is almost identical to its 7-day water cured counterpart. The reference mix shows a steady trending strength increase up until the 28-day mark where hydration process seems to slow down significantly. meanwhile the 35%FA mix sustains most of its strength development between 7- and 28-day mark with no significant strength increase when the curing time exceeds 28 days and ended up approximately 20 mPa weaker than both of the other mixes. The 50%FA mix had a similar but slightly slower strength development than the reference concrete and ended with minimal strength difference between the 2 except for the extremely early strength.

Compressive strength air cured (mPa)					
Specimen	**3 days**	**7 days**	**28 days**	**56 days**	**90 days**
FA15-1 (A)	39,24	62,65	77,66	80,29	83,08
FA15-2 (A)	39,73	62,85	75,21	79,23	48,10*
FA15-avarage (A)	39,5	62,8	76,4	79,8	83,1
FA35-1 (A)	44,17	49,46	60,41	62,41	61,87
FA35-2 (A)	43,18	47,14	62,20	63,77	62,87
FA35-avarage (A)	43,7	48,3	61,3	63,1	62,4
FA50-1 (A)	35,69	58,5	76,26	78,89	80,49
FA50-2 (A)	34,82	59,39	73,44	78,94	83,02
FA50-avarage (A)	35,3	58,9	74,9	78,9	81,8
*This data point is not included as it is deemed as an extreme outlier					

Table 4-9: Compressive strength of the different concrete mixes when cured in open air

The strength classification of each concrete mix is determined by looking at the specimen's compressive strength after 28 days of curing. The refence mix (15%FA) is rated as B55 and B 65 for air cured and water cured respectively. The 35%FA mix is rated as B45 for both curing conditions (air cured and water cured) and the 50%FA mix falls in the B55 category for both curing conditions.

Strength class	**B10**	**B20**	**B25**	**B30**	**B35**	**B45**	**B55**	**B65**	**B75**	**B85**	**B95**
f_{cck}	10	20	25	30	35	45	55	65	75	85	95
f_{ck}	12	25	30	37	45	55	67	80	91	100	110

f_{cck} is the characteristic cylinder strength
f_{ck} is the characteristic cube strength

Table 4-10: The different strength classifications used in Norway

4.6. Conclusion

The experimental high fly ash content concrete (50%FA) performed very well comparatively to the reference and 35%FA concretes. When using techniques that help keep the moisture during curing, a greater 90-day strength was observed as the slow hydration process which is typical of fly ash concretes is allowed to continue optimally. This highlights the loss of compressive strength when compared to "on site" curing conditions where a 23% difference was observed between the water cured and air cured specimens. The strength difference between the 35%FA and 50%FA concrete was rather substantial, this was most likely due to the increase in matrix volume which allows the Portland-fly ash binder to optimally transfer stresses due to its increased density. Even when considering the least favorable curing conditions (air curing) the 50%FA concrete managed to achieve similar compressive strength to the regular concrete suggesting that the strength loss can be compensated by an increased matrix. All three mixes satisfied the criteria of a minimum strength classification of B45; therefore, it can be concluded that adequate strength can be achieved while incorporating large amounts of fly ash. Further in-depth analysis of the 50%FA properties are discussed in a fellow student's thesis [82].

There was a noticeable difference in each of the concrete's workability. The high volumes of fly ash (35%FA and 50%FA) had adequate slump and flow however a significant increase in their cohesiveness was noticed making them progressively more difficult to handle and work with by hand. Due to the increased matrix and slump/flow properties the 50%FA concrete should be able to be pumped, casted and compacted with relatively similar results to the reference concrete. Handling/casting large volumes of 50%FA concrete by hand is not advised due to the high packing density and cohesiveness making it extremely cumbersome.

To conclude the basic testes performed showed that the 50%FA experimental environmental concrete's compressive strength and flow are satisfactory and is deemed as an acceptable replacement for the use in the construction of a parking garage (case study). Further testing may be needed if additional criteria are demanded such as specific exposure and durability conditions.

5. Case study: Concrete parking garage

In order to examine and quantify the environmental impact of using environmental concrete a case study will performed. As the main focus is the use of concrete as a building material and reducing the climate impact though the use of SCMs, the building type has been selected as a concrete parking garage. This is to ensure that the concrete volume used is sufficient as to provide a clearer indication of how effective environmental concrete is in reducing climate impacts. As this is a conceptual design created to showcase the impact of the different concrete mix designs and not an actual constructed building, multiple assumptions have been made in order to keep the focus at the environmental concrete level.

5.1. Goal and scope of study

The goal of this case study is twofold: (i) to evaluate the effectiveness of using fly ash as an SCM to reduce the environmental impact of concrete; and (ii) to evaluate how impactful the reduction is in relation to the total environmental impacts of a complete building.

The LCA will be process based and performed on the building level in accordance with NS-EN 15978 meanwhile all process and material LCAs are performed by the manufacturer providing the said process or material. All process/product level LCAs are performed in accordance with NS-EN 15804 and adapted for use in the NS-EN 15978 building LCA format. All products and processes used in the study have to adhere to the CEN TC350 series of standards to ensure the correct methods, impacts and characterization factors have been used.

The use of methodologies such as ReCiPe, CML or IMPACT world+ would add additional impact categories and detail. However, in order to perform comprehensive LCAs using these methodologies, expensive software and databases are required which were not accessible. Free versions are available but do not provide specific enough data or are outright missing important datasets needed for this analysis. The baseline methodology provided in NS-EN 15978 will therefore be followed for this study.

The selected impact categories for this study as suggested by NS-EN 15978 to achieve a wholistic environmental impact assessment are: [83]

- Global warming potential
- Ozone depletion potential
- Photochemical ozone creating potential
- Acidification potential
- Eutrophication potential
- Abiotic depletion potential of minerals
- Abiotic depletion potential of fossil fuels

The CEN/TC 350 standards provide a standardized format for all building related LCAs. The format divides each step of the LCA into individual modules to allow for better transparency and interpretation of the results. The modules are separated among 5 different stages: the product stage including modules A1-A3, the construction process including modules A4-A5, the use stage including modules B1-B7, the end-of-life stage including modules C1-C4 and final beyond system boundary stage including module D.

As will be mentioned in the assumptions section, modules B1-B5 and B7 are assumed to not generate any waste within the buildings design service life and will therefore be excluded. The selected modules which will be assessed in this study are highlighted in Table 5-1: The life cycle stages considered in the analysis.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction – inst. process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse/recovery/recycling
x	x	x	x	x	-	-	-	-	-	x	-	x	x	x	x	x

Table 5-1: The life cycle stages considered in the analysis

Assumptions

The first important thing to note regarding this case study is that the building itself is not meant to be representative of a real-world structural bearing system in regard to criteria provided by the Eurocodes. All concrete structures should have reinforcement steel included in their design in order to assure sufficient tensile, compressive, torsional and shear strength as well as to control deflection, crack formation and development. As this study focuses on concrete as a building material the calculations for the necessary steel reinforcement and placement needed in each member is not included. Instead, an assumption of 80 kg of reinforcement steel per cubic meter of concrete is used in order to quantify the environmental impact. The amount of steel will vary as loading conditions are unique for each project. Additionally, the frame and supporting slabs and columns are taken as generic standard structural concrete elements meaning that they are not specifically design/optimized for this parking garage's loading. Although their dimensions are not specifically designed and calculated all necessary structural elements (foundation, supporting beams, supporting columns, floor slabs and shear walls) are included in the case study as to represent a generic conceptual parking garage.

The data collected throughout the analysis is assumed to be sufficiently accurate for this study as it is acquired through manufacturing EPD's and verified databases which are in accordance with ISO 14040 and NS-EN 15804. In the case of missing data for a particular process or material a substitution will be made with a similar product or process, additional assumptions regarding data are stated where relevant.

Foundation calculations have not been performed as this require extensive testing of the soil, therefore a basic generic foundation has been included to represent the concrete volume require for the foundation of the building. The soil is assumed to be adequate enough to not require piles and instead foundation pads and backfilled aggregates are included underneath each column as well as foundation walls under the shear walls. It is assumed that the pads and walls are not subject to any type of failure as well as no additional settlement of the backfilled soil or surrounding soil will occur throughout the building life cycle. The service life of the structure will be taken as 60 years.

It is assumed that the parking garage does not directly generate any waste products through its use phase and does not need replacement or refurbishment throughout its designed service life. This is excluding any extreme events such as accidents or natural disasters.

Location

The location of the concrete parking garage is set to be behind Petroleumstilsynet's offices in Stavanger, Norway next to UiS. This location was chosen due to it being a realistic alternative where a parking garage could have been built as a replacement to the regular parking lots currently present. The multistory parking garage would provide sufficient amounts of parking spaces while simultaneously occupying less total land area. It is assumed that the parking garage would be connected to the nearby water and electrical grid without any need for expansion of the existing capacity.

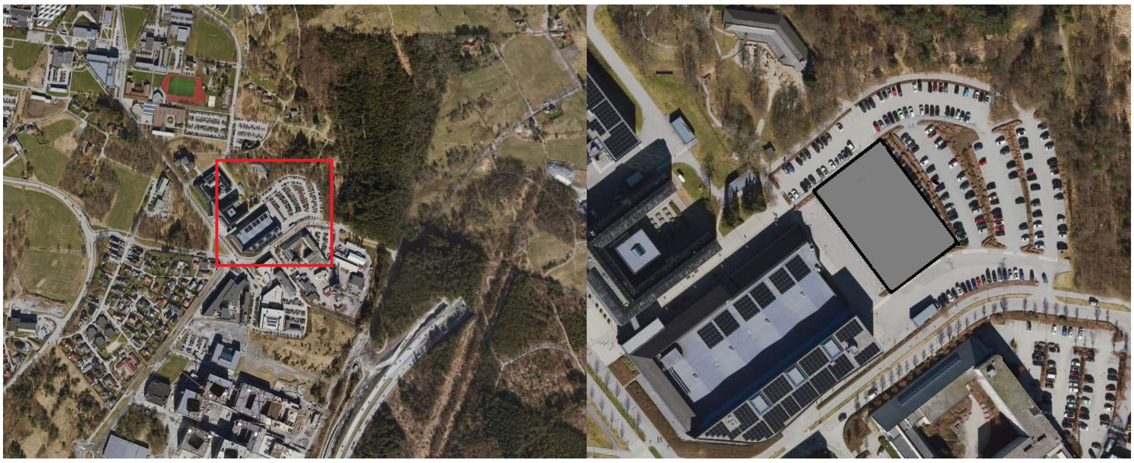


Figure 5-1:Location of the parking garage

Dimensions

The parking garage is made to be 55 meters long and 30 meters wide, these dimensions were assumed to be suitable for the location and provide a large enough base to accommodate the car traffic within the parking garage. The garage has 3 floors which are usable for parking and a roof to protect from rain and snow bringing it to a total height of 9.8 meters. The ceiling height is 2.8 meters which satisfies the minimum requirement of 2.4 meters provided by Diriktoratet for byggnings kvalitet in TEK17. [84] As the parking garage is meant as a replacement to the existing parking lots, 3 floors of parking are deemed as a sufficient substitution. The floor design is staggered to provide enough room for the ramps between floors and so they do not have an excessive incline. The ramps are 5 meters wide to allow for cars to move in both directions simultaneously and 10 meters long to create a smooth transition between floors. Additionally, each floor has a 1-meter-tall safety wall surrounding it to prevent cars from accidently driving/rolling off. Accessibility between floors is also provided through a staircase located by the entrance of the garage.

The floors are designed as a solid 150 mm slab supported by beam system (seen in Figure 5-5). The beam system consists of 300x600 mm vertical beams and 200x400 horizontal beams. The beam system is supported by equally spaced 300x300 mm columns and 2 300 mm thick shear walls on either side (seen in Figure 5-2). The entire building is supported by 16 2000x2000x600 mm foundation pads located 1.6 meters below ground under each column and 900x600 mm foundation walls under each shear wall (seen in Figure 5-5). The total volume of concrete needed to construct the building including the foundation is $1505\ m^3$.

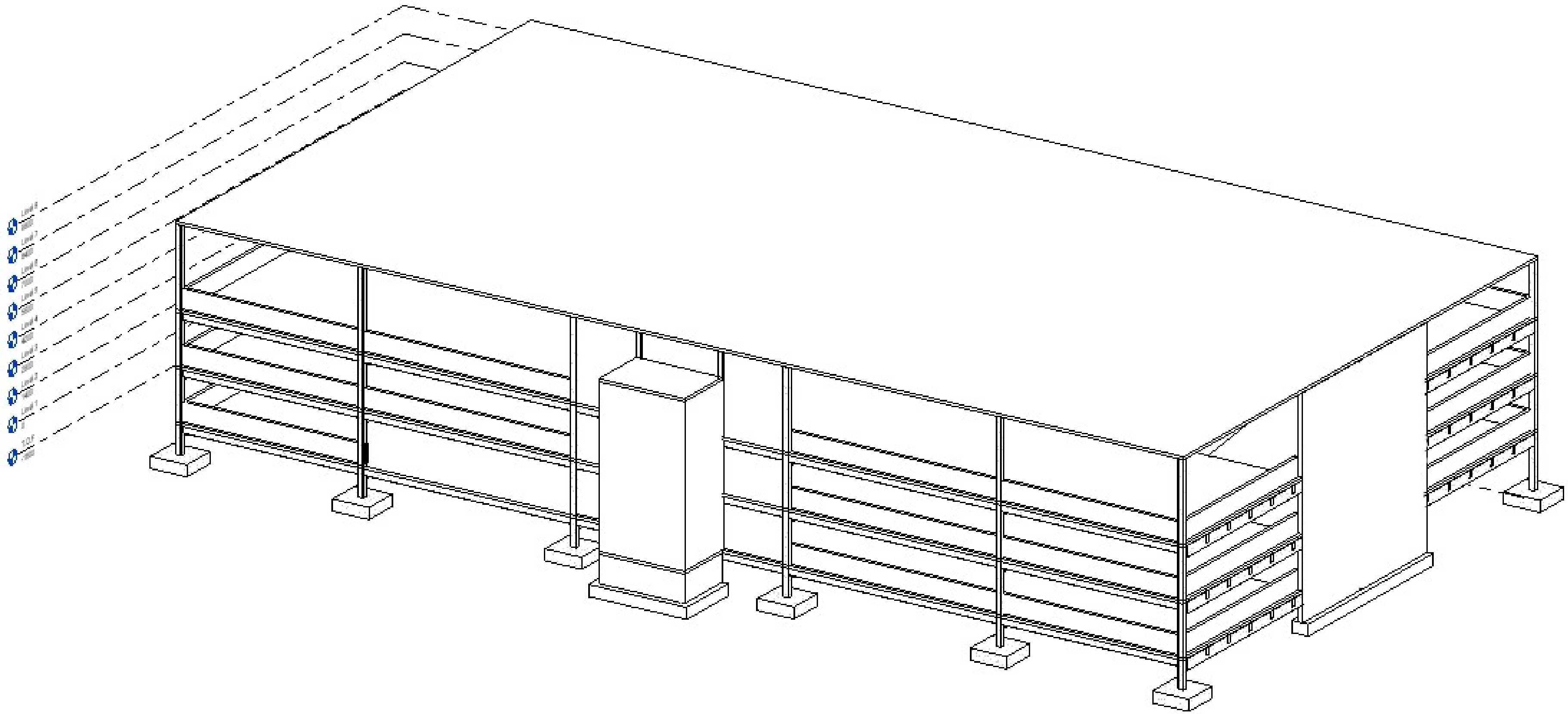


Figure 5-2: 3D model of the parking garage including the foundation

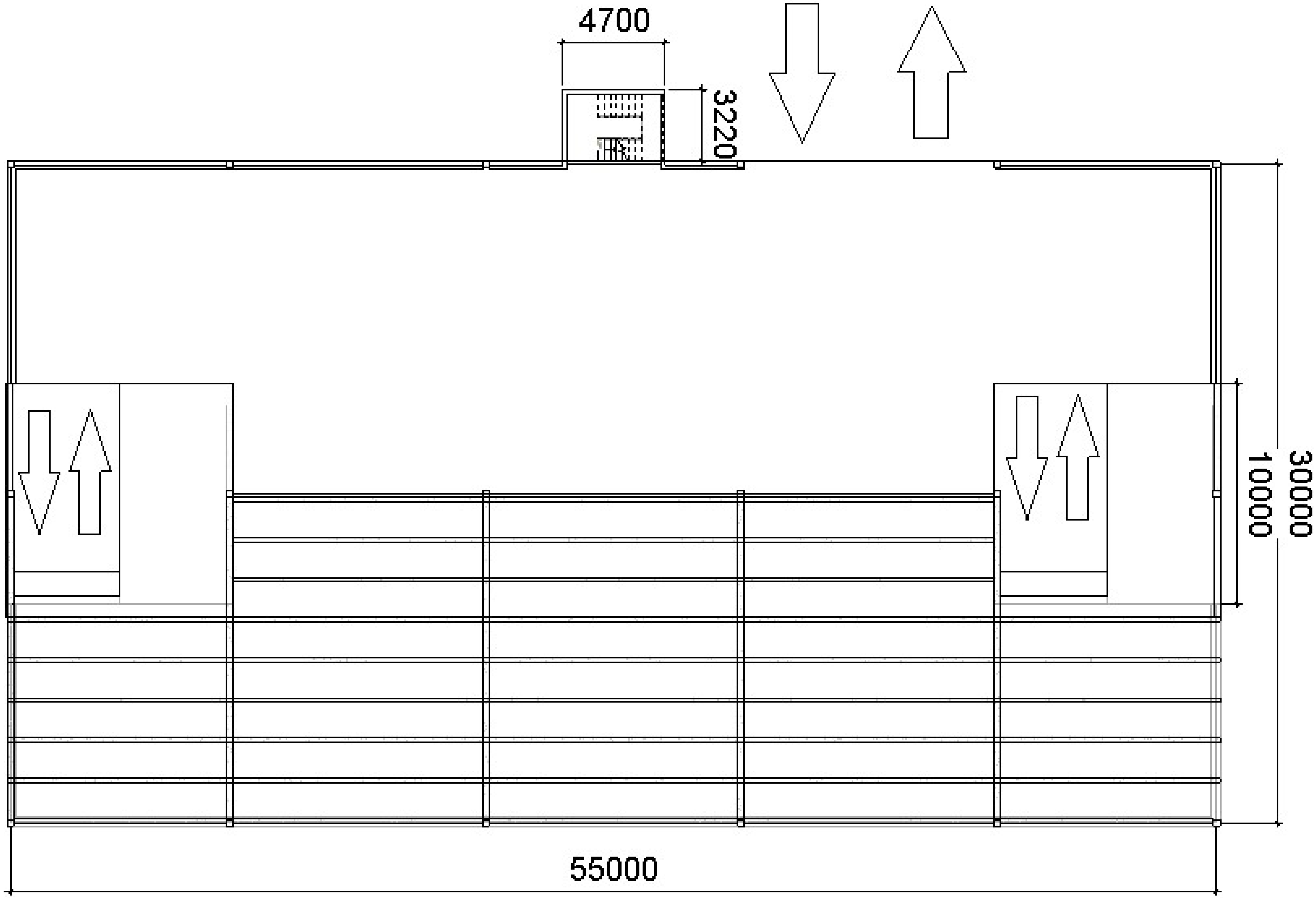


Figure 5-3: Floor plan of the parking garage

Figure 5-4: Side view of the parking garage including the foundation level

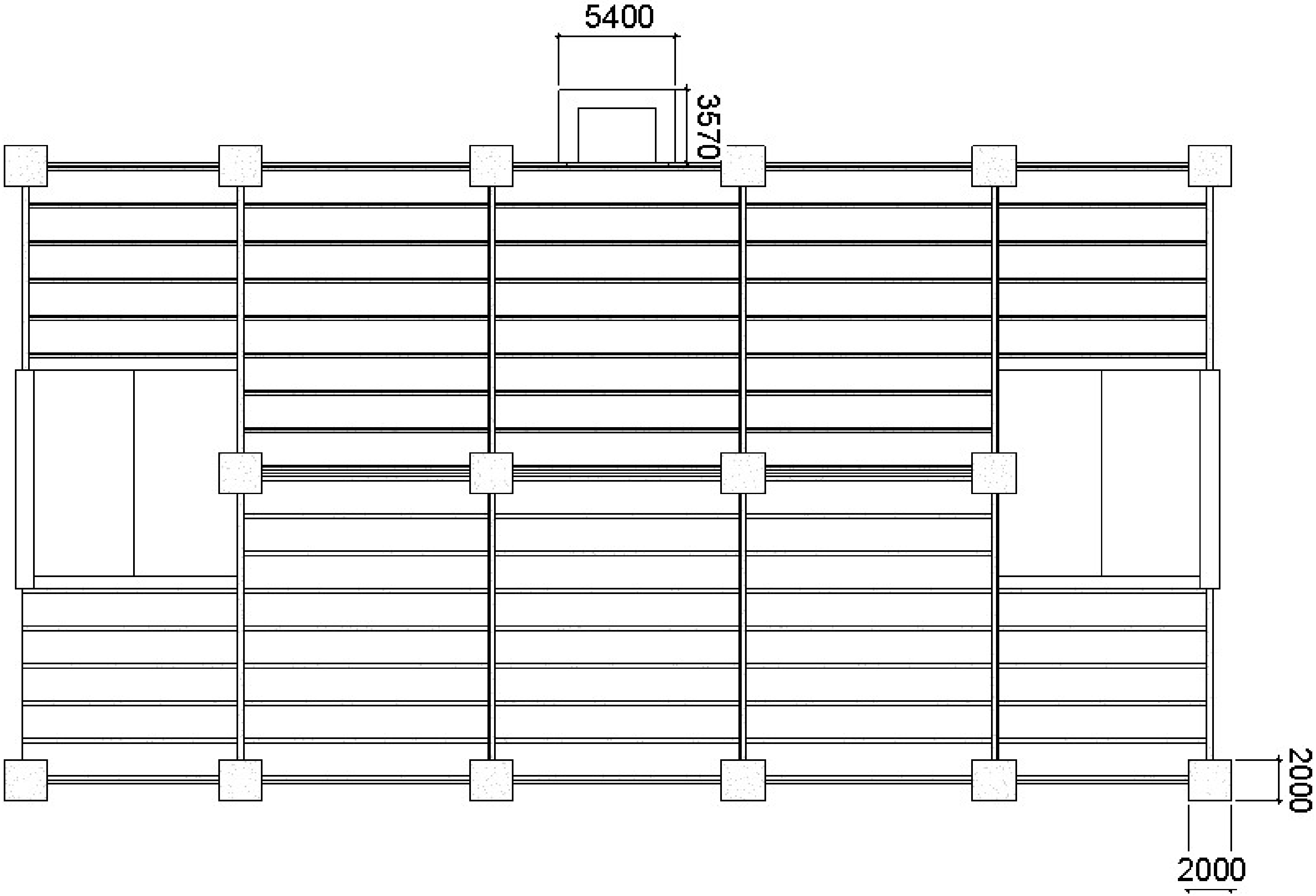


Figure 5-5: The structural support system of the parking garage including foundation pads and support beams

5.2. Life cycle inventory

The LCI phase of the LCA is one of the most important steps as the quality and detail of the data collected during this phase dictates the entirety of the results and relevance of the study. Here the environmental impacts for each of the processes and materials that contribute to the construction of the parking garage are included and collected as per functional unit of the defined process and material. The proper collection, presentation and declaration of assumptions is vital in order to achieve the necessary transparency of the study.

5.2.1. Building materials

The table below shows the environmental impact that cement has through the selected indicators, during section 5.2 refer to Table 5-1: The life cycle stages considered in the analysis for clarification of what each module encompasses. As the main focus of the study is to investigate the differences of using varying amounts of cement and SCM in a building project, the data regarding the cement was collected directly from the supplier for the exact cement used in the laboratory mixes. This ensures that the representation of the cement's environmental impact is as accurate as possible. The transportation impacts covered in module A4 are taken as an average from Norcem's customers in Norway and it is therefore assumed that they are representative of the distance from the factory to the construction site.

Indicator	Unit	A1	A2	A3	A4
GWP	$kg\ CO_2 - eq$	4,02E+00	1,59E+01	5,76E+02	2,49E+00
ODP	$kg\ CFC11 - eq$	3,50E-07	3,16E-06	1,21E-06	4,88E-07
POCP	$kg\ C_2H_4 - eq$	9,39E-04	1,07E-02	4,54E-03	1,66E-03
AP	$kg\ SO_2 - eq$	2,11E-02	4,02E-01	4,31E-02	6,09E-02
EP	$kg\ PO_4^{-3} - eq$	2,40E-03	4,13E-02	1,88E-02	5,96E-03
ADPM	$kg\ Sb - eq$	5,82E-05	9,90E-05	2,63E-04	1,06E-05
ADPE	MJ	4,51E+01	2,04E+02	8,37E-+02	2,21E+01

Table 5-2: Anleggsement FA impacts per 1 ton

The fly ash used in the concrete mixes was Norcem fly ash sourced from a coal powerplant, however Norcem did not have any EPD data available for their specific fly ash. A substitution was used in order to quantify the impacts of the fly ash. The substitute used is Emineral's fly ash, this was found as suitable substitute due to the fly ash's origin being from coal powerplants as well as being a Danish product meaning standardizations are applicable to Norway due to its close proximity in Scandinavia. Fly ash is already established as very low impact compared to cement and therefore the possibility of slight variations between Norcem's and Emineral's fly ash is assumed to be negligible when regarding the total impact of the building. Module A4 was not provided through the supplier's data, therefore Oneclick LCA's database was used to determine the impacts from transporting the fly ash from the factory to the building site. The closest available data to Norway was from Finland where it was assumed that a 40-ton trailer is used at 50% capacity with an average delivery distance 70 km to customers. The emissions from the return of the empty trailer back to the factory are also included. A 50% capacity of the trailer was chosen as this is the most unfavorable situation and provides the worst-case scenario. This was done due to the unavailability of data directly from the manufacturer and therefore accounts for some of the uncertainty in using averages from a database.

Indicator	Unit	A1-A3	A4
GWP	$kg\ CO_2 - eq$	1,98E-01	3,57E+00
ODP	$kg\ CFC11 - eq$	1,21E-13	8,07E-07
POCP	$kg\ C_2H_4 - eq$	3,84E-04	5,82E-04
AP	$kg\ SO_2 - eq$	6,50E-05	1,84E-02
EP	$kg\ PO_4^{-3} - eq$	1,36E-05	4,27E-03
ADPM	$kg\ Sb - eq$	1,72E-09	1,71E-05
ADPE	MJ	2,08E+00	1,05E+02

Table 5-3:Fly ash impacts per 1 ton

Both aggerate sizes (0-8mm and 8-16mm) used in the concrete mixes are from Norstone Årdal however Norstone doesn't provide detailed information about the processing specifically regarding their aggregate from Årdal. Therefore, the impacts caused by the aggregates are taken form Norstone's quarry in Halden instead. There should be minimal difference as the processing operations for both quarries are near identical, the main differing factor between the quarries is the aggregates physical properties which are negligible when it comes to the total environmental impact. In order to achieve the desired fineness, the stone has to go through multiple crushing processes. Each process (quarry, primary crushing, and secondary crushing) include modules A1-A3.

Indicator	Unit	Quarry	Primary crushing	Secondary crushing	A4
GWP	$kg\ CO_2 - eq$	1,87E+00	1,89E+00	1,97E+00	4,14E+00
ODP	$kg\ CFC11 - eq$	2,30E-07	2,32E-07	2,42E-07	8,50E-07
POCP	$kg\ C_2H_4 - eq$	7,38E-04	7,42E-04	7,64E-04	6,47E-04
AP	$kg\ SO_2 - eq$	5,25E-02	5,26E-02	5,30E-02	1,07E-02
EP	$kg\ PO_4^{-3} - eq$	1,32E-02	1,33E-02	1,34E-02	1,47E-03
ADPM	$kg\ Sb - eq$	5,63E-06	5,95E-06	6,84E-06	9,85E-06
ADPE	MJ	2,36E+01	2,38E+01	2,49E+01	6,79E+01

Table 5-4: Aggregate impacts per 1 ton

The specific make of the doors used in the multi-story parking garage is not relevant, therefore a standard exterior door from a Norwegian provider (NorDan) was chosen. The chosen doors are taken as NorDan external door which are described as external doors for use in exterior walls of domestic and commercial buildings.

Indicator	Unit	A1-A3	A4
GWP	$kg\ CO_2 - eq$	2,82E+01	4,04E+00
ODP	$kg\ CFC11 - eq$	6,39E-06	7,80E-07
POCP	$kg\ C_2H_4 - eq$	1,59E-02	4,98E-04
AP	$kg\ SO_2 - eq$	1,70E-01	8,25E-03
EP	$kg\ PO_4^{-3} - eq$	3,43E-02	9,01E-04
ADPM	$kg\ Sb - eq$	4,42E-04	8,69E-05
ADPE	MJ	2,82E+02	6,34E+01

Table 5-5:Impacts per door

As previously mentioned in the assumptions section, the design of the steel reinforcement within the concrete is not focused on in this study and therefore a blanket value of 80 kg of steel reinforcement per cubic meter of concrete is chosen. The steel reinforcement chosen for this study is taken as B500NC camshaft steel produced by Norsk stål AS and is manufactured to the specifications provided in NS 3576.

Indicator	Unit	A1-A3	A4
GWP	$kg\ CO_2 - eq$	3,93E-01	1,02E-02
ODP	$kg\ CFC11 - eq$	1,34E-08	1,92E-09
POCP	$kg\ C_2H_4 - eq$	7,97E-05	1,54E-06
AP	$kg\ SO_2 - eq$	1,29E-03	2,40E-04
EP	$kg\ PO_4^{-3} - eq$	2,22E-04	3,15E-05
ADPM	$kg\ Sb - eq$	3,19E-07	3,17E-10
ADPE	MJ	3,47E+00	1,54E-01

Table 5-6:Rienfomrcemnt steel impacts per 1 kg steel

The most applicable lighting fixtures for a concrete garage with sufficient available data were lights intended for commercial or industrial use manufactured by Fischer Lighting Denmark. The manufacturer however does not provide data for the environmental impacts from the transportation of the lights to the construction site. The Oneclick LCA database was therefore used to estimate these impacts, the transportation vehicle was chosen as a large van with a 9-ton capacity and a capacity utilization of 50% including returns. The choice is based on Oneclick LCA's most accurate assumption made by comparing averages from former LCAs conducted using their software.

Indicator	Unit	A1-A3	A4
GWP	$kg\ CO_2 - eq$	3,11E+01	1,87E-02
ODP	$kg\ CFC11 - eq$	2,62E-06	3,6E-09
POCP	$kg\ C_2H_4 - eq$	1,96E-01	1,56E-06
AP	$kg\ SO_2 - eq$	1,38E-01	7,57E-05
EP	$kg\ PO_4^{-3} - eq$	1,76E-02	1,63E-05
ADPM	$kg\ Sb - eq$	1,31E-02	5,23E-10
ADPE	MJ	4,68E+02	5,22E-01

Table 5-7: Lighting fixtures impacts per 1 lighting system

In accordance with the Norwegian Building act (plan- og bygningsloven) and NS-EN 12845:2015+A1:2019 all buildings with a total floor area exceeding 1000 square meters or a height of more than 8 meters require an automatic fire extinguishing system such as a sprinkler system. All sprinklers and valves required for the system have been simplified under one product as all the different sprinklers and valves are manufactured from similar raw materials and processes. The sprinklers and valves chosen are manufactured by Cimberio and defined as valves for system plants of different sectors.

Indicator	Unit	A1	A2	A3	A4
GWP	$kg\ CO_2 - eq$	6,39E+00	1,55E-02	7,64E+00	3,65E-01
ODP	$kg\ CFC11 - eq$	3,26E-05	3,01E-09	1,03E-05	6,72E-08
POCP	$kg\ C_2H_4 - eq$	7,75E-03	2,52E-06	2,89E-03	5,45E-05
AP	$kg\ SO_2 - eq$	1,91E-01	5,46E-05	6,86E-01	8,61E-04
EP	$kg\ PO_4^{-3} - eq$	1,24E-01	1,26E-05	1,26E-01	1,93E-04
ADPM	$kg\ Sb - eq$	2,94E-03	2,79E-08	2,83E-03	1,04E-06
ADPE	MJ	6,95E+01	2,46E-01	9,66E+01	5,50E+00

Table 5-8: Sprinklers and valves impacts per 1 kg of valves

Water supply in the parking garage is externally supplied and transported within the building through PVC pipes of different diameters. The production process for different pipes is similar and therefore a single type of product is selected to cover all pipe needs within the building. The selected pipes are 1m PVC sewage pipes manufactured by Pipelife Sverige AB as they were the best fit to model the plumbing within the garage.

Indicator	Unit	A1-A3	A4
GWP	$kg\ CO_2 - eq$	5,34E+00	3,25E-02
ODP	$kg\ CFC11 - eq$	7,90E-06	6,68E-09
POCP	$kg\ C_2H_4 - eq$	8,30E-04	5,09E-06
AP	$kg\ SO_2 - eq$	1,80E-02	8,40E-05
EP	$kg\ PO_4^{-3} - eq$	3,09E-03	1,16E-05
ADPM	$kg\ Sb - eq$	6,89E-05	7,74E-08
ADPE	MJ	1,39E+02	5,34E-01

Table 5-9: PVC water pipe impacts per 1m of pipe

Cables and wires are required to supply all lighting and emergency systems within the parking garage. A single type of cable product is chosen to represent all wiring as the manufacturing impacts are similar. The chosen electrical cables are SE-N1XE-R XLPE-insulated power cables manufactured by Draka. The cables are suitable for use in commercial buildings and are designed for permanent installation both indoors and water outdoors making them durable enough for use in a parking garage.

Indicator	Unit	A1	A2	A3	A4
GWP	$kg\ CO_2 - eq$	1,52E+00	5,87E-02	8,34E-02	1,40E-02
ODP	$kg\ CFC11 - eq$	1,12E-06	1,11E-08	3,49E-09	2,65E-09
POCP	$kg\ C_2H_4 - eq$	1,71E-03	8,12E-06	1,21E-05	1,83E-06
AP	$kg\ SO_2 - eq$	4,03E-02	1,38E-04	2,25E-04	2,83E-05
EP	$kg\ PO_4^{-3} - eq$	2,33E-03	1,50E-05	3,23E-05	3,08E-06
ADPM	$kg\ Sb - eq$	7,39E-04	1,03E-06	2,52E-06	2,42E-07
ADPE	MJ	2,48E+01	9,02E-01	2,72E-02	2,16E-01

Table 5-10: Wiring impacts per 1 m of cable

The superplasticizer used in the concrete mixes is Dynamon SX-N by Mapei. However, the data for Mapei's superplasticizers is provided in a different format than the one used in this study. This means that the data and indicators are not comparable and cannot be aggregated with the rest of the building materials. The environmental impacts would need to be appropriately converted through the use of similar characterization factors and units. Instead, the data is taken from the European Federation of Concrete Admixtures Associations (EFCA). EFCA provides the average environmental impacts caused by superplasticizer admixtures in Europe.

Indicator	Unit	A1-A3	A4
GWP	$kg\ CO_2 - eq$	1,88E+00	5,74E-03
ODP	$kg\ CFC11 - eq$	2,30E-01	1,13E-09
POCP	$kg\ C_2H_4 - eq$	2,92E-03	3,24E-07
AP	$kg\ SO_2 - eq$	1,03E-03	2,65E-05
EP	$kg\ PO_4^{-3} - eq$	3,12E-04	5,76E-06
ADPM	$kg\ Sb - eq$	1,10E-06	1,56E-09
ADPE	MJ	2,91E+1	1,64E-01

Table 5-11: Superplasticizer impacts per 1 kg

It is assumed that the soil the garage is built on requires backfilling in order to achieve favorable soil properties. The soil/aggregates used for backfilling are taken as the same used in the mixing of the concrete. Norstone Årdal aggregates are describes as suitable for use as backfilling material by the manufacturer. As the backfilling material is required to be compact enough to provide support to the building, the aggerates need to go through both primary and secondary crushing.

Indicator	**Unit**	**Quarry**	**Primary crushing**	**Secondary crushing**	**A4**
GWP	$kg\ CO_2 - eq$	1,87E+00	1,89E+00	1,97E+00	4,14E+00
ODP	$kg\ CFC11 - eq$	2,30E-07	2,32E-07	2,42E-07	8,50E-07
POCP	$kg\ C_2H_4 - eq$	7,38E-04	7,42E-04	7,64E-04	6,47E-04
AP	$kg\ SO_2 - eq$	5,25E-02	5,26E-02	5,30E-02	1,07E-02
EP	$kg\ PO_4^{-3} - eq$	1,32E-02	1,33E-02	1,34E-02	1,47E-03
ADPM	$kg\ Sb - eq$	5,63E-06	5,95E-06	6,84E-06	9,85E-06
ADPE	MJ	2,36E+01	2,38E+01	2,49E+01	6,79E+01

Table 5-12: Aggregates used for backfilling per 1 ton

5.2.2. Construction phase

Due to the case study being of a conceptual parking garage design which has not been built, the quantification of module A5 becomes a challenge. This is because the environmental impacts caused by constructing a building vary greatly on a case-by-case basis and cannot be entirely accurate until a project has been physically built. Only after a building project has been completed is it possible to look at and document all the operations conducted on the building site. As the parking garage is entirely constructed out of reinforced concrete, general data for concrete casting is used to model the onsite activities. The main processes included are installation of formwork, curing, use of pumps, machinery, vehicles, and fuel consumption. Jaro AS which manufactures concrete elements provided the environmental impacts of casting concrete per 1 ton. The use of impacts only associated with casting of concrete elements is far more relevant than building site averages as most other buildings consist of composite frames rather than pure reinforced concrete.

Indicator	**Unit**	**A5**
GWP	$kg\ CO_2 - eq$	7,42E+00
ODP	$kg\ CFC11 - eq$	1,29E-06
POCP	$kg\ C_2H_4 - eq$	8,09E-04
AP	$kg\ SO_2 - eq$	1,67E-02
EP	$kg\ PO_4^{-3} - eq$	1,59E-03
ADPM	$kg\ Sb - eq$	1,51E-05
ADPE	MJ	1,02E+02

Table 5-13: Impacts of casting concrete elements and members per 1 ton

The excavation and backfilling process also faces some of the same challenges as the building site activities. The actual impacts can only be accurately quantified once the building process has been complete, and all activities involved in excavating and backfilling are documented and assessed. Therefore, in this case the Oneclick LCA database is used to gather data on the average environmental impacts caused by excavation and backfilling across many different building projects in the UK.

Indicator	Unit	A5
GWP	$kg\ CO_2 - eq$	1,39E+00
ODP	$kg\ CFC11 - eq$	2,35E-07
POCP	$kg\ C_2H_4 - eq$	2,1E-04
AP	$kg\ SO_2 - eq$	2,04E-03
EP	$kg\ PO_4^{-3} - eq$	4,17E-04
ADPM	$kg\ Sb - eq$	2,36E-06
ADPE	MJ	2,13E+01

Table 5-14: Impacts for digging and backfilling foundation per cubic meter

5.2.3. Demolition process

As the demolition process of a building can greatly vary on a case-by-case basis depending on the methods and machinery used, the environmental impacts are taken as an average. The Oneclick LCA database is used for average demolition and deconstruction processes of buildings in the UK. The ADMP for modules C3 and C4 are deemed negligible (<1% of total ADPM) and were therefore not included.

Indicator	Unit	C1	C2	C3	C4
GWP	$kg\ CO_2 - eq$	3,41E+00	9,63E-01	7,07E-02	1,63E-04
ODP	$kg\ CFC11 - eq$	5,53E-07	1,89E-07	8,41E-09	2,94E-11
POCP	$kg\ C_2H_4 - eq$	5,24E-04	5,62E-05	2,00E-05	3,27E-08
AP	$kg\ SO_2 - eq$	6,3E-03	4,41E-03	4,42E-04	1,20E-06
EP	$kg\ PO_4^{-3} - eq$	1,19E-03	9,60E-04	6,39E-05	2,57E-07
ADPM	$kg\ Sb - eq$	6,14E-06	3,56E-08	-	-
ADPE	MJ	6,03E+01	2,74E+01	1,92E+00	2,41E-03

Table 5-15: Demolition impacts per 1 square meter of demolished building

5.2.4. Energy use during use phase

The yearly energy demand of the parking garage is taken as an average from Enova's 2017 statistical report regarding energy use of different types of buildings in Norway. [85] Once the annual energy demand is established, Oneclick LCA's tool was used to derive the environmental impacts associated with the energy consumptions. Parking garages were reported to generally only use 2 sources of energy, namely electric energy, and district heating. The electricity is sourced as Norwegian electricity and based on an IEA2020 profile in order to calculate the environmental impacts caused by the Norwegian electrical production. The district heating is sourced as district heating from Stavanger, Norway and impact calculation is done based on a LyseNeo201 profile.

Source	Percent usage	Usage per m^2 per year	Total usage per year
Electric	63,8%	75,28 kwh	439 710 kwh
Gas	0	0	0
Fossil fuel	0	0	0
District heating	36,2%	42,72 kwh	211 444 kwh
Biofuel	0	0	0

Table 5-16: Average energy use per year for parking garages in Norway

5.2.5. End of life stage

Indicator	Unit	D
GWP	$kg\ CO_2 - eq$	-1,38E04
ODP	$kg\ CFC11 - eq$	1,05E-04
POCP	$kg\ C_2H_4 - eq$	-1,97E00
AP	$kg\ SO_2 - eq$	-3,76E00
EP	$kg\ PO_4^{-3} - eq$	1,78E-01
ADPM	$kg\ Sb - eq$	-
ADPE	MJ	-1,4E04

Table 5-17: Benefits from end-of-life stage

5.2.6. Data sources

The data quality and sources used in an LCI govern the applicability and relevance of the result. Therefore, the best available data at the time is used for each process and material. The major limitation being not having access to larger databases intended either for internal or commercial/business use. When possible environmental impacts were sourced directly from the manufacturer in the form of an EPD, the EPDs provided are all independently verified, conducted in accordance with ISO 14025:2010/NS-EN 15804 and are required to follow the product category rules (PCR) for the respective product of which they are reporting on. EPD data was specifically used for all materials associated with the different types of concrete tested to ensure accurate results. In certain cases, the EPDs provided were missing modules needed for the LCA model and were therefore supplemented with data from the Oneclick LCA database. The Oneclick LCA database mainly models its processes through the use of the larger Ecoinvent database. Ecoinvent is one of the most used process databases within the environmental assessment field. It is important to note that data sourced from the Oneclick LCA database is taken as an average value.

Process/material	Module	Data source
Cement	A1-A4	EPD [86]
Fly ash	A1-A3	EPD [87]
Fly ash	A4	Oneclick LCA database [88]
Aggregates	A1-A4	EPD [89]
Superplasticizer	A1-A3	EPD [90]
Superplasticizer	A4	Oneclick LCA database [88]
Doors	A1-A4	EPD [91]
Steel reinforcement	A1-A4	EPD [92]
Lighting fixtures	A1-A3	EPD [93]
Lighting fixtures	A4	Oneclick LCA database [88]
Water sprinklers	A1-A4	EPD [94]
Piping	A1-A4	EPD [95]
Electrical cables	A1-A4	EPD [96]
Mixing and pouring concrete elements	A5	EPD [97]
Excavating foundation and backfilling	A5	Oneclick LCA database [88]
Energy use	B6	Enova statistical report [85]
Energy impacts	B6	Oneclick LCA database [88]
Demolition	C1-C4	Oneclick LCA database [88]

Table 5-18: Data sources for each module in the LCI

5.2.7. Total materials and processes

The required amount of materials and processes for each of the three building scenarios has been gathered and presented in terms of functional units. This allows for all materials and processes to be directly aggregated in order to quantify the total environmental impacts caused the concrete parking garage. Some material use has been approximated based on Norwegian guidelines provided in the standards. The amounts of valves and sprinklers needed for the sprinkler system in the parking garage is based on the hazard level of the building. In accordance with NS-EN 12845 the concrete parking garage can be classified as low hazard as it doesn't contain large amounts of flammable materials. The spacing of the sprinkler is therefore taken as 6 meters. NS-EN 12464 provides the guidelines for illumination of indoor workplaces. The lighting fixtures are approximated as 6-10 meters apart in accordance with the standard. Cables and piping are roughly approximated as 1000 m of each.

Process/material	Weight	Functional units
Cement	481 892 kg	481,9
Fly ash	85 040 kg	85
Aggregates 0-8mm	1 432 074 kg	1432,1
Aggregates 8-16mm	1 429 215 kg	1429,2
Superplasticizer	6 771 kg	6 771
Water (for concrete)	181 624 kg	181 624
Doors	N/A	3
Steel reinforcement	120 368 kg	120 368
Lighting fixtures	N/A	66
Water sprinklers	N/A	135
Piping	N/A	1000
Electrical cables	N/A	1000
Mixing and pouring concrete elements	N/A	3600
Excavating foundation and backfilling	N/A	3300
Aggregates for backfilling	7 260 000 kg	7 260
Demolition	N/A	6600

Table 5-19: Total amount of materials and processes needed for constructing a concrete parking garage with regular 15%FA concrete

Process/material	Weight	Functional units
Cement	370 983 kg	371
Fly ash	199 413 kg	199,4
Aggregates 0-8mm	1 432 074 kg	1 432,1
Aggregates 8-16mm	1 429 215 kg	1 429,2
Superplasticizer	6 771 kg	6 771
Water (for concrete)	166 416 kg	166 416
Doors	N/A	3
Steel reinforcement	120 368 kg	120 368
Lighting fixtures	N/A	66
Water sprinklers	N/A	135
Piping	N/A	1000
Electrical cables	N/A	1000

Mixing and pouring concrete elements	N/A	3600
Excavating foundation and backfilling	N/A	3300
Aggregates for backfilling	7 260 000 kg	7 260
Demolition	N/A	6600

Table 5-20: Total amount of materials and processes needed for constructing a concrete parking garage with 35%FA concrete

Process/material	Weight	Functional units
Cement	344 119 kg	344,12
Fly ash	342 162 kg	342,16
Aggregates 0-8mm	1 369 550 kg	1 370
Aggregates 8-16mm	1 366 540 kg	1 367
Superplasticizer	8 278 kg	8 278
Water (for concrete)	159 861 kg	159 861
Doors	N/A	3
Steel reinforcement	120 368 kg	120 368
Lighting fixtures	N/A	66
Water sprinklers	N/A	135
Piping	N/A	1000
Electrical cables	N/A	1000
Mixing and pouring concrete elements	N/A	3600
Excavating foundation and backfilling	N/A	3300
Aggregates for backfilling	7 260 000 kg	7 260
Demolition	N/A	6600

Table 5-21: Total amount of materials and processes needed for constructing a concrete parking garage with 50%FA concrete

5.3. Life cycle inventory assessment

In the LCIA three base cases are considered, this first being constructing the parking garage with regular concrete (containing 15% FA), the second being constructing the parking garage with environmental concrete (containing 35% FA) and the last being constructing the parking garage with experimental environmental concrete (50% FA). As the structural system and all other variables are kept the same, results depict to what degree the use of different concrete types effects the total environmental impact. The data collected in the LCI is aggregated and calculated according to the amount of functional units for each case. A basic matrix calculation routine as described in NS-EN 15978:2011 is used. [83]

$$\begin{pmatrix} a_{1,i} \\ a_{2,i} \\ a_{3,i} \\ a_{\dots,i} \\ a_{n,i} \end{pmatrix} \bullet \begin{bmatrix} GWP_{a_{1,i}} \\ ODP_{a_{1,i}} \\ POCP_{a_{1,i}} \\ AP_{a_{1,i}} \\ EP_{a_{1,i}} \\ ADPM_{a_{1,i}} \\ ADPE_{a_{1,i}} \end{bmatrix} \begin{bmatrix} GWP_{a_{2,i}} \\ ODP_{a_{2,i}} \\ POCP_{a_{2,i}} \\ AP_{a_{2,i}} \\ EP_{a_{2,i}} \\ ADPM_{a_{2,i}} \\ ADPE_{a_{2,i}} \end{bmatrix} \begin{bmatrix} GWP_{a_{3,i}} \\ ODP_{a_{3,i}} \\ POCP_{a_{3,i}} \\ AP_{a_{3,i}} \\ EP_{a_{3,i}} \\ ADPM_{a_{3,i}} \\ ADPE_{a_{3,i}} \end{bmatrix} \begin{bmatrix} GWP_{a_{\dots,i}} \\ ODP_{a_{\dots,i}} \\ POCP_{a_{\dots,i}} \\ AP_{a_{\dots,i}} \\ EP_{a_{\dots,i}} \\ ADPM_{a_{\dots,i}} \\ ADPE_{a_{\dots,i}} \end{bmatrix} \begin{bmatrix} GWP_{a_{n,i}} \\ ODP_{a_{n,i}} \\ POCP_{a_{n,i}} \\ AP_{a_{n,i}} \\ EP_{a_{n,i}} \\ ADPM_{a_{n,i}} \\ ADPE_{a_{n,i}} \end{bmatrix} = \begin{pmatrix} GWP_i \\ OPD_i \\ POCP_i \\ AP_i \\ EP_i \\ ADPM_i \\ ADPE_i \end{pmatrix}$$

Each environmental indicator (EI) can be expressed as:

$$EI_i = \vec{a_i} \times \mathrm{M}$$

Where,

i is the module being assessed, i = [A1, A2, A3, A4, A5, B6, C1, C2, C3, C4, D].
EI_i is the value of the indicator for module i.
$\vec{a_i}$ is the vector containing the total amount of products and services used in module i.
M is the matrix containing the environmental indicators per unit of products and services in module i.

The procedure is exemplified using GWP but is performed for each selected indicator.

$$GWP_i = a_{1,i} * GWP_{a_{1,i}} + a_{2,i} * GWP_{a_{2,i}} + a_{3,i} * GWP_{a_{3,i}} + \cdots + a_{n,i} * GWP_{a_{n,i}}$$

The total environmental impacts for each case are presented in Table 5-22, Table 5-23 and Table 5-24.

	Unit	A1-A3	A4	A5	B6	C1	C2	C3	C4	D	Sum
GWP	$kg\ CO_2 - eq$	4,29E+05	4,48E+04	3,13E+04	1,94E+06	2,25E+04	6,36E+03	4,67E+02	1,08E+00	-1,38E+04	2,47E+06
ODP	$kg\ CFC11 - eq$	3,11E+03	9,17E-03	5,42E-03	2,46E-01	3,65E-03	1,25E-03	5,55E-05	1,94E-07	1,05E-04	3,11E+03
POCP	$kg\ C_2H_4 - eq$	9,67E+01	7,60E+00	3,61E+00	2,71E+02	3,46E+00	3,71E-01	1,32E-01	2,16E-04	-1,97E+00	3,83E+02
AP	$kg\ SO_2 - eq$	2,18E+02	1,69E+0	6,69E+01	4,86E+03	4,16E+01	2,91E+01	2,92E+00	7,92E-03	-3,76E+00	7,35E+03
EP	$kg\ PO_4^{-3} - eq$	5,05E+02	2,20E+01	7,10E+00	1,04E+03	7,85E+00	6,34E+00	4,22E-01	1,70E-03	1,78E-01	1,59E+03
ADPM	$kg\ Sb - eq$	2,90E+00	1,07E-01	5,21E-02	8,75E+03	4,05E-02	2,35E-04	-	-	-	8,76E+03
ADPE	MJ	1,88E+06	7,29E+05	4,37E+05	1,77E+08	3,98E+05	1,18E+05	1,27E+04	1,59E+01	-1,40E+04	1,81E+08

Table 5-22: Total resulting environmental impacts for parking garage constructed with regular 15%FA concrete

	Unit	A1-A3	A4	A5	B6	C1	C2	C3	C4	D	Sum
GWP	$kg\ CO_2 - eq$	3,63E+05	4,50E+04	3,13E+04	1,94E+06	2,25E+04	6,36E+03	4,67E+02	1,08E+00	-1,38E+04	2,41E+06
ODP	$kg\ CFC11 - eq$	3,11E+03	9,21E-03	5,42E-03	2,46E-01	3,65E-03	1,25E-03	5,55E-05	1,94E-07	1,05E-04	3,11E+03
POCP	$kg\ C_2H_4 - eq$	9,49E+01	7,49E+00	3,61E+00	2,71E+02	3,46E+00	3,71E-01	1,32E-01	2,16E-04	-1,97E+00	3,81E+02
AP	$kg\ SO_2 - eq$	2,13E+03	1,64E+02	6,69E+01	4,86E+03	4,16E+01	2,91E+01	2,92E+00	7,92E-03	-3,76E+00	7,29E+03
EP	$kg\ PO_4^{-3} - eq$	4,98E+02	2,19E+01	7,10E+00	1,04E+03	7,85E+00	6,34E+00	4,22E-01	1,70E-03	1,78E-01	1,56E+03
ADPM	$kg\ Sb - eq$	2,85E+00	1,08E+01	6,21E-02	8,75E+03	4,05E-02	2,35E-04	-	-	-	8,76E+03
ADPE	MJ	1,86E+06	7,39E+05	4,37E+05	1,77E+08	3,98E+05	1,18E+05	1,27E+04	1,59E+01	-1,40E+04	1,81E+08

Table 5-23: Total environmental impact for parking garage constructed with 35%FA concrete

	Unit	A1-A3	A4	A5	B6	C1	C2	C3	C4	D	Sum
GWP	$kg\ CO_2 - eq$	3,49E+05	4,49E+04	3,13E+04	1,94E+06	2,25E+04	6,36E+03	4,67E+02	1,08E+00	-1,38E+04	2,39E+06
ODP	$kg\ CFC11 - eq$	3,46E+03	9,21E-03	5,42E-03	2,46E-01	3,65E-03	1,25E-03	5,55E-05	1,94E-07	1,05E-04	3,46E+03
POCP	$kg\ C_2H_4 - eq$	9,86E+01	7,44E+00	3,61E+00	2,71E+02	3,46E+00	3,71E-01	1,32E-01	2,16E-04	-1,97E+00	3,85E+02
AP	$kg\ SO_2 - eq$	2,10E+03	1,64E+02	6,69E+01	4,86E+03	4,16E+01	2,91E+01	2,92E+00	7,92E-03	-3,76E+00	7,26E+03
EP	$kg\ PO_4^{-3} - eq$	4,92E+02	2,21E+01	7,10E+00	1,04E+03	7,85E+00	6,34E+00	4,22E-01	1,70E-03	1,78E-01	1,58E+03
ADPM	$kg\ Sb - eq$	2,84E+00	1,09E-01	6,21E-02	8,75E+03	4,05E-02	2,35E-04	-	-	-	8,76E+03
ADPE	MJ	1,88E+06	7,45E+05	4,37E+05	1,77E+08	3,98E+05	1,18E+05	1,27E+04	1,59E+01	-1,40E+04	1,81E+08

Table 5-24: Total environmental impact for parking garage constructed with 50%FA concrete

Comparison of the concrete mixes

The comparison of the different types of concrete is interesting in order to get an idea how much the environmental impacts different on a material level excluding the entire building system. The system boundaries for this comparison are limited to A1-A3, meaning all environmental impacts from raw material extraction to manufacturing are included. The contribution of each ingredient used in the making of the concrete is shown in Figure 5-6. As can be clearly seen, even in the case where fly ash makes up 50% of the binder content the environmental impacts are negligible across all the selected indicators. This makes fly ash a particularly good SCM. The cement in the concrete contributes the most to the total greenhouse gases released with ranges between 86%-91% of total the GWP and 71%-77% of the mineral resource depletion. The superplasticizer completely dominates the ODP of the concrete accounting for 99.9% and 58%-67% of the POCP. Meanwhile the aggregates have their largest contribution of 79%-84% to the EP and 66%-73% to the AP of the concrete. The total energy use is evenly shared between the super plasticizer and aggregates with cement accounting for 23%-16%.

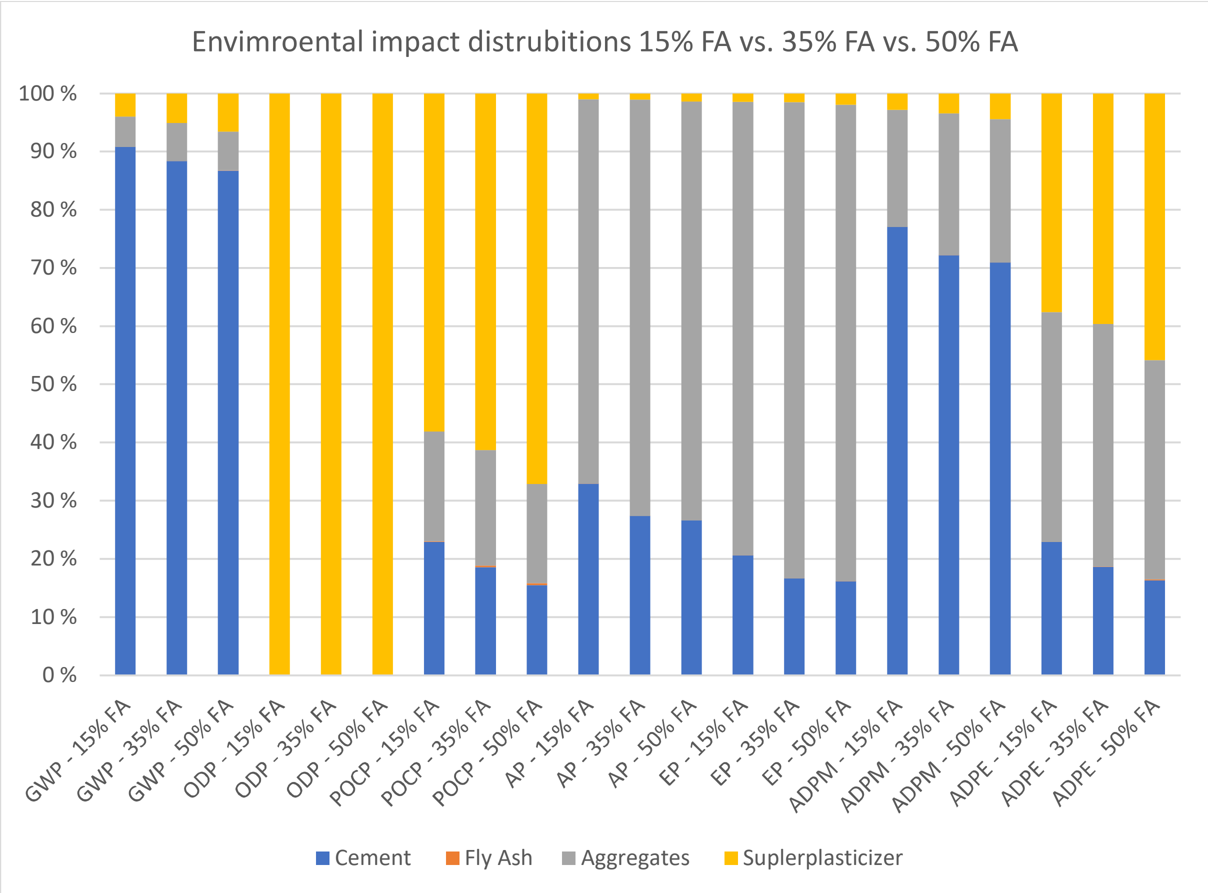


Figure 5-6:Comparison of environmental impacts for each of the concrete mixes

Comparison of the entire building system

While the environmental impacts of the different concrete mixes on their own are interesting when purely considering a more environmentally friendly material, the impacts related to the entire building system provides a better understanding of their total effectiveness. For each of the three cases all modules listed in Table 5-1 are included excluding the energy used during the buildings operating stage meaning the results represent a "cradle to grave" scenario for each parking garage case. The energy use was not included in order to allow for evaluation of the building itself without external contributions. When comparing the environmental impacts of the cement to all the other building materials and processes, the total contribution to carbon dioxide release is still significant and dominant. In contrast to the isolated concrete cases, the cement accounts for 46%-55% of the total GWP of the building while the rest is distributed among the remaining materials and processes excluding fly ash. Even when considering the total building system, the superplasticizer still accounts for 99.9% of the ODP but is not as dominating in the POCP as compared to the isolated concrete cases. There is also a large difference in mineral depletion where the internal materials of the building such as pipes, cables, lights etc. lead with a 78%-81% contribution compared to the isolated concrete cases where the cement was responsible for over 70% of the ADPM.

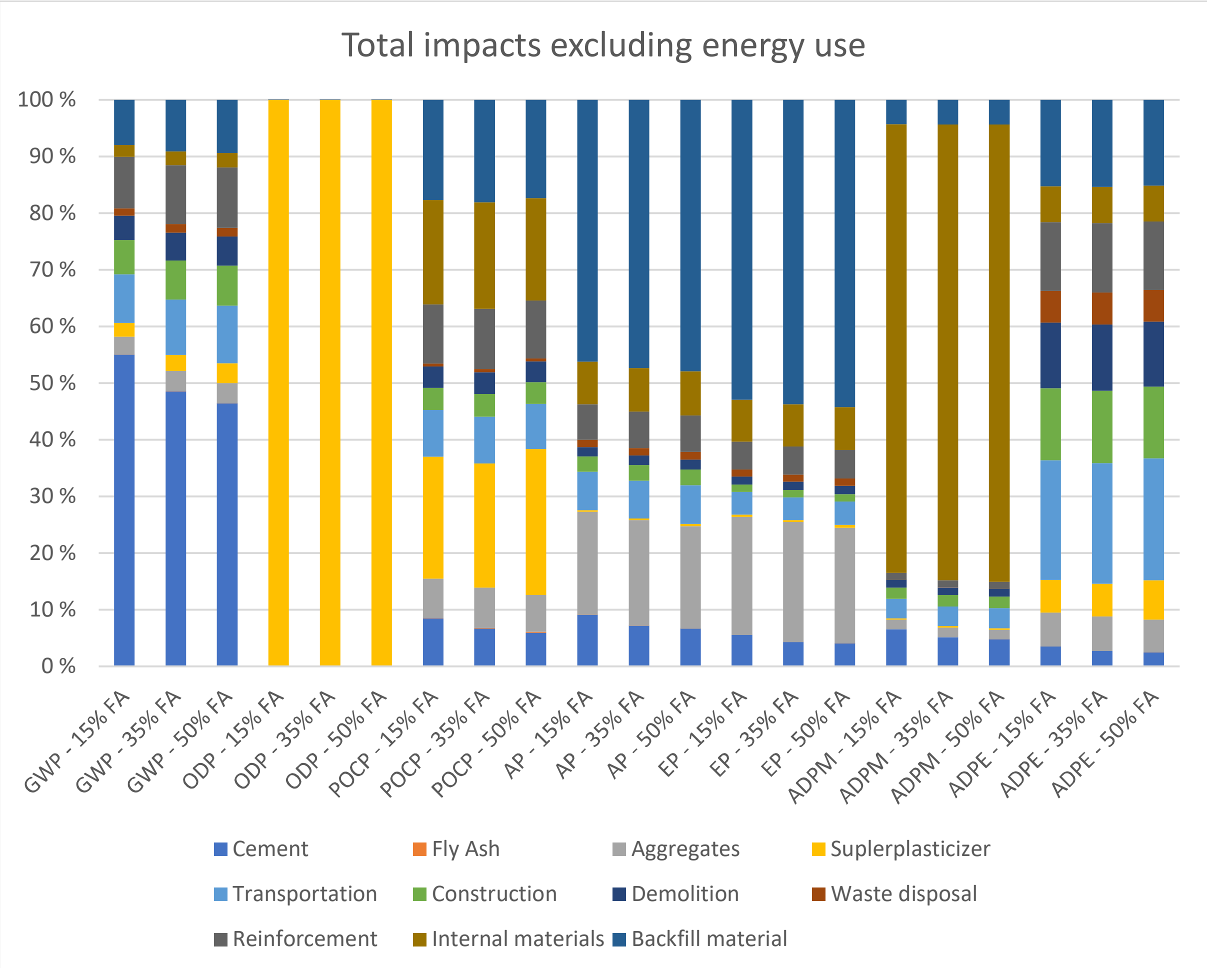


Figure 5-7: Comparison of the total environmental impacts for the entire parking garage excluding the energy use throughout the building's life cycle

Comparison of the entire building system including use phase

The total energy used during the parking garages life cycle is also important to consider due to the large amounts of environmental impacts emerging from power generation. The impacts from the energy use are calculated only for the buildings 60-year design service life, these impacts may be higher if additional repair and rehabilitation work is done to extend the life of the building. The energy impacts dominate all the impact categories with the exception of the ODP, the energy usage accounts for at least 60% of the total GWP, POCP, AP, EP, ADPM and ADPE with some indicators like ADPM and ADPE being entirely dominated by the energy use at over 95%. Even with 60 years of energy use the superplasticizer still accounts for 99.9% of the buildings total ODP.

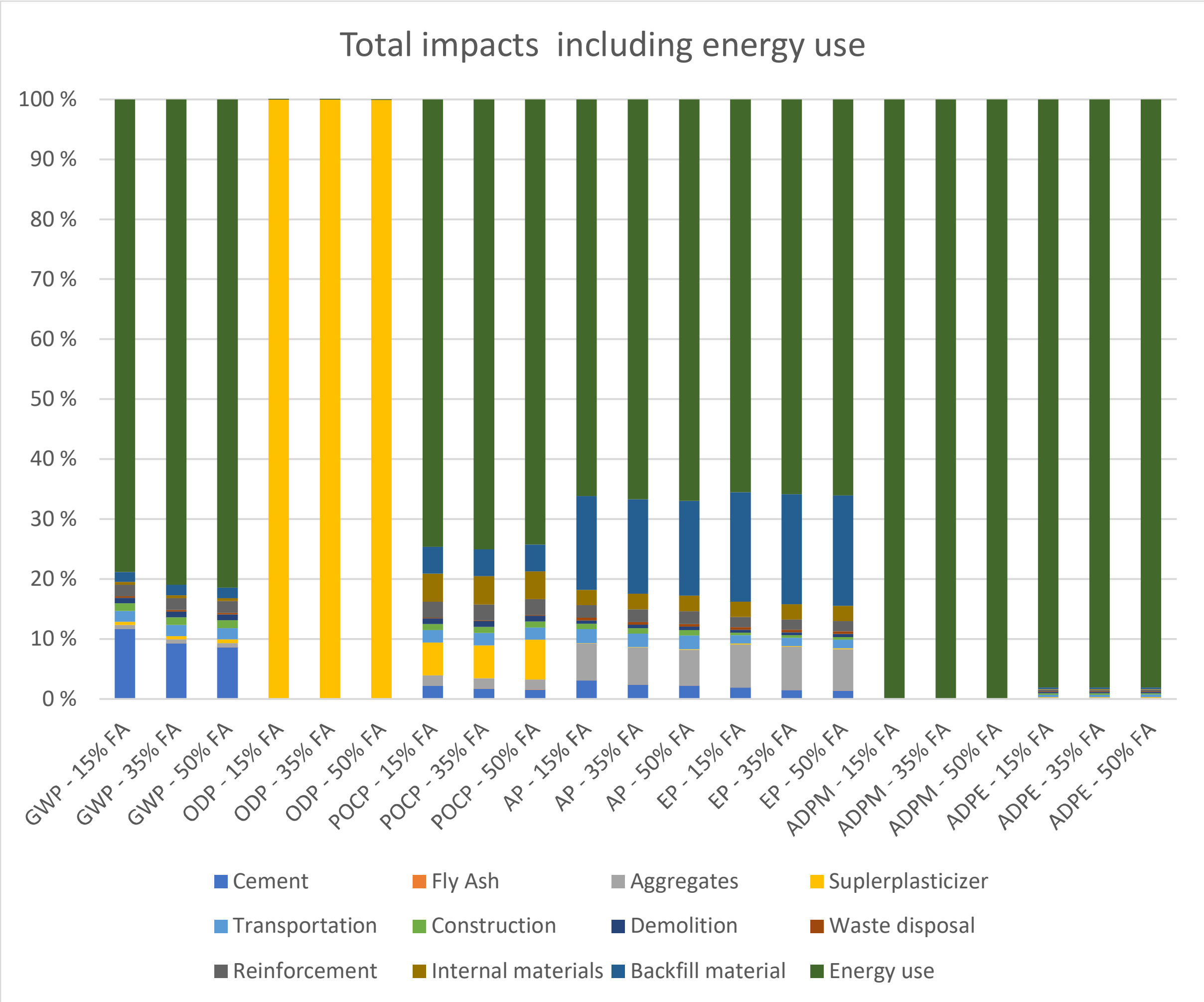


Figure 5-8: Comparison of the total environmental impacts for the entire parking garage including the energy use throughout the building's life cycle

Relative reduction in environmental impact

The most common environmental impact indicator is typically GWP as a measure of a products/process' carbon dioxide footprint. When comparing just the three concrete mixes not including the building system the total GWP reduction compared to the reference 15% FA concrete was 20,87% and 25,23% for concrete containing 35% FA and 50% FA respectively. When accounting for the entire building system the GWP reduction is 12,7% and 15,28% for concrete containing 35% FA and 50% FA respectively. The parking garage constructed with 50% FA concrete exhibited a 21,79% increase in ODP meanwhile all other selected indicators remained within 4% of each other with no significant outliers.

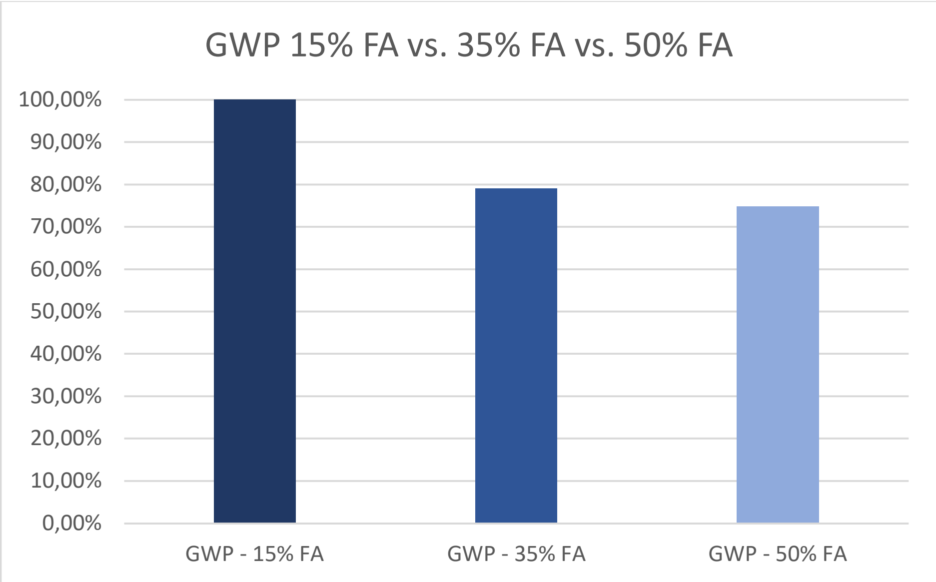


Figure 5-9: total GWP for each concrete mix

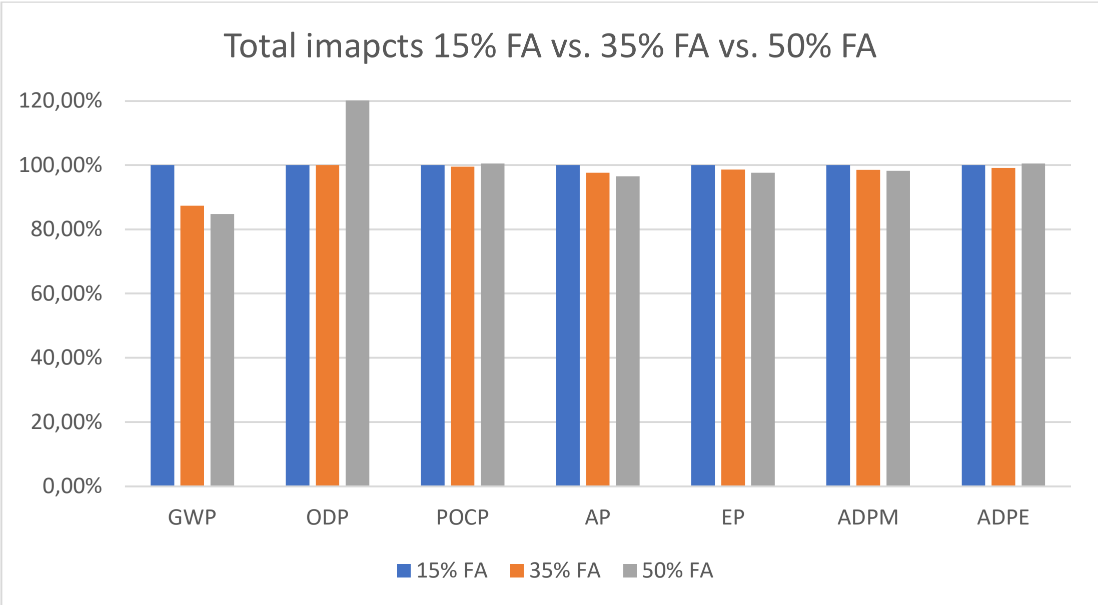


Figure 5-10: Comparison of total environmental impacts of the parking garage

5.4. Interpretation and discussion of results

GWP

GWP is the most widely known and used indicator to measure how much of an impact a product or process has on climate change. As the main focus of the study is to investigate how beneficial the use of fly ash as a cement replacement is, GWP is of particular interest. This is due to the large amount of greenhouse gases which are released during the production of clinker all of which exacerbate global warming.

When looking at the material scale (modules A1-A3 of the concrete) a notable difference was seen in the total GWP where the environmental concrete mixes with 35% FA and 50% FA saw a significant reduction. When increasing the FA content by 20% from 15% to 35% there was almost a 1:1 correlation in the reduction of GWP. This shows how dominant the cement is in its contribution to GWP compared to the other main ingredients such as aggregates, FA, water, and superplasticizers. The main challenge when increasing the FA content further is the loss of workability and flow of the concrete. This is due to the FA particle being very fine and filling the voids between he cement particles thus resulting in increased viscosity and making the concrete harder to work with. In order to combat this a larger matrix volume was required in addition to an increase in superplasticizer. The matrix volume was increased from 300 to 330 liters per cubic meter of concrete meaning that even with the reduction of cement binder portion from 65% to 50%, the total amount of cement reduction is not 1:1. The reduction of GWP when going from 35% FA to 50% FA was rather low with a total reduction of 4,36% indicating diminishing returns when increasing FA content due to the workability challenges. When comparing to the reference concrete which only contains 15% FA to the experimental environmental concrete with 50% FA the total GWP reduction observed was 25,23% which is rather significant especially for projects where large volumes of concrete are needed. As FA is only a direct replacement of cement, the remaining ingredient quantities remained roughly the same with only the 50% FA recipe requiring more superplasticizer. Therefore, no reduction in GWP through less aggregate or superplasticizer use was observed with all other materials used in the concrete only accounting for 9%-14% of the total GWP.

When comparing the GWP of the different concretes in relation to the whole building system we can see that the total portion of GWP for which cement is directly responsible has significantly decreased. Cement was responsible for 86%-91% of the GWP of the concrete but only 46%-55% of the entire building's GWP. This highlights the importance of considering environmental impact reduction in relation to all other materials and processes involved. When using 50% FA concrete the total GWP was reduced by 15,28% compared to using regular 15% FA concrete meaning that there is still a benefit of using FA to reduce the environmental impact. However, only looking at the concrete may be misleading. The difference between 35% FA and 50% FA was 2,58%. Transportation, demolition, and construction together account for 21%-26% of the building's GWP and no specific efforts were made to make these processes more environmentally friendly during this study. This shows the potential of using more environmentally friendly alternatives such as electric engines instead of fossil fuel-based engines or not using single use components in the construction process. In addition, the transportation of materials can be optimized though shorter routes and/or more efficient transportation vehicles. The steel reinforcement used in the concrete is declared at 98% recycled which is typical for most types of steel reinforcement meaning that the material is already optimized for a lower environmental impact. Additional optimization would come from reduction of transportation emissions and production machinery. Through these additional measures further reduction of the building's greenhouse gas emissions could be achieved.

Including the total energy used by the parking garage over its 60-year designed service life provides an interesting perspective on how small the environmental impacts associated with the materials, construction and demolition process really are. In the 60-year life span of the parking garage the concrete used for its construction is only responsible for 10%-13% of the total GWP and the other materials and process are responsible for around 6%-7%. The remaining greenhouse gas emissions are all due to the energy use. The distribution of energy use for parking garages is 63,8% electric and 36,8% district heating with each contributing 29%-30% and 51%-53% to the buildings GWP respectively. Due to Norway's unique electricity mix of mostly renewable environmentally friendly energy sources such as hydro and wind power, the environmental impacts of the electrical portion are significantly lower than the district heating despite being responsible for 63.8% of the total energy. The most significant reduction of GWP would come from lowering the total energy needed/consumed by the parking garage, this could be done by increasing insulation or using 100% electric energy. However, the main challenge would be the costs as district heating is often times cheaper. Alternative designs of a passive parking garage could be developed where only lighting is required but heating is often also required in order to ensure moisture control, comfort, vehicle maintenance and to prevent ice from forming within the structure.

ODP

The ODP of a material or process is important as it signifies its ability to break down the ozone layer located in the earth's atmosphere. The ozone layer serves as a protective layer that stops harmful ultraviolet radiation from reaching the earth's surface. Actively trying to reduce the ODP of system directly benefits human health as the result of a reduced ozone layer is an increase in skin cancer, cataracts, and other health problems.

The ODP is entirely dominated by the superplasticizer on the concrete scale, building system scale and building system including energy use scale. In all three cases 99.9% of the ODP is caused by the superplasticizer used during the concrete production. Superplasticizers are typically made up of sulfonated melamine formaldehyde condensates or sulfonated naphthalene formaldehyde condensates and have a very high ODP compared to all other materials used in the building process. This is due to the high presence of chlorine atoms in their chemical structure and chlorine atoms are highly reactive and react with the ozone in our atmosphere.

The concrete containing 50% FA required an increase in matrix volume to achieve sufficient workability thus resulting in an increase of superplasticizer as the amount is set to 1,2% of the total binder volume. Therefore the 50% FA concrete had a 21,79% increase in total ODP due to the aforementioned increase in superplasticizer needed. An increase in matrix volume was not needed for the 35% FA concrete meaning the ODP was identical to the 15% FA concrete. In the case of whether 35% FA or 50% FA concrete is more preferable is not always straight forward, the choice will depend on the specific scope, goals, and applications of the material. Higher FA content leads to lower total GWP but a higher ODP from superplasticizer use and lower FA leads to higher total GWP but lower ODP. Often times reducing the greenhouse gas footprint of a building is preferred as global warming is a much more far reaching and long-lasting problem which is continuing to worsen. The depletion of the ozone layer has been reduced significantly thanks to the success of the Montreal protocol which is an international agreement to phase out substances with high ODPs.

POCP

POCP indicates the potential of a material of process to contribute to the formation ground level ozone. This is typically resulting from the release of nitrogen oxides and other VOCs into the atmosphere. Ground level ozone in harmful to human health as it's responsible for a plethora of health issues such as respiratory problems, cardiovascular problems, reduced lung function, damage to vegetation and the creation of smog. The importance of a buildings POCP depends on the local environmental context, in large urban areas where air pollution and smog are significant problems POCP should be more heavily focused. This is particularly interesting in the context of a finished building as the constructed building often doesn't directly release large amounts of nitrogen oxides and VOCs. The POCP is instead generated at the manufacturing sites of the individual components and materials which all may be sources from different locations with different local environments. This makes for a much more complex evaluation of the relevance of reducing the POCP for a particular building project.

On the concrete scale there was minimal reduction of the POCP when reducing the cement content as the cement already only accounted for a small portion of the total POCP. The main contributor to the POCP is the superplasticizer meaning that the 50% FA concrete has an ever so slightly higher total POCP due to the increased matrix volume and increased amount of superplasticizer. On the building system scale the three main contributors to the majority of the POCP are the superplasticizer, internal materials (cables, pipes, doors etc.) and backfill material with cement only accounting for 5%-8% of the buildings total POCP.

When including the 60-year service life energy use the majority of the POCP is generated by the energy use at around 72%-75%. This make the miniscule difference between the different concrete types insignificant as reducing the cement quantity does not affect the total POCP by any meaningful amount especially when considering the parking garages total energy use.

AP

AP is an important indicator when considering the environmental impact of a material or building as acidification of the surrounding environment can lead to ecological and human health damage. The most common result of high acidification is acid rain which causes damage to plant life and a lowering of the pH of water bodies making them toxic to a majority of life within them. Acidification also leads to acidic air pollution which can result in respiratory problems. The acidification results from the emission of SO_2 and NO_x which are commonly emitted through the burning of fossil fuels in processes such as transportation of materials, cement production and machinery used during the construction and demolition of the building.

The reduction of cement through the use of fly ash resulted in a decrease from 33% to 26% of the concretes total AP when only looking at the concrete scale. When including the entire building system, the drop in AP is only 2,5% when going from 15% FA concrete to 50% FA concrete. Among all the modules included demolition of the building showed to be the highest contributor to the AP of the parking garage at 45%-47,5% of the total AP. This is due to the use of heavy machinery such as bulldozers and excavators as well as the release of large amounts of dust during the demolition. Including the energy use during the parking garages 60-year service life shows that energy use is responsible for 66%-67% of the buildings total AP. This means that the use of environmental concrete is not particularly effective at reducing the AP footprint of a building however other measure such as appropriate planning and selection of machinery during the demolition and higher overall energy efficiency can prove to be effective.

EP

Eutrophication refers to the increase of nutrients such as nitrogen and phosphorus in aquatic bodies resulting in unnatural amounts of alae growth which can block sunlight from reaching other organisms further down in the water. In all three concrete mixes cement only accounts for 16%-21% of the AP with the majority being caused by the aggregates. The percent contribution of each material and process is very similar to the AP with demolition being slightly more dominant. The same conclusion can be made as for the AP, the use of environmental concrete doesn’t significantly lower the buildings total EP and other measures should instead be taken.

ADPM and ADPE

The depletion of nonrenewable resources such as fossil fuels, minerals and metals is a concern due to their finite amount which can’t be replaced once they are depleted. The construction industry continues to grow, innovate, and place an increasing focus on sustainability, this can directly be translated into the depletion of nonrenewable resources. A building with a low ADPM and ADPE is therefore highly preferable as it ensures more resources are available for future generations as well as directly lowering other environmental impacts through requiring less burning of fossil fuels, excavating, and processing of metals and minerals.

There are minor improvements to both the ADPM and ADPE when using environmental concrete however the concrete used during the construction of the parking garage accounts for 5%-7% of the buildings total ADPM and ADPE. The majority of ADPM is due to the internal materials requiring nonrenewable metals during their manufacturing process. In general, any reduction is insignificant as the energy use of the parking garage over its 60-year service life accounts for 99.9% of the ADPM and 97% of the ADPE.

5.5. Future studies

Within the concrete field, the investigation of even higher amounts of fly ash (>50%) should be investigated in order to see how the mechanical and rheological properties are effected. The replacement of a large portion of the cement in the binder could lead to an even greater reduction in emissions if the strength and workability of the concrete are not compromised. Additional tests with different types of SCMs other than fly ash such as slag, silica fume and slag/fly ash combination to see how they perform in exceedance of the guidelines set by NS-EN 206. The rheological properties need to be thoroughly researched and evaluated, this is due to the technical limitations on building sites and other practical uses. These experimental environmental concretes may perform well in testing conditions however working, curing, pouring, mixing, and pumping conditions vary greatly in situ and present new challenges. An absolute upper limit of SCM to cement ratio would be interesting to test/find in order to see where regular pure Portland concretes and environmental concretes’ mechanical and rheological properties start to deviate from each other. As well as evaluating how much deviation is acceptable.

Within the LCA field, performing an LCA of a building with a composite frame using environmental concrete for comparison would be useful. This thesis focuses on exclusively using environmental concrete in order to reduce a buildings environmental footprint, a study combing environmentally friendly solutions within all materials and processes used would be beneficial to quantify the difference between a truly “green” structure and a regular one. Additionally, a new LCA of the same case study could be performed using additional indicators and professionally licensed software and databases to achieve even better quantifications of the environmental benefits of using high amounts of SCM in concrete structures.

6. Conclusion

This master thesis focuses on the environmental impacts caused by the building industry and more specifically on the emissions due to concrete production and usage. In order to reduce the large amounts of greenhouse gas emissions and other environmental damage caused by Portland cement, SCMs can be used as a partial replacement in the concrete's binder. This results in lower total cement usage and production in turn reducing the damage to the environment.

Difficulties can arise when talking about environmental impacts due to the techniques and transparency of the assessment methods used to quantify these impacts. In the European union and Norway specific guidelines and methodologies have been developed in order to standardize the quantification of environmental impacts. The current practice is to follow the CEN/TC 350 standards, namely EN 15804 regarding EPDs and EN 15978 for conducting building LCAs. EPDs developed according to the EN 15804 methodology and guidelines have proven to be particularly useful when comparing the environmental impacts of different building materials due to the pre-defined, selected indicators and units allowing for a direct comparison. Building's environmental performance can likewise be assessed through methods (CML, EI99, ReCiPe etc.) adhering to the EN 15978 guidelines and allows for more accurate and transparent environmental certification. Furthermore, this allows for easy comparison and leads to better optimization in the design and construction of new structures.

The case study performed showcased the effect that environmental concrete had on the total environmental impacts of a multi-story parking garage constructed entirely out of concrete. When considering only the building system excluding the operational energy use throughout its lifetime, a significant reduction of 15,28% in GWP was achieved through the use of 50% fly ash concrete. However, when considering the energy demand of the building throughout its 60-year design service life it is apparent that the environmental impacts due to heating and electrical demands greatly outweigh the reduction due to the environmental concrete.

In conclusion using high amounts of fly ash provides notable results regarding the reduction of greenhouse gas emissions of concrete buildings. The strength and workability are affected resulting in a slower hydration/strength development and increased cohesion and density of the concrete. The use of SCMs alone seems to not be enough to significantly lower emissions when looking at it from a holistic perspective, it is however a step in the right direction if paired with other "green" building materials, building/transportation processes and most importantly renewable and green energy/electricity sources.

7. References

[1] A. Forty, Concrete and Culture A Material History, London : reaktionbooks, 2012.

[2] N. Betongforening, "Lavkarbonbetong nr. 37," Norsk Betongforening, 2020.

[3] t. constructor, "the constructor," [Online]. Available: https://theconstructor.org/concrete/environmental-impact-concrete/16223/. [Accessed 3 February 2023].

[4] D. L. N. F. a. P. F. Thomas Hills, "Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting," ACS publications, 2016.

[5] "specifyconcrete," 18 July 2019. [Online]. Available: https://www.specifyconcrete.org/blog/eco-friendly-alternatives-to-traditional-concrete. [Accessed 3 February 2023].

[6] F. M. Lea, "Britannica," Britannica, 26 July 1999. [Online]. Available: https://www.britannica.com/technology/cement-building-material/Extraction-and-processing. [Accessed 4 February 2023].

[7] K. T. Fosså, "Cement hydration," Kjell Tore Fosså, Stavanger, 2022.

[8] Standard Norge , NS-EN 196-6:2018 Methods of testing cement - Part 6: Determination of fineness, Standard Norge, 2019.

[9] K. T. Fosså, "Intro + Cement I," UiS, Stavanger, 2022.

[10] Standard Norge, NS-EN 197-1:2011 Cement - Part 1: Composition, specifications and conformity criteria for common cements, Standard Norge, 2011.

[11] S. M. Levy, onstruction Calculations Manual, Butterworth Heinemann, 2012.

[12] Standard Norge, NS-EN 12350-2:2019 Testing fresh concrete - Part 2: Slump test, Standard Norge, 2019.

[13] K. T. Fosså, "Aggregates and Admixtures," UiS, Stavanger, 2022.

[14] SINTEF, "Byggforsk," [Online]. Available: https://www.byggforsk.no/dokument/589/sement_typer_egenskaper_og_bruksomraa. [Accessed 4 February 2023].

[15] N. B. Winter, Understanding cement, WHD Microanalysis Consultants, 2005.

[16] K. T. Fosså, "Cement Hydratisering II," UiS, Stavanger, 2022.

[17] R. W. G. Ph.D, Combustion Ash Residue Management, 6.3.3.1 Cement Fineness, Elsevier, 2014.

[18] Y. Yan, Cement and Concrete Research, Elsevier, 2022.

[19] Sika Group, "Sika," [Online]. Available: https://www.sika.com/en/construction/concrete-protection.html. [Accessed 6 february 2023].

[20] M. L. Peter C. Hewlett, Lea's Chemistry of Cement and Concrete, BH, 2017.

[21] P. W. B. Nasser Mostafa, "Heat of hydration of high reactive pozzolans in blended cements: Isothermal conduction calorimetry," ResearchGate, 2005.

[22] UltraTech Cement Ltd., "Effect of Pore structure on Durability of Concrete," 2012.

[23] K. T. Fosså, "Cement - Powers modell lecture," UiS, Stavanger, 2022.

[24] J. K. J. P. F. H. H. F. Ash Ahmed1, "Chemical Reactions in Pozzolanic Concrete," Lupine, 2019.

[25] Standard Norge, "NS-EN 206:2013+A2:2021+NA:2022 Concrete — Specification, performance, production and conformity," Standard Norge, 2022.

[26] N. H. M. b. Seham S. Alterary a b, "Fly ash properties, characterization, and applications: A review," Sciencedirect, 2021.

[27] Vantage market research, 14 November 2022. [Online]. Available: https://www.globenewswire.com/en/news-release/2022/11/14/2555191/0/en/Global-Fly-Ash-Market-Size-Share-to-Surpass-Valuation-of-by-2028-16-9-Bn-China-Produces-over-50-of-Global-Fly-Ash-Market.html. [Accessed 15 Februar 2023].

[28] P. Michael Thomas, "Optimizing the Use of Fly Ash in Concrete," University of New Brunswick, 2007.

[29] S. Norge, "NS-EN 450-1:2012 Fly ash for concrete - Part 1: Definition, specifications and conformity criteria," Standard Norge, 2012.

[30] ASTM, "C618-19 Standard specification for coal fly ash and raw or calcinated natural prozzolan for use in concrete," ASTM, 2022.

[31] Z. W. Z. J. Xueying Li, "Influence of Curing on the Strength Development of Calcium-Containing Geopolymer Mortar," ResearchGate, 2013.

[32] P. o. Concrete, Adam M. Neville, Pearson, 2011.

[33] D. W. S. Z. P. D. Juntao Ma, "Influence of Particle Morphology of Ground Fly Ash on the Fluidity and Strength of Cement Paste," 2021.

[34] D. K. P. E. al., "Developments in the Formulation and Reinforcement of Concrete; Supplementary cementing materials," Woodhead Publishing, 2019.

[35] D. D. Chung, "Cement-Matrix Composites," Butterworth-Heinemann, 2017.

[36] J. K. B. H. N. Jinwoo An, "Investigation on Impacts of Municipal Solid Waste Incineration Bottom Ash on Cement Hydration," ResearchGate, 2017.

[37] G. M. J. E. Ruben Snellings, Supplementary Cementitious Materials, Leuven, 2012.

[38] K. T. Swee Liang Mak, "Strength development of high strength concretes with and without silica fume under the influence of high hydration temperatures," Elsevier, 1995.

[39] A. C. A. B. Uzbas, "Microstructural Analysis of Silica Fume Concrete with Scanning Electron Microscopy and X-Ray Diffraction," 2020.

[40] A. E. E. a. M. Nili, "EFFECT OF SILICA FUME ON HYDRATION HEAT AND STRENGTH DEVELOPMENT OF HIGH STRENGTH CONCRETE," 2009.

[41] N. K. A. E. al., "EFFECT OF SILICA FUME ON STRENGTH AND DURABILITY PARAMETERS OF CONCRETE," 2012.

[42] B. H. J. Z. Shanshan Jin, "Fractal analysis of effect of air void on freeze–thaw resistance of concrete," 2013.

[43] P. J. M. P. Kumar Mehta, Concrete microstructure, properties and materials, McGraw-Hill.

[44] N. T. Y. K. T. K. Kazuhiro HORII, "Processing and Reusing Technologies for Steelmaking Slag," Nippon steel, 2013.

[45] F. S. E. al., "Development of steel slag composite grouts for underground engineering," Journal of Materials Research and Technology, 2020.

[46] H. M. E. al., "Revisiting the Effect of Slag in Reducing Heat of Hydration in Concrete in Comparison to Other Supplementary Cementitious Materials," 2018.

[47] K. T. fosså, "Fresh concrete - proportioning," UiS, Stavanger , 2022.

[48] Hazell and Jefferies LTD, "THE BENEFITS OF USING RECYCLED AGGREGATES," Hazell and Jefferies LTD, 2020.

[49] Specify Concrete, "Using Recycled Concrete Aggregate," Specify Concrete, 2019.

[50] I. I. Wilfred Zieri, "Alternative Fuels from Waste Products in Cement Industry," in *Handbook of Ecomaterials*, Springer, 2019, p. pp 1183–1206.

[51] Heidelberg Materials , "Heidelberg Materials," Heidelberg Materials , [Online]. Available: https://www.heidelbergmaterials.com/en/carbon-capture-and-storage-ccs.

[52] environdec, "The International EPD System," environdec, [Online]. Available: https://www.environdec.com/all-about-epds/the-epd. [Accessed 3 March 2023].

[53] Standard Norge, "NS-EN 15804:2012+A2:2019+AC:2021 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products," Standard Norge.

[54] A. K. Miroslav RUSKO, "TYPES I, II AND III OF ECOLABELS," 2013.

[55] E. S. e. al., "Environmental assessment of bio-based building materials," in *Performance of Bio-based Building Materials*, Woodhead publishing, 2017, pp. 547-591.

[56] Echochain, "Echochain," Echochain, [Online]. Available: https://ecochain.com/knowledge/impact-categories-lca/. [Accessed 3 March 2023].

[57] I. 2. 5, "ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines," ISO, 2006.

[58] United States Environmental Protection Agency, "EPA," United States Environmental Protection Agency, [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials. [Accessed 5 March 2023].

[59] G. H. R. L. H. U. d. H. A. W. S. J.B. Guinée, ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF PRODUCTS, Leiden: Multicopy, 1992.

[60] IPCC, "Global Warming Potentials Report: The Scientific basis," IPCC, N/A.

[61] LCA.no, "LCA," LCA.no, [Online]. Available: https://lca.no/en/environmental-impact-en-15804-a2/. [Accessed 9 march 2023].

[62] E. a. M.E. Jenkin, "Photochemical ozone creation potentials for volatile organic compounds: Rationalization and estimation," in *Atmospheric Environment*, ScienceDirect, 2017, pp. 128-137.

[63] ISO/TC 207/SC 5, "ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework," ISO , 2006.

[64] A. H. E. al., "Comparative life cycle assessment (LCA) of concrete mixtures: a critical review," European Journal of Environmental and Civil Engineering , 2022.

[65] European Commission - Joint Research Centre - Institute for Environment and Sustainability, "International Reference Life Cycle Data System (ILCD) Handbook General guide for Life Cycle Assessment," Publications Office of the European Union, Luxembourg, 2010.

[66] M. S.-S. S. S. A. J. P. C. Olivier Jolliet, ENVIRONMENTAL LIFE CYCLE ASSESSMENT, Boca Raton: Taylor and Francis Group, 2015.

[67] S. M. Jordaan, LCA Framework, Methods, and Application, 2021.

[68] Scientific Applications International Corporation (SAIC), "Life Cycle Assessment: Principles and Practice," EPA, 2006.

[69] Society of Environmental Toxicology aand Chemisty, "Guildines for Life-Cucle Assessment: A "code of practice"," SETAC, 1993.

[70] A. P. Gursel, "Life-Cycle Assessment of Concrete: Decision-Support Tool and Case Study Application," University of California, Berkley, 2014.

[71] R. Azari, "Economic Input-Output-Based Life Cycle Assessment," Sustainable Construction Technologies, 2019.

[72] S. S. Jessica Perkins, "Uncertainty Implications of Hybrid Approach in LCA: Precision versus Accuracy," ACS Publications, 2019.

[73] PRe Consultants BV, "The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment," PRe Consultants BV, 2001.

[74] EPA, "Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI)," EPA, 2012.

[75] H. Gabathuler, "LCA History: Centrum voor Milieukunde Leiden (CML)," Core UK, 2006.

[76] JRC European Commision, "ILCD Handbook_ AAAnalysis of exisity Enviromental Impact assessment methodologies for uis in Life Cycle Assessment," JRC, 2010.

[77] National Instutute for Public health and the Environment, "ReCiPe 2016 v1.1: A harmonized life cycle impact assessment method at midpoint and endpoint level," PRe-sustainability, 2016.

[78] O. J. e. a. Cécile Bulle, "IMPACT World+: a globally regionalized life cycle impact assessment method," The International Journal of Life Cycle Assessment, 2019.

[79] F. ZAKIR, "alpinme," ALPIN, 23 March 2022. [Online]. Available: https://www.alpinme.com/guide-to-breeam/. [Accessed March 2023].

[80] USGBC, "USGBC," USGBC, 16 December 2020. [Online]. Available: https://www.usgbc.org/articles/green-building-101-what-leed. [Accessed March 2023].

[81] Norsk Betongforening, "Parkeringshus i betong Prosjektering – Bygging – Vedlikehold," Norsk Betongforening, 2020.

[82] T. J. Dymbe, "Chloride ingress and durability of concrete with supplementary cementious materials," UiS, Stavanger, 2023.

[83] Standard Norge, "NS-EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method," Staandard Norge, 2011.

[84] "TEK 17 - Regulations on technical requirements for construction works," Norwegian Building Authority, 2017.

[85] Enova SF, "Enovas byggstatistikk 2017," Enova, 2017.

[86] Norcem, "EPD Norcem Anleggsement FA, Brevik - CEM II/A-V 42,5 N," epd-norge, 2022.

[87] Emineral as, "EPD flyveaske," epddanmark, 2022.

[88] Oneclick LCA, "Oneclick LCA database for materials and processes," Oneclick LCA.

[89] Norstone , "EPD Knust fjell produsert ved Svingen, Halden," epd-norge, 2022.

[90] European Federation of Concrete Admixtures Associations Ltd. (EFCA), "EPD Concrete admixtures – Plasticisers and Superplasticisers," Institut Bauen und Umwelt e.V. (IBU), 2015.

[91] NorDan, "EPD NorDan Bor Ytterdörr 801 Lejonet," epd-norge, 2023.

[92] Norsk stål, "EPD Kamstål til bruk i betong," epd-norge, 2021.

[93] Fischer Lighting, "EPD lighting systems," epddanmark, 2021.
[94] Cimberio, "Product-specific Type III EPD of Cimberio valves," epd-norge, 2020.
[95] Pipelife, "EPD PVC Sewage pipe 160x4,7 SN8 1m," epd-norge, 2021.
[96] Draka, "EPD SE-N1XE-R Light 4G16," epd-norge, 2022.
[97] JARO as, "EPD Massiv betongelement - Vegg, lavkarbonbetong," epd-norge, 2022.

DYNAMON SX-N

Superplastiserende tilsetningsstoff

EN 934-2
T 3.1-3.2

BESKRIVELSE

Dynamon SX-N er et svært effektivt superplastiserende tilsetningsstoff basert på modifiserte akrylpolymerer. Produktet tilhører **Dynamon-systemet** basert på den Mapei-utviklede DPP-teknologien (DPP = Designed Performance Polymers), der tilsetningsstoffenes egenskaper skreddersys til ulike betongformål.
Dynamon-systemet er utviklet på basis av Mapeis egen sammenstilling og produksjon av monomerer.

BRUKSOMRÅDER

Dynamon SX-N er et tilnærmet allround-produkt som er anvendelig i all betong for å øke støpeligheten og/eller redusere tilsatt vannmengde.

Noen spesielle bruksområder er:

- Vanntett betong med krav til høy eller svært høy fasthet og med strenge krav til bestandighet i aggressive miljøer.
- Betong med særlige krav til høy støpelighet; i konsistensklasser S4 og S5 etter NS-EN 206.
- Selvkomprimerende betong med ønske om lengre åpentid. Om nødvendig kan SKB stabiliseres med en viskositetsøker - **Viscofluid** eller **Viscostar**.
- Til produksjon av frostbestandig betong - da i kombinasjon med luftinnførende tilsetningsstoffer - **Mapeair**. Valg av type luftinnførende stoff gjøres ut fra egenskapene til de andre delmaterialer som er tilgjengelige.
- Til golvstøp for å oppnå en smidig betong med bedret støpelighet. Store doseringer og lave temperaturer kan retardere betongen noe.

EGENSKAPER

Dynamon SX-N er en vannløsning av aktive akrylpolymerer som effektivt dispergerer (løser opp) sementklaser.

Denne effekten kan prinsipielt utnyttes på tre måter:

1. For å redusere mengden tilsatt vann, men samtidig beholde betongens støpelighet. Lavere v/c-forhold gir høyere fasthet, tetthet og bestandighet i betongen.

2. For å forbedre støpeligheten sammenlignet med betonger med samme v/c-forhold. Fastheten forblir dermed den samme, men muliggjør forenklet utstøping.

3. For å redusere både vann og sementmengde uten å forandre betongens mekaniske styrke. Gjennom denne metoden kan en blant annet redusere kostnadene (mindre sement), redusere betongens svinnpotensial (mindre vann) og redusere faren for temperaturgradienter på grunn av lavere hydratasjonsvarme. Spesielt er denne siste effekten viktig ved betonger med større sementmengder.

KOMPATIBILITET MED ANDRE PRODUKTER

Dynamon SX-N lar seg kombinere med andre Mapei tilsetningsstoffer, som f.eks størkningsakselererende stoffer som **Mapefast** og størkningsretarderende stoffer som **Mapetard**.

Produktet lar seg også kombinere med luftinnførende tilsetningsstoffer, **Mapeair**, for produksjon av frostbestandig betong.
Valg av type luftinnførende stoff gjøres ut fra egenskapene til de andre delmaterialer som er tilgjengelige.

DOSERING

Dynamon SX-N tilsettes for å oppnå ønsket resultat (styrke, bestandighet, støpelighet, sementreduksjon) ved å variere doseringen mellom 0,4 og 2,0 % av sement + flyveaske + mikrosilika. Ved økt dosering økes også betongens åpentid, dvs. tiden betongen lar seg bearbeide. Større doseringsmengder og lave betongtemperaturer gir en retardert betong. Vi anbefaler alltid prøvestøper med aktuelle parametere.
Til forskjell fra konvensjonelle melamineller naftalenbaserte superplastiserende tilsetningsstoffer, utvikler **Dynamon SX-N** maksimal effekt uavhengig av tilsettingstidspunkt, men tilsetningstidspunktet kan påvirke nødvendig blandetid.
Dersom **Dynamon SX-N** tilsettes etter at minst 80 % av blandevannet er inne vil blandetiden generelt være kortest. Det er likevel viktig med utprøvinger tilpasset eget blandeutstyr.
Dynamon SX-N kan også tilsettes direkte i automikser på bygg- eller anleggsplass. Betongen bør da blandes med maksimal hastighet på trommelen i ett minutt pr. m^3 betong i lasset, men minimum 5 minutter.

EMBALLASJE

Dynamon SX-N leveres i 25 liters kanner, 200 liters fat, 1000 liter IBC-tanker og i tank.

LAGRING

Produktet må oppbevares ved temperaturer mellom +8°C og +35°C. I lukket emballasje bevarer produktet sine egenskaper i minst 12 måneder. Hvis produktet utsettes for direkte sollys, kan det føre til variasjoner i fargetonen uten at dette påvirker egenskapene til produktet.

SIKKERHETSINSTRUKSJONER FOR KLARGJØRING OG BRUK

For instruksjon vedrørende sikker håndtering av våre produkter, vennligst se siste utgave av sikkerhetsdatablad på vår nettside **www.mapei.no**

PRODUKT FOR PROFESJONELL BRUK.

TEKNISKE DATA (typiske verdier)

PRODUKTBESKRIVELSE	
Form:	væske
Farge:	gulbrun
Viskositet:	lettflytende; < 30 mPa·s
Tørrstoffinnhold (%):	17,0 ± 1,0
Densitet (g/cm^3):	1,05 ± 0,02
pH:	6,5 ± 1
Kloridinnhold (%):	< 0,05
Alkaliinnhold (Na_2O-ekvivalenter) (%):	< 2,0

MERK

De tekniske anbefalinger og detaljer som fremkommer i denne produktbeskrivelse representerer vår nåværende kunnskap og erfaring om produktet. All ovenstående informasjon må likevel bli betraktet som retningsgivende og gjenstand for vurdering. Enhver som benytter produktet må på forhånd forsikre seg om at produktet er egnet for tilsiktet anvendelse. Brukeren står selv ansvarlig dersom produktet blir benyttet til andre formål enn anbefalt, eller ved feilaktig utførelse.

Vennligst referer til siste oppdaterte versjon av teknisk datablad som finnes tilgjengelig på www.mapei.no

JURIDISK MERKNAD

Innholdet i dette tekniske databladet kan kopieres til andre prosjektrelaterte dokumenter, men det endelige dokumentet må ikke suppleres eller erstatte betingelsene i det tekniske datablad, som er gjeldende, når MAPEI produktet benyttes. Det seneste oppdaterte datablad er tilgjengelig på vår hjemmeside www.mapei.no

ENHVER ENDRING AV ORDLYDEN ELLER BETINGELSER, SOM ER GITT ELLER AVLEDET FRA DETTE TEKNISKE DATABLADET, MEDFØRER AT MAPEI SITT ANSVAR OPPHØRER.

6392-06-2018-no

PRODUKTDATABLAD

ANLEGGSEMENT FA

CEM II/A-V 42,5 N

SIST REVIDERT MARS 2023

Sementen tilfredsstiller kravene i NS-EN 197-1:2011 til Portland flygeaskesement CEM II/A-V 42,5 N.

Egenskap		Deklarerte data	Krav ifølge NS-EN 197-1:2011
Finhet (Blaine m^2/kg)		390	
Spesifikk vekt (kg/dm^3)		3,02	
Volumbestandighet (mm)		1	≤10
Begynnende størkning (min)		165	≥60
Trykkfasthet (MPa)	1 døgn	12	
	2 døgn	21	≥10
	7 døgn	37	
	28 døgn	53	≥42,5 ≤62,5
Sulfat (% SO_3)		≤3,5	≤3,5
Klorid (% Cl^-)		≤0,07	≤0,10
Vannløselig krom (ppm Cr^{6+})		≤2	≤2 [1)]
Alkalier (% Na_2O_{ekv}) [2)]		0,5	
Klinker (%)		81	80-94
Flygeaske (%)		15	6-20
Sekundær bestanddel (%)		4	<5

[1)] I henhold til EU-forordning REACH Vedlegg XVII punkt 47 krom VI-forbindelser

[2)] Alkali-innholdet i sementen fratrukket alkalibidraget fra flygeaskedelen (iht NB21 pkt. 4.4, og bruk av den generelle grensen på 2,5 kg Na_2O ekv / m^3 betong). I betong beregnes alkalibidraget fra sementdelen slik: Sementmengde (kg/m^3) x 0,5%.

Heidelberg Materials

Heidelberg Materials Sement Norge AS,
Postboks 143, Lilleaker, NO-0216 Oslo
firmapost@heidelbergmaterials.com
www.sement.heidelbergmaterials.com

PRODUKTDATABLAD

FLYGEASKE

TILLEGGSMATERIALE

SIST REVIDERT MARS 2023

Flygeasken er sertifisert i overensstemmelse med kravene i NS-EN 450-1, klasse A

Egenskap	Deklarerte data	Krav ifølge NS-EN 450-1
Glødetap (%)	≤5,0	Tilfredsstiller krav gitt NS-EN 450-1
Klorid (% Cl^-)	≤0,10	Tilfredsstiller krav gitt NS-EN 450-1
Sulfat (% SO_3)	≤3,0	Tilfredsstiller krav gitt NS-EN 450-1
Fritt kalsiumoksid (% fri CaO)	≤1,5	Tilfredsstiller krav gitt NS-EN 450-1
Reaktivt kalsiumoksid (% reaktiv CaO)	≤10	Tilfredsstiller krav gitt NS-EN 450-1
Partikkeldensitet (kg/m³	2300	Deklarert verdi +/- 200 kg / m³
Øvrige kjemiske og fysiske parametre		Tilfredsstiller krav gitt NS-EN 450-1

Heidelberg Materials Sement Norge AS ivaretar salg og distribusjon av flygeaske til sement- og betongproduksjon. Flygeaske er et bearbeidet restprodukt fra kull brukt i kullkraftverk. Flygeaske er silikatholdig, og er et pozzolan som sammen med sement og vann gir tettere betong. Kombinert med sement har flygeaske vært i bruk i Norge siden 1980-tallet. Heidelberg Materials sine FA-sementer inneholder flygeaske.

Heidelberg Materials

Heidelberg Materials Sement Norge AS
Postboks 143, Lilleaker, NO-0216 Oslo
Tlf. +47 22 87 84 00   firmapost@sement.heidelbergmaterials.com

Concrete Mix design

SKANSKA

Project	Masteroppgave Tollak
Batch number	FA15
Quality requirements	
Executed by	Tollak og Nikolay
Date	01.01.2023

Initialparametre	**Value**
m = w/(c+Σkp)	0,39
Air content	2,0 %

Cement type	**Part**	**Part of clinker**	**Part FA**	**Part slagg**	**[kg/m^3]**	**Alkalis**	**Chlorides**
Norcem Anlegg FA	100,0 %	85,0 %	15,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	100,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	100,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Additions	**Type**	**Andel (av b)**	**k**	**[kg/m^3]**	**Alkalis**	**Chlorides**
Elkem Microsilica	Silika	0,0 %	2,0	2200	0,1 %	0,1 %
Normineral flyveaske	FA	0,0 %	0,7	2300	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Admixtures	**% av b**	**[kg/m^3]**	**Dry stof**	**[kg/m^3] TS**	**Alkalis**	**Chlorides**
Mapei Dynamon SX-N	1,2 %	1050	16,0 %	1424	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	**Vol %**	**[kg/m3]**
	0,0 %	7800
	0,0 %	1050

Matrix	**Value**
Desired matrix volume [l/m^3]	300
Obtained matrix volum [l/m3]	300
Clinker part in binder	85,0 %
Total FA- content of binder	15,0 %

Total slag content of binder	0,0 %
Volume cement paste [l/m^3]	273,0
Effectiv water content [l/m^3]	146,9
w/p	0,33
Effectiv binder [kg/m^3]	377
Totalt binder [kg/m^3]	377

Beregn

Comments:
Yellow blanket is filled in, green is calculated.
The red background in the cell for obtained matrix volume indicates that the computation macro has not been run, and there is no response between it and the obtained matrix volume. This will also give the blanket the recipe form.

Concrete mix design

SKANSKA

Ö2015-09-21 ss

Project	Masteroppgave Tollak
Batch nr	FA15
Quality requirement	0
Executed by	Tollak og Nikolay
Date	01.01.2023

w/b-ratio	0,39
Matrix volume (l/m^3)	300
Volume cement paste (l/m^3)	273
Assumed air content (%)	2,0
Effectiv binder (kg/m3)	377

"Obtained" equ "Desired"; Ctrl+N

Reset volume correction; Ctrl+K

Concrete mix

Materials	**kg/m^3**	Desired **kg**	Obtained **kg**	**corr.luft**	**corr.dens**	**Corrigert**
Norcem Anlegg FA	376,8	13,2	39,5	0,0	-3,3	391,8
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Elkem Microsilica	0,0	0,0	2,1	0,0	-0,2	20,8
Normineral flyveaske	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Free water	146,9	5,1	16,7	0,0	-1,4	165,9
Absorbed water	7,6	0,3	0,9	0,0	-0,1	8,9
Årdal 0/8 mm	951,8	33,3	85,4	0,0	-7,2	847,1
Årdal 0/2 mm	0,0	0,0	0,0	0,0	0,0	0,0
Årdal 8/16mm	949,9	33,2	0,0	0,0	0,0	0,0
Årdal 16/22 mm	0,0	0,0	0,0	0,0	0,0	0,0
Stalite	0,0	0,0	49,6	0,0	-4,2	492,0
Test	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Test	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Mapei Dynamon SX-N	4,52	0,16	0,50	0,0	0,0	4,96
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Prop. Concrete dens. (kg/m^3)	2434			0,0	-16,5	1927

volum ok

Fresh concrete

Properties	
Desired volume (l)	35,0
Weight volume (l)	100,0
Measured air content (%)	2,0
Measured concrete density (kg	1930
Effectiv w/(c+Σkp)	0,383

Aggressives	
Chloride content [% of c]	0,09 %
Alkalis [kg/m^3]	5,27
Part react. rocks [%]	0,0

Volume corrections

Comments:

Comments:

Yellow fields are filled in, green is calculated.

The matrix volume includes aggregate particles less than 0.125 mm.

When moisture in the aggregate is determined on the basis of oven-dried aggregate, absorbed moisture shall be stated with measured value. The associated density should then also be based on dry aggregate. If moisture in the aggregate is given on an SSD basis, absorbed moisture equal to 0. In this case, the densities should also be stated as SSD density.

All sub-materials except water and TSS are indicated in dry weight. When calculating volume, densities and mass ratios, the water content of Admixture is taken into account in the free water volume. This also applies to corrected recipes . If the weighed amount of Admixtur deviates from the proportioned amount, the mass ratio and the amount of free water in the corrected recipe are automatically corrected.

Note that for pozzolanes, fillers and admixtures, the soild content and moisture are stated on a dry basis. Fiber is not included in the matrix volume.

Mix proporsion

SKANSKA

Project	Masteroppgave Tollak
Batch no	FA15
Quality requirements	0

Batch volume:	35 liter
Date:	
Time for water addition:	
Responsible:	
Executed by:	

Materials	**Mix** kg/m^3	**Batch** kg	**Moisture*** %	**Corr.** kg	**Weight**** kg	
Norcem Anlegg FA	376,8	13,186			13,186	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000			0,000	
	0,0	0,000			0,000	
Free water	146,9	5,143		-1,198	3,944	4,211
Absorbed water	7,6	0,266			0,266	
Årdal 0/8 mm	951,8	33,313	2,2	0,733	34,046	
Årdal 0/2 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8/16mm	949,9	33,247	1,0	0,332	33,579	
Årdal 16/22 mm	0,0	0,000	0,5	0,000	0,000	
Stalite	0,0	0,000	2,0	0,000	0,000	
Test	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Test	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Mapei Dynamon SX-N	4,5	0,158	84	0,133	0,158	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept" ** NB! Våte mengder, også for silikaslurry

Fresh concrete					
Time after water addition					
Slump					
Slump flow					
Air					
Density					

Samples (number)					
Casted time:					
Cubes					
150x300 cylindre					
100x200 cylindre					

Combined aggregate

Fraction	Name	Density	Abs. Mois	Alk. react.	Chlorids	Batch		Use
		[kg/m3]	[%]	Sv[%]	[%]	volume	weight	
I	Årdal 0/8 mm	2680	0,3	0,0	0,00	0,502	0,500	ok
II	Årdal 0/2 mm	2650	0,5	0,0	0,00	0,000	0,000	
III	Årdal 8/16mm	2700	0,5	0,0	0,00	0,498	0,500	ok
IV	Årdal 16/22 mm	2700	0,5	0,0	0,00	0,000	0,000	
V	Stalite	1420	0,0	0,0	0,00	0,000	0,000	
VI	Test	2700	0,0	0,0	0,00	0,000	0,000	
VII		2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX	Test	2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2690		0,0	0,00	1,000	1,000	

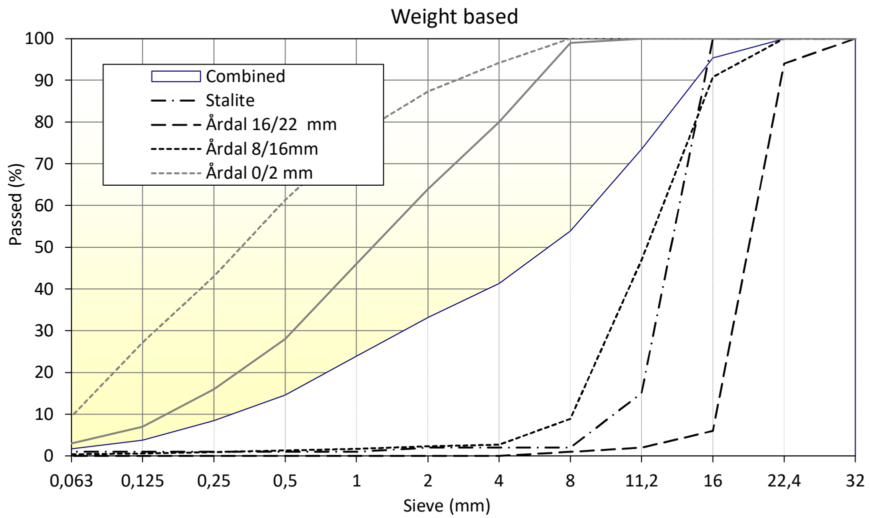
Finenes modulus	
FM_{vekt} =	4,77
FM_{vol} =	4,77
FM_{ref} =	5,07
FMg =	5,55

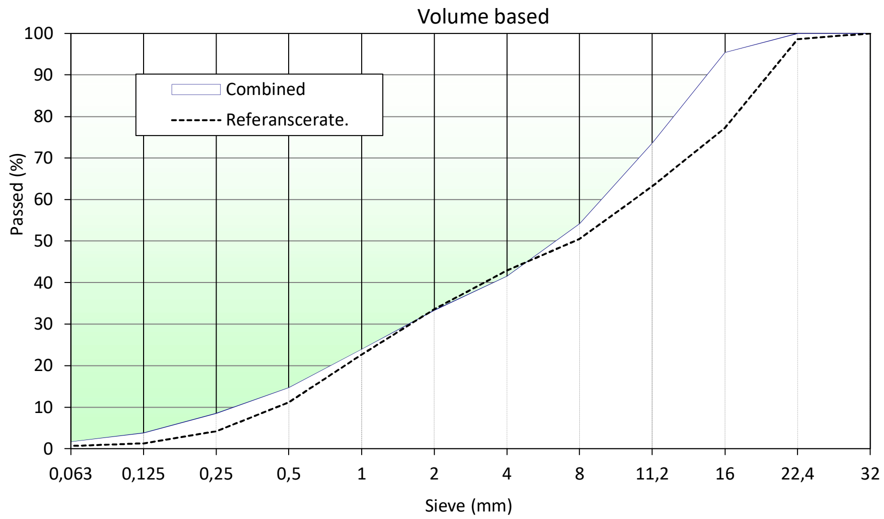
Adjust to ref rating, Ctrl T

Set ref rating, Ctrl R

Adjust to FMg, Ctrl F

Size	Passed		Ref. grad.	Weight at adaption
	vol.[%]	vekt [%]	[vol. %]	
32	100,0	100,0	100,0	1
22,4	100,0	100,0	98,6	1
16	95,4	95,4	77,3	1
11,2	73,6	73,5	63,2	1
8	54,2	54,0	50,5	1
4	41,5	41,4	42,9	1
2	33,3	33,2	33,6	1
1	24,0	23,9	22,7	2
0,5	14,7	14,7	11,2	2
0,25	8,5	8,5	4,2	2
0,125	3,8	3,8	1,3	2
0,063	1,7	1,7	0,7	2

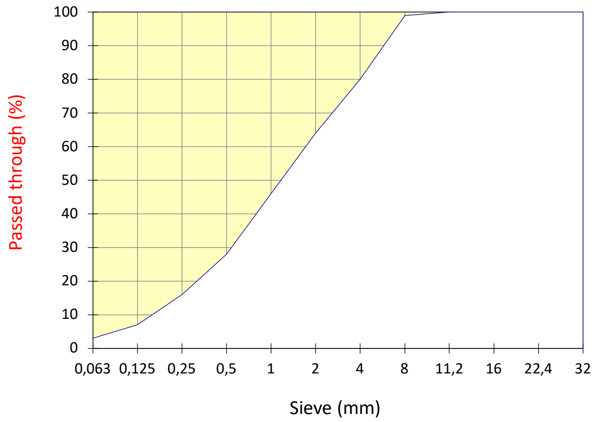




fractionI

Type:	Årdal 0/8 mm
Date:	07.01.2014
FM =	3,14

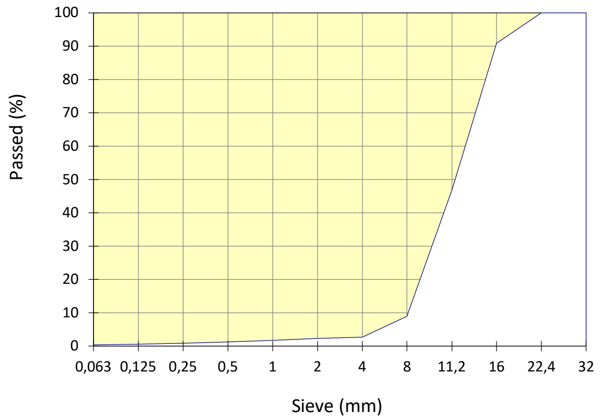
Opning	sieve residue (g)		sieve residue (%)	Passed-through (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	1	1	1,0	99,0
4	20	20	20,0	80,0
2	36	36	36,0	64,0
1	54	54	54,0	46,0
0,5	72	72	72,0	28,0
0,25	84	84	84,0	16,0
0,125	93,0	93,0	93,0	7,0
0,063	97,0	97,0	97,0	3,0
Bottom	100	100		



Fraction III

Type:	Årdal 8/16mm
Date:	07.01.2014
FM =	6,41

Opning	Sieve residue (g)		Sieve residue	Passed-Through
	1	2	(%)	(%)
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	9,2	9,2	9,2	90,8
11,2	53,1	53,1	53,1	46,9
8	91,1	91,1	91,1	8,9
4	97	97	97,3	2,7
2	98	98	97,7	2,3
1	98	98	98,3	1,7
0,5	99	99	98,7	1,3
0,25	99	99	99,1	0,9
0,125	99	99	99,4	0,6
0,063	100	100	99,6	0,4
Bottom	100	100		



Mix proporsion

SKANSKA

Project	Masteroppgave
Batch no	FA50
Quality requirements	0

Batch volume:	50 liter
Date:	01.01.2023
Time for water addition:	
Responsible:	
Executed by:	

Materials	**Mix** kg/m³	**Batch** kg	**Moisture*** %	**Corr.** kg	**Weight**** kg	
Norcem Anlegg FA	269,0	13,452			13,452	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	187,0	9,348			9,348	
	0,0	0,000			0,000	
Free water	132,6	6,632		-1,685	4,947	5,311
Absorbed water	7,3	0,363			0,363	
Årdal 0/8 mm	909,8	45,491	2,2	1,001	46,492	
Årdal 0/2 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8/16mm	908,0	45,400	1,0	0,454	45,854	
Årdal 16/22 mm	0,0	0,000	0,5	0,000	0,000	
Stalite	0,0	0,000	2,0	0,000	0,000	
Test	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Test	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Mapei Dynamon SX-N	5,5	0,274	84	0,230	0,274	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept" ** NB! Våte mengder, også for silikaslurry

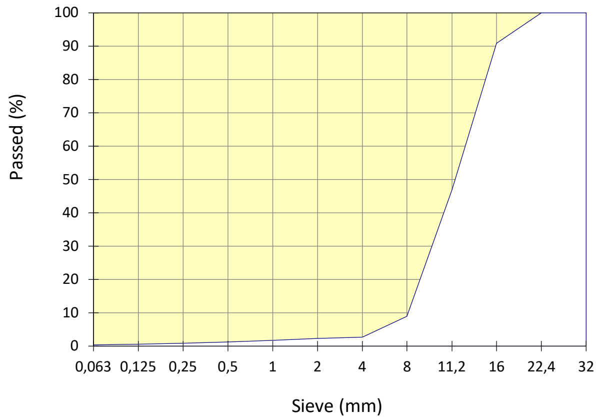
Fresh concrete					
Time after water addition					
Slump					
Slump flow					
Air					
Density					

Samples (number)					
Casted time:					
Cubes					
150x300 cylindre					
100x200 cylindre					

Fraction III

Type:	Årdal 8/16mm
Date:	07.01.2014
FM =	6,41

Opning	Sieve residue (g)		Sieve residue	Passed-Through
	1	2	(%)	(%)
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	9,2	9,2	9,2	90,8
11,2	53,1	53,1	53,1	46,9
8	91,1	91,1	91,1	8,9
4	97	97	97,3	2,7
2	98	98	97,7	2,3
1	98	98	98,3	1,7
0,5	99	99	98,7	1,3
0,25	99	99	99,1	0,9
0,125	99	99	99,4	0,6
0,063	100	100	99,6	0,4
Bottom	100	100		



Combined aggregate

Fraction	Name	Density [kg/m³]	Abs. Mois [%]	Alk. react. Sv[%]	Chlorids [%]	Batch volume	Batch weight	Use
I	Årdal 0/8 mm	2680	0,3	0,0	0,00	0,502	0,500	ok
II	Årdal 0/2 mm	2650	0,5	0,0	0,00	0,000	0,000	
III	Årdal 8/16mm	2700	0,5	0,0	0,00	0,498	0,500	ok
IV	Årdal 16/22 mm	2700	0,5	0,0	0,00	0,000	0,000	
V	Stalite	1420	0,0	0,0	0,00	0,000	0,000	
VI	Test	2700	0,0	0,0	0,00	0,000	0,000	
VII		2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX	Test	2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2690		0,0	0,00	1,000	1,000	

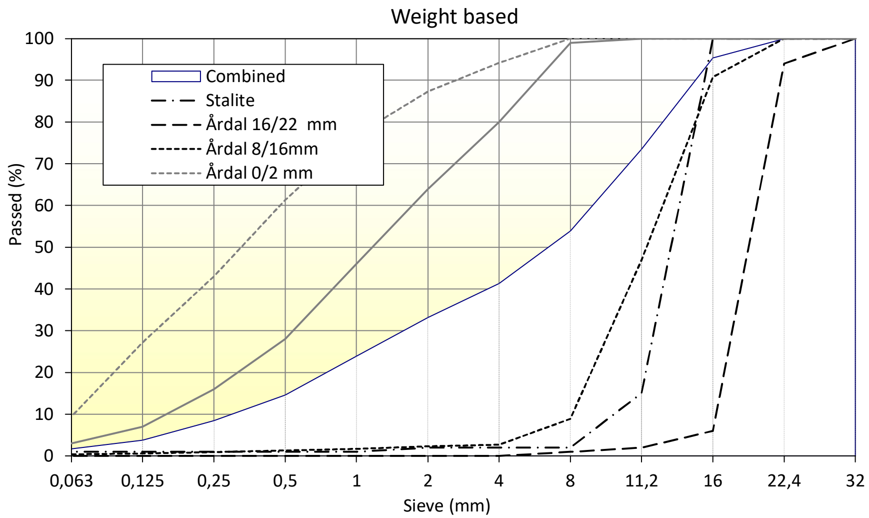
Finenes modulus	
FM_{vekt} =	4,77
FM_{vol} =	4,77
FM_{ref} =	5,07
FMg =	5,55

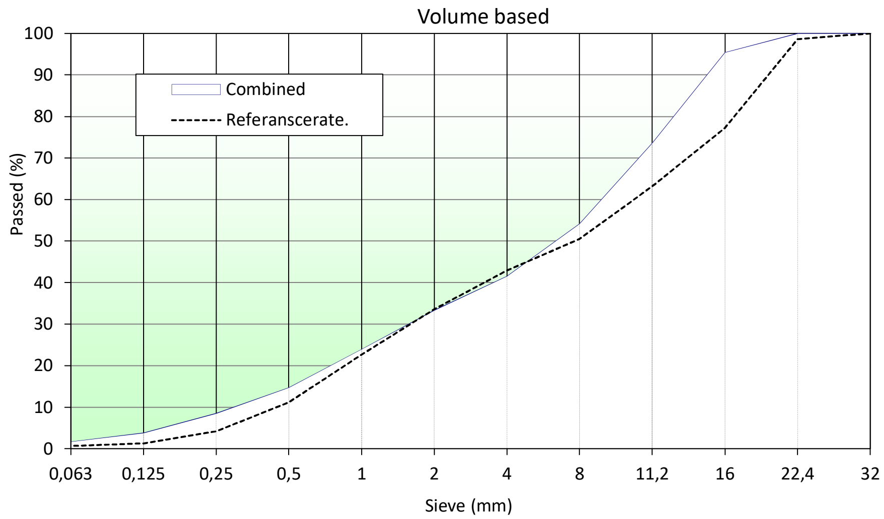
Adjust to ref rating, Ctrl T

Set ref rating, Ctrl R

Adjust to FMg, Ctrl F

Size	Passed vol.[%]	Passed vekt [%]	Ref. grad. [vol. %]	Weight at adaption
32	100,0	100,0	100,0	1
22,4	100,0	100,0	98,6	1
16	95,4	95,4	77,3	1
11,2	73,6	73,5	63,2	1
8	54,2	54,0	50,5	1
4	41,5	41,4	42,9	1
2	33,3	33,2	33,6	1
1	24,0	23,9	22,7	2
0,5	14,7	14,7	11,2	2
0,25	8,5	8,5	4,2	2
0,125	3,8	3,8	1,3	2
0,063	1,7	1,7	0,7	2

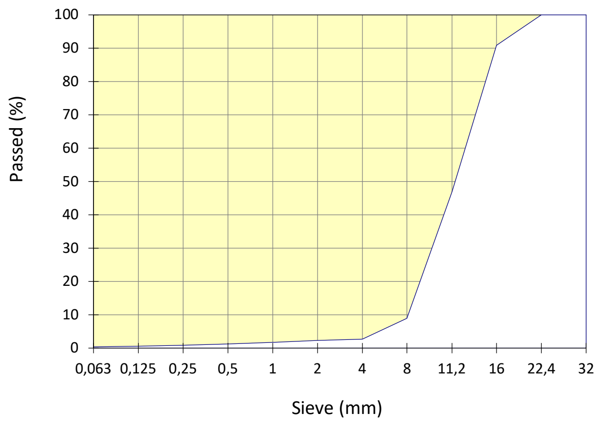




Fraction III

Type:	Årdal 8/16mm
Date:	07.01.2014
FM =	6,41

Opning	Sieve residue (g)		Sieve residue (%)	Passed-Through (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	9,2	9,2	9,2	90,8
11,2	53,1	53,1	53,1	46,9
8	91,1	91,1	91,1	8,9
4	97	97	97,3	2,7
2	98	98	97,7	2,3
1	98	98	98,3	1,7
0,5	99	99	98,7	1,3
0,25	99	99	99,1	0,9
0,125	99	99	99,4	0,6
0,063	100	100	99,6	0,4
Bottom	100	100		



Concrete mix design

SKANSKA

Ó2015-09-21 ss

Project	Masteroppgave
Batch nr	FA50
Quality requirement	0
Executed by	Tollak og Nikolay
Date	01.01.2023

w/b-ratio	0,39
Matrix volume (l/m^3)	330
Volume cement paste (l/m^3)	304
Assumed air content (%)	2,0
Effectiv binder (kg/m3)	340

"Obtained" equ "Desired"; Ctrl+N

Reset volume correction; Ctrl+K

Concrete mix

Materials	kg/m^3	Desired kg	Obtained kg	corr.luft	corr.dens	Corrigert
Norcem Anlegg FA	269,0	13,5	39,5	0,0	-3,5	392,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Elkem Microsilica	0,0	0,0	2,1	0,0	-0,2	20,8
Normineral flyveaske	187,0	9,3	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Free water	132,6	6,6	16,7	0,0	-1,5	165,9
Absorbed water	7,3	0,4	0,9	0,0	-0,1	8,9
Årdal 0/8 mm	909,8	45,5	85,4	0,0	-7,7	847,5
Årdal 0/2 mm	0,0	0,0	0,0	0,0	0,0	0,0
Årdal 8/16mm	908,0	45,4	0,0	0,0	0,0	0,0
Årdal 16/22 mm	0,0	0,0	0,0	0,0	0,0	0,0
Stalite	0,0	0,0	49,6	0,0	-4,4	492,3
Test	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Test	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Mapei Dynamon SX-N	5,47	0,27	0,50	0,0	0,0	4,96
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Prop. Concrete dens. (kg/m^3)	2415			0,0	-17,4	1928

volum ok

Fresh concrete

Properties	
Desired volume (l)	50,0
Weight volume (l)	99,9
Measured air content (%)	2,0
Measured concrete density (kg	1930
Effectiv w/(c+Σkp)	0,402

Aggressives	
Chloride content [% of c]	0,17 %
Alkalis [kg/m^3]	5,64
Part react. rocks [%]	0,0

Volume corrections

Comments:

Comments:

Yellow fields are filled in, green is calculated.

The matrix volume includes aggregate particles less than 0.125 mm.

When moisture in the aggregate is determined on the basis of oven-dried aggregate, absorbed moisture shall be stated with measured value. The associated density should then also be based on dry aggregate. If moisture in the aggregate is given on an SSD basis, absorbed moisture equal to 0. In this case, the densities should also be stated as SSD density.

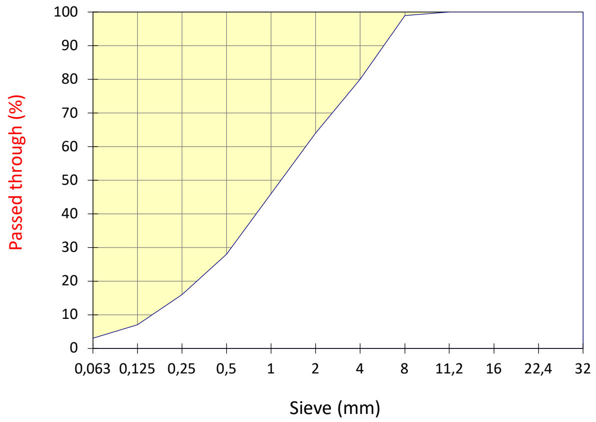
All sub-materials except water and TSS are indicated in dry weight. When calculating volume, densities and mass ratios, the water content of Admixture is taken into account in the free water volume. This also applies to corrected recipes . If the weighed amount of Admixtur deviates from the proportioned amount, the mass ratio and the amount of free water in the corrected recipe are automatically corrected.

Note that for pozzolanes, fillers and admixtures, the soild content and moisture are stated on a dry basis. Fiber is not included in the matrix volume.

fractionI

Type:	Årdal 0/8 mm
Date:	07.01.2014
FM =	3,14

Opning	sieve residue (g)		sieve residue (%)	Passed-through (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	1	1	1,0	99,0
4	20	20	20,0	80,0
2	36	36	36,0	64,0
1	54	54	54,0	46,0
0,5	72	72	72,0	28,0
0,25	84	84	84,0	16,0
0,125	93,0	93,0	93,0	7,0
0,063	97,0	97,0	97,0	3,0
Bottom	100	100		



Concrete mix design

SKANSKA

Ó2015-09-21 ss

Project	Masteroppgave
Batch nr	FA35
Quality requirement	0
Executed by	Tollak og Nikoolay
Date	01.01.2023

w/b-ratio	0,39
Matrix volume (l/m^3)	300
Volume cement paste (l/m^3)	273
Assumed air content (%)	2,0
Effectiv binder (kg/m3)	352

"Obtained" equ "Desired"; Ctrl+N

Reset volume correction; Ctrl+K

Concrete mix

Materials	kg/m^3	Desired kg	Obtained kg	corr.luft	corr.dens	Corrigert
Norcem Anlegg FA	289,7	14,5	39,5	0,0	-3,5	391,9
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Elkem Microsilica	0,0	0,0	2,1	0,0	-0,2	20,8
Normineral flyveaske	89,0	4,4	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Free water	137,3	6,9	16,7	0,0	-1,5	165,9
Absorbed water	7,6	0,4	0,9	0,0	-0,1	8,9
Årdal 0/8 mm	951,8	47,6	85,4	0,0	-7,5	847,4
Årdal 0/2 mm	0,0	0,0	0,0	0,0	0,0	0,0
Årdal 8/16mm	949,9	47,5	0,0	0,0	0,0	0,0
Årdal 16/22 mm	0,0	0,0	0,0	0,0	0,0	0,0
Stalite	0,0	0,0	49,6	0,0	-4,3	492,2
Test	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Test	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Mapei Dynamon SX-N	4,54	0,23	0,50	0,0	0,0	4,96
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,00	0,00	0,00	0,0	0,0	0,00
	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0
Prop. Concrete dens. (kg/m^3)	2426			0,0	-17,1	1928

volum ok

Fresh concrete

Properties	
Desired volume (l)	50,0
Weight volume (l)	99,9
Measured air content (%)	2,0
Measured concrete density (kg	1930
Effectiv w/(c+Σkp)	0,402

Aggressives	
Chloride content [% of c]	0,14 %
Alkalis [kg/m^3]	4,95
Part react. rocks [%]	0,0

Comments:

Comments:

Yellow fields are filled in, green is calculated.

The matrix volume includes aggregate particles less than 0.125 mm.

When moisture in the aggregate is determined on the basis of oven-dried aggregate, absorbed moisture shall be stated with measured value. The associated density should then also be based on dry aggregate. If moisture in the aggregate is given on an SSD basis, absorbed moisture equal to 0. In this case, the densities should also be stated as SSD density.

All sub-materials except water and TSS are indicated in dry weight. When calculating volume, densities and mass ratios, the water content of Admixture is taken into account in the free water volume. This also applies to corrected recipes . If the weighed amount of Admixtur deviates from the proportioned amount, the mass ratio and the amount of free water in the corrected recipe are automatically corrected.

Note that for pozzolanes, fillers and admixtures, the soild content and moisture are stated on a dry basis. Fiber is not included in the matrix volume.

Delark "Proporsjonering"

Combined aggregate

Fraction	Name	Density [kg/m³]	Abs. Mois [%]	Alk. react. Sv[%]	Chlorids [%]	Batch volume	Batch weight	Use
I	Årdal 0/8 mm	2680	0,3	0,0	0,00	0,502	0,500	ok
II	Årdal 0/2 mm	2650	0,5	0,0	0,00	0,000	0,000	
III	Årdal 8/16mm	2700	0,5	0,0	0,00	0,498	0,500	ok
IV	Årdal 16/22 mm	2700	0,5	0,0	0,00	0,000	0,000	
V	Stalite	1420	0,0	0,0	0,00	0,000	0,000	
VI	Test	2700	0,0	0,0	0,00	0,000	0,000	
VII		2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX	Test	2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2690		0,0	0,00	1,000	1,000	

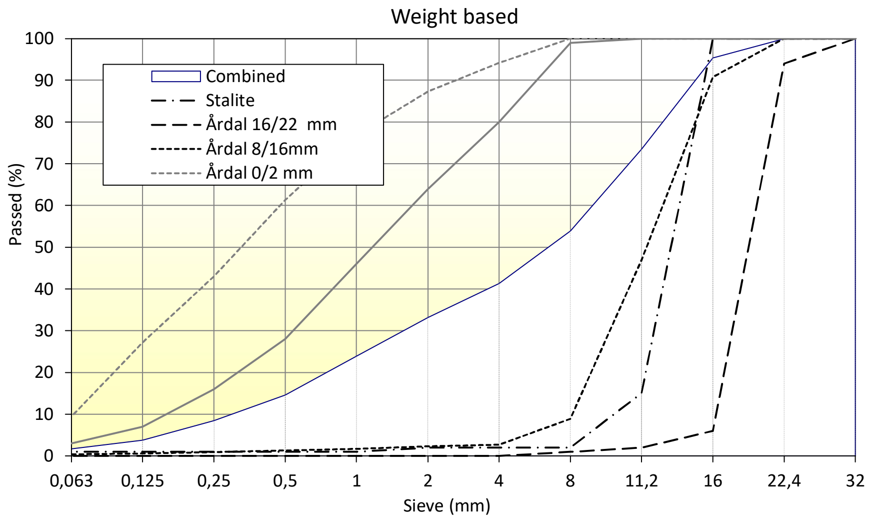
Finenes modulus	
FM_{vekt} =	4,77
FM_{vol} =	4,77
FM_{ref} =	5,07
FMg =	5,55

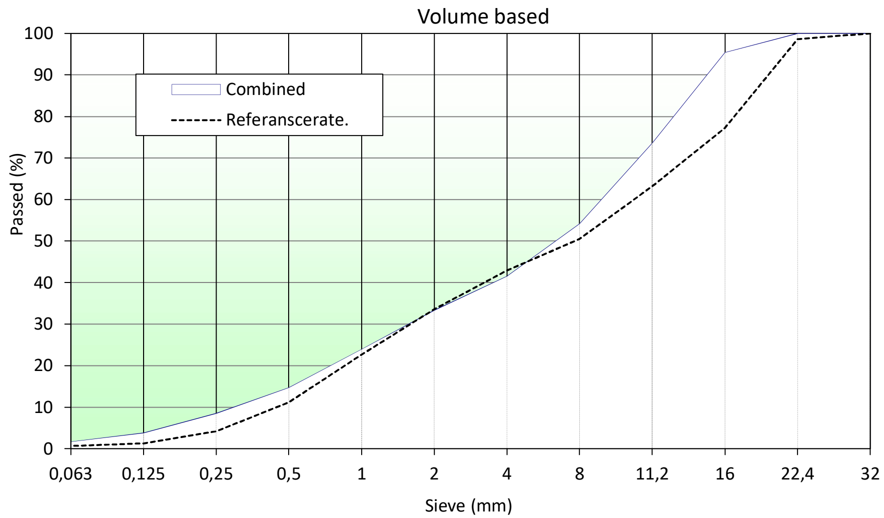
Adjust to ref rating, Ctrl T

Set ref rating, Ctrl R

Adjust to FMg, Ctrl F

Size	Passed vol.[%]	Passed vekt [%]	Ref. grad. [vol. %]	Weight at adaption
32	100,0	100,0	100,0	1
22,4	100,0	100,0	98,6	1
16	95,4	95,4	77,3	1
11,2	73,6	73,5	63,2	1
8	54,2	54,0	50,5	1
4	41,5	41,4	42,9	1
2	33,3	33,2	33,6	1
1	24,0	23,9	22,7	2
0,5	14,7	14,7	11,2	2
0,25	8,5	8,5	4,2	2
0,125	3,8	3,8	1,3	2
0,063	1,7	1,7	0,7	2

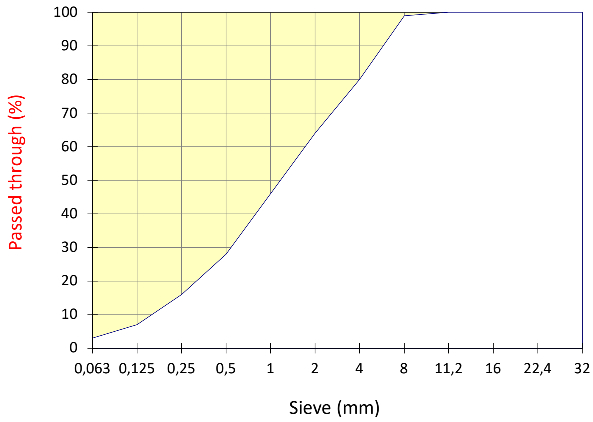




fractionI

Type:	Årdal 0/8 mm
Date:	07.01.2014
FM =	3,14

Opning	sieve residue (g)		sieve residue (%)	Passed-through (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	1	1	1,0	99,0
4	20	20	20,0	80,0
2	36	36	36,0	64,0
1	54	54	54,0	46,0
0,5	72	72	72,0	28,0
0,25	84	84	84,0	16,0
0,125	93,0	93,0	93,0	7,0
0,063	97,0	97,0	97,0	3,0
Bottom	100	100		



Mix proporsion

SKANSKA

Project	Masteroppgave
Batch no	FA35
Quality requirements	0

Batch volume:	50 liter
Date:	01.01.2023
Time for water addition:	
Responsible:	
Executed by:	

Materials	**Mix** kg/m^3	**Batch** kg	**Moisture*** %	**Corr.** kg	**Weight**** kg	
Norcem Anlegg FA	289,7	14,484			14,484	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	89,0	4,449			4,449	
	0,0	0,000			0,000	
Free water	137,3	6,863		-1,713	5,151	5,531
Absorbed water	7,6	0,380			0,380	
Årdal 0/8 mm	951,8	47,590	2,2	1,047	48,637	
Årdal 0/2 mm	0,0	0,000	0,0	0,000	0,000	
Årdal 8/16mm	949,9	47,496	1,0	0,475	47,971	
Årdal 16/22 mm	0,0	0,000	0,5	0,000	0,000	
Stalite	0,0	0,000	2,0	0,000	0,000	
Test	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Test	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Mapei Dynamon SX-N	4,5	0,227	84	0,191	0,227	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept" ** NB! Våte mengder, også for silikaslurry

Fresh concrete					
Time after water addition					
Slump					
Slump flow					
Air					
Density					

Samples (number)					
Casted time:					
Cubes					
150x300 cylindre					
100x200 cylindre					

Concrete Mix design

SKANSKA

Project	Masteroppgave
Batch number	FA50
Quality requirements	
Executed by	Tollak og Nikolay
Date	01.01.2023

Initialparametre	**Value**
m = w/(c+Σkp)	0,39
Air content	2,0 %

Cement type	**Part**	**Part of clinker**	**Part FA**	**Part slagg**	**[kg/m³]**	**Alkalis**	**Chlorides**
Norcem Anlegg FA	100,0 %	85,0 %	15,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	100,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	100,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Additions	**Type**	**Andel (av b)**	**k**	**[kg/m³]**	**Alkalis**	**Chlorides**
Elkem Microsilica	Silika	0,0 %	1,0	2200	0,1 %	0,1 %
Normineral flyveaske	FA	41,0 %	0,4	2300	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Admixtures	**% av b**	**[kg/m³]**	**Dry stof**	**[kg/m³] TS**	**Alkalis**	**Chlorides**
Mapei Dynamon SX-N	1,2 %	1050	16,0 %	1424	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	**Vol %**	**[kg/m3]**
	0,0 %	7800
	0,0 %	1050

Matrix	**Value**
Desired matrix volume [l/m³]	330
Obtained matrix volum [l/m3]	330
Clinker part in binder	50,2 %
Total FA- content of binder	49,9 %

Total slag content of binder	0,0 %
Volume cement paste [l/m^3]	304,2
Effectiv water content [l/m^3]	132,6
w/p	0,25
Effectiv binder [kg/m^3]	340
Totalt binder [kg/m^3]	456

Beregn

Comments:
Yellow blanket is filled in, green is calculated.
The red background in the cell for obtained matrix volume indicates that the computation macro has not been run, and there is no response between it and the obtained matrix volume. This will also give the blanket the recipe form.

Concrete Mix design

SKANSKA

Project	Masteroppgave
Batch number	FA35
Quality requirements	
Executed by	Tollak og Nikoolay
Date	01.01.2023

Initialparametre	**Value**
m = w/(c+Σkp)	0,39
Air content	2,0 %

Cement type	**Part**	**Part of clinker**	**Part FA**	**Part slagg**	**[kg/m^3]**	**Alkalis**	**Chlorides**
Norcem Anlegg FA	100,0 %	85,0 %	15,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	100,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	100,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Additions	**Type**	**Andel (av b)**	**k**	**[kg/m^3]**	**Alkalis**	**Chlorides**
Elkem Microsilica	Silika	0,0 %	1,0	2200	0,1 %	0,1 %
Normineral flyveaske	FA	23,5 %	0,7	2300	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Admixtures	**% av b**	**[kg/m^3]**	**Dry stof**	**[kg/m^3] TS**	**Alkalis**	**Chlorides**
Mapei Dynamon SX-N	1,2 %	1050	16,0 %	1424	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	**Vol %**	**[kg/m3]**
	0,0 %	7800
	0,0 %	1050

Matrix	**Value**
Desired matrix volume [l/m^3]	300
Obtained matrix volum [l/m3]	300
Clinker part in binder	65,0 %
Total FA- content of binder	35,0 %

Total slag content of binder	0,0 %
Volume cement paste [l/m^3]	273,0
Effectiv water content [l/m^3]	137,3
w/p	0,30
Effectiv binder [kg/m^3]	352
Totalt binder [kg/m^3]	379

Beregn

Comments:
Yellow blanket is filled in, green is calculated.
The red background in the cell for obtained matrix volume indicates that the computation macro has not been run, and there is no response between it and the obtained matrix volume. This will also give the blanket the recipe form.

Parameter table:

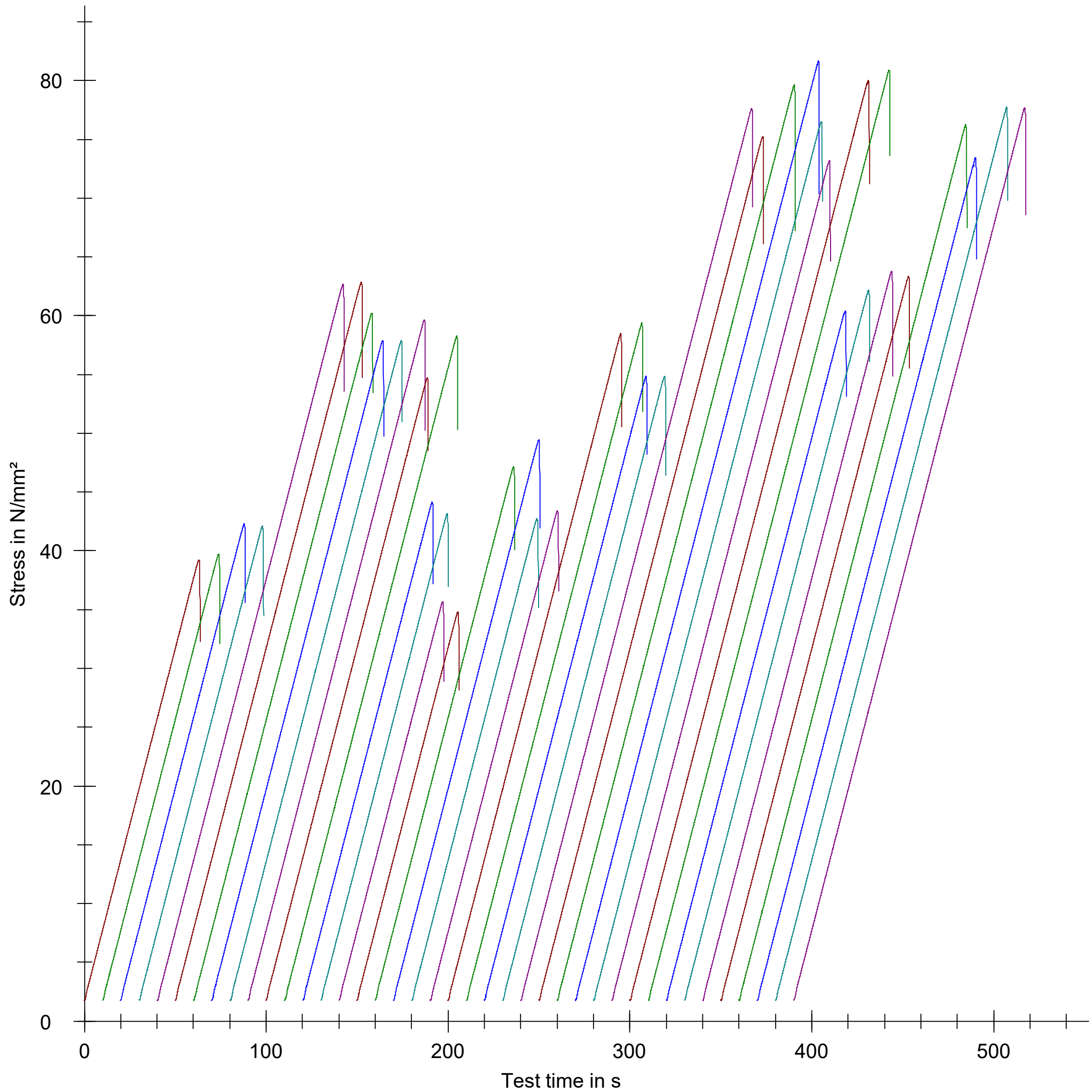
Test protocol :
Tester :
Customer :
Test standard :
Other :

Type strain extensometer :
Machine data : Controller TT1412
PistonStroke
LoadCell 3 MN

Results:

Nr	Date	ID	a mm	b mm	F_m kN	Clock time	σ_m N/mm²
1	27.02.2023	A1	100,0	100,0	392,37	13:42:53p.m.	39,24
2	27.02.2023	A2	100,0	100,0	397,32	13:45:23p.m.	39,73
3	27.02.2023	C1	100,0	100,0	422,97	13:47:31p.m.	42,30
4	27.02.2023	C2	100,0	100,0	420,99	13:49:43p.m.	42,10
5	03.03.2023	A3	100,0	100,0	626,49	10:04:32a.m.	62,65
6	03.03.2023	A4	100,0	100,0	628,47	10:07:13a.m.	62,85
7	03.03.2023	C3	100,0	100,0	602,23	10:10:25a.m.	60,22
8	03.03.2023	C4	100,0	100,0	579,00	10:13:21a.m.	57,90
9	03.03.2023	B3	100,0	100,0	578,94	10:16:24a.m.	57,89
10	03.03.2023	B4	100,0	100,0	596,71	10:19:14a.m.	59,67
11	03.03.2023	D3	100,0	100,0	547,23	10:22:17a.m.	54,72
12	03.03.2023	D4	100,0	100,0	583,03	10:24:50a.m.	58,30
13	06.03.2023	E1	100,0	100,0	441,71	12:08:03p.m.	44,17
14	06.03.2023	E2	100,0	100,0	431,80	12:10:13p.m.	43,18
15	06.03.2023	G1	100,0	100,0	356,88	12:12:17p.m.	35,69
16	06.03.2023	G2	100,0	100,0	348,16	12:14:22p.m.	34,82
17	10.03.2023	E4	100,0	100,0	471,43	19:10:37p.m.	47,14
18	10.03.2023	E3	100,0	100,0	494,62	19:14:02p.m.	49,46
19	10.03.2023	F3	100,0	100,0	427,54	19:16:16p.m.	42,75
20	10.03.2023	F4	100,0	100,0	433,95	19:18:37p.m.	43,40
21	10.03.2023	G3	100,0	100,0	584,99	19:21:17p.m.	58,50
22	10.03.2023	G4	100,0	100,0	593,90	19:24:40p.m.	59,39
23	10.03.2023	H3	100,0	100,0	548,51	19:27:28p.m.	54,85
24	10.03.2023	H4	100,0	100,0	548,55	19:29:49p.m.	54,85
25	24.03.2023	A5	100,0	100,0	776,59	18:52:18p.m.	77,66
26	24.03.2023	A6	100,0	100,0	752,14	18:55:21p.m.	75,21
27	24.03.2023	B5	100,0	100,0	796,76	18:58:55p.m.	79,68
28	24.03.2023	B6	100,0	100,0	816,73	19:02:17p.m.	81,67
29	24.03.2023	C5	100,0	100,0	765,41	19:07:51p.m.	76,54
30	24.03.2023	C6	100,0	100,0	732,19	19:10:45p.m.	73,22
31	24.03.2023	D5	100,0	100,0	800,59	19:14:24p.m.	80,06
32	24.03.2023	D6	100,0	100,0	809,09	19:17:35p.m.	80,91
33	31.03.2023	E5	100,0	100,0	604,06	12:31:04p.m.	60,41
35	31.03.2023	E6	100,0	100,0	622,00	12:34:13p.m.	62,20
36	31.03.2023	F5	100,0	100,0	638,08	12:37:19p.m.	63,81
37	31.03.2023	F6	100,0	100,0	633,82	12:39:48p.m.	63,38
38	31.03.2023	G5	100,0	100,0	762,64	12:42:39p.m.	76,26
39	31.03.2023	G6	100,0	100,0	734,42	12:46:48p.m.	73,44
40	31.03.2023	H5	100,0	100,0	777,60	12:49:36p.m.	77,76
41	31.03.2023	H6	100,0	100,0	776,85	12:52:39p.m.	77,68

Series graphics:



Statistics:

Series n = 40	a mm	b mm	F_m kN	σ_m N/mm²
n	40	40	40	40
$\overline{x}$	100,0	100,0	596,42	59,64
s	0,0	0,0	143,06	14,31
max.	100,0	100,0	816,73	81,67
min	100,0	100,0	348,16	34,82
med	100,0	100,0	595,31	59,53
ν	0,00	0,00	23,99	23,99

Parameter table:

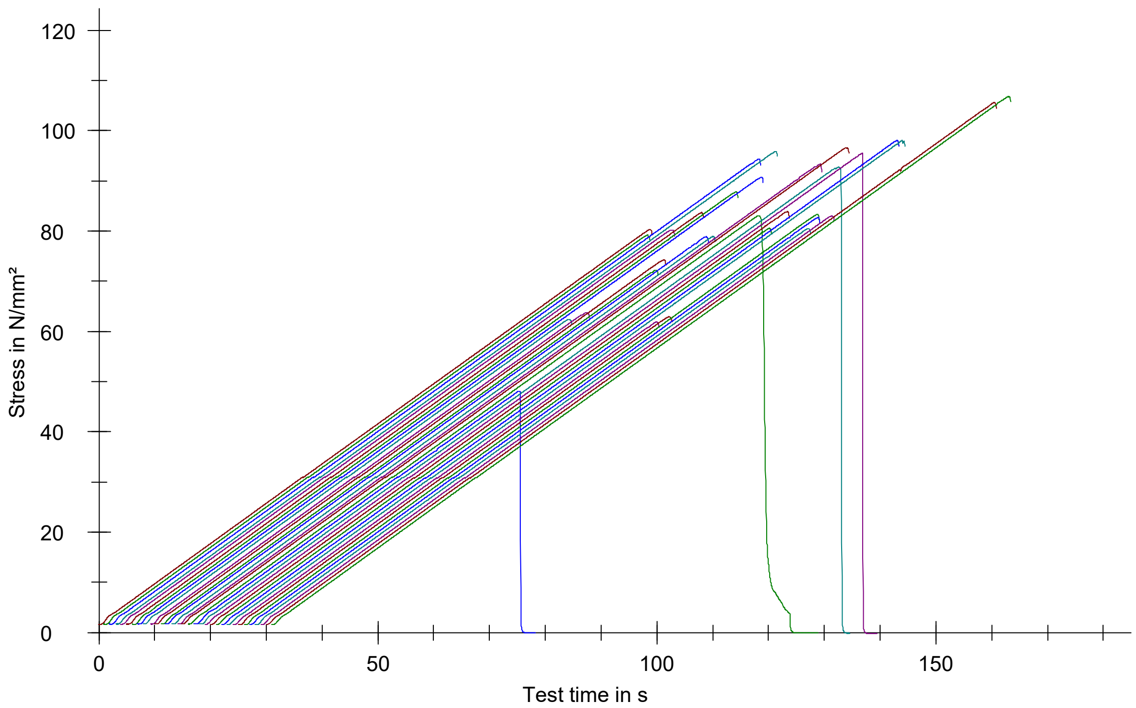
Test protocol : Compression test for cubes
Tester :
Customer :
Test standard : NS-EN 12390-3:2019
Strength grade :
Creation date : April 2023
Age :
Other :

Type strain extensometer :
Machine data : Controller TT0322
PistonStroke
LoadCell 3 MN

Results:

Nr	Date	ID	a mm	b mm	A mm²	h mm	F_m kN	σ_m N/mm²
1	21.04.2023	A7	100,0	100,0	10000,0	100,0	802,90	80,29
2	21.04.2023	A8	100,0	100,0	10000,0	100,0	792,30	79,23
3	21.04.2023	B7	100,0	100,0	10000,0	100,0	942,92	94,29
4	21.04.2023	B8	100,0	100,0	10000,0	100,0	958,81	95,88
5	21.04.2023	C7	100,0	100,0	10000,0	100,0	802,27	80,23
6	21.04.2023	C8	100,0	100,0	10000,0	100,0	837,03	83,70
7	21.04.2023	D7	100,0	100,0	10000,0	100,0	878,34	87,83
8	21.04.2023	D8	100,0	100,0	10000,0	100,0	907,59	90,76
9	28.04.2023	E7	100,0	100,0	10000,0	100,0	624,05	62,41
10	28.04.2023	E8	100,0	100,0	10000,0	100,0	637,73	63,77
11	28.04.2023	F7	100,0	100,0	10000,0	100,0	742,76	74,28
12	28.04.2023	F8	100,0	100,0	10000,0	100,0	722,25	72,22
13	28.04.2023	G7	100,0	100,0	10000,0	100,0	788,92	78,89
14	28.04.2023	G8	100,0	100,0	10000,0	100,0	789,39	78,94
15	28.04.2023	H7	100,0	100,0	10000,0	100,0	933,84	93,38
16	28.04.2023	H8	100,0	100,0	10000,0	100,0	966,28	96,63
17	19.05.2023	A9	100,0	100,0	10000,0	100,0	830,76	83,08
18	19.05.2023	A10	100,0	100,0	10000,0	100,0	481,04	48,10
19	19.05.2023	B9	100,0	100,0	10000,0	100,0	927,54	92,75
20	19.05.2023	B10	100,0	100,0	10000,0	100,0	955,61	95,56
21	19.05.2023	C9	100,0	100,0	10000,0	100,0	838,94	83,89
22	19.05.2023	C10	100,0	100,0	10000,0	100,0	805,51	80,55
23	19.05.2023	D9	100,0	100,0	10000,0	100,0	980,44	98,04
24	19.05.2023	D10	100,0	100,0	10000,0	100,0	980,25	98,03
25	26.05.2023	E9	100,0	100,0	10000,0	100,0	618,71	61,87
26	26.05.2023	E10	100,0	100,0	10000,0	100,0	628,91	62,89
27	26.05.2023	F9	100,0	100,0	10000,0	100,0	832,96	83,30
28	26.05.2023	F10	100,0	100,0	10000,0	100,0	827,45	82,74
29	26.05.2023	G9	100,0	100,0	10000,0	100,0	804,94	80,49
30	26.05.2023	G10	100,0	100,0	10000,0	100,0	830,20	83,02
31	26.05.2023	H9	100,0	100,0	10000,0	100,0	1056,72	105,67
32	26.05.2023	H10	100,0	100,0	10000,0	100,0	1067,81	106,78

Series graphics:



Statistics:

Series n = 32	a mm	b mm	A mm²	h mm	F_m kN	σ_m N/mm²
$\bar{x}$	100,0	100,0	10000,0	100,0	831,10	83,11
s	0,0	0,0	0,0	0,0	134,23	13,42
ν	0,00	0,00	0,00	0,00	16,15	16,15