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Pervious Concrete

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Civil and Environmental Engineering (2 year)
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SUMMARY:
Pervious concrete is a material with a high degree of permeability but generally low strength. The material is primarily used for paving applications but has shown promise in many other areas of usage. This thesis investigates the properties of pervious concrete using normal Norwegian aggregates and practices. An overview of important factors when it comes to designing and producing pervious concrete is the result of this investigation. In addition to this, several experiments have been performed in the concrete research facility at NTNU, Trondheim.
The importance of the void content of pervious concrete cannot be overstated. Too much void content leads to low strength while not enough void and permeability suffers and the concrete can hardly be called pervious. Proper design of pervious concrete is therefore largely dependent on finding the balance between strength and water permeability. The large interconnected voids in the material is achieved by using a near single sized aggregate of relatively large grains. The packing of this coarse aggregate leads to large voids due to the similar sizes of the grains. The amount of void left in the final concrete is then determined by how much binder is allowed to be mixed into the aggregates.

Ten different batches of mortar has been produced with the intention of investigating the application of said mortars as the binder in pervious concrete. Six different batches of pervious concrete has been produced and tested for such properties as strength, permeability, density and void content. The goal of the experiments is to find and evaluate methods of determining the properties of pervious concrete. Mixing method of the material in addition to varying theoretical void content has been the focus of the experimental work.

The results from the experimental work show that alternating the mixing method of the pervious concrete has a positive effect on several properties in the final concrete. Varying the void and sand content in the concrete has effectively illustrated the balance one must find to produce efficient pervious concrete.

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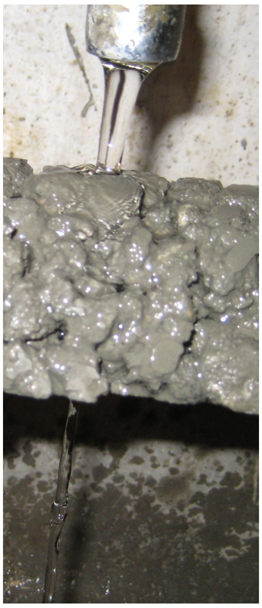
Master's Thesis:

Pervious Concrete



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June 11, 2012

Foreword

This master's thesis is written by Øyvind André Hoff Torsvik at the Norwegian University of science and technology (NTNU) in the spring of 2012. This work signifies the end of 5 years of studies towards the degree Master of Science within the field Civil and Environmental Engineering. At the time of writing this work is the equivalent of 30 ECTS credits.

The work of producing this thesis was performed from January to June 2012 (22 weeks). The laboratory work associated with this thesis was done at the NTNU concrete research facility. The professionals that work there were a great help but due to medical reasons and the amount of work that had to be done with other projects, most of the concrete production was performed by the author alone. Generally the first iteration of an experiment was done under the supervision of the staff, and the rest of the work was done by one man.

Øyvind André Hoff Torsvik
NTNU, Trondheim June 2012

Abstract

Pervious concrete is a material with a high degree of permeability but generally low strength. The material is primarily used for paving applications but has shown promise in many other areas of usage. This thesis investigates the properties of pervious concrete, produced using normal Norwegian aggregates and practices. An overview of important factors when it comes to designing and producing pervious concrete is the result of this investigation. In addition to this, several experiments have been performed in the concrete research facility at NTNU, Trondheim.

The importance of the void content in pervious concrete cannot be overstated. Too much void content leads to low strength while not enough void and permeability suffers and the concrete can hardly be called pervious. Proper design of pervious concrete is therefore largely dependent on finding the balance between strength and water permeability. The large interconnected voids in the material is achieved by using a near single sized aggregate of relatively large grains. The packing of this coarse aggregate leads to large voids due to the similar sizes of the grains. The amount of void left in the final concrete is then determined by how much binder is allowed to be mixed into the aggregates.

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Sammendrag

Permeabel betong er et materiale med høy grad av permeabilitet men generelt lav fasthet. Materialet er hovesaklig tatt i bruk til vei og planering men har også vist seg å være velegnet i flere andre bruksområder. Denne oppgaven undersøker egenskapene til permeabel betong som er produsert med materialer som er normalt i bruk i norsk praksis. Denne undersøkelsen munner ut i en oversikt over de viktigste faktorene som må tas hensyn til når man skal produsere permeabel betong. Flere forsøk har også blitt utført ved betong laboratoriet ved NTNU i Trondheim.

Viktigheten av hulrom i betongen i produksjon av permeabel betong kan ikke overvurderes. For mye hulrom fører til lav fasthet mens for lite hulrom fører til en tett betongstruktur noe som fører til at betongen knapt kan kalles permeabel. Det å bestemme balansen mellom styrke og permeabilitet er derfor særs viktig for korrekt design av permeabel betong. Store mengder med sammenkoblet hulrom blir dannet ved bruk av tilslag med nært ensartet store størrelser. Pakningsgraden av dette tilslaget gjør at det er naturlig store hulrom mellom kornene. Det resterende hulromet som blir igjen i den endelige betongen blir da bestemt av hvor mye bindemiddel som blandes sammen med det grove tilslaget.

Ti resepter med mørtel har blitt blandet for å undersøke deres anvendbarhet som bindemiddel i permeabel betong. Seks forskjellige resepter med permeabel betong har blitt blandet, støpt og testet for egenskaper som fasthet, permeabilitet, tetthet og hulroms prosent. Målet med disse eksperimentene er å finne og evaluere metoder for å bestemme egenskaper i permeabel betong. Blandingsprosedyre for ingrediensene i materialet samt varierende teoretisk hulrom har vært i fokus ved det eksperimentelle arbeidet.

Resultatene fra det eksperimentelle arbeidet viser at forandret blandeprosedyre har en positiv effekt på flere av egenskapene til den støpte betongen. Varierende hulrom- og sandinnhold i betongen har illustrert balansen som må finnes for å produsere en effektiv permeabel betong.

Acknowledgments

The author acknowledges the help and guidance from Mette Rica Geiker and Knut O. Kjellsen during the development of this master's thesis. For their invaluable help during the many different experiments in the concrete research facility at NTNU the following people deserve regards: Ove Loraas, Gøran Loraas, Steinar Seehuus and Ragnar Moen.

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Contents

1 Introduction

The topic of this Master's Thesis is Pervious Concrete. Pervious concrete is a little or no fines concrete with generally high permeability producing a high percolation rate through the material. The material is known to be weak when it comes to frost deterioration, and is thus not gained any widespread usage in cold climates like Norway[2]. In warmer parts of the world, like the southern parts of the U.S.A., the material has gained a foothold in paving applications[7]. Pavements comprised of pervious concrete has a similar texture to that of tarmac or asphalt, but during rains it remains much drier and free of puddles[14]. The open structure of the material leads to exposed grains of coarse aggregate however, which in turn leads to raveling of the surface. Using pervious concrete as an alternative to other impervious materials reduces the need to create retention ponds and allows rainfall to regenerate the groundwater of the underlying sub base[2].

1.1 Objectives

This master's thesis takes aim to explore the uses and techniques used to produce pervious concrete. Pervious concrete is a rarely used material in Norway due to low frost durability and because of little known knowledge of the material. In other countries ,such as the U.S.A., pervious concrete is used in greater extent. This work serves to add to the general knowledge of this material in Norway, using regular Norwegian materials. This thesis has several key goals:

1. Create an overview of the important factors that must be considered when producing pervious concrete.

2. Investigate the composition of the binder in the material to study the effects of Sand content, amount of air entraining admixture and mixing method when producing cement paste for use with pervious concrete.

3. Produce pervious concrete with a binder based on the results from the preceding binder investigation with materials and admixtures normally used in Norway. Study the effects of different void and filler contents in the concrete batches.

4. Study the effect that the method of mixing has on the pervious concrete.

5. The low frost durability of pervious concrete stops the application of pervious concrete in cold areas. This thesis also aims to continue the search for a frost-durable pervious concrete so that the usage area of the material may be expanded to colder climates.

1.2 Methodology

The methods used to reach the goals and objectives of this thesis is shortly described here. The explanations are numbered in the same order as the objectives in 1.1.

1. This work entailed literary studies from many sources of published works which deals with the subject pervious concrete or factors important to pervious concrete. Concrete properties such as compressive strength, void content, air content, frost durability and permeability are considered especially important in regards to pervious concrete and is discussed based on results in other projects and literary works.

2. The binder composition was investigated by producing and testing 10 mortar batches with varying sand content, air entraining content and mixing method. The resulting binder was rated based on the density and air content of the fresh mortar. The most promising mortar was chosen for further use in pervious concrete based on workability, properties of the fresh concrete and stability of the mix.

3. Pervious concrete was produced using the most promising mortar mix from the preceding binder experiment. Six batches of 50 liters each was produced and cast in various forms. This concrete was tested to investigate the effect of several variables such as void content and sand content. Since pervious concrete lacks standardized testing methods for many parameters, some methods have been tried and some have been produced as a result of this thesis.

4. Two different mixing procedures was tried to investigate the effect of this on the fresh and hardened pervious concrete. The basic idea is that if the binder is mixed prior to mixing in the bulk aggregate, the binder will be more prone to

evenly coat the stones of the aggregate and thus create a more stable structure in the final concrete.

5. 150x150x150 mm cubes was cast for the purpose of determining the frost resistance of the pervious concrete. Several methods of testing the frost resistance of concrete was considered for use with pervious concrete. Two modified methods of the standard Borås test after NS-EN 12390-9[11] was chosen.

1.3 Limitations

The laboratory work is primarily done by the author alone. In the end, this reduced the spread of different sample compositions and variables that could be studied. All testing of the material is also done at a small scale in standardized forms. How the material behaves in full scale is therefore difficult to predict based only on the results of this thesis.

1.4 Thesis Structure

This thesis is written in two parts both following an inverted pyramid structure.

The first part deals with the existing knowledge about concrete and pervious concrete in particular, serving as an overview of the most important properties of the material. General information is presented first, with more specific factors being dealt with later.

The second part deals with the experimental work relating to this master's thesis. The what and how of the work done is presented first with results and discussion following after.

Figures and Tables are numbered chronologically from start to finish in the thesis. Lists of the numbered figures and tables with their respective page numbers

2 Background

This section covers some general information about the material pervious concrete. Examples of how the material can be used and how it should be constructed are presented here.

2.1 What is pervious concrete?

Pervious concrete is a material that is designed to be water-permeable. This is achieved by producing a mix of concrete that contains little or no fines with a low water-binder ratio and a fairly uniform coarse aggregate size[2]. This leads to large voids which in turn leads to a rapid rate of permeation through the concrete[7]. This also leads to low strength and unpredictable durability conditions. The main reason for using pervious concrete is to reduce storm-water runoff and the accumulation of water puddles or ponds on constructional surfaces. The use of pervious concrete has also been linked to decreasing pollution of groundwater and may lead to environmental and thus economical benefits due to such programs as the LEED credit system[1].

Pervious concrete is mainly used for paving areas such as parking lots, sidewalks or low traffic roads. Pervious concrete can however be used for a wide variety of applications such as green house floors or tennis courts where it is especially important to keep the surface clear of water[7][14]. Pervious concrete has many advantages over conventional paving materials such as:

- Greatly decreasing the danger of hydroplaning and glare from wet roads.[7]
- Reducing noise levels stemming from the interaction between vehicle tires and the pavement.[7]
- Reducing the need for water-retention areas as any storm water runoff is absorbed into the ground.[2][7]
- Negating the need for a structured drain system as the concrete may function as a drain itself.[2]

Disadvantages considering the use of pervious concrete include:

- Extended curing times due to premature drying as a result of low w/c and open structure. Pervious concrete must be covered in hot weather conditions to keep the desired amount of water available in the concrete.[7]

- Low viscosity leads to low workability and difficult placing and compacting practices.[14]

- Relatively low strengths limits the use of the material in heavy vehicle traffic areas.[7]

- Traditionally little use of the material has led to a lack of standardized testing methods.[7]

- Poor performance in freeze/thaw conditions using road salts.[14]

- Increased maintenance needs to prevent clogging of the concrete structure.[7]

2.2 Why use pervious concrete?

During the urbanization of an area, large areas of pervious surfaces usually becomes impervious due to leveling of the surface with low-permeability materials. The earth and ground that has formed large intricate systems for handling surface water over many years becomes lost and unused. This surface water that stems from flooding because of heavy rains, must now flow over the impervious areas until it reaches a pervious area to percolate through[2]. This pervious area is usually man-made drains that leads to retention systems or directly into city sewage systems. During periods of much rain these systems may not be sufficient, damaging buildings and equipment costing considerable amounts of money.

Building with pervious concrete relieves the irrigation system needed toled water away from the construction site by allowing precipitation to percolate through the constructional layer. The water can then continue along the naturally occurring transport systems that existed before urbanization ever reached the area. This reduces the amount of area that becomes impervious as a result of constructing buildings.

2.3 Construction of pervious pavements

The use of pervious concrete requires a sub-base of a adequate percolation rate as it must be assured that water that percolates through the concrete is led away from the construction as opposed to remaining in the layer of concrete. Placement and compacting of the concrete is quite different from conventional concrete as the earthy material has very low workability[14]. Placing of a pervious concrete pavement starts by preparing and placing a sub-base and sub-grade that is capable of draining the required amount of water stipulated by the designer[2]. This groundwork must support the concrete layer as well as allowing for an adequate percolation rate through the base so that standing water is led away from the pavement construction. This is essential in areas where freezing and thawing is a concern as freezable water in the construction of the pavement could prove devastating for the pervious concrete.

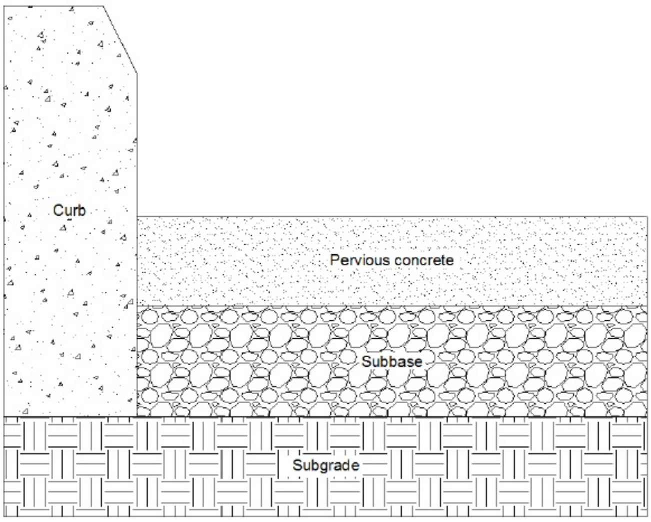


Figure 1: Construction of a permeable pavement[14]

The placing and compacting of pervious concrete is also of particular importance. The relatively dry surface of the binder coated grains in the material means that extra care must be applied to secure adequate contact between them in the concrete structure. This makes the material difficult and laborious to properly cast. Because of this, the correct handling of the material has a large effect on the performance of pervious concrete[14].

3 Material properties

This section describes the material composition and various properties that can be achieved by use of pervious concrete. Some typical property data for pervious concrete can be found in table 1.

Pervious concrete is constructed by a system of interconnected voids that is held together by a low w/c binder. The system of interconnected voids must be so prominent that water can permeate the concrete. Studies have shown that for void contents lower than 15 % there is not enough inter connectivity between the voids to support rapid percolation of water through pervious concrete[7]. Frost resistance has been known to suffer for higher porosities though, with the amount of scaling from Freeze/thaw testing showing a considerable increase for concrete with more than 17 % porosity[13]. In this thesis “percolate” is used for the rate a given volume of water above pervious concrete is absorbed into the material while “permeate” is used to describe transport of water into the material.

Source	w/c-ratio	Void content	Compression Strength	Percolation rate
ACI(2010)[7]	0.26 - 0.40	15 - 35 %	2.8 - 28 MPa	0.001 - 10 cm/s
Sugiyama(1998)[9]	0.25	28 %	16.6 - 17.8 MPa	-
Hokkaido(1995)[16]	0.25	18 - 25 %	17 - 19.9 MPa	-
Iowa State(2005)[15]	0.27 - 0.43	12.9 - 41.8 %	5.4 - 22.7 MPa	0.04 - 1.45 cm/s

Table 1: Typical property values of pervious concrete

3.1 Aggregates & binder

Aggregates in pervious concrete are normally uniform-sized coarse aggregates with a low degree of eigen packing. The coarse aggregates should be coated with a a cement paste with little, or no fines which will harden between the stones. Portland cement is often used as the main binder with a w/c in the area of 0.26-0.4[7]. Using an aggregate of uniform grading , the natural packing of the aggregate creates a large amount of void. Coating this aggregate with a relatively dry binder will further push the grains apart and locks the void between the stones in place. This construction ensures a open porous structure that should easily absorb water from the top and release it into the underlying ground.

3.2 Strength

The strength of pervious concrete is normally substantially lower than other Portland cement concretes of similar w/c. Both the flexural and compressive strength of pervious concrete is highly influenced by mixture proportions and compacting. The flexural strength of structures produced in pervious concrete suffers due to the fact that infiltration of water and corrosive elements makes pervious concrete generally ineligible for reinforcing with steel. Compressive strengths in high permeability pervious concrete are usually in the order of approximately 3 MPa but can be increased up to around 28 MPa by sacrificing void space and thus the percolation rate through the material[7].

3.3 Void content

The void content in pervious concrete directly affects the rate of percolation and strength in the material. High void content leads to low strength and high permeability, while low void content leads to higher strengths with low permeability. Designing pervious concrete is therefore based on finding the balance between these two factors. For a concrete to be called pervious it must be able to transport water through its structure. As a general rule this means that a void content of approximately 15 % is a minimum[7].

3.4 Percolation rate

To obtain a high percolation rate through pervious concrete, it must be produced with an open structure with large amounts of void[7]. These voids must also be interconnected so that permeated water can find its way through the material with little effort. If the binder is overly viscose, it will separate from the aggregate during compacting and fill the bottom of the material. This will lead to a lower percolation rate and may even lessen the adhesion of the concrete as there is less binder to distribute among the aggregate higher in the construction layer.

3.5 Freeze/thaw resistance

Due to the open structure of pervious concrete the material is very exposed to high degrees of saturation. This, in addition to low strength, makes the material especially exposed to frost damage. If the binder between pieces of coarse aggregate becomes overly saturated and exposed to freezing and thawing, it must contain sufficient entrained air bubbles to avoid cracking open and unraveling the structure of the concrete. This makes the entrainment of air in the binder of pervious concrete a very important factor.

4 Frost deterioration of concrete

Frost deterioration is the main complaint when it comes to the application of pervious concrete in colder climates. This section covers some general information about frost in concrete and the testing procedures used to investigate concrete performance in freeze/thaw conditions. Factors especially important for frost in pervious concrete are discussed here.

4.1 General

Frost damage occurs in concrete as in all materials as a result of liquid freezable water turning solid in the material. The transformation of water from a liquid to a solid state leads to an increase in volume of approximately 9% which in turn leads to internal pressure forces acting on the material[6]. In standard Portland Cement Concrete(PCC), there are three main groups of pores or air pockets where water can be absorbed:

1. Capillary pores that stems from the chemical hydration of cement. Long strings of CSH is formed while cement is reacting with water. These strings overlap and intertwine so that air becomes trapped inside. These are called capillary pores in this thesis[8].

2. Void spaces like cracks due to load or imperfections in casting[6].

3. Pores within certain aggregates themselves, like the volume of sand that fills with water during saturation[6].

As a result of water absorption in these pores, water may predominantly freeze in three different places in concrete:

1. In the capillary pores of the cement paste

2. In the void spaces such as air voids and defects

3. In the porous aggregate

Freezing of water in these parts of the concrete will lead to two main forms of frost damage:

- **Surface scaling:** Parts of the concrete scales off as a result of increased local pressure due to enclosed freezing water in cracks and surface imperfections. Given a situation where this water no longer has room to expand, the hydraulic pressure of this chemical response will easily overcome the strength of most concretes. This form of frost damage is characterized by flaking or material-pop-out.
- **Internal cracking:** Non-visible cracking of concrete from the inside will create unpredictable weaknesses in the concrete and should by all means be avoided. Frost susceptible aggregates will carry freezable water into the concrete, possibly entraining a sufficient amount so that internal cracking will be a risk.

4.2 Frost deterioration with regard to pervious concrete

The low contact area between the solid materials of the pervious concrete makes it particularly exposed to frost deterioration. The large voids and porous construction of pervious concrete changes the conditions for frost deterioration in the material as opposed to in non-pervious concrete. If the thin layer of binder between the coarse aggregate in pervious concrete is subject to frost deterioration, this could lead to raveling of the concrete surface[14]. Where freezing of water in cracks and air voids can lead to material pop out on the surface of non-pervious concrete, freezing of water in the large void system of the pervious concrete would surely force the coarse aggregate apart and lead to serious raveling of the surface or possibly the entire structure of the material. It is therefore critical that water that permeates into the pervious concrete also can percolate through the concrete so that the layer of concrete does not remain submerged in water over time in cold weather applications.[7].

Since pervious concrete is mainly used for its storm water and runoff control, it must be resistance to frost in highly saturated conditions. The large voids in the concrete also makes almost all of the binder susceptible to saturation from all directions when the voids are filled with water. It is therefore important that the sub-base under the pervious concrete is porous enough to lead water away from the constructional

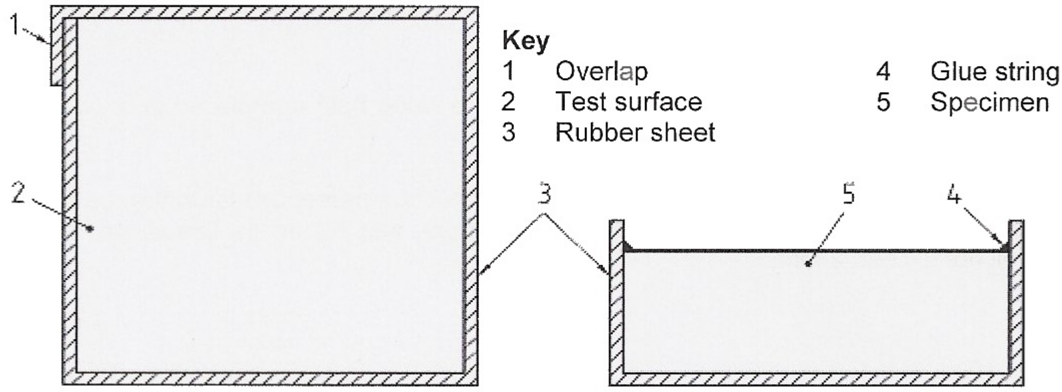


Figure 2: Insulation of cored samples [11]

surface. If this sub-base is clogged or not sufficiently permeable, the concrete will be critically saturated during freezing. This will certainly lead to massive deterioration of the material as such large amounts of water will infiltrate the structure of the concrete slab and expand.

4.3 Freeze/thaw testing procedures

There are several proposed testing procedures for investigating concrete performance in freeze/thaw cycles. A selection of these methods are discussed and illustrated here. The general methods are presented first with evaluations with regards to pervious concrete following after.

4.3.1 Borås method SS 13 72 44 & CEN/TS 12390-9

Principle: The Borås method is initially a modification of the preceding testing procedure ASTM C 672 in regards to temperature gradients. The method aims to create more a more realistic variation of temperature for testing concrete in the laboratory[6].Testing occurs one-dimensionally so that only the testing surface is exposed while all other sides of the specimen is insulated using rubber sheets[11]. The exposed testing-surface is then covered with either a 3% saline solution or tap water before freeze/thaw testing can begin. The specimen is thermally encased using polystyrene to secure the correct temperature variation in the testing process. The concrete specimens will then endure a temperature change from +20ºC to -18ºC

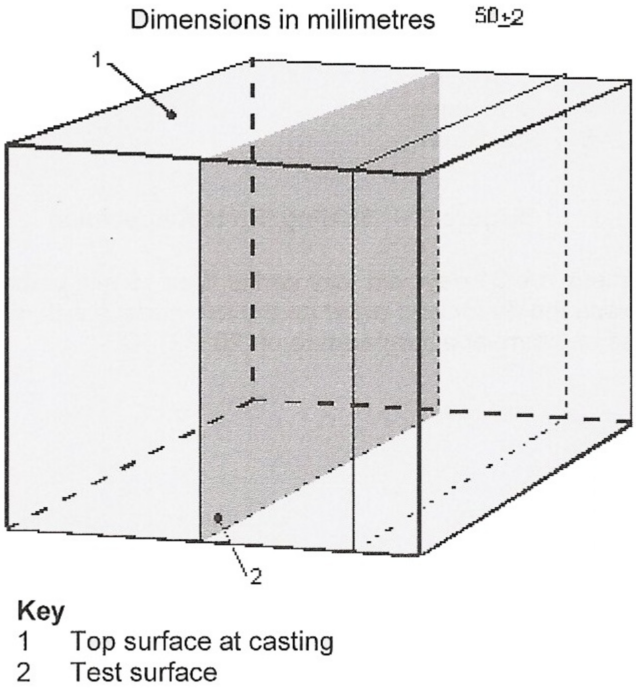
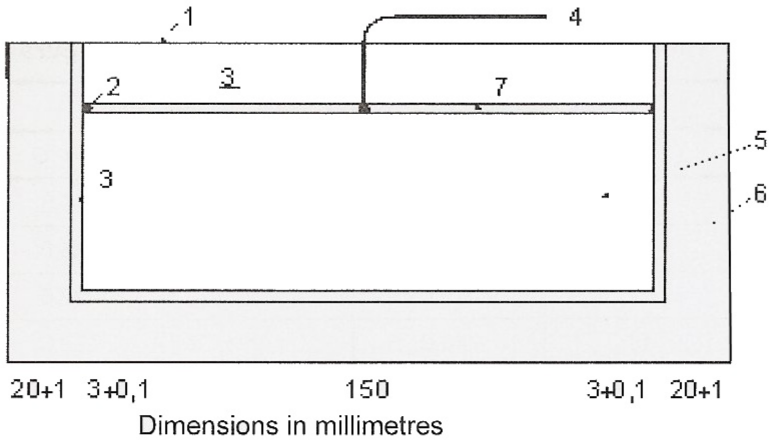


Figure 3: Sawing of concrete sample [11]

over a time period of 24 hours. The frost resistance of the concrete specimens are measured by how much mass scales off at given intervals during the testing cycles.

Procedural description: Four concrete cubes measuring 150x150x150 mm are cast and set in forms. After 24±2 hours the cubes are removed from their forms and cured in water until they are 7 days old. The specimens are then removed from the water and placed in a climate chamber/room where the temperature is (20 ± 2)ºC and the evaporation rate is (45 ± 15)g/(m^2h). The samples will remain in this climate until testing commences.

When the cubes are 21 days old a core specimen that measures (50 ± 2)mm in thickness is sawed from each cube perpendicular to the casting surface as shown in *figure 3*. The core specimen must then be returned to the climate chamber/room as soon as possible. At (25±1) days after casting, rubber sheet (3 ± 0,5)mm thick is glued to all sides of the cored specimen except the testing surface as illustrated in *figure 2*. 28 days after casting the prepared concrete cubes are re-saturated using a layer of approximately 3 mm of DE-ionized water. This layer of water is maintained



Key
1 Polyethylene sheet
2 Glue string
3 Rubber sheet
4 Temperature measuring device in contact with the test surface
5 Specimen
6 Thermal insulation
7 Freezing medium

Figure 4: Final freeze/thaw setup [11]

as the concrete is saturated over a period of (72 ± 2) hours. Before testing begins all surfaces except the testing surface is covered in a (20 ± 1)mm thick polystyrene cellular plastic as shown in *figure 4* and all samples are weighed.

The testing shall be started when the specimen is 31 days old. No sooner than 15 minutes before the testing begins the 3mm layer of water is replaced by the freezing medium. The freezing medium is either a 3mm layer of tap water or the same volume of a 3% NaCl solution. The freezing medium is protected against evaporation by applying a horizontal polyethylene sheet at least 15mm from the testing surface as shown in *figure* 4 The temperature development in the freeze/thaw cycles are given in NS-CEN/TS 12390-9[11] and specifies the temperature state given in Table 2 and *figure 5.*

This heat development covers a time period of 24 hours and is defined as one temperature cycle in the testing process. Freeze/thaw testing proceeds over 56 of these cycles where scaling of material from the test specimen are measured periodically. Scaling is measured by removing the sample from the freezing chamber, removing loose material by lightly brushing it and weighing the remaining mass. This measurement should be executed after (7 ± 1), (14± 1), (28± 1), (42± 1) and (56± 1) cycles. After each measurement, except the last, the samples are returned to the freezer with the same volume of freezing medium (3 mm height = 67ml for

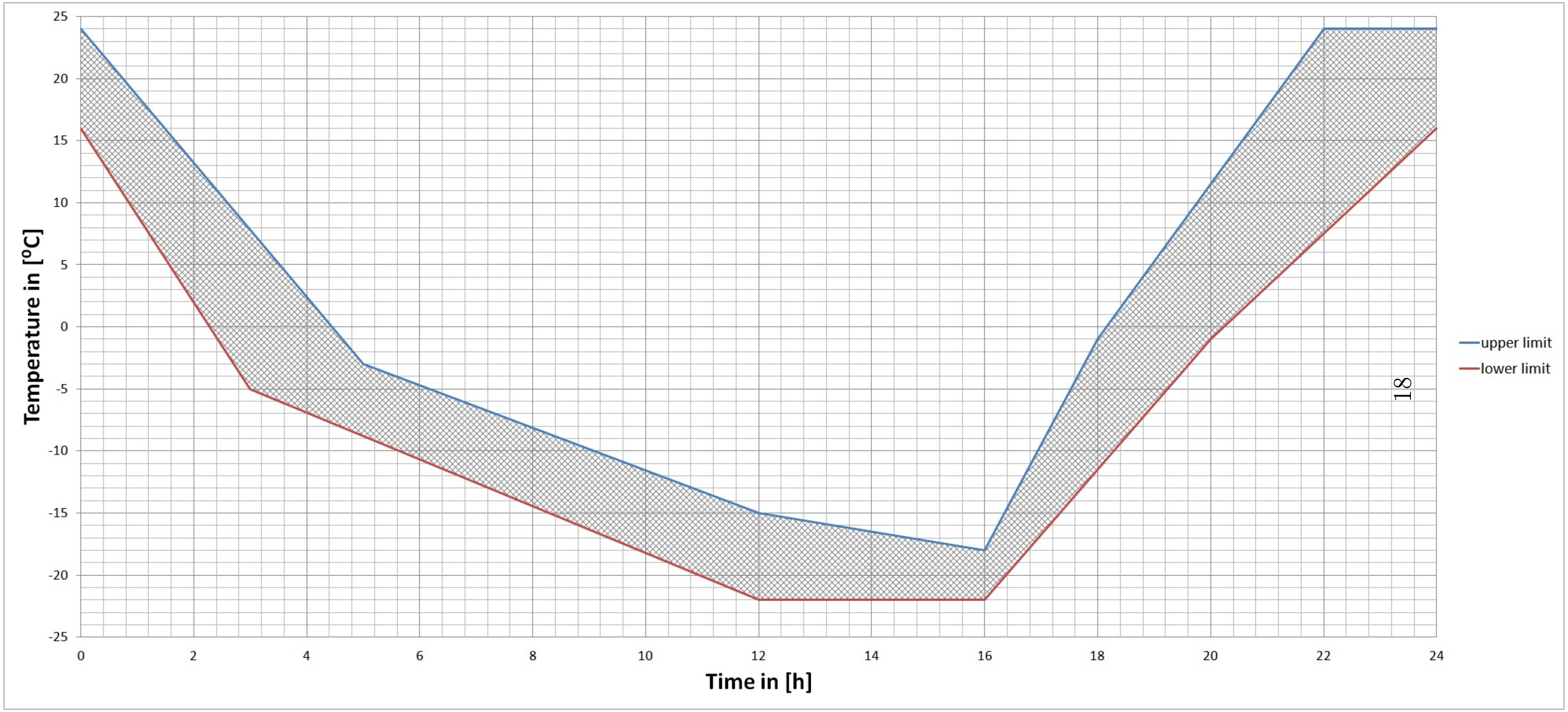


Figure 5: The time-temperature cycle in the freezing medium at the center of the test surface [11]

upper limit		lower limit	
t in h	T in ºC	t in h	T in ºC
0	+ 24,0	0	+ 16,0
5	- 3,0	3	- 5,0
12	- 15,0	12	- 22,0
16	- 18,0	16	- 22,0
18	- 1,0	20	- 1,0
22	+ 24,0	24	+ 16,0

Table 2: Points specifying the shaded area in *figure 5 [11]*

150x150mm).

Evaluation of results: The testing measurement leads to a scaling rate $S_n = \frac{m_{s,n}}{A} \cdot 10^3 \frac{kg}{m^2}$[11] that represents the speed of which material is expelled from the samples with regards to the size of the testing surface after n cycles. The testing period can exceed 56 days and in some cases e.g. for testing paving blocks 28 days may be sufficient.[11, 10]The range, and rough evaluation of results are given as[6]:

- Very Good: S_{56} average < 0.10 kg/m^2
- Good: S_{56} average < 0.20 kg/m^2
- Acceptable: S_{56} average < 1.00 kg/m^2 and $S_{56}/S_{28} < 2$
- Otherwise unacceptable

4.3.2 Modifications of the Borås method

The Borås testing method is a general testing procedure and is thus developed to suit most concrete types. In the case of pervious concrete, however, the method leaves something to be desired. The large void volume in pervious concrete makes the re-saturation of the samples difficult due to the fact that the layer of DE-ionized water and freezing medium will instantly permeate through the concrete by design. Two modifications of the Borås method has been suggested for use with pervious concrete[3][14]:

Due to the high amount of voids in the pervious concrete the re-saturation process was modified in both methods. Instead of re-saturating the concrete for three days as prescribed in the standard Borås method, the concrete samples were submerged in water for approximately 30 minutes and then placed in a high relative humidity chamber for 3 days.

Cup method: Samples are cast, conditioned and prepared as stipulated in the standard Borås method but the samples are now placed with the test surface down so that the 3 mm layer of liquid is absorbed through the concrete face at the bottom instead of having a static layer of liquid on top. The layer of liquid should now be 2 mm over the edge of the sample. Doing this ensures the intended action between the liquid and the testing face. The testing setup in this method is illustrated in *figure 6*

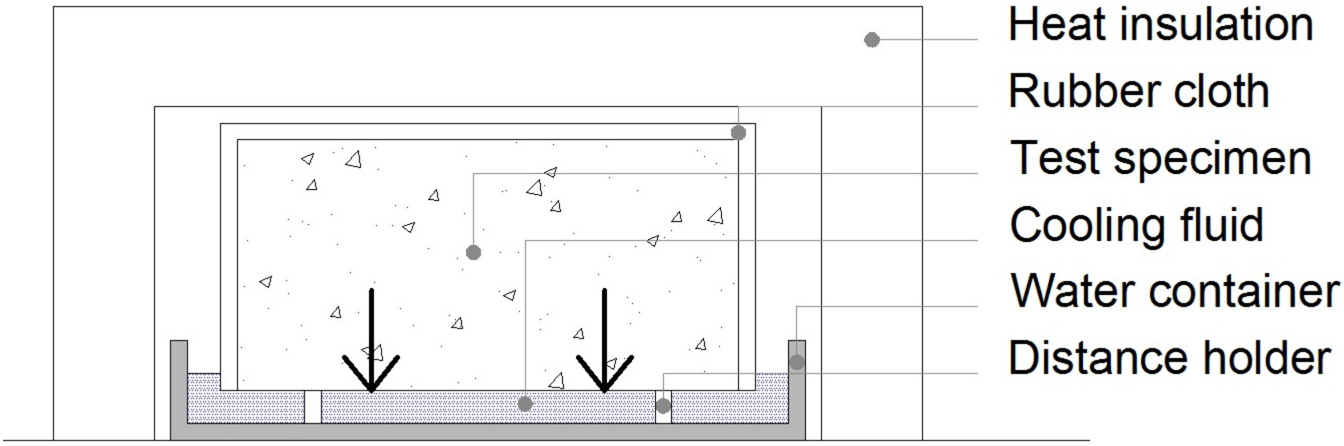


Figure 6: Cup method setup [14]

Flow method: Samples are cast and conditioned as in the standard Borås method but they are prepared somewhat differently. The (20 ± 1)mm thick polystyrene cellular plastic is now only applied to the side edges of the cored sample while the top and bottom remain exposed. This will make it possible for liquids to permeate or flow through the entire height of the specimen. The testing setup in this method is illustrated in *figure 7*

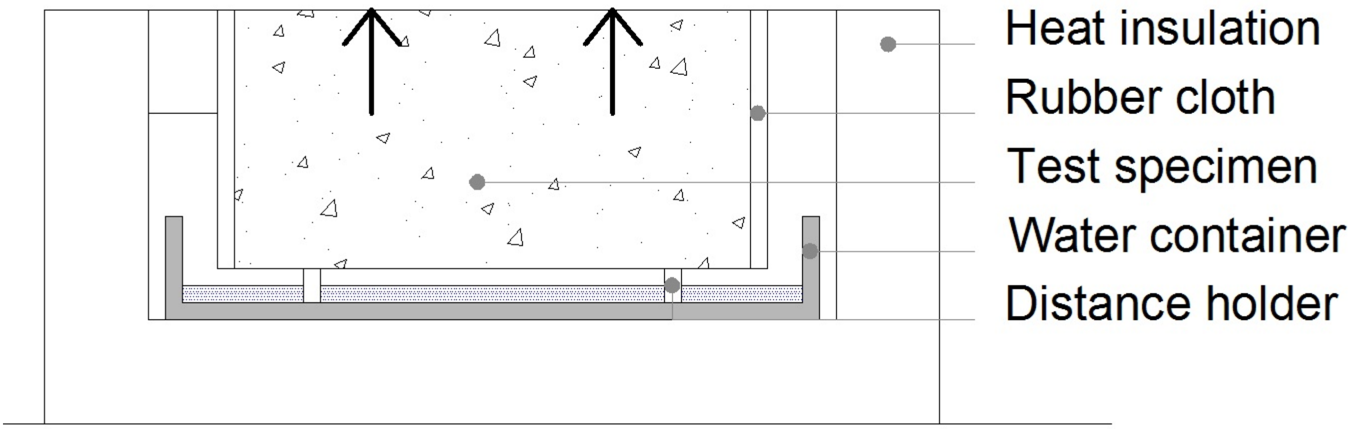


Figure 7: Flow method setup [14]

4.3.3 Freeze/thaw testing of concrete paving blocks NS-EN 1338

The NS-EN 1338[10] gives a modified freeze/thaw testing procedure with regards to testing paving blocks or concrete in similar areas of usage. The method stands similar to the Borås method but with key exceptions. The samples in this method are only tested with a freezing medium containing 3% NaCl and 97% tap water by mass. The requirements for the duration of the testing also differs from the standard method as the samples are tested for 28 days and not the standard 56 days.

The relevance of this method in the use of pervious concrete lies in the usage of the two materials. Low strength and rough surface of the pervious concrete limits the use of the material to areas of low load and exposure conditions. Because of this the two materials may have quite a few overlapping areas of application. It then stands to reason that the two should have the same requirements when it comes to environmental durability.

4.3.4 Freeze/thaw testing of pervious concrete

In standardized testing, pervious concrete generally performs poorly. In some cases, however, have shown that certain placements of pervious concrete has performed well in the field for more than 20 years[17]. This suggests that the testing procedures designed for standard PC concrete may not as adequately describe the performance of pervious concrete in field conditions. As a result, more specialized methods must be considered for use with pervious concrete.

Because of the large interconnected void system in pervious concrete, using the standard Borås method would demand that the entire void structure be filled with freezing medium. This means keeping a constant level of about 0.3-0.5 liters of freezing medium in the sample during testing. This is of course in far excess of what is intended by the standardized method of keeping a constant 3 mm layer of freezing medium over the concrete.

The cup method is probably the closest method to the standard test when it comes to exposing pervious concrete to the freezing medium. Roughly the same amount of liquid is in contact with the testing surface during testing and although gravity now works against the permeation of the liquid, this seems to be the closest method regarding saturation status during testing compared to the standard method(with standard concrete).

The flow method does not as closely resemble the standard case as the cup method, but it is however more similar to field conditions than the standard case. Correctly placed and compacted pervious concrete should not be in constant contact with a body of water. It should continually drain such bodies away from the structure and as a result periodically re-saturate the entire structure of the concrete. This is essentially what happens between test points in the flow method. As the freezing medium is re-applied after testing, it permeates into the concrete like moisture would in field conditions. The main complaint with this method is then that the re-application of freezing medium is not done often enough. 100 ml of moisture per 2 weeks in later stages of the testing seems optimistic to say the least in comparison to field conditions.

5 Experimental design

Several laboratory activities have been conducted in context of this thesis. This chapter will provide a description of the experimental design of these activities. All experimental activity was performed at the concrete research facility at NTNU in Trondheim, Norway, 2012. The experimental work done in connection with this thesis can be divided into two main groups: Mortar experiments and Concrete experiments.

Due to the paramount importance of the binder composition in concrete, and especially in pervious concrete, various mortar composition were mixed and evaluated to provide a basis for the binder to be used in pervious concrete. A total of 5 different mixes of mortar were produced with varying sand content and air-entraining agent. In addition, all batches of mortar were mixed with two different mixing procedures to investigate the importance of the mechanical aspect of the compounding. All the mortars share the same base composition(w/c-ratio) and consists of the same materials so that the difference between them would mainly be due to the 3 variables: content of air-entraining agent, sand content and mixing method. Therefore, a spread of five different batches of mortar was each produced twice:

Sika Aer ↓ \ sand →	0 kg/m^3	150 kg/m^3	300 kg/m^3
0,75%		M005	
1,5%	M003	M002	M004
3,0%		M001	

Table 3: Classification of mortar mixes

Pervious concrete was then cast and tested in a total of 6 batches of 50 liters each. Results from the mortar experiment influenced the choice of binder composition while the eigen-packing of the coarse aggregate was used to predict and vary the theoretical void content in the different batches. The different batches are numbered from 1 to 6 with the authors initials ØT to identify the different samples. These parameters leads to the following spread of concrete:

	ØT1	ØT2	ØT3	ØT4	ØT5	ØT6
Void content	15 %	15 %	15 %	15 %	10 %	20 %
Sand content [kg/m^3]	150	150	0	0	150	150
Mixing method	1	2	1	2	1	1

Table 4: Classification of concrete batches

The cast concrete was tested for a number of key properties: Strength, permeability, void content and resistance to frost.

Materials were chosen to coincide with those used in the pervious concrete produced by Tingstveit(2011)[14]. The reason for this is to create a correlation of results between the projects. The materials in the concrete were also chosen to accommodate the fact that the concrete should be easy to produce with materials that are commonly used in Norway. The materials also coincide with the chosen materials used in the mortar test. Based on these parameters the following materials were chosen for use in the batches of pervious concrete and the same materials, except for the coarse aggregate, were used to produce the mortar[1]:

- Cement: NORCEM Standard FA, PR-nr: 26276
- Fine aggregate/Sand: Norstone, Årdal NSBR 0-8mm A-3714
- Coarse aggregate: Norstone, Årdal NSBR 8-16mm A-3714
- Air-entraining agent: Sika Aer with 9% solids, 04 1274-CPD-701
- DE-ionized tap water

5.1 Mortar Mixing

5.1.1 Testing Equipment

The different batches of mortar was mixed and tested using the following equipment:

- Mixer of type Hobart model N-50 with a 3 liter mixing container as shown in *figure 8a.*

[1]Documentation of the materials can be found in Appendix A

- Air void content measurer marked form+test with a 1 liter container shown in *figure 8b*.

(a) Hobart N-50

(b) Air void content measurer

Figure 8: Equipment for mixing and measuring of mortar

The mixer is of special interest because it has been used as the benchmark for for different mixing methods. The mixer has three different speeds in which the rotary whisk turns. These speeds are numbered from 1 to 3 and form the basis for the mixing setup described in 5.1.3.

5.1.2 Producing recipes: Mortar

w/c ratio The w/c ratio was chosen in coherence with recommendations from ACI[7] and the previously performed master's thesis on pervious concrete by Jon Heck Tingstveit.[14] Therefore a **w/c** of **0.3** formed the binder basis for all mortars in this experiment.

Sand content The sand content was varied between 0 and 300 kg/m^3based on previous pervious concrete performance.[14] The moisture content of the sand was also measured and accounted for in the following fashion:

1. A weight of 500g of sand is measured in a cauldron

2. The cauldron is placed on a heat source for approximately 15 minutes until the sand is completely dry.

3. The weight of the sand is then measured again to determine the materials dry weight $\mathbf{w_{dry}}$

4. The moisture content of the material is then calculated as $\frac{500g-w_{dry}}{w_{dry}}$

Content of air-entraining agent The recommended amount of Sika Aer in regular concrete is given as 0.01-0.08% of cement mass. However in pervious concrete Sika recommends a substantially higher amount in the binder. Therefore the amount of Sika Aer was varied from 0 to as much as 3% of cement mass in this experiment.

The recipes were produced using a excel sheet for concrete proportioning by SKANSKA and Sverre Smeplass. This was done by manipulating the matrix volume in the theoretical concrete from the excel sheet to accommodate the desired sand content in the mortars to be tested. The w/c-ratio, the amount of Sika Aer and given a volume of 1.2 liters was also input to account for any discrepancy. The aforementioned variables leads to the following specific recipes:

Mortar #	w/c ratio	c [kg/m^3]	w [kg/m^3]	Sand [kg/m^3]	Sika Aer % of c	Volume [L]
M001	0.3	1471.5	441.5	150	3 %	1.2
M002	0.3	1474.0	442.2	150	1.5 %	1.2
M003	0.3	1562.4	468.7	0	1.5 %	1.2
M004	0.3	1385.5	415.7	300	1.5 %	1.2
M005	0.3	1475.2	442.6	150	0.75 %	1.2

Table 5: Mortar recipes

5.1.3 Mixing procedure: Mortar

Two different methods of mixing was utilized in this experiment: One "standard" method where all dry materials are mixed together before adding the liquids and one alternate method where the cement is added in portions instead of bulk. This is to investigate if the mixing procedure will have any effect on the properties of the fresh mortar, and as a result, change the properties of the binder in fresh concrete.

The Hobart mixer which was used has three different mixing speeds denoted 1, 2 and 3 where mixing speed 3 is the quickest. Only the 2 first speeds were used due to the viscosity of the mix made it difficult to control the material at higher speeds. The concentrated solution of Sika Aer was added to the water prior to mixing and was therefore added simultaneously with the water in the mixing procedure.

The two suggested mixing methods are produced based on the standard mixing procedure of concrete at the lab and aims to simulate the conditions the binder undergoes during the mixing of concrete. The two different mixing methods are described below:

Standard mixing method:

- All dry materials are added from greatest to finest grain size in that order. These dry materials are then mixed at mixing speed 1 for **1 min**.
- The liquids are added over a period of 30 seconds while the batch is being mixed at mixing speed 1 for **1 min**.
- The speed of the mixer is increased to level 2 and the mortar mixes for **1 min**.
- The mixing stops and rests for **2 min**.
- The mortar remixes at mixing speed 2 for **1 min**.

Alternate mixing method:

- Three quarters of the cement and the rest of the dry materials are added from greatest to finest grain size in that order. These dry materials are then mixed at mixing speed 1 for **1 min**.
- The liquids are added over a period of 30 seconds while the batch is being mixed at mixing speed 1 for **1 min**.
- The speed of the mixer is increased to level 2 and the mortar mixes for **1 min**.
- The mixing stops and the remaining quarter of the cement is added over a time period of **1 min**.

Figure 9: Mortar in 1 liter container

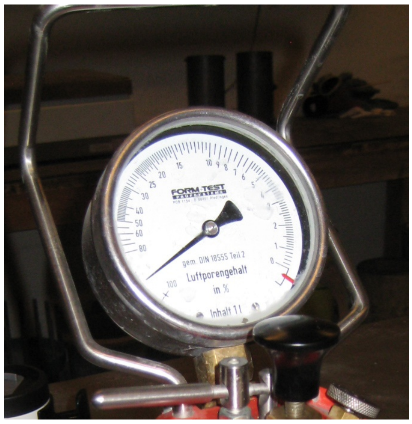


Figure 10: Pressure gauge for testing air content of mortar

- The mixing resumes at mixing speed 1 for **1 min**.
- The speed of the mixer is again increased to level 2 and the mortar mixes for **1 min**.
- The mixing stops and rests for **2 min**.
- The mortar remixes at mixing speed 2 for **1 min**.

5.2 Mortar testing

The material properties that were extracted from this experiment was density and air content. The equipment used for analyzing both these values is illustrated in *figure 8b*.

5.2.1 Density

Density was measured by filling each of the mortar mixes into a 1 liter container of a given mass. Practically this was solved by placing the empty container on a scale and redefining this weight as the Tare weight or zero-weight. This obviously allows for scaling only the material within the container and not the container itself. Given the weight and volume the density is naturally given by: $density = \frac{Weight}{Volume}$

5.2.2 Air content

The 1 liter container of each mortar is now sealed with an airtight lid with two valves and a pressure scale fixed to it. The mortar is then filled with water through one of the two valves until water comes out of the other valve. The two valves are then closed securing that all excess air have been removed from the system prior to pressure testing. The mortar and water will then be pressurized so that all air pockets in the mortar will be saturated. When the pressure is released the amount of air in the volume is given on a pressure gauge in percentage of volume. The pressure gauge is shown in *figure10* .

5.3 Concrete Mixing

This section contains a description of how the concrete produced in this thesis is mixed and cast. The method of which the concrete recipes was produced is also explained here.

5.3.1 Casting & Compacting

The concrete samples were compacted using a Kangoo hammer of type: Kangoo 950. This tool was used to compact the concrete from the top instead of vibrating the sample from the bottom using a vibrotable as is normal with conventional concrete. This choice was made to counteract the tendency that pervious concrete has to separate during this compacting. This effect was thoroughly tested in Tingstveit(2011)[14] and was therefore not considered a variable in this thesis. All produced concrete specimens was compacted using the Kangoo hammer. The forms were filled in thirds with compacting in between each third of concrete volume and the top of the filled form. Concrete was topped off and manually compacted with a spatula filling the entire form. The compacting itself was done in three short bursts of vibration from the Kangoo hammer through a shim plate. The total time of compaction per layer of concrete was then approximately 4-5 seconds.

(a) Kangoo Hammer 950

(b) Filled compacted forms and shim plate

Figure 11: Compacting of concrete

5.3.2 Producing recipes: Pervious concrete

The pervious concrete produced as a result of this thesis was based on the preceding mortar experiment. The mortar M002 has shown the most promise and was therefore chosen as the basis for the binder in the concrete. There was produced 6 different batches of pervious concrete with three major variables: Theoretical void content, sand content and different mixing method. Other variables were kept constant so that every batch of concrete shared certain traits:

- w/c = 0.3
- Sika Aer = 1.5-weight% of cement

The eigen-packing of the coarse aggregate was also examined. The use of large uniform aggregates in pervious concrete leads to large voids between coarse particles in the concrete. It is therefore important to estimate how much void the aggregate in itself contains. Practically this is solved by filling a container of known volume V with a material of known density ρ, and determining the weight of this contained volume of material, m. Comparison can then be drawn between the theoretical solid volume of the material corresponding to the density and the actual weight of the material in a container. The quotient of these two weights must then be the ratio of solid material in a given volume, also known as the $Eigen - packing = \frac{m}{V \cdot \rho}$.

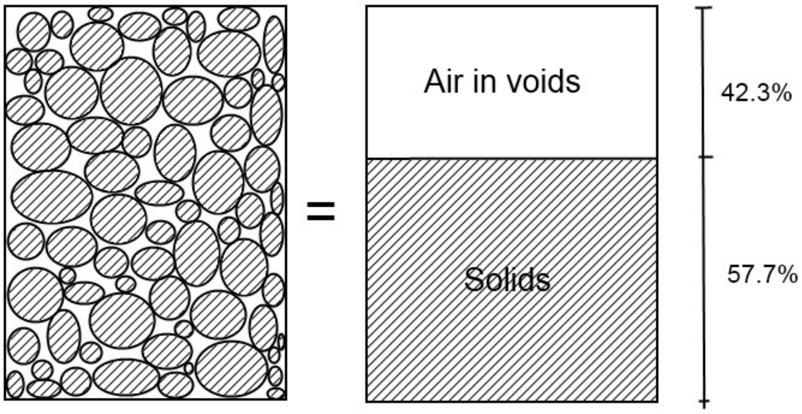


Figure 12: Eigen-packing of coarse aggregate

The specific recipes were produced by a volumetric assessment based on the eigen-packing of the coarse aggregate. The theoretical void space of the concrete was varied at 10, 15 or 20% of total volume. While the amount of coarse aggregate was kept constant with assumed accurate degree of eigenpacking the theoretical void space in the cast concrete is the amount of eigenpacking voids minus the volume of matrix. This is illustrated in *figure 13* .

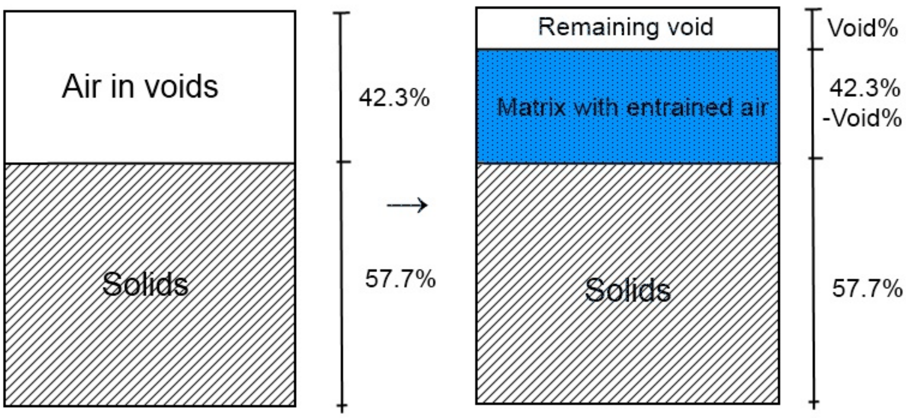


Figure 13: Theoretical void content of concrete

The other variable, sand content, was also varied in the binder and the same method for producing recipes was repeated for different amount of sand in the concrete.

Batch #	description	mix. method	w/c ratio	Agg.8-16mm [kg/m^3]	Agg. 0-8mm [kg/m^3]	Cement [kg/m^3]	Water [kg/m^3]	Sika Aer [1,5%ofc]
ØT1	S150-V015	1	0.3	1528	30.76	302.2	90.67	4.533
ØT2	S150-V015	2	0.3	1528	30.76	302.2	90.67	4.533
ØT3	S000-V015	1	0.3	1528	0.000	317.9	95.37	4.768
ØT4	S000-V015	2	0.3	1528	0.000	317.9	95.37	4.768
ØT5	S150-V010	1	0.3	1528	36.38	357.5	107.2	5.362
ØT6	S150-V020	1	0.3	1528	25.13	247.0	74.09	3.704

Table 6: Produced pervious concrete recipes

5.3.3 Mixing procedures: Pervious concrete

Two different procedures for mixing the concrete was used in this thesis. The first is a standard mixing procedure used in most conventional concrete testing. The second is a method which focuses on mixing the binder in the pervious concrete before adding the coarse aggregate. This is done to study the effects of premixing the binder before “coating” the coarse aggregate with this binder.

Method 1 Standard mixing:

- Dry mix. All the dry materials and aggregates are added according to grain size from finest to coarsest and mixed for **1 min.**
- Wet mix. The water containing all liquid admixtures is added to the dry mix over the course of 30 seconds. The wet mix is blended for **2 min.**
- Setting. The machine is stopped and the mix is allowed to set for **2 min**.
- Remix. The machine is started again and the mixture is mixed for an additional **1 min**.

Method 2 Modified mixing:

- Mortar mix. All components of the binding mortar are mixed for **2 min**.
- The coarse aggregate is added while the machine is stopped
- The binder and the coarse aggregate is mixed together, coating the aggregate, for **2 min**.
- Setting. The machine is stopped and the mix is allowed to set for **2 min**.
- Remix. The machine is started again and the mixture is mixed for an additional **1 min**.

5.3.4 Choice of freeze/thaw testing procedure

The frost durability of concrete is based on the saturation state in the concrete. Many testing methods for determining this parameter is therefore based on saturating the concrete at constant conditions. Since pervious concrete has such a porous structure and contain large amounts of void, this can make the determination of this parameter difficult. The cup- and flow method was chosen to test the frost durability of the pervious concrete.

The cup method was chosen because it is seemingly the only method that will secure a constant saturation state in the concrete specimen over the course of the testing. The flow method was chosen to complement the cup method in areas where it is not so strong. The cup method requires the concrete to absorb the freezing medium through the testing surface against the pull of gravity. The concrete that is located higher in the specimen will therefore be less likely to be as saturated as the concrete near the testing surface. The flow method, though not securing the same constancy of saturation, will be more prone to spread the freezing medium evenly through the height of the specimen.

These two methods should then be suited to at least illustrate a tendency of the pervious concretes ability to resist frost. This is also the methods described and used by the technicians at the CBI concrete institute at Borås in Sweden for use with pervious concrete[3].

5.4 Concrete testing

This section covers the testing method of concrete in this thesis. Each of the examined parameters and corresponding testing procedure is described here while the results from said testing can be found in section 6.2.

5.4.1 Permeability

The measurement of the concrete permeability was conducted by considering a simple modified falling-head test using apparatus and a method conceived by Tingstveit(2011)[14]. The test starts by fixing a cylindrical concrete specimen measuring 10x20 mm, 10 being the diameter and 20 being the height, to the bottom of a PVC pipe measuring 10x760 mm. The specimen is secured to the pipe by the use of metal clamps around a rubber tube surrounding the cylinder. This minimizes the amount of water that can flow around the specimen and thus maximizes the flow of water through the specimen.

The PVC tube will be filled with water until the water level reaches an outlet 760 mm from the top of the concrete specimen. This will ensure that a water column of constant size rests over the specimen during the testing period. The entire testing setup is shown in *figure 14*.

(a) Permeameter

(b) Flow during testing

Figure 14: Setup for testing permeability

Water from the static column over the specimen will then percolate through the concrete and into a bucket on a scale that records weight every two seconds. Given the density of water ρ_w, the volumetric amount of water that flows through the concrete specimen over given time intervals can then be determined:

$$Q = \frac{(W_2 - W_1)}{t \cdot \rho_w},$$

where W_2 and W_1 is the weight measured in the bucket at the end and beginning of the time interval t respectively. Given this volume and the cross sectional area of the standing water column A_c over the specimen, determining the **coefficient of permeability** is given through Darcy's law[5]:

$$K = \frac{Q \cdot \mu}{A_c \cdot \Delta P \cdot L}$$

In this application of Darcy's law, we consider the constant water pressure ΔP, dynamic viscosity of water μ and the length of the specimen L. In this thesis $\mu = 1.002 \cdot 10^{-3} \frac{N \cdot s}{m^2}$ at 20 ºC is used[4]. This coefficient K is the theoretical permeability of the material and can be used for further analysis of the material. However, it is not very descriptive of the actual water flow through said material. To further illustrate how the material performs during the test, the **percolation rate** k is also calculated.

The percolation rate of the concrete samples is then given as

$$k = \frac{Q}{A_c}$$

where A_c is the cross-sectional area of the concrete samples (10x20cm) $A_c = \pi \cdot (0.5dm)^2 \cong 0.7854dm^2$,

and Q is the volumetric equivalent of the water percolation rate from table 12 applying a water density of $\rho_w = 1000 \frac{kg}{m^3}$. In other words , Q is the volume of water that flows through the concrete per second time. The principle of determining k is illustrated in *figure 15.* This number represents the rate the height of which the water column percolates through the material assuming a minimal flow of water along the sides of the concrete. Due to the fact that the water column above the concrete specimen is kept constant during testing, the pressure gradient ΔP is calculated to be the weight of the constant water column over the specimen W_{wcolumn} divided by the surface area of the supporting concrete A_c.

$$\Delta P = \frac{W_{wcolumn} \cdot 9{,}81 \frac{N}{kg}}{A_c}$$

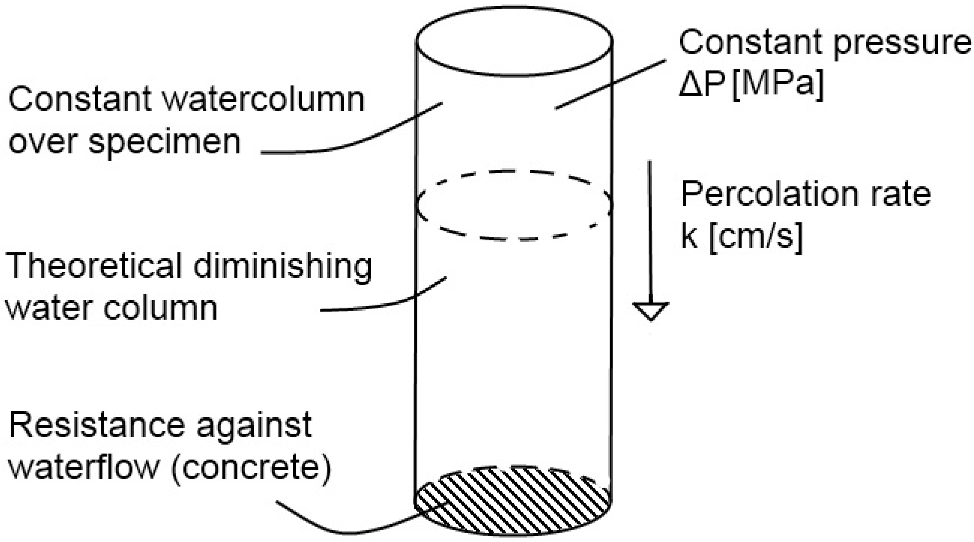


Figure 15: Principle of the factor k

5.4.2 Volume voids

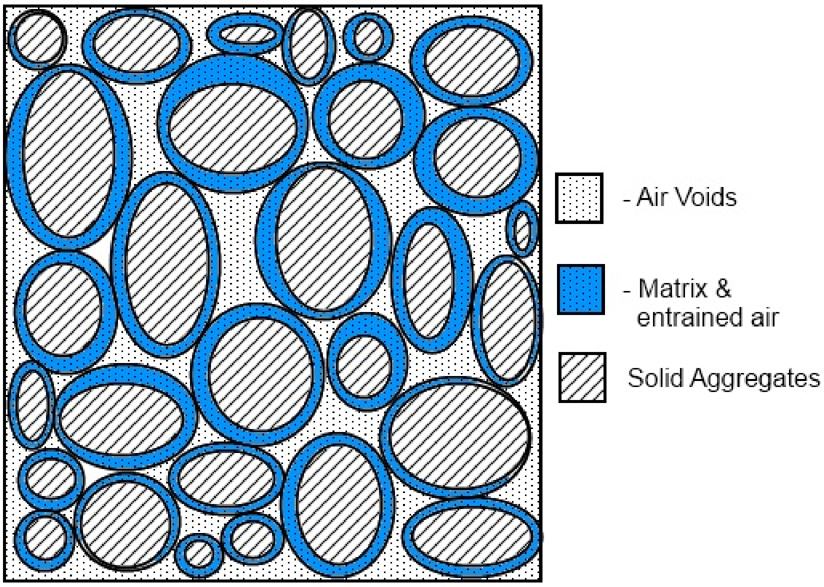
Pervious concrete is designed for its void content. As the amount of voids in concrete is directly related to the strength and durability of the material, it remains the perhaps most important factor for designing and evaluating pervious concrete. As the pore structure in concrete can be somewhat complicated, it has been simplified as three major kinds of air pores/pockets in this thesis: Voids, Entrained air and Entrapped air. A modified PF-method is devised in this thesis for use with pervious concrete to investigate the volumes of each of the different kinds of air pockets in the concrete.

The **voids** are the large open air pockets that largely stems from the eigenpacking of the coarse aggregate. The matrix-binder surrounds the coarse aggregate and occupies part of the eigenpacking voids. The binder contains round evenly spaced **entrained air** bubbles that originates from the air entraining admixtures added to the concrete. These even bubbles are very stable and it is assumed that the concrete must be subjected to over-pressurization for these pores to fill with water. The chemical process of setting concrete also yields gel- and capillary pores which are very fine but irregular shaped. These fine pores are assumed to absorb water directly or passively if submerged, and are denoted **entrapped air** in this thesis.

This testing is performed directly after the preceding permeability testing with the same specimen as in that test. In this thesis, the amount of voids in the previous concrete is determined by use of a simplified PF-method described in the TKT 4215 Concrete Technology 1 compendium.[8] The method determines the porosity of the concrete in several different states:

1. After initial draining for 1 day at 65% RH, leading to the weight W_0
2. After drying for 2 days at 105 °C, leading to the weight W_1
3. After saturating submerged in water for 2 days and draining until surface dry, leading to the weight W_2
4. At this saturated state, the weight of the specimen submerged in water is measured. This leads to the weight W_3
5. After pressure saturating the specimen at approx. 5 MPa water pressure overnight, leading to the weight W_4

These three states effectively describe the air pores in the concrete and in the case of pervious concrete the large voids. The geometrical volume of the specimen is also needed to relate the weight to volume. In this thesis this volume is assumed to be the theoretically perfect 10x20 cm cylinder where $V = \pi \cdot r^2 \cdot h$. The difference between W_1 and W_2 is assumed to be that only the entrapped gel- and capillary pores in the paste are filled with water.[8] These pores can absorb water directly given enough time while the entrained uniform pores from admixtures will only be filled by the means of a pressure chamber. The difference between W_3 and W_2 is the buoyancy created by the concrete not filled by water, thereby describing the volume of void in the concrete. The difference between W_4 and W_2 is that all the entrained pores in the binder have been forced to fill with water because of an external pressure. An overview of the process is illustrated in Table *7* . The calculated volumes and formulas for calculation are given in 6.2.3.



Water saturated:	Gel pores	Capillary pores	Entrained pores	Voids
Drained surface dry W_0	x	x	-	-
Dried for 2 days at 105°C W_1	-	-	-	-
Passively saturated in water W_2	x	x	-	-
Submerged sample W_3	x	x	-	x
Actively saturated under pressure W_4	x	x	x	-

Table 7: Assumed saturation status in concrete

Investigation of the volume voids is carried out on the same three 10x20 cm cylinders that was exposed to the permeability test. All the samples were dried at 105 °C over a period of 2 days. All samples were weighed and then submerged in water for another 2 days. At this time the samples were removed from water and allowed to drain internal water until the specimen is surface-dry.

Then the water-saturated specimen are weighed, first in air, then submerged in water using a hanging shelf under the scale. The samples are then placed in the pressure chamber. All samples are placed in bags with known weight in case of any specimen rupturing under pressure. The pressure chamber is pressurized to 5 MPa of water pressure and the samples remain in this condition for 3 days until removed from water, drained then weighed. The entire process is photo-illustrated in *figure 16.* The resulting weights from this method is given in table 14.

(a) Drying of specimen

(b) weighing of dry specimen

(c) Submerged samples

(d) Weighing in air

(e) Weighing in water

(f) Specimen placed in pressure chamber

(g) Pressure chamber

(h) Pressurized to 5 MPa

Figure 16: Simplified PF-method

5.4.3 Strength

Cylindrical specimens measuring 10x20 cm were tested for compressive strength over the course of this experimental process. Testing of compressive strength is carried out after NS-EN 12390-3.[12] A series of three cylinders per batch of concrete was cast and hardened in water until they were 28 days old when they were tested until fracture. The failure loads are given for each specimen of concrete in table 15a, and the average of the three failure loads forms the basis for calculating the strength of the concrete. These calculated strengths are given in table 15b.

(a) Specimen in testing machine

(b) Soft inlay after testing

Figure 17: Strength test setup

Due to the fact that the pervious concrete has such irregular surfaces, a soft inlay pad was used to even out the pressure zone between the testing machine and the concrete cylinder. This was done to manage the surface strain on the specimen, and minimize moments in the concrete due to eccentric load during testing.

5.4.4 Resistance to frost

Four Cubes measuring 150x150x150 mm were cast from each of the 6 different concrete batches for the purpose of freeze/thaw testing. This yields a total of 48 samples due to the fact that each specimen was sawed in half prior to testing.

There is therefore 8 pieces from each batch available for frost testing. These 8 are distributed with regards to freezing- method and medium in the fashion described in Table 8. Each of the pieces were named after their batch number, freeze/thaw method and cube number. In this legend, cube number 1 of 2 insulated for use with the cup method comprised of concrete from batch ØT3 is named ØT3C1. In addition to this the denoted sample is marked either with a W signifying that the freezing medium is pure water, or an S which means the freezing medium is a 3% NaCl solution. All the concrete samples tested for frost durability has been named in this fashion.

As described earlier the freeze/thaw testing procedure chosen in this thesis is the two modified Borås test methods designated cup- and flow method, described in 4.3.2, Tingstveit(2011)[14] and the technical report from Borås[3]. These methods are designed specifically for use with pervious concrete and were chosen so that results would be comparable to those produced by Tingstveit(2011). The rubber insulation used was a 3M Scotch™ Vinyl/Mastic tape with a Sikaflex®-11FC+ sealant to prevent the flow of freezing medium along the sides of the testing specimen. both the cup- and the flow method is photo-illustrated in appendix C. In addition to this the insulated specimen was covered with a 2 cm Styrofoam plate around all the edges of the sample for the flow method, and around all sides but the bottom for the cup method.

	Pure water	3%NaCl sol.
Cup method	2 pcs.	2 pcs.
Flow method	2 pcs.	2 pcs.

Table 8: Distribution of frost samples

Unfortunately, due to technical difficulties, several modification to the freeze/thaw experiment had to made. The testing was performed using two freeze/thaw cabinets where the temperature was supposed to conform to the requirements found in NS-EN 12390-9[11]. The correct temperature cycle could however not be achieved once all the concrete specimens were inserted. The temperature cycles for the duration of the experiment is given in appendix B. An overview of which concrete batches was placed in which cabinet is given in table 9.

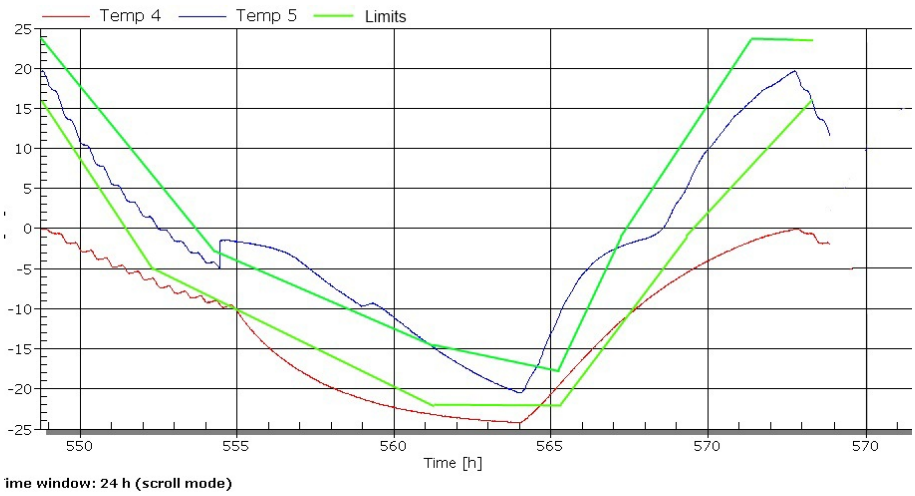


Figure 18: Temperature in cabinets vs. NS-EN 12390-9

Cabinet	Color in documentation	Containing batches		
Temp 5	blue	ØT1	ØT2	ØT3
Temp 4	red	ØT4	ØT5	ØT6

Table 9: Distribution of concrete batches in freeze/thaw cabinets

As illustrated, the first week of the experiment the temperature in both cabinets deviated wildly from the standard temperature cycle. The problem was identified as being not enough room in the cabinets to secure sufficient air flow. To combat this, one of the two pure water specimens from each batch of concrete were removed from the cabinets. This resulted in a much better temperature performance but it turned out that one of the cabinets, denoted temp 4 in the documentation, could not heat the samples sufficiently. This made testing of those specimen impossible, as they never thawed out before starting another freeze cycle. The other cabinet, denoted temp 5 in the documentation, is still partly outside of the standardized area but is close enough to at least illustrate the trend of the frost durability in the containing samples. The temperature cycle of the cabinets after the first week with the requirements from the standard is illustrated in *figure 18.* The remaining specimen could only be tested until 42 days before this thesis was due. The remaining 56 day test will be performed and the result delivered to the concrete technology institute at NTNU after delivery of this thesis.

6 Results

This section contains the results from the experimental activity. The results are complemented with explanations portraying the specific way the data was obtained, as opposed to the general design of the experiments given in section 5.

6.1 Results of mortar experiment

The density and air-content of the mortar for the two different mixing procedures are given in this section in table 10.

	M001		M002		M003	
	Std.mix	Alt.mix	Std.mix	Alt.mix	Std.mix	Alt.mix
Density [kg/m^3]	1105.1	1055.0	1307.9	1487.6	1287.9	1446.3
Air content	38 %	40 %	29 %	25 %	29 %	25 %

	M004		M005	
	Std.mix	Alt.mix	Std.mix	Alt.mix
Density [kg/m^3]	1828.0	1567.7	1667.0	1522.7
Air content	12 %	23 %	16 %	23 %

Table 10: Results of mortar experiment

6.2 Concrete testing results

The specifics of the testing of the cast concrete and the results from said testing is presented in this section.

6.2.1 Fresh concrete

The density of the fresh concrete was measured in the same way as the mortar density was measured, but it is important to notice that the concrete in the testing bucket was compacted just as the rest of the concrete samples. The density of each batch of concrete is given in table 11. The air content in the concrete was also planned to be tested in the same fashion as the mortar, but because of the large void percentage in the concrete this proved difficult to determine. The amount of water required to fill the testing apparatus would most certainly change the concrete

batch #	ØT1	ØT2	ØT3	ØT4	ØT5	ØT6
Density [kg/m^3]	1729.8	1694.5	1679.1	1741.6	1826.4	1743.7

Table 11: Density of fresh concrete

Batch #	Sample#1	Sample#2	Sample#3	Total average
ØT1	360.6 $\frac{g}{s}$	388.1 $\frac{g}{s}$	392.8 $\frac{g}{s}$	380.5 $\frac{g}{s}$
ØT2	495.1 $\frac{g}{s}$	449.3 $\frac{g}{s}$	496.6 $\frac{g}{s}$	480.3 $\frac{g}{s}$
ØT3	412.6 $\frac{g}{s}$	395.8 $\frac{g}{s}$	451.1 $\frac{g}{s}$	419.8 $\frac{g}{s}$
ØT4	533.2 $\frac{g}{s}$	503.8 $\frac{g}{s}$	513.2 $\frac{g}{s}$	516.7 $\frac{g}{s}$
ØT5	292.2 $\frac{g}{s}$	278.9 $\frac{g}{s}$	271.2 $\frac{g}{s}$	280.8 $\frac{g}{s}$
ØT6	378.1 $\frac{g}{s}$	423.6 $\frac{g}{s}$	397.2 $\frac{g}{s}$	399.6 $\frac{g}{s}$

Table 12: Averaged water flow rate Q of concrete samples

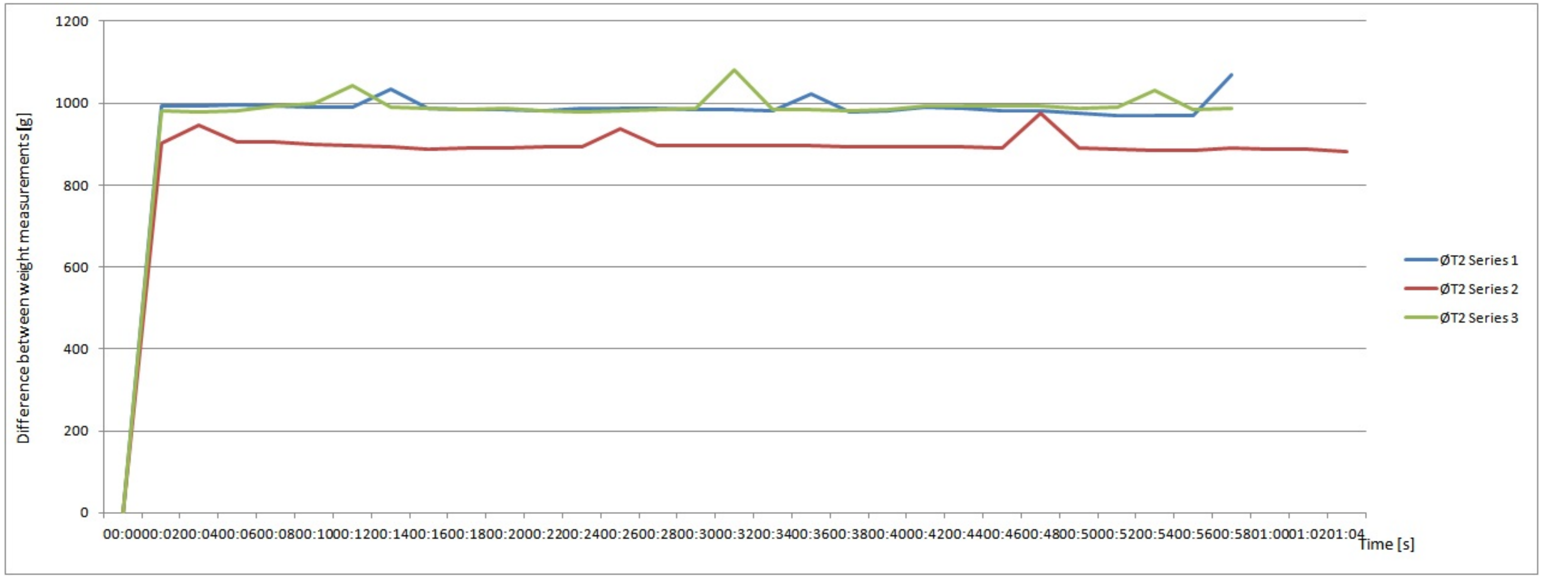
in such a way that the measured air content would not be descriptive of the situation in the cast concrete. Therefore only the density was measured in the fresh concrete.

6.2.2 Permeability results

A series of three 10x20 cylinders was tested from each of the six batches of concrete, making a total of 18 concrete samples. The data from the weight was analyzed by observing the difference between two measurements over the given time interval of two seconds. This yields the weight of water that has percolated through the concrete over these two seconds. This difference was graphed and is displayed in *figure 19* to *figure 21*.

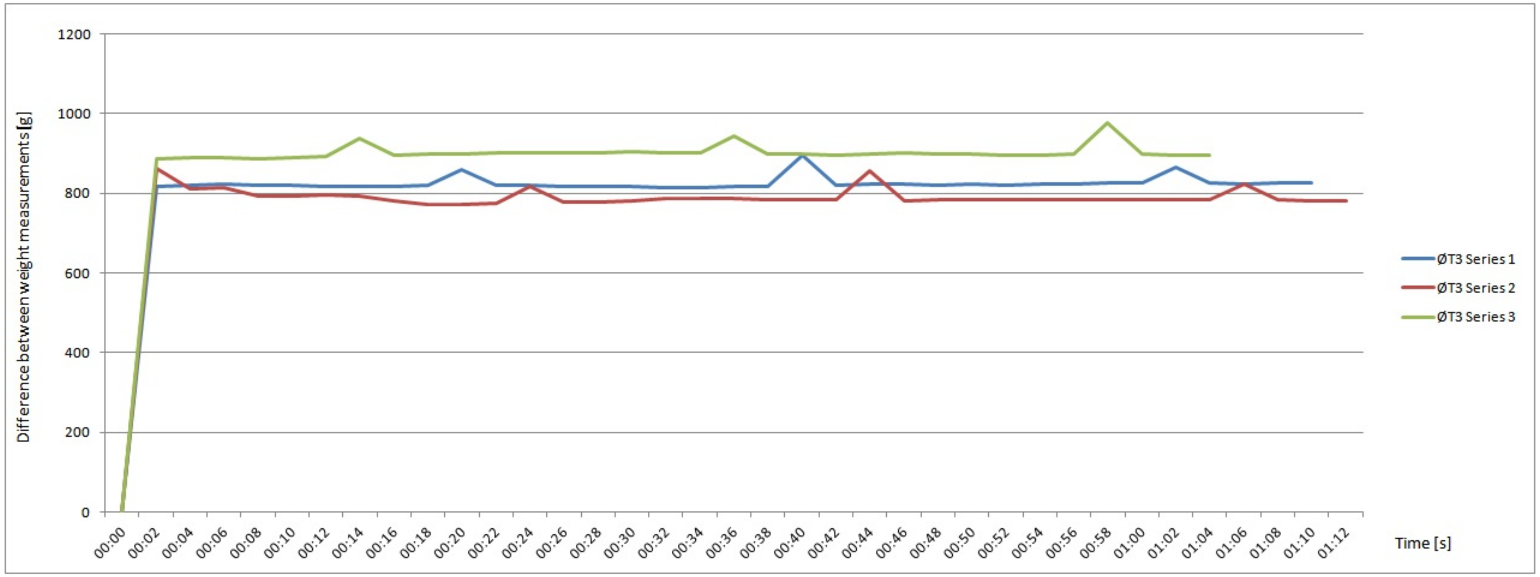
The most linear area of the graphs is averaged and divided by 2 seconds. This forms the basis for the permeability of the concrete samples as grams of water per second shown in table 12. The Average of all three samples from each batch is used to calculate the permeability coefficient K and the percolation rate k in table 13a and table 13b respectively.

(a) ØT1

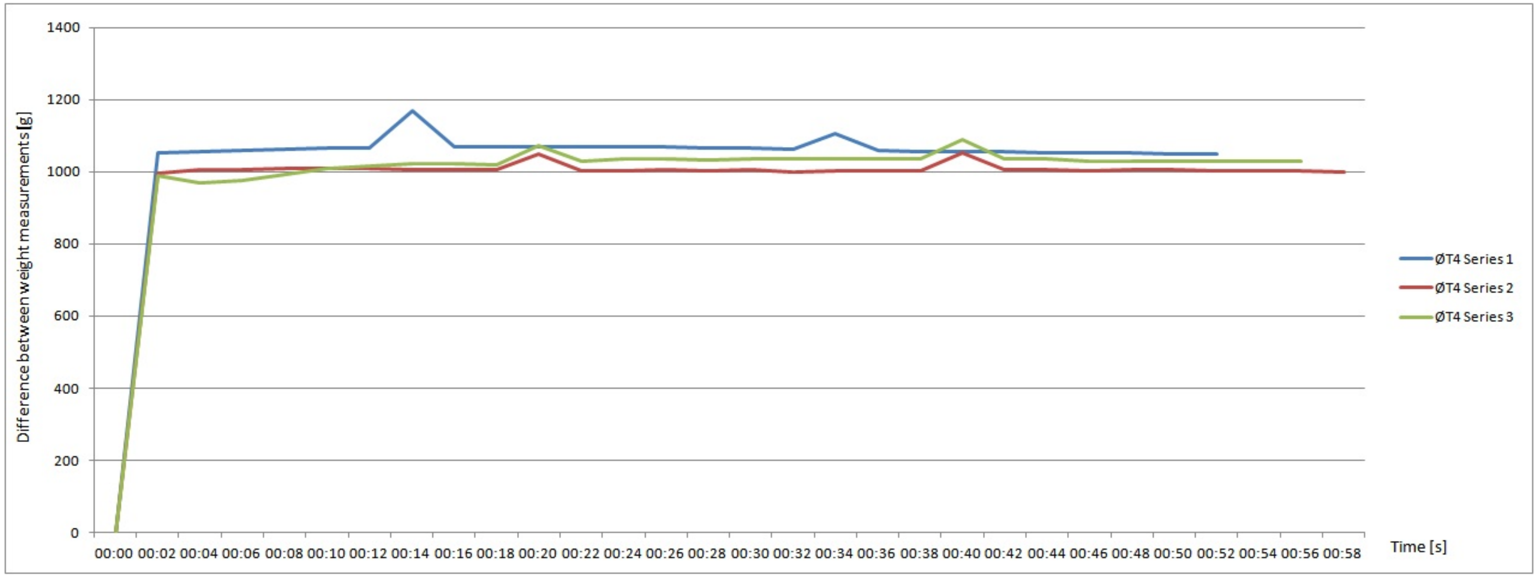


(b) ØT2

Figure 19: Water percolation in test samples ØT1 and ØT2

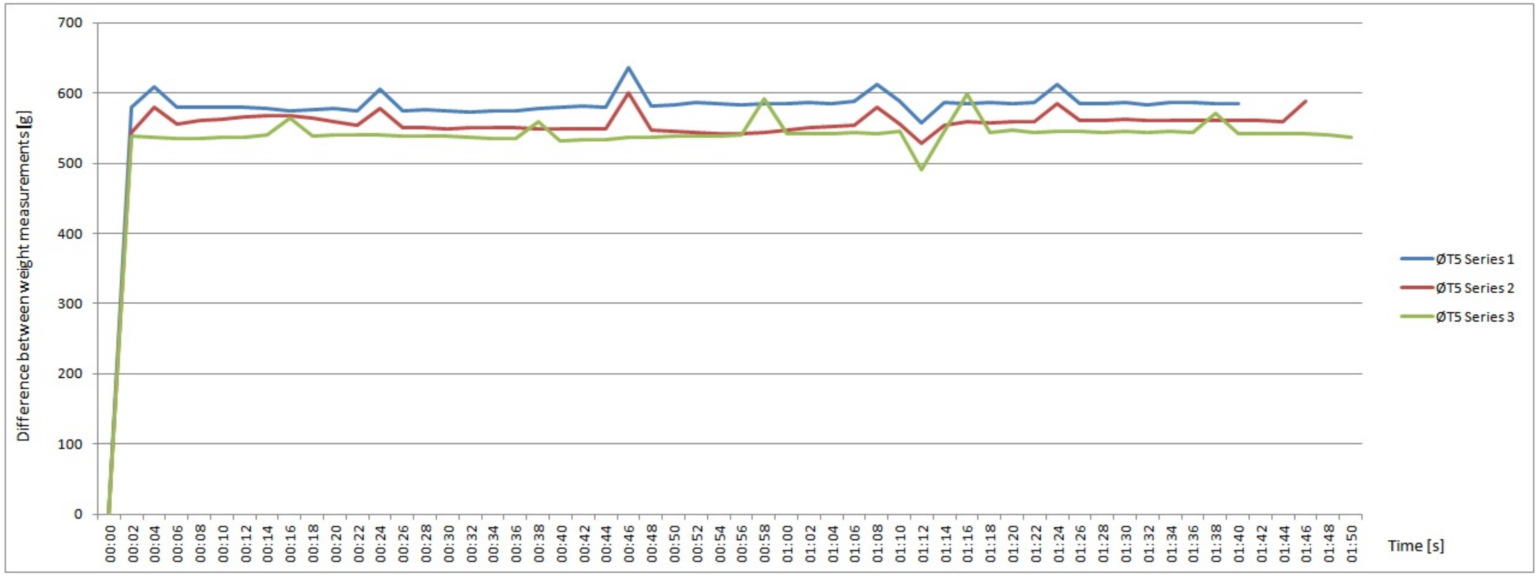


(a) ØT3

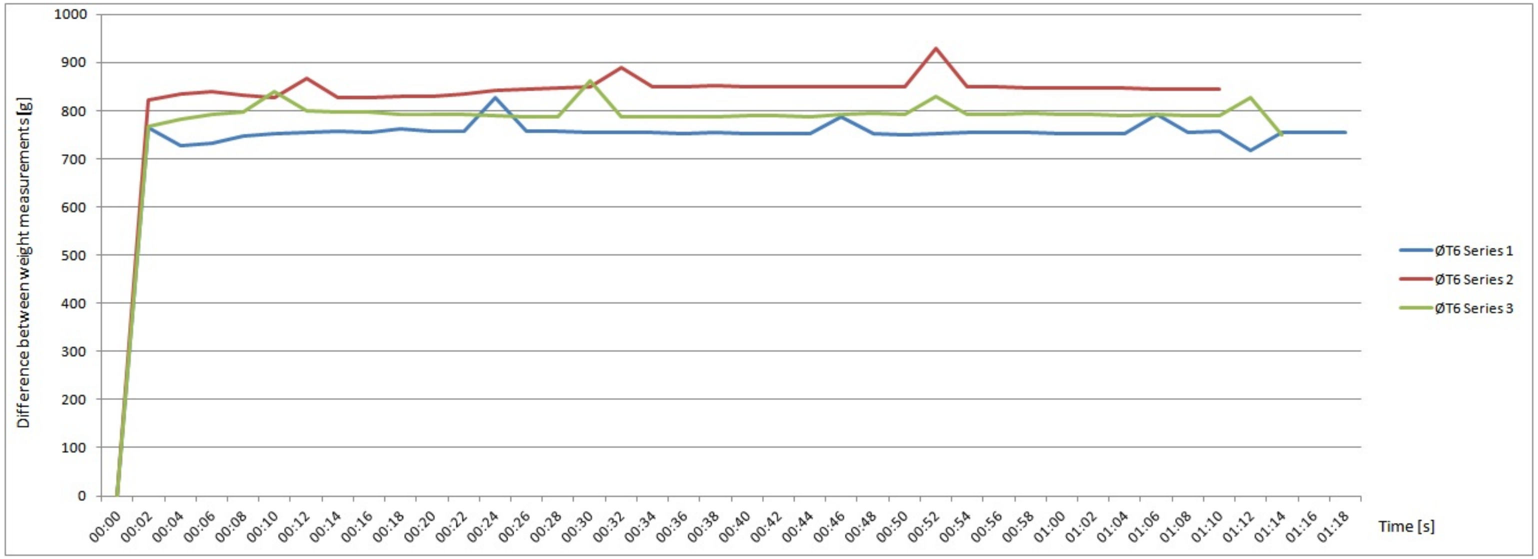


(b) ØT4

Figure 20: Water percolation in test samples ØT3 and ØT4



(a) ØT5



(b) ØT6

Figure 21: Water percolation in test samples ØT5 and ØT6

Batch #	$K = \frac{Q \cdot \mu}{A_c \cdot \Delta P \cdot L}$		
	Min	Max	Mean
ØT1	$1.23 \cdot 10^{-6} m^2$	$1.35 \cdot 10^{-6} m^2$	$1.30 \cdot 10^{-6} m^2$
ØT2	$1.54 \cdot 10^{-6} m^2$	$1.70 \cdot 10^{-6} m^2$	$1.64 \cdot 10^{-6} m^2$
ØT3	$1.36 \cdot 10^{-6} m^2$	$1.54 \cdot 10^{-6} m^2$	$1.44 \cdot 10^{-6} m^2$
ØT4	$1.73 \cdot 10^{-6} m^2$	$1.83 \cdot 10^{-6} m^2$	$1.77 \cdot 10^{-6} m^2$
ØT5	$9.28 \cdot 10^{-7} m^2$	$1.00 \cdot 10^{-6} m^2$	$9.61 \cdot 10^{-7} m^2$
ØT6	$1.29 \cdot 10^{-6} m^2$	$1.45 \cdot 10^{-6} m^2$	$1.37 \cdot 10^{-6} m^2$

(a) Permeability coefficient K

Batch #	$k = \frac{V_c}{A_c}$		
	Min	Max	Mean
ØT1	$4.59 \frac{cm}{s}$	$5.00 \frac{cm}{s}$	$4.84 \frac{cm}{s}$
ØT2	$5.72 \frac{cm}{s}$	$6.32 \frac{cm}{s}$	$6.12 \frac{cm}{s}$
ØT3	$5.04 \frac{cm}{s}$	$5.74 \frac{cm}{s}$	$5.35 \frac{cm}{s}$
ØT4	$6.41 \frac{cm}{s}$	$6.79 \frac{cm}{s}$	$6.58 \frac{cm}{s}$
ØT5	$3.45 \frac{cm}{s}$	$3.72 \frac{cm}{s}$	$3.57 \frac{cm}{s}$
ØT6	$4.81 \frac{cm}{s}$	$5.39 \frac{cm}{s}$	$5.09 \frac{cm}{s}$

(b) Percolation rate k of pervious concrete

Table 13: Permeability results

6.2.3 Volume voids results

The results from the simplified PF method is the weight of three cylinders from each batch in five different saturation situations. These Weights are given in table 14a and 14b. These weights lead to four separate derived volumes that represent the amount of voids, entrapped and entrained air in the concrete. These volumes are given in table 14c.

6.2.4 Compressive strength results

The tests were performed using a testing machine with a scale of kilo ponds to determine the pressure in the hydraulic oil in the machine. The smallest step on the scale was 50 kp, corresponding to roughly 50 kg of pressure, and thus each result was rounded to the nearest 50 kp, before averaging.

Three 10x20 cylinders from each batch was tested for compressive strength. The maximum, minimum and average of the strength's are given.

	ØT1 [kp]	ØT2 [kp]	ØT3 [kp]	ØT4 [kp]	ØT5 [kp]	ØT6 [kp]
Test specimen #1	2550	4600	2800	4300	4500	4300
Test specimen #2	2900	3300	2550	4850	4100	4500
Test specimen #3	2800	2500	2450	5300	4200	4400
Average	2750	3467	2600	4817	4267	4400

(a) Yield-load of all tested concrete specimen

Batch #	28 day compressive strength (MPa)		
	Min	Max	Average
ØT1	3.18	3.62	3.43
ØT2	3.12	5.74	4.33
ØT3	3.06	3.50	3.25
ØT4	5.37	6.62	6.01
ØT5	5.12	5.62	5.33
ØT6	5.37	5.62	5.49

(b) Calculated compressive strength

Table 15: Compressive strength of pervious concrete

Batch #	ØT1			ØT2			ØT3		
Test specimen #	#1	#2	#3	#1	#2	#3	#1	#2	#3
Reference weight W_0[g]	2718.2	2752.8	2716.5	2647.4	2712.8	2606.1	2655.7	2600.5	2666.0
Dried weight W_1[g]	2617.3	2653.0	2616.9	2557.3	2605.6	2519.3	2557.3	2501.7	2552.5
Saturated weight in air W_2[g]	2757.4	2790.8	2753.0	2692.0	2759.6	2649.6	2708.2	2641.2	2710.6
Saturated weight in water W_3[g]	1619.9	1648.5	1627.2	1597.2	1525.2	1574.9	1593.3	1558.0	1583.1
Pressure saturated weight W_4[g]	2772.2	2810.9	2778.8	2710.0	2781.3	2666.3	2729.9	2661.0	2734.6

(a) Weights of concrete cylinders in different saturation states ØT1-ØT3

Batch #	ØT4			ØT5			ØT6		
Test specimen #	#1	#2	#3	#1	#2	#3	#1	#2	#3
Reference weight W_0[g]	2705.5	2789.9	2720.0	2929.0	2929.6	2898.1	2780.3	2888.0	2815.3
Dried weight W_1[g]	2618.0	2697.8	2627.3	2804.6	2810.8	2782.1	2699.8	2794.3	2726.8
Saturated weight in air W_2[g]	2739.4	2821.2	2751.1	2972.8	2969.0	2937.1	2832.7	2933.2	2865.3
Saturated weight in water W_3[g]	1641.8	1689.3	1644.8	1730.5	1743.9	1729.0	1686.8	1739.2	1700.8
Pressure saturated weight W_4[g]	2750.2	2831.4	2760.6	2992.7	2984.8	2950.9	2842.2	2944.3	2875.3

(b) Weights of concrete cylinders in different saturation states ØT4-ØT6

Description	formula	ØT1	ØT2	ØT3	ØT4	ØT5	ØT6
Volume% of passively filled pores	$V_1 = \frac{W_2 - W_1}{\rho_w \cdot V}$	8.79 %	8.89 %	9.52 %	7.82 %	10.22 %	8.71 %
Volume% of solid material in concrete	$V_2 = \frac{W_2 - W_3}{\rho_w \cdot V}$	72.27 %	72.23 %	70.57 %	70.79 %	78.00 %	74.37 %
Volume% of voids in the concrete[a]	$V_3 = 1 - \frac{W_2 - W_3}{\rho_w \cdot V}$	27.73 %	27.77 %	29.43 %	29.21 %	22.00 %	25.63 %
Theoretical void		15 %	15 %	15 %	15 %	10 %	20 %
Volume% of pores filled by external pressure	$V_4 = \frac{W_4 - W_2}{\rho_w \cdot V}$	1.29 %	1.20 %	1.34 %	0.65 %	1.05 %	0.65 %

(c) Calculated averaged volumes

Table 14: Results from simplified PF-method

[a]Excluding pores not passively filled

	Starting weight [g]	Scaling after # cycles [kg/m²]				
		7	14	28	42	56
ØT1C1S	2932.4	8,55	30,13	Crushed[2]	...	...
ØT1C2S	2962.9	1.70	10,91	Crushed	...	...
ØT1C1W	3089.6	0.05	0,09	0,25	0,37	...
ØT2C1S	3074.4	0.45	1,74	Crushed	...	...
ØT2C2S	2944.8	0.52	5,97	Crushed	...	...
ØT2C1W	2886.3	0.08	0,12	0,29	0,38	...
ØT3C1S	2883.1	0.07	0,78	Crushed	...	...
ØT3C2S	2972.3	0.03	0,19	3,71	14,13	...
ØT3C1W	3034.5	0.11	0,15	0,27	0,46	...
ØT1F1S	2970.6	0.04	0,09	0,26	0,61	...
ØT1F2S	3017.2	0.00	0,01	0,10	0,17	...
ØT1F1W	3030.4	0.01	0,03	0,10	0,27	...
ØT2F1S	2961.5	0.00	0,00	0,18	0,44	...
ØT2F2S	2939.1	0.00	0.00	0,04	0,12	...
ØT2F1W	2798.6	0.00	0,00	0,01	0,04	...
ØT3F1S	2975.6	0.00	0,02	0,04	0,05	...
ØT3F2S	2995.8	0.00	0,01	0,06	1,14	...
ØT3F2W	2898.8	0.00	0,02	0,04	0,06	...

Table 16: Results from freeze/thaw experiment

6.2.5 Frost durability results

The scaling from the samples was tested after 14 days or 336 hours after the freeze/thaw cycle began. This was done because this time coincides with 7 days after the remaining cabinet started running properly. The scaling of material from all the samples in cabinet temp 5 were tested at 336, 504, 840, 1176 and 1512 hours in the documentation. This was done because this time coincides with 7, 14, 28, 42 and 56 days after the remaining cabinet started running properly. Granted these specimen has undergone some additional strain due to the one week of variation from approximately -5 to 20 °C but this is probably not to severe considering the gradual incline of the temperature curve in this case, and that the temperature remains above freezing for most of the period.

7 Discussion

The results from the experimental activity is discussed in this section.

7.1 Discussion of mortar results

7.1.1 Sand as a variable

There was a decent spread of results for the given variable variation. The series of M003, M002 and M004 all contained the same amount of air entraining admixture and varied only by the amount of sand in the mortar. It is clear from this series that the increase from no sand to 150 kg/m^3 gave little or no effect on either the density or air content of the mortar. The increase from 150 kg/m^3 to 300 kg/m^3 was however quite noticeable and this suggests that a sand content in the lower part of this area could result in a light binder with high amounts of air-content. It is also apparent that with the increase of sand content it becomes more difficult to obtain a high air content. The highest amount of sand in the mortar leads to the lowest amounts of entrained air in the mixture, but interestingly it also leads to the largest gap between the two testing procedures.

	M003		M002		M004	
Sand content [kg/m^3]	0		150		300	
	Std.mix	Alt.mix	Std.mix	Alt.mix	Std.mix	Alt.mix
Density [kg/m^3]	1287.9	1446.3	1307.9	1487.6	1828.0	1567.7
Air content	29 %	25 %	29 %	25 %	12 %	23 %

Table 17: Series M003, M002 and M004: Sand content as variable

7.1.2 Air entraining agent as a variable

The series M005, M002 and M001 varies only by the amount of air entraining admixture and contains a constant amount of 150 kg/m^3 of sand. This series clearly depicts a trend of increased air-content and decreasing density with increased amounts of air-entraining admixtures. Since this amount of the specific air-entraining agent is so high above the recommended dosage for normal concrete, large variations are to

Figure 22: Erratic air content in M001

	M005		M002		M001	
Sika Aer[% of c]	0.75 %		1.5 %		3.0 %	
	Std.mix	Alt.mix	Std.mix	Alt.mix	Std.mix	Alt.mix
Density [kg/m^3]	1667.0	1522.7	1307.9	1487.6	1105.1	1055.0
Air content	16 %	23 %	29 %	25 %	38 %	40 %

Table 18: Series M005, M002 and M001: Air content as variable

be expected. It is clear that the increase of air-entraining admixture has a huge effect on the density of the mortar. The increase from 0,75 % to 1,5 % nearly doubles the air content in the mortar for the standard mixing procedure where the difference is smaller for the alternate mixing procedure. The highest air-content and lowest density is measured with 3,0 % of the Sika Aer admixture. However, this mortar was noticeably unstable with regards to air content as seen in *figure 22.* This unstable nature could lead to a unpredictable material and was therefore not considered as a viable alternative for use in the final concrete.

7.1.3 Mixing method as variable

The mixing method used to produce the mortars in this experiment clearly impacts the density and air content. Generally the alternate mixing procedure had a stabilizing effect on the air content in the mortar. The alternate mixing procedure had the most effect on M004 and M005 which was also the most dense mixtures. The results from M004 shows a greater tendency to decrease density with increased amounts of sand. Despite actually increasing the density in M002 and M003 the alternate mixing procedure shows that experimenting with the mixing clearly influences the end product. The mixing method seems to have an increasing effect with increasing density of the mixture.

The mortar mixture of M002 and M001 shows the most promise for use as the binder in pervious concrete but due to the unstable nature of the M001 the M002 was chosen to continued development of the concrete binder.

7.2 Discussion of concrete results

7.2.1 Fresh concrete

The most relevant variable to study in the fresh concrete is the difference between the mixing methods. All the batches of concrete shows approximately the same density for similar calculated void spaces but where the alternate mixing procedure decreases the density from ØT1 and ØT2, it increases the density for ØT3 and ØT4. However, these results are so similar that the difference may merely be the product of statistical variation in the material and packing.

7.2.2 Volume voids

It seems that the mixing procedure has not had any significant effect on the void in the concrete. Both the ØT1&2 series and ØT3&4 series has virtually the same measured void space as the other. All the batches have significantly larger measured void than the theoretical 10, 15 or 20 %. This is due to the fact that when the binder surrounds the coarse aggregate in the pervious concrete each grain/stone in the aggregate-binder mix increases in volume. This in turn will increase the amount of space between each stone and thus increasing the void volume as a whole. This is illustrated in *figure 23.*

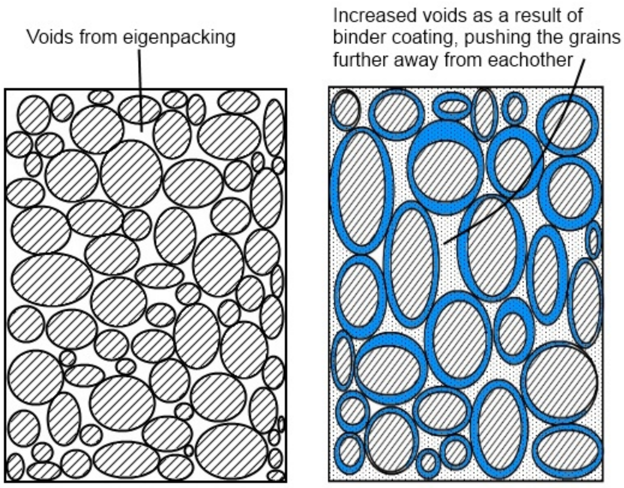


Figure 23: Increasing void space as a result of binder coating

The void volume decreases as expected when considering the ØT5 batch, which contains a theoretical void content of only 10%, but unexpectedly the batch of ØT6 concrete that should contain 20 % voids has been measured as containing less voids than the 15 % comparative series. Since pervious concrete has such a coarse structure and is made in small forms, this discrepancy could be attributed to a different eigen-packing of the coarse concrete leading to a denser structure than the other batches. The volume is still over the theoretical value but not by as much as the other batches.

7.2.3 Permeability

Interestingly, the permeability of the concrete increases in the case of the two batches that are produced using the alternate mixing procedure. It is apparent that mixing the binder for then to stir the coarse aggregate into the mix has influenced the internal void system towards a more open structure. Both series of concrete with varying mixing method(ØT1&2 and ØT3&4) show this tendency. This likely due to the same effect as seen with the increase of volume voids due to the alternate mixing method. All the batches also show a very high degree of permeability and percolation rate compared to results from others. This suggests that the produced concrete in this thesis is overly porous and that the compressive strength will be in the lower part of the comparable spectrum.

It is clear that compared to other sources, the pervious concrete produced in the context of this thesis is very permeable. The percolation rate observed here is considerably higher than most other sources studied, and this has had an effect on the average strength of the material.

7.2.4 Compressive strength

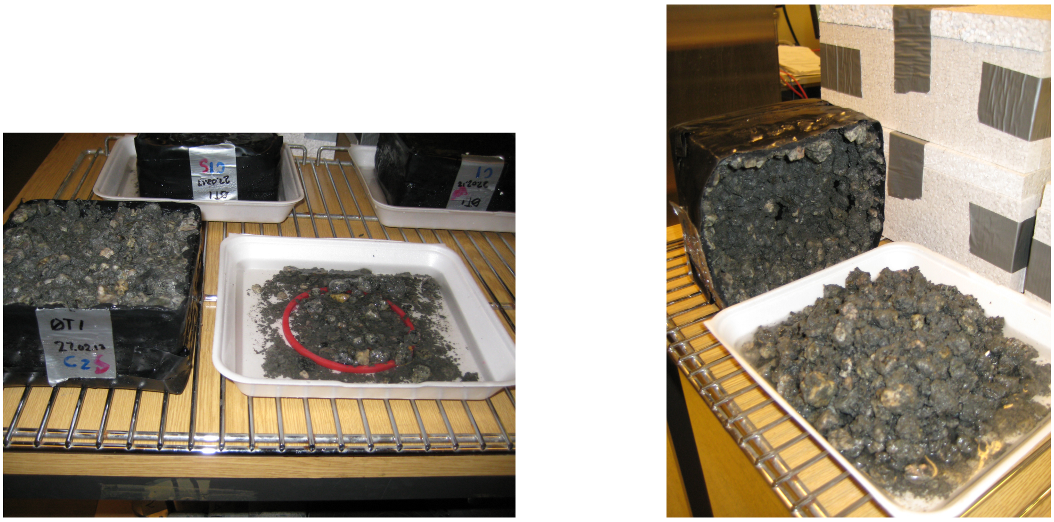
The difference between testing pervious concrete as opposed to conventional concrete comes down to the surface of the materials. The rough edges of pervious concrete makes it more likely to be exposed to local fractures and even endure moments due to eccentricity of the fracture load. It was difficult to determine if the fracture form was acceptable or not since the cylinders split into gravel when destroyed. The testing surface was also noticeably uneven and may have transferred forces away from the center of mass of the surface. It is therefore likely that the strength recorded here is closer to the minimum found for the concrete these geometrical factors would certainly weaken the material. These tests should nonetheless provide a reasonably accurate strength for each of the six batches of concrete.

Figure 24: Uneven test surface

As is the case for permeability, it seems also the strength of the pervious concrete has greatly benefited from the alternate mixing procedure. One series (ØT3&4) has seen an averaged increase of as much as 85% considering only the mixing procedure has changed between the two batches of concrete. Also the other comparative series (ØT1&2) has seen a substantial increase in strength.

7.2.5 Frost durability

The results from the freeze/thaw experiment are erratic at best. There can be found a clear relation between the frost performance and whether or not the concrete is exposed to salt. All cup method specimen that is tested with a 3% salt solution have failed before 28 days of testing except for ØT3C2S. The scaling of this specimen is however also very high although performing better than the others. Also the degree of saturation obviously has a huge effect on the durability of the frost samples as the cup method samples that have been exposed to salt have all performed at unacceptable levels when the flow method samples exposed to salt are much more resistant to frost.



(a) Deteriorating specimen

(b) "Crushed" specimen

Figure 25: Deterioration of frost specimen

Even though it is hard to predict how much the concrete has been deteriorated in that first week of little temperature variation, the results clearly indicates that these batches of concrete are not sufficiently resistant to frost when it comes to traffic applications where road salts are sure to be in use. The huge difference seen between the two different testing methods is also quite pronounced. In every exposure form the cup method samples have been further deteriorated than their flow method counterparts. As discussed earlier, the cup method serves as the method most similar to the standardized case while the flow method serves as a more realistic approach to the exposure the concrete would endure in the field but with less re-saturation than is likely to occur. They are therefore arguably the worst and best case scenario in a field application. The true performance of the concrete in the field is then likely somewhere between these two cases.

8 Conclusion

Studies in the field of pervious concrete has identified the most important factors to the performance of water permeable concrete. Void & sand content in addition to a binder with relatively low w/c-ratio and stable air entraining is highly important for producing a satisfactory pervious concrete. A good batch design is not enough to ensure good performance however. Experimental and professional work has shown that the placing and compacting of pervious concrete is of even greater importance than for normal Portland cement concrete. Compacting of the material by an experienced contractor can be just as important as the batch design.

Experimentation with the binder/mortars has suggested that the mixing method of the binder, and as a result the concrete, has great importance for the properties of fresh mortars. It has also shown that increasing the amount of air entraining agent without adding a stabilizing factor leads to erratic behavior of the fresh concrete. Sand content in the binder leads to higher densities and thus lower air content, but it also increases the effect the mixing procedure has on the binder mix.

Results have shown that a pervious concrete can definitely be produced using the normal aggregates and admixtures that are readily available in Norway. The produced concrete is in the higher range of permeability compared to other sources and understandably in the lower part of compressive strength. Strength decreases with increased void content while permeability increases while the permeability of the concrete increased slightly in the case of the batches without sand.

The mixing method of the pervious concrete has had a profound effect on several factors such as permeability, percolation rate and strength. Alternating the mixing method has had a positive effect on every considered factor in the hardened concrete except for the fresh concrete which remained largely unchanged. This warrants further study to optimize the method of which pervious concrete is mixed and examine the effect on the material.

The results suggest that the pervious concrete produced in this thesis cannot withstand the frost deterioration associated with road applications. However, some concerns have been raised as to the testing methods applied are to harsh compared to the real-life exposure a correctly placed concrete slab would have to endure. A full size field study of pervious concrete should be performed and compared to the freeze/thaw results of these methods to investigate the validity of the testing method.

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Appendix

A Material documentation

Construction

SikaAer® -S

Luftinnførende tilsetningsstoff for betong og mørtel

Produktbeskrivelse	SikaAer®-S er et luftinnførende tilsetningsstoff basert på syntetisk tensider. SikaAer® -S danner et finfordelt luftporesystem i betongens sementpasta. Luftporene fungerer som ekspansjonskammer når fukten/vannet i den herdnede betongen utvider seg ved frysing. Luftporene vil også gjøre betongen mer lettarbeidelig og smidig.
Anvendelsesområder	SikaAer®-S anvendes i betong for å øke frostbestandigheten i konstruksjoner som er utsatt for frysing/tining i nedfuktet tilstand. SikaAer®-S kan også anvendes for å forbedre betongens støpelighet eller betongens stabilitet og dermed redusere faren for bleeding og separasjon.
Produktegenskaper	SikaAer® -S forbedrer betongens egenskaper som følger: ■ Forbedret bearbeidelighet ■ Økt frostbestandighet ■ Økt vanntetthet ■ Gir mulighet for å styre luftinnføring i betong. ■ Gir stabilt luftinnhold i betong, også egnet til betong med flyveaske eller flyveaskesement ■ God stabilitet i varmbetong.

Produktdata

Tekniske data

■ **Type:**	Væske på basis av syntetisk tensider
■ **Farge:**	Gul
■ **Densitet:**	1,02 ± 0,01 kg/l
■ **Viskositet:**	Lettflytende
■ **Tørrstoff:**	9,0 ± 1 %
■ **pH:**	7 ± 1 %
■ **Kloridinnhold (Cl-):**	< 0,10 % (vekt)
■ **Alkaliinnhold (Na2O ekv.):**	< 0,10 % (vekt)
■ **Normaldosering:**	0,01 – 0,08 % av sementvekt

For å oppnå mer nøyaktig dosering anbefales at SikaAer®-S fortynnes med vann for eksempel i forholdene 1:9, 1:19 eller lignende avhengig av doseringsbehov og vektkapasitet. Tilsett først vannet, deretter SikaAer®-S (konsentrat).

Nødvendig dosering for å oppnå spesifisert luftinnhold avhenger av sementtype, blandertype, tilslagets gradering, innholdet av fint materiale (< 0,25 millimeter), betongens konsistens og temperatur, Innenfor temperaturområdet +10 °C - +30 °C avtar effekten noe med økende temperatur. For optimal dosering anbefales forforsøk.

Doseringstidspunkt

SikaAer®-S tilsettes sammen med blandevannet.
SikaAer®-S kan også tilsettes i automikser. Beregn minimum 5 minutter blandetid på full hastighet.

Kombinasjoner	SikaAer®-S kan kombineres med andre produkter fra Sika som følger: ■ Plastiment® BV-40 ■ SP-stoff i Sikament eller ViscoCrete-serien ■ Sika Stabilizer ■ Sika® Pump ■ Sika® Rapid 2 og 3 ■ Sika® Retarder ■ Sika® Ferrogard 901
Bivirkninger	Overdosering reduseres betongens trykkfasthet.
Godkjenninger	SikaAer®-S er omfattet av samsvarserklæring 1257-CPD-701 og er CE-merket som angitt nedenfor. SikaAer®-S er tildelt miljømerket EQ-Seal av den Europeiske tilsetnings-stofforeningen EFCA. Miljømerket tildeles produkter som ikke har negative effekter på menneske og miljø.

CE

1274

Sika Sverige AB
Veddestavägen 18-20
S-175 06 Järfälla, Sverige

04

1274-CPD-701

Sika Aer-S

Luftinnførende
tilsetningsstoff for betong
EN 934-2:2001: T5

Maks. kloridinnhold: < 0,1 %
Maks. alkali-innhold: < 0,1 % Na_2O-ekv.

Produktet er merket IRRITERENDE,
se tilhørende HMS-datablad

Emballasje	SikaAer®-S leveres i kanner à 5, 10 og 25 liter, fat à 200 liter, container à 1000 liter eller med tankbil.
Oppbevaring, holdbarhet og avfallshåndtering	Ved frostfri lagring i uåpnet emballasje, er holdbarheten min. 9 måneder fra produksjonsdato. Produktet er ikke klassifisert som spesialavfall. For avfallshåndtering, se tilhørende HMS-datablad. Sika Norge AS er med på Materialreturordningen, og betaler gebyr for all produkt- og forsendelsesemballasje. Vi anbefaler at all tomemballasje leveres til gjenvinning.
Helse, Miljø og Sikkerhet	Se tilhørende HMS-datablad.
	Produktet er produsert i en bedrift som er sertifisert i henhold til ISO 9001:2000 og ISO 14001. Ønskes ytterligere opplysninger, står våre konsulenter samt vår kundeservice til din disposisjon. Forespørsel om HMS-datablad kan rettes til vår HMS-ansvarlig, eller gå inn på våre internettsider: www.sika.no

Produktansvar

Denne informasjonen og i særdeleshet anbefalingene i forbindelse med anvendelse av Sika-produkter er gitt i god tro, basert på Sikas inneværende kunnskap og erfaring med produktene når de er riktig lagret, behandlet og anvendt under normale forhold.

I praksis vil forskjellene i materialer, underlag og lokale forhold være av en slik karakter at verken denne informasjonen, andre skriftlige anbefalinger eller noen annen form for råd kan innebære noen garanti med hensyn til det bearbeidede produktets omsetnings-potensial eller egnethet for et bestemt formål, ei heller noen annen form for juridisk ansvar.

Tredjeparts eiendomsrett må respekteres.

Enhver ordre aksepteres i henhold til Sikas gjeldende salgs- og leveringsbetingelser. Brukere skal alltid forholde seg til sist oppdaterte versjon av produktdatablad og HMS-datablad for det aktuelle produktet. Kopier av gjeldende versjoner finnes på Sika Norges internettsider: www.sika.no.

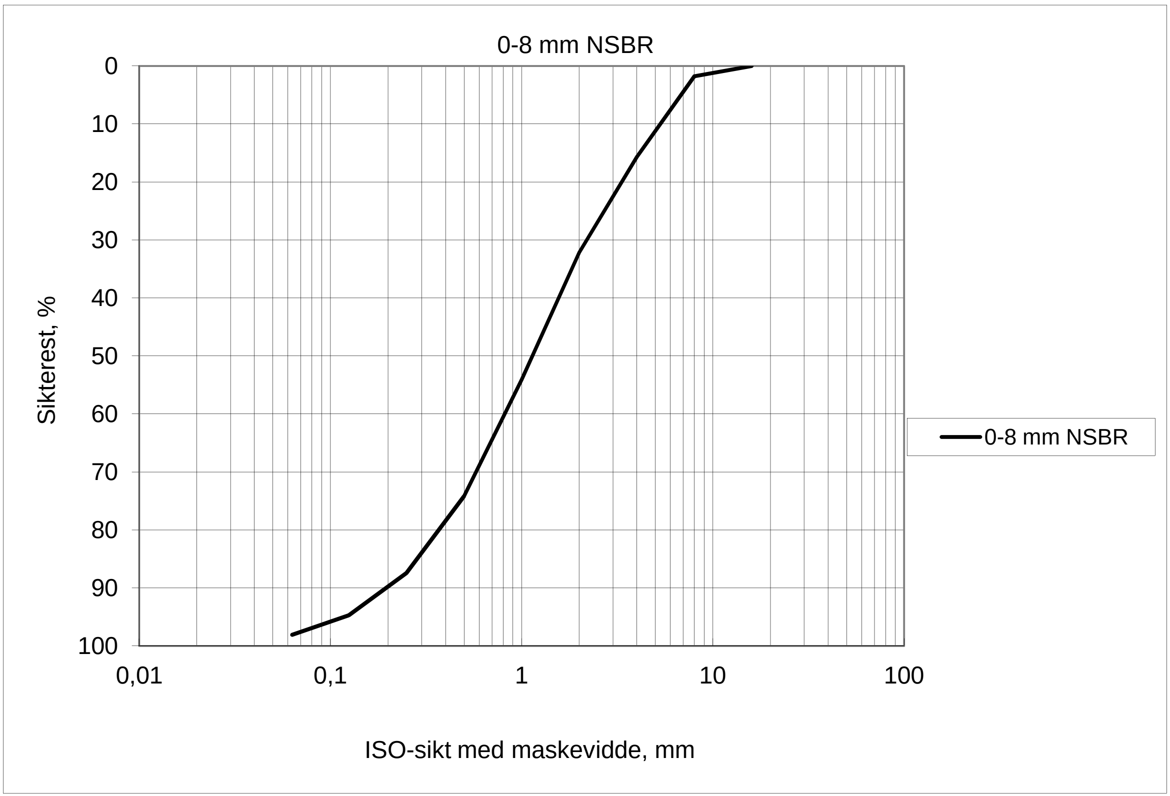
Sika Norge AS
Industriveien 22
Postboks 76
1483 SKYTTA
Norge

Tel. 67 06 79 00
Fax 67 06 15 12
www.sika.no

Laboratorietilslag
NorStone Årdal
Ankom Mars 2011
A-3714

TILSLAGSGRADERING

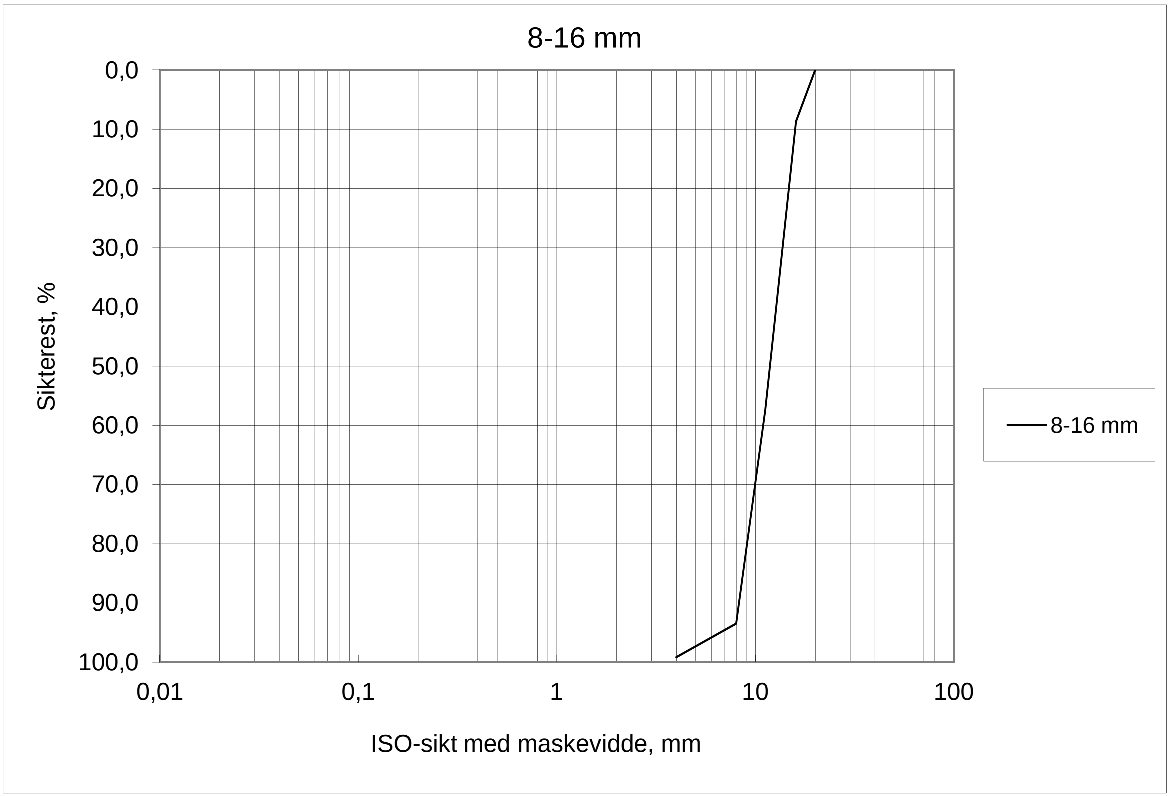
Vårt merke	Sikterest i % på sikt maskevidde, mm										
	0,063	0,125	0,25	0,5	1	2	4	8	16	32	
0-8 mm NSBR	98,1	94,7	87,4	74,2	54,1	32,2	15,7	1,8	0		



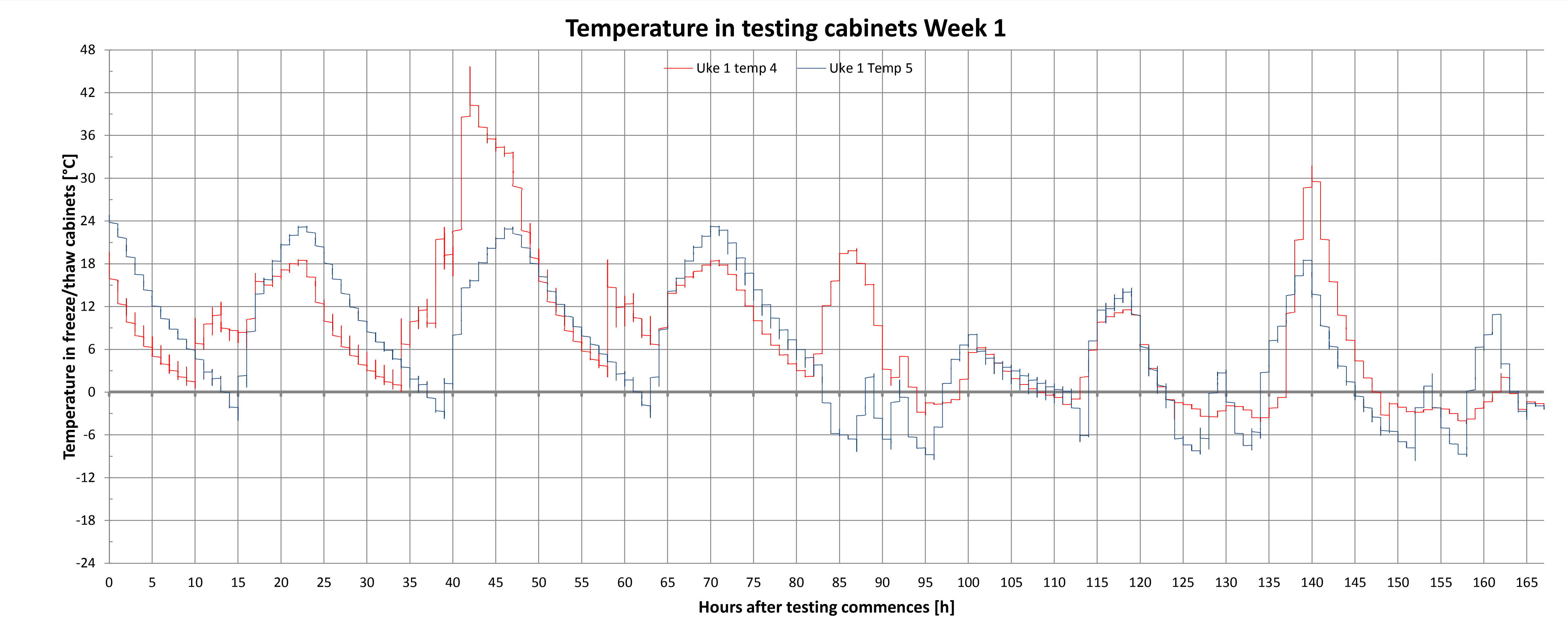
Laboratorietilslag
NorStone Årdal
Ankom Mars 2011
A-3714

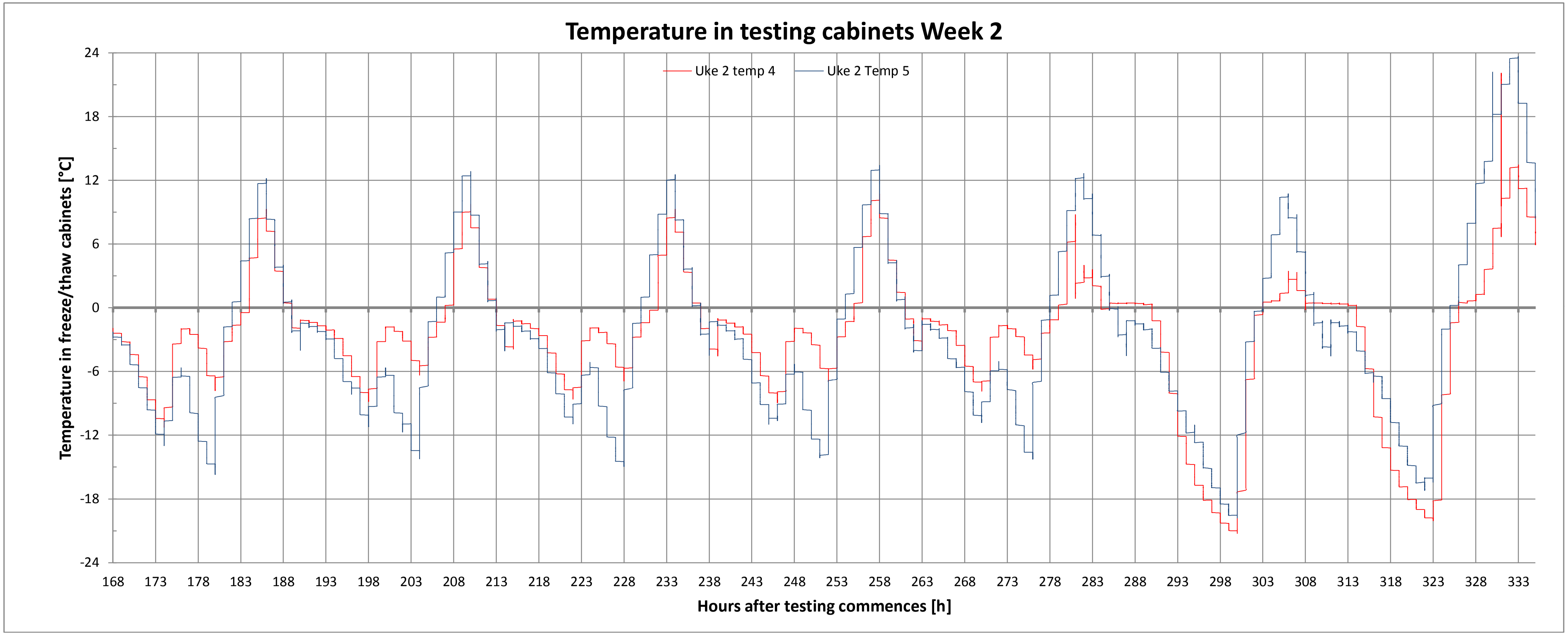
TILSLAGSGRADERING

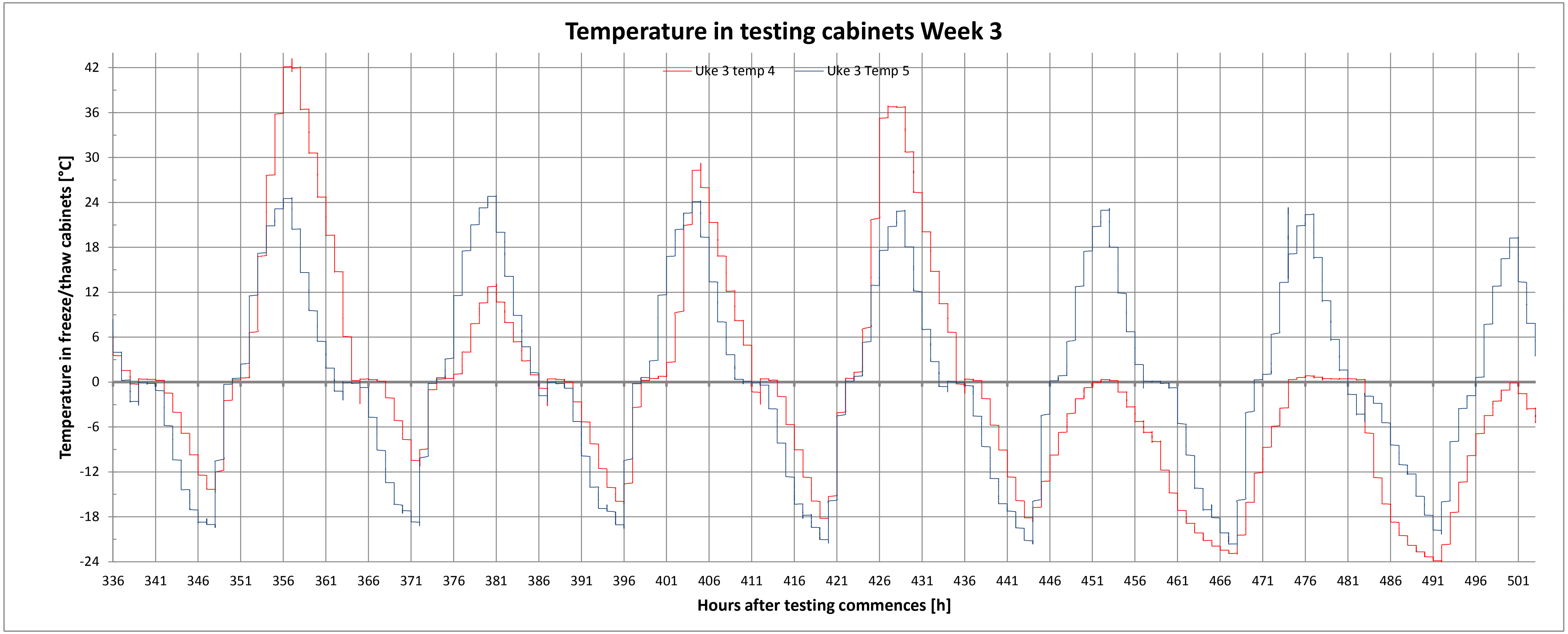
Vårt merke	Sikterest i % på sikt maskevidde, mm										
	0,063	0,125	0,25	0,5	1	2	4	8	11,2	16	20
8-16 mm							99,2	93,5	57,4	8,7	0

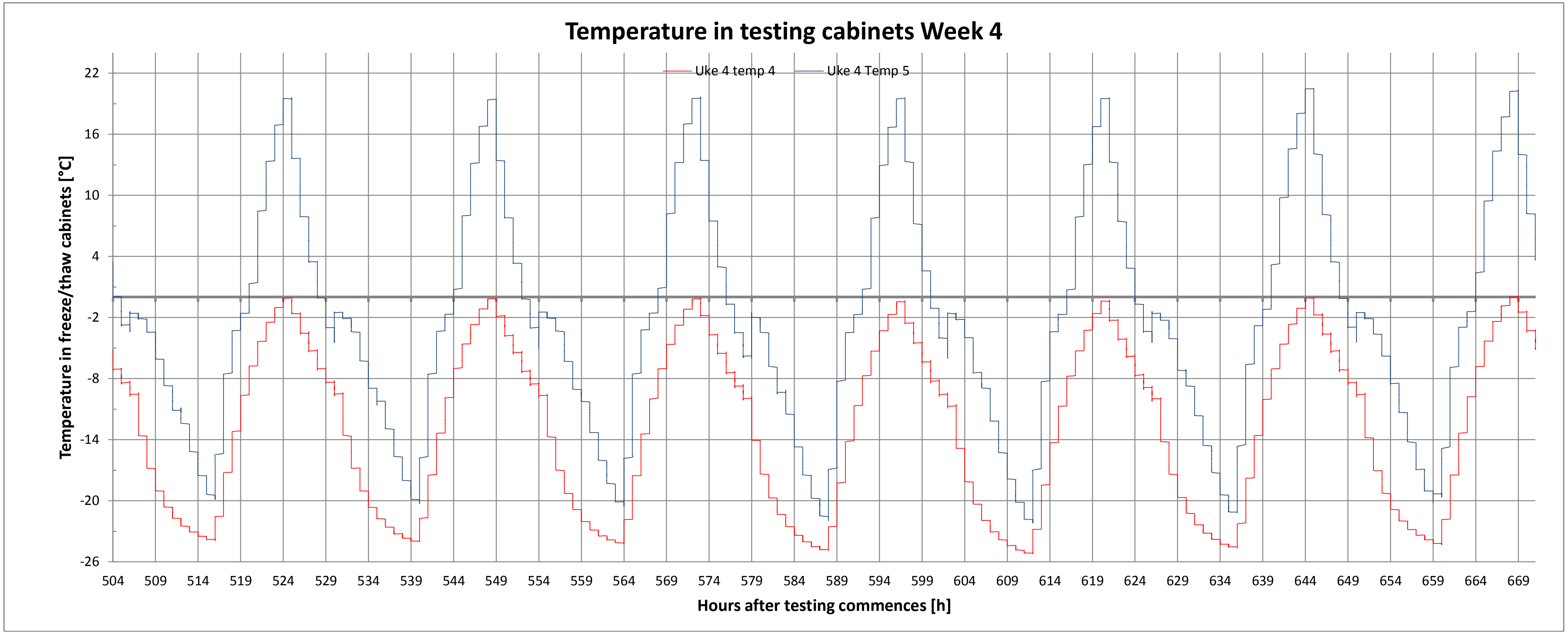


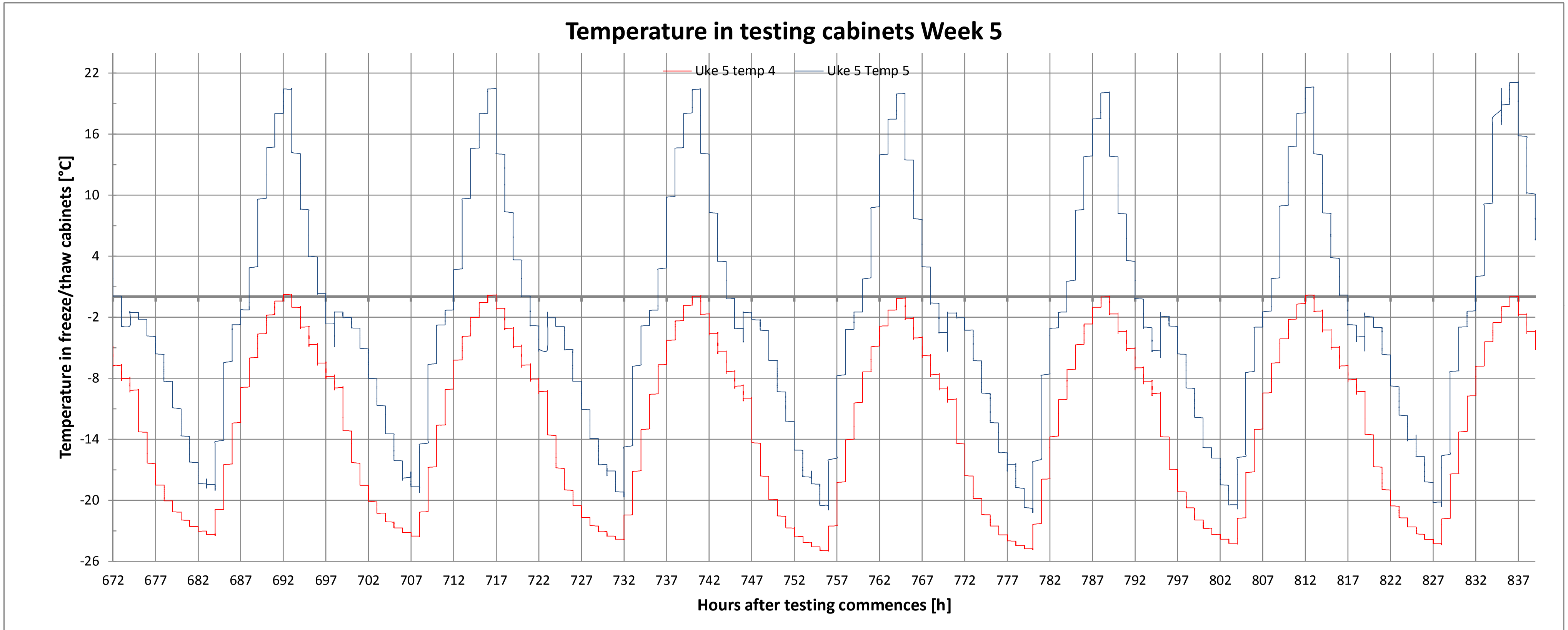
B Freeze/Thaw temperature cycles

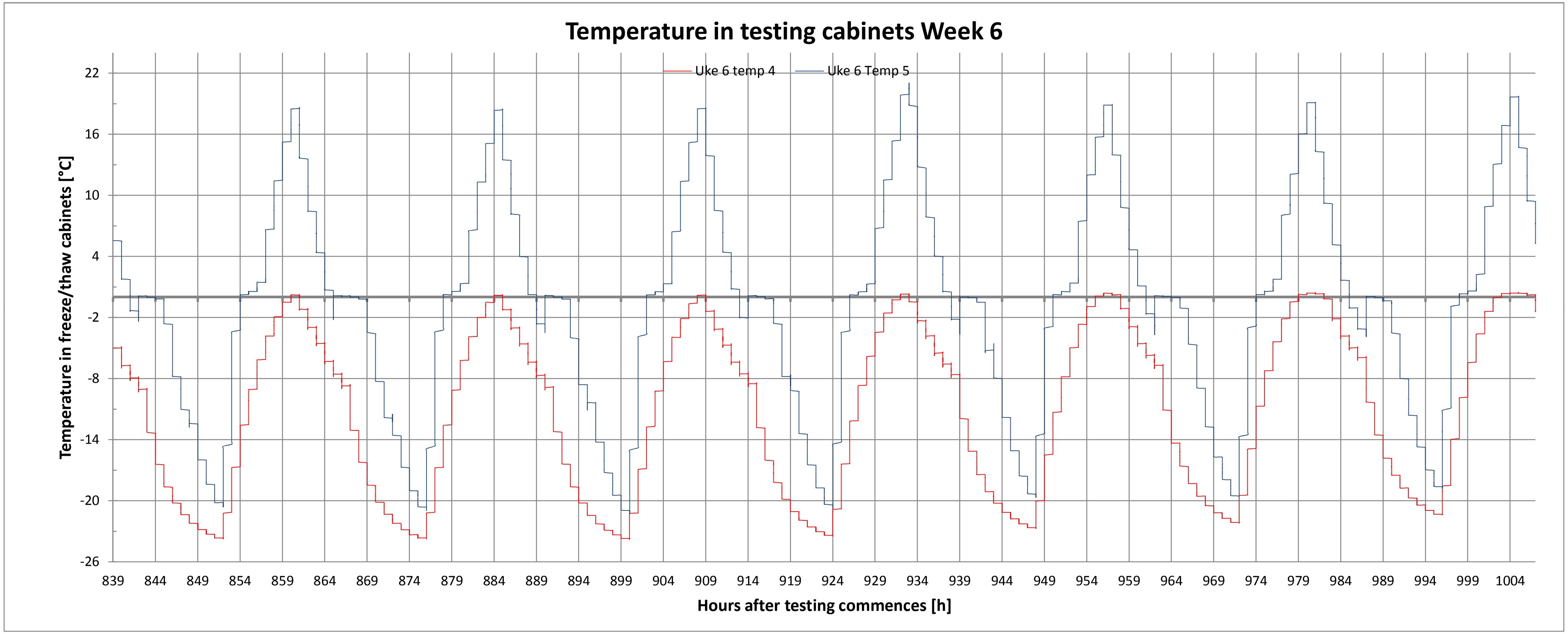

Temperature in testing cabinets Week 1
Uke 1 temp 4
Uke 1 Temp 5
48
42
36
30
24
18
12
6
0
-6
-12
-18
-24
Temperature in freeze/thaw cabinets [°C]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
Hours after testing commences [h]

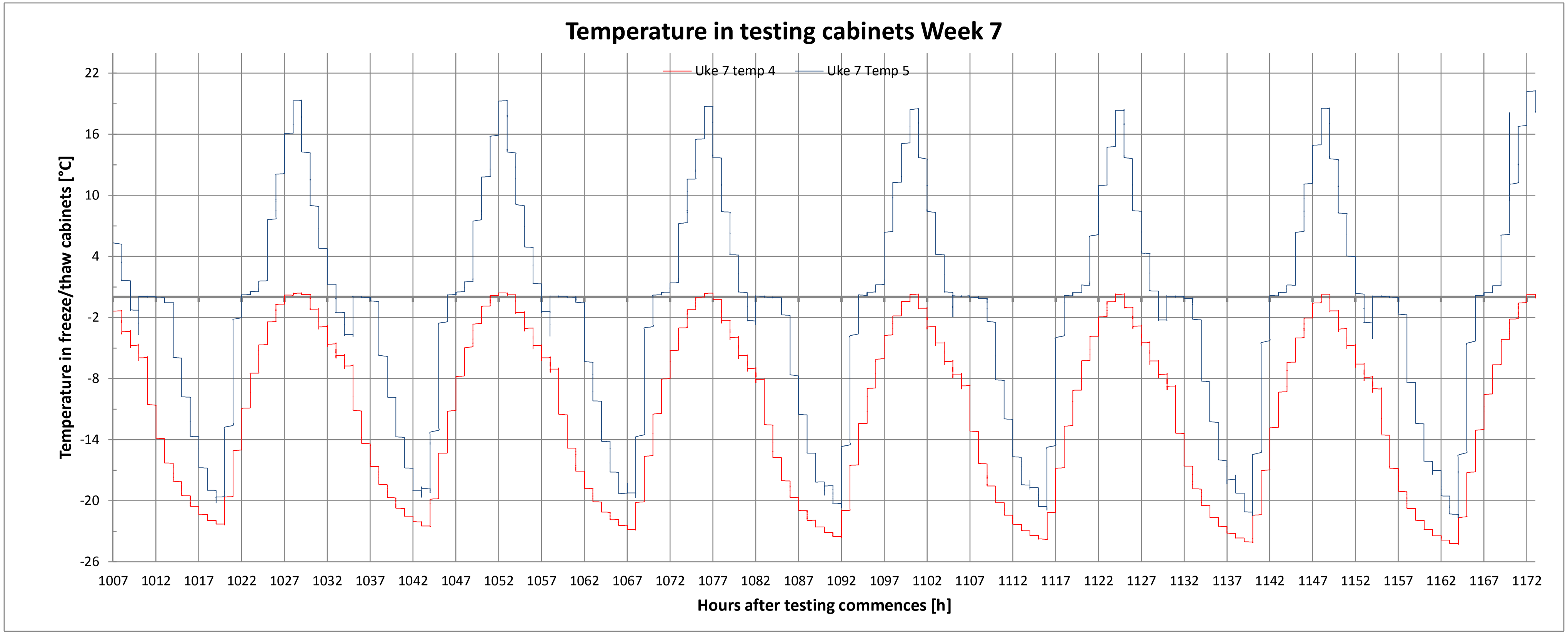

Temperature in testing cabinets Week 2
Uke 2 temp 4
Uke 2 Temp 5
24
18
12
6
0
-6
-12
-18
-24
Temperature in freeze/thaw cabinets [°C]
168
173
178
183
188
193
198
203
208
213
218
223
228
233
238
243
248
253
258
263
268
273
278
283
288
293
298
303
308
313
318
323
328
333
Hours after testing commences [h]


Temperature in testing cabinets Week 3
Uke 3 temp 4
Uke 3 Temp 5
Temperature in freeze/thaw cabinets [°C]
42
36
30
24
18
12
6
0
-6
-12
-18
-24
336
341
346
351
356
361
366
371
376
381
386
391
396
401
406
411
416
421
426
431
436
441
446
451
456
461
466
471
476
481
486
491
496
501
Hours after testing commences [h]


Temperature in testing cabinets Week 4
Uke 4 temp 4
Uke 4 Temp 5
Temperature in freeze/thaw cabinets [°C]
22
16
10
4
-2
-8
-14
-20
-26
504
509
514
519
524
529
534
539
544
549
554
559
564
569
574
579
584
589
594
599
604
609
614
619
624
629
634
639
644
649
654
659
664
669
Hours after testing commences [h]


Temperature in testing cabinets Week 5
Uke 5 temp 4
Uke 5 Temp 5
Temperature in freeze/thaw cabinets [°C]
22
16
10
4
-2
-8
-14
-20
-26
672
677
682
687
692
697
702
707
712
717
722
727
732
737
742
747
752
757
762
767
772
777
782
787
792
797
802
807
812
817
822
827
832
837
Hours after testing commences [h]


Temperature in testing cabinets Week 6
Uke 6 temp 4
Uke 6 Temp 5
Temperature in freeze/thaw cabinets [°C]
22
16
10
4
-2
-8
-14
-20
-26
839
844
849
854
859
864
869
874
879
884
889
894
899
904
909
914
919
924
929
934
939
944
949
954
959
964
969
974
979
984
989
994
999
1004
Hours after testing commences [h]



Temperature in testing cabinets Week 7
Uke 7 temp 4
Uke 7 Temp 5
22
16
10
4
-2
-8
-14
-20
-26
Temperature in freeze/thaw cabinets [°C]
1007 1012 1017 1022 1027 1032 1037 1042 1047 1052 1057 1062 1067 1072 1077 1082 1087 1092 1097 1102 1107 1112 1117 1122 1127 1132 1137 1142 1147 1152 1157 1162 1167 1172
Hours after testing commences [h]

C Construction of frost specimen

Construction

Sikaflex®-11 FC+

1-komponent elastisk fugemasse og lim

Produkt-beskrivelse	Sikaflex®-11 FC+ er en 1-komponent, fuktighetsherdende, elastisk fugemasse og lim basert på polyuretan. Anvendelig for innendørs og utendørs bruk.
Bruksområder	Sikaflex®-11 FC+ er både en fugemasse og et lim, og har derfor mange bruksområder: ■ Sikaflex®-11 FC+ kan brukes som en *fugemasse* for vertikale og horisontale fuger, som lydtetting ved rørgjennomføringer og ventilasjonssystemer. Fuging av skillevegger, fuging i metall og trekonstruksjoner etc. ■ Sikaflex®-11 FC+ kan brukes som et *universallim.* Det egner seg for innendørs og utendørs liming av vindusomramninger, terskler, trappetrinn, fotlister, forskalingsbord, prefabrikerte elementer og en rekke andre bruksområder.
Produktegenskaper	*Sikaflex®-11 FC+ er:* ■ 1-komponent, klar til bruk ■ Fleksibel og elastisk ■ Løsemiddelfri og luktfri ■ Meget lav emisjon *Fugemasse:* ■ Herder uten bobler ■ Meget god vedheft til de fleste bygningsmaterialer ■ Høy mekanisk motstandsdyktighet ■ God vær- og aldringsbestandighet ■ Ingen sig *Lim:* ■ Ikke korrosiv ■ Absorberer støt og vibrasjoner
Godkjenning / Standard	EMICODE EC 1 PLUS "meget lav emisjon". ISEGA sertifikat for bruk i områder med matvarer.

Produktdata

Form

Farger	Hvit, grå, brun, sort
Emballasje	300 ml patroner 600 ml poser

Lagring

Oppbevaring / holdbarhet	15 måneder fra produksjonsdato, oppbevart i original og uåpnet emballasje, i tørre omgivelser, beskyttet mot direkte sollys og ved temperatur mellom +10 °C og +25 °C.

Tekniske data

Kjemisk base	1-komponent polyuretan, herder ved luftens fuktighet
Egenvekt	~ 1,35 kg/l
Skinndannelse	~ 65 minutter (+23 °C / 50 % r.f.)
Herdehastighet	~ 3,5 mm / 24t (+23 °C / 50 % r.f.)
Fugedimensjonering	Min. bredde = 10 mm / maks bredde = 35 mm
Sigehastighet	0 mm, meget god
Temperaturbestandighet	-40 °C til +80 °C

Mekaniske / Fysiske Egenskaper

Strekkfasthet	~ 1,5 N/mm^2
Rivefasthet	~ 8 N/mm^2
Hardhet Shore A	~ 37 etter 28 dager (+23 °C / 50 % r.f.)
E-modul	~ 0,6 N/mm^2 etter 28 dager (+23 °C / 50 % r.f.)
Forlengelse ved brudd	~ 700 % etter 28 dager (+23 °C / 50 % r.f.)
Elastisk tilbakegang	> 80 % etter 28 dager (+23 °C / 50 % r.f.)

Bestandighet

Kjemisk bestandighet	Bestandig mot vann, sjøvann, fortynnede alkalier, sementmørtel og vaskemidler løst i vann. Ikke bestandig mot alkoholer, organiske syrer, konsentrerte alkalier og konsentrerte syrer, klorinerte og aromatiske hydrokarboner.

System-informasjon

Bruksdetaljer

Forbruk / Fugedesign

Fuger:
Fugens bredde må dimensjoneres for å passe bevegelseskapasiteten til fugemassen. Generelt må fugebredden være > 10 mm og < 35 mm.
Et bredde / dybde forhold på ~ 1 : 0,8 (for gulvfuger) og ~ 1 : 2 (for fasade fuger) skal etterfølges.

Alle fuger må designes og dimensjoneres grundig av konsulent / beskrivende ledd og hovedentreprenør. Dette må gjøres iht. gjeldende standarder da endringer og tilpasninger oftest ikke er gjennomførbare på en tilfredsstillende måte etter at byggearbeidene er avsluttet. Grunnlaget for beregning av nødvendig fugebredde er tekniske data for fugemassen, de tilstøtende bygningsmaterialene, bygningens eksponering, byggemetode og dimensjoner.

Fuger < 10 mm er kun for risskontroll og dermed ikke bevegelsesfuger. Den relevante bredden er den fugen har ved påføring (verdi ved +10 °C).

Omtrentlig forbruk (for gulvfuger)

Fugebredde	10 mm	15 mm	20 mm	25 mm	30 mm
Fuge dybde	10 mm	12 - 15 mm	17 mm	20 mm	25 mm
Fugelengde / 600 ml	~ 6,0 m	~ 2,5 – 3,0 m	~ 1,8 m	~ 1,2 m	~ 0,8 m
Fugelengde / 300 ml	~ 3,0 m	~ 1,5 m	~ 0,9 m	~ 0,6 m	~ 0,4 m

Minimum fugebredde for forbindelsesfuger rundt vinduer: 10 mm.

Bunnfylling: Bruk kun bunnfyllingslist av polyetylenskum med lukkede celler.

Liming:

- Punktliming:
  1 patron til 100 x 3 cm punkter av Sikaflex®-11 FC+
  (Diameter = 3 cm; tykkelse = 0,4 cm)
- Stripeliming:
  1 patron til 12 meter Sikaflex®-11 FC+ med en triangelform på 5 x 5 mm.
  I gjennomsnitt 0,2 – 0,6 kg/m^2 avhengig av underlaget.

Underlagets beskaffenhet

Rent og tørt, homogent, fritt for olje og fett, støv og løse eller skjøre partikler. Sementslam og maling som ikke er kompatibel med fugemassen må fjernes.

Forbehandling av underlaget / Priming

Sikaflex®-11 FC+ har generelt sterk heft til de fleste rene og hele overflater. Primer og rensevæske må brukes for optimal heft og ved kritisk bruk med høye påkjenninger som i høyhus, limforbindelser med store påkjenninger eller i tilfeller med ekstrem værpåkjenning. Dersom det er tvil, påfør produktet på et testområde først.

Ikke porøse underlag:
Glaserte fliser, pulverlakkerte metaller, aluminium, eloksert aluminium, rustfritt stål og galvanisert stål må renses med en fin slipesvamp og Sika® Aktivator-205 på en ren klut. Tørketiden er minimum 15 min - maks 6 timer.

Alle andre metallflater som ikke er nevnt ovenfor må renses med en fin slipesvamp og Sika® Aktivator-205 på en ren klut. Etter en tørketid på minimum 15 min, påføres Sika® Primer-3 N med en pensel.
Fugingen kan starte etter en ventetid på min. 30 min. (maks 8 timer).

På PVC brukes Sika® Primer-215 i stedet for Sika® Primer-3 N. Fugingen kan starte etter en ventetid på min. 30 min. (maks 8 timer).

Porøse underlag:
Betong, lettbetong og sementbaserte pussemørtler, mørtler, tegl etc. må primes med Sika® Primer-3 N som påføres med en pensel.
Fugingen kan starte etter en ventetid på min. 30 min. (maks 8 timer).

Viktig:
Primere virker kun vedheftsforbedrende. De vil aldri erstatte riktig rengjøring av overflaten og de vil heller aldri forbedre underlagets styrke signifikant.

Primere forbedrer fugens langtidsegenskaper. For ytterligere informasjon se Sika® Primer tabell.

Påføringsforhold / Begrensninger

Overflatetemperatur	+5 °C min. / +40 °C maks
Omgivelsestemperatur	+5 °C min. / +40 °C maks
Overflatefuktighet	Tørr
Duggpunkt	Overflatetemperaturen må være 3 °C over duggpunktet.

Påførings-instruksjoner

Påføringsmetode / Verktøy	Sikaflex® -11 FC+ leveres klar til bruk. Etter at fugen og overflaten er rengjort og klar, legges Sika®-Bunnfyllingslist i foreskrevet dybde og om nødvendig påføres primer. Legg patron/pose i fugepistolen og påfør Sikaflex® -11 FC+ jevnt inn i fugen. Fugemassen må være fullstendig i kontakt med overflatene. Fyll fugen og unngå luftbobler. Sikaflex® -11 FC+ bearbeides med en fugepinne slik at fullstendig kontakt og god vedheft oppnås. Maskeringstape kan brukes der en skarp og nøyaktig kant er ønsket. Fjern tapen mens fugemassen er bløt. Glatt fugen med glattevæske for å oppnå en perfekt overflate. Liming: Etter at underlaget er ferdigbehandlet påføres Sikaflex®-11 FC+ i striper eller klatter på limflaten med noen få centimeters avstand. Press delene sammen for hånd og juster. Dersom nødvendig benyttes SikaTack-Panel fikseringstape for fiksering i de første timene. Ved upresis plassering kan elementene lett tas fra hverandre og justeres i løpet av de første minuttene etter påføring. Elementene settes så i press igjen. Optimal limstyrke oppnås etter at Sikaflex®-11 FC+ er fullstendig herdet, f.eks. etter 24 til 48 timer ved en temperatur på +23 °C og en tykkelse på mellom 2 til 3 mm.
Rengjøring av verktøy	Rengjør verktøy og påføringsutstyr med Sika® Remover-208 eller Sika® TopClean-T umiddelbart etter bruk. Herdet materiale kan kun fjernes mekanisk.
Merknader om bruk / Begrensninger	Elastiske fugemasser bør ikke overmales da malinger har begrenset elastisitet, og derfor vil krakelere ved bevegelser i fugen. Kompatible malinger kan dekke fugekantene med maks 1 mm. Kompatibilitet må testes iht. DIN 52 452-2. Fargeforskjeller kan oppstå som følge av påvirkning fra kjemikalier, høye temperaturer og UV-stråling (spesielt på hvit masse). Endring i farge vil ikke negativt påvirke fugemassens tekniske egenskaper og yteevne. Før bruk på naturstein bør vår tekniske avdeling kontaktes. Ikke bruk Sikaflex®-11 FC+ som fugemasse på glass, på bituminøse underlag, naturgummi, EPDM gummi eller på bygningsmaterialer som kan svette olje, mykgjørere eller løsemidler som kan angripe fugen. Sikaflex®-11 FC+ skal ikke benyttes i svømmebasseng. Ikke egnet for fuger med vanntrykk eller fuger som er permanent under vann. **Ikke bland med eller utsett uherdet Sikaflex®-11 FC+ for stoffer som kan reagere med isocyanater, spesielt alkoholer som ofte finnes i f.eks. tynnere, løsemidler, rensemidler og formoljer. En slik kontakt kan påvirke eller forhindre herdeprosessen i materialet.**

Målte verdier

Alle opplysningene i dette produktdatabladet er basert på laboratorietester. De målte data kan avvike på grunn av omstendigheter utenfor vår kontroll.

Lokale regler

Vennligst bemerk at som et resultat av lokale bestemmelser kan egenskapene til dette produktet variere fra land til land. Vennligst konferer lokalt produktdatablad for eksakt beskrivelse av bruksområder og egenskaper.

Construction

Helse, miljø og sikkerhet	For informasjon og råd om sikker behandling, lagring og avhending av kjemiske produkter skal brukeren konsultere oppdatert sikkerhetsdatablad som inneholder fysiske, økologiske, toksikologiske og andre sikkerhetsrelaterte data.
Produktansvar	Denne informasjonen og i særdeleshet anbefalingene i forbindelse med anvendelse av Sikaprodukter er gitt i god tro, basert på Sikas inneværende kunnskap og erfaring med produktene når de er riktig lagret, behandlet og anvendt under normale forhold. I praksis vil forskjellene i materialer, underlag og lokale forhold være av en slik karakter at verken denne informasjonen, andre skriftlige anbefalinger eller noen annen form for råd kan innebære noen garanti med hensyn til det bearbeidede produktets omsetningspotensiale eller egnethet for et bestemt formål, ei heller noen annen form for juridisk ansvar. Tredjeparts eiendomsrett må respekteres. Enhver ordre aksepteres i henhold til Sikas gjeldende salgs- og leverings-betingelser. Brukere skal alltid forholde seg til sist oppdaterte versjon av produktdatablad og sikkerhetsdatablad for det aktuelle produktet. Kopier av sist oppdaterte versjon finnes på Sika Norges internettsider: www.sika.no.

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3M Scotch® Vinyl Mastic Tape

3M™ Scotch® Vinyl Mastic Tape is a rubber based mastic laminated to an all-weather 7 mil (0.18 mm) vinyl, which provides double duty protection in one wrap. Vinyl Mastic (VM) tape seals out moisture and protects against corrosion without the need for heating tools or using multiple tapes. VM tape is two tapes in one (vinyl and mastic) and specifically designed for cable sheath repair, splice case and load coil case protection, auxiliary sleeve and cable reel end sealing, drop wire insulating, conduit repair and protection of CATV components as well as other general taping applications. 3M Scotch Vinyl Mastic Tape is RoHS compliant.*

VM tape is available in four sizes ranging from 1 ½" to 22" (38 mm-559 mm) in width to cover the majority of application needs in the field.

Ordering Information

Part Number	Description	Stock Number	MOQ
VM-1.5x20	(1 ½" x 20') Vinyl Mastic Tape	80050045014	10
VM-22x10	(22" x 10') Vinyl Mastic Tape	80050045048	1
VM-4x10	(4" x 10') Vinyl Mastic Tape	80050045022	10
VM-6x10	(6" x 10') Vinyl Mastic Tape	80050045030	1

*RoHS: compliant with EU RoHS Directive (2005/95/EC)
"RoHS Compliant 2005/95/EC" means that the product or part ("Product") does not contain any of the substances in excess of the maximum concentration values in EU Directive 2002/95/EC, as amended by Commission Decision 2005/618/EC, unless the substance is in an application that is exempt under RoHS. This information represents 3M's knowledge and belief, which may be based in whole or in part on information provided by third party suppliers to 3M.

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Figure 26: Construction of flow method samples

Figure 27: Construction of Cup method samples