UiA Universitetet i Agder

Silica Green Stone as an SCM in concrete paving stones production

In order to reduce the total environmental footprint

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Preface

This Master`s Thesis has been formulated at the *Faculty of engineering and science* in the *Department of Engineering Sciences* at the *University of Agder (UiA)* during the spring semester of 2021. This thesis is the ending product of the Master`s programme for Civil and Structural Engineering at UIA. The thesis is the ending report of the subject BYG508 in the master`s programme, which as the ending subject of the programme, builds upon all the previous subjects and is directly connected to the results of the preliminary project subject BYG507. The overarching goal of subject BYG508 is to teach the writer how to execute and manage a large research project and how to properly present all facets of said project in a report thesis.

For this specific thesis, the aim is to further investigate how Silica Green Stone (SiGS) can impact the production process and the resulting products when used as a Supplementary Cementitious Material (SCM) in the production of concrete paving stones. This thesis will run concurrently with research into more standard concrete, so if necessary, will be referencing from that. This thesis will look at strength development, durability and geometric stability over a longer time period and the practicality and visual challenges over a shorter time period.

Firstly, I want to show appreciation to Eramet and thank them for seeing multiple levels of environmental potential in a largely untapped by-product and for being willing to invest time and money into getting the research into that by-product underway. Furthermore, I want to thank UIA for being willing to immediately take part in this project, for providing me with the time, support and resources to find my place in the project, and to provide the research I could to the overarching project. Thirdly I wish to give thanks to the primary and secondary supervisors I have had on this project. Rein Terje Thorstensen from the university, Per Anders Eidem and Bjarte Øye from SINTEF, Svein Willy Danielsen, and Frode Aaltvedt from Aaltvedt Betong has provided me with assistance, feedback and industry knowledge that was invaluable throughout the project timeline. The last major contributors I would like to take the opportunity to thank are the teams of laboratory engineers at UIA and at Aaltvedt Betong. Specifically, Anette Heimdal, Rita Sølvi Ditlefsen and Roar Knutsen have guided and supported me through the practical challenges that occurred during the project.

This is a project that has already seen contributions from many people and organizations at various degrees and at various levels. I would like to take this last opportunity to thank those people as well. SINTEF Norge, Norcem AS, Block Berge Bygg, Aaltvedt Betong, Magne Dåstøl, Camilla Sommerseth, Veronica Kongevold, Ada Louise Heyerdahl Jervell, Rune Nilsen, Emil Dæhlin, Bjørn Richard Dahl, Egil Skybakmoen, Geir Hauge Eide, Hoai Thi Kim Nguyen, Stein Espen Bøe, Kristin Søiland, Leif Hunsbedt and all former students that have contributed, at all levels and degrees, to the overarching project during their time as students at UIA.

Lars Normann Hartz, University of Agder
01.05.2021, Grimstad

Summary

The cement industry is responsible for around 7% of the global CO2 emissions. Reducing this number has been on the forefront of the industry's mind for decades, but even with constant improvement and constant reduction in CO2 emissions per tonne cement used, the increasing globalization has kept the emissions high. Research in the industry has discovered supplementary cementitious materials (SCMs), that when partly replacing cement will produce most of the same results. SCMs are by-products from other industries and natural progression has led to the need for new ones. This thesis is, together with UiA, Aaltvedt Betong, SINTEF and Eramet, looking at how silicomanganese slag, called Silica Green Stone (SiGS), from Eramet can potentially be used as an SCM in concrete paving stones.

This Master's Thesis will research primarily how changes in the solidification method and substitution level of SiGS, when used as an SCM in concrete paving stones, influences the quality of those stones. The thesis will look at how the two kinds of solidification, air-cooled and granulated, and the four substitution levels 20%, 30%, 40% and 50%, interacts with categories such as: Compressibility, density, strength development, durability, water absorption, frost resistance, geometric stability and visual qualities. to look at all of these categories a small literature study was combined with a different method for each category.

The thesis suggests:

That different kinds and amounts of SiGS influences all of the categories of paving stones in different ways. It seems like only replacing cement with SiGS, and not changing anything else, produces varying results. These are well within the requirements, but still worse than without using SiGS.

That air-cooled SiGS might create better density than granulated, but results contradict each other. It seems like the density generally falls when the SiGS amount increases, that air-cooled is better then the granulated against water absorption, but that other factors are more important than substitution levels, that the ability to compress paving stones are not ruled by SiGS type or amount and that SiGS is generally easy enough to work with.

That the strength development is generally better for granulated SiGS than air-cooled, but that everything creates consistent results. It seems like strength development often falls with rising SiGS levels, but that 50% replacement produces interestingly strong strength results.

That air-cooled SiGS has worse frost resistance than granulated, that increasing the substitution also lowers the frost resistance, that size and texture barely changes up to 76 days, that air-cooled SiGS creates slightly darker stones and that granulated SiGS might create unwanted reactions and an unwanted surface colour.

Table of contents

List of figures

List of tables

1. Introduction

Cement is a necessary building block of modern society, but it also has major environmental challenges and potentially permanent negative effects on the earth. Globalization and population growth, with expanding infrastructure and urbanization, have led to an expected increase in cement production of 12-23% between 2014 and 2050 [1]. With a global cement production of about 4.171 billion tonnes per year in 2014 [1], about 3.99 bt/yr in 2018 [2], but still expected to rise to 6.0 bt/yr by 2050 [3], the production numbers are massive. When also calculating in the fact that CO_2-emission numbers can fluctuate between 1 tonne CO_2 per tonne cement [4] and 589.8 kg CO_2 per tonne cement [5] the possible emissions in 2050 can average out to 4.77 bt CO_2 every year. This is around 7% of the global CO_2-emissions [1], which again is more than most developed countries.

The work to diminish the impact from cement has been a major concern in the building industry for decades. The International Energy Agency (IEA) highlighted in 2009 four primary levers for emission reduction, with their *Cement Technology roadmap* [3]. These four were energy efficiency, alternative fuels, CO_2 capture and storage and clinker substitution [3]. This report was later updated in 2018, with the *Technology Roadmap Low-Carbon Transition in the Cement Industry* [1], to investigate the efforts that had already been made and the areas that still needed work. As the 2018 report showed, the improvements in CO_2-emission reduction, since 2009, has been significant in many areas [1]. China, which is the largest cement producer in the world, Europe and the Americas has invested billions of dollars in reducing energy usage, using alternative fuels and inventing CO_2 capture facilities [1]. There is not really anymore to gain in this area, which leaves the last category clinker substitution and using what is called supplementary cementitious materials (SCMs). Using SCMs in concrete production has turned out to be the strategy with the lowest economic impact and the lowest impact on the performance categories [3]. It is actually a fact that SCMs can even be used to drastically improve the mechanical properties and the durability of concrete, not only short-term but long-term as well [3, 6].

The use of SCMs has many, many positive consequences, but there are also major challenges connected to using them. With a main source of SCMs coming from the by-products/waste-products of other industrial processes, the SCM industry has been reliant on the production levels these industries can manage to sustain [3]. Different societal and environmental changes have led to shortages in some SCMs. This has again led to the constant need for research into possible new SCMs and possible new waste/by-products that can be repurposed for positive gains.

This master's thesis is a part of a Norwegian research project, together with Eramet Norway, Aaltvedt Betong, Block Berge Bygg, SINTEF and the University of Agder (UiA), to investigate if a by-product from the industries of the manganese alloy producer Eramet can be used as a new SCM. The by-product in question is technically called silicomanganese slag, but has been given the product name of Silica Green Stone (SiGS) [7]. Eramet estimates a total amount of SiGS available every year of 300 000t, just from their Norwegian factories [7], and with a possibility of 1t CO_2 per 1t cement, it is possible to save 300 000t CO_2 just in Norway. When also considering the fact that most of this at best is used as a filling material [7], the environmental possibilities, if SiGS can become a SCM, are sizable and the monetary possibilities for Eramet is extensive.

This thesis is building on a significant pool of research [8-12] already in the project and a pre-project report [13] having been finished by the writer of this thesis in 2020. The research, with smaller experiments and documents also existing, has already shown SiGS to have promising possibilities, with high levels of silica and lime. Silica and lime are the two main ingredients in cement and SCMs, so having high levels of those are positive. To further the research project, this thesis will collaborate with Aaltvedt Betong, UiA, Eramet Norway and SINTEF to investigate if the SiGS material can work as an SCM in the production of concrete paving stones specifically, since that area of concrete has much less regulations to consider. A hope with this thesis is that by combining a literature study of existing research with a multitude of laboratory testing, both at UiA and at the concrete production facility at Aaltvedt Betong, the research project can enter the next stage. This stage is to start producing these paving stones regularly with SiGS moving forward for even more testing.

2. Societal perspective

Climate change, as a consequence of CO_2 emissions, is the biggest solvable threat facing the globe as a collective. Decades and decades of industrialization, modernization and globalization have led to a rise in global temperatures, rising sea-levels and massive movement of people. Island nations all over the world are fortifying their coastal lines against the erosion of the sea [14] and in 2017 it was estimated that 22.5-24 million people [15] were forcibly displaced from their homes, as a consequence of climate change. The next year, in 2018, the estimation by the World Bank was that this number would increase to 143 million by 2050 [15]. This means that not only the direct impact, but the secondary impact on other countries will be massive.

The fight against this development has been ongoing for some time already. In 2015 the Paris Agreement was signed [16] to help formalize the process, and to put numbers to the expected levels of CO_2 reduction for each nation. This is an international treaty that later was ratified into the Norwegian law system in 2016 [17] before being reworked and increased by Norway in 2020. This increase is a stated promise of reducing the CO_2-emission down to around 50% of the levels found in 1990, by 2030 [18]. The Paris agreement is a section in the United Nations Framework Convention on Climate Change (UNFCCC) and after being signed by most of the world, it is a way for nations to hopefully hold each other accountable and to reach the goals together.

This fight to reduce CO_2 has been ongoing for quite some time and constant evolution in technology and information have led to giant reductions in many areas of society. Between 1990 and 2016 the EU had already managed to reduce their emissions from 3.24Gt CO_2e to 2.44Gt CO_2e [19]. This means that many industries have already put in significant work, to get to this point, but there is still work to be done. One such area is the cement industry, which as the central part of concrete is a massive contributor to the emissions. Concrete, with its central part in anything from infrastructure to high-rises and oil platforms, can emit as much as 1t CO_2 pr. tonne cement clinker [4]. With an estimation of 3.99 Bt cement produced in 2018 alone [2], then we are talking 3.99 Bt CO_2 a year, just from cement production. This is as much as 4-8% of all global CO_2 emissions [4, 20], which is more than most countries.

60% of this 4 Bt CO_2 comes from the burning and splitting apart of limestone in the cement calcination process [21]. This highly CaO rich material is difficult to completely replace, but efforts have been made to find partial replacements for it. These partial replacements, or SCMs, are by-products from other industries that can then be reused in the cement industry. By either adding SCMs into the production process or mixing them together afterwards, it is possible to get as good or better resulting products with much less CO_2 emissions. The most commonly used SCMs are now starting to see shortages and this is where SiGS comes in.

Silica Green Stone (SiGS) is a by-product from the production process of a central component in the steel industry, silicomanganese alloy. SiGS has traditionally not seen any functional use and has until now only been used as filling materials or been dumped in “landfills”. SiGS has a lot of the properties found in other SCMs and with a “production number”, in just Norway, of 300 000 tonnes [7], there is a massive potential lying dormant here. Should it then, in an ideal scenario, be possible to replace 300 000 tonnes limestone/cement, in all the different possible ways, with SiGS, then saving 300 000 tonnes CO_2 would be massive. Making a thought experiment out of the numbers, with the assumed conversion of 3.13 kg CO_2 per kg petrol burned [22], then the possible savings are the same as 95847 tonnes petrol every year.

As outlined in the introduction, SCMs are heavily dependent on the production from other industries and here is where the challenges have started to appear. Examples of this are for one of the main SCMs used today, fly ash, already starting to become serious. Fly ash is a by-product from power plants using coal as fuel and with the examples of the US having shut down 40% of these power plants, the UK planning to shut down all of theirs by 2025 and other countries in Europe by 2030 the shortage will only get worse [3]. Another major SCM is Ground Granulated Blast Furnace Slag (GGBFS), which is a by-product resulting from the blast furnaces used in the iron and steel industry [6]. A shortage of this SCM is also starting to become concerning. With Electric Arc Furnaces, which does not produce GGBFS, slowly replacing Blast Furnaces, import of SCMs from China has started to become a major source needed to maintain the total needs of the concrete industry [23]. These are just some factors that lead to an increase in the secondary emissions, from transportation and production, which again have led to the constant need for research into possible new SCMs.

The hope is then that instead of importing SCMs over far distances, from areas that almost exclusively use fossil fuels, it can be possible to find a new waste/by-product, SiGS, that can be repurposed for positive gains. This would not only save on the use of cement and SCMs, but it would also prevent areas from having to become dumping grounds for unused SiGS in the future.

3. Theoretical background

In order to make this main chapter straightforward and optimally legible it has been divided into sub-chapters, with their own necessary sub-chapters. The information in this chapter is an amalgamation of chapter 3 of the pre-project report [13], seen in appendix 1, previously acquired school knowledge and general information found through specific research. This extra research for information has been done with a literature search for background theory and introductory knowledge that can be seen in appendix 2. More explanation about literature studies can be found in the literature study chapter of this thesis, chapter 6.1. Generally, the rules of referencing where information comes from does not cover widely accepted and accessible information, but this will obviously have some exceptions. These will then be referenced when they appear.

3.1. Earth-moist concrete/dry-concrete/mortar

Chapter 1 of this thesis, *introduction,* gave an insight into how extensive the use of cement is on a global scale and through that how massive the consumption of concrete actually is. Starting at the birthplace of “concrete” in Israel 10000 years ago, moving through the Egyptian and Greek empires, being refined and widespread by the romans, being rediscovered and modernized in the 19th century and then slowly gaining in use ever since, concrete has gone through many iterations and unimaginable levels of production [6]. This has evolved into the concrete of today being specialized for every situation and every purpose. This thesis is only looking at 1 specific type of concrete and as a consequence of that, only that will be researched. For a look at the more general theme of concrete, chapter 3.1 of the pre-project report [13], in appendix 1, covered that. The one special concrete looked at here is what is used in the production of concrete paving stones, which is known as earth-moist concrete, mortar or dry-concrete.

3.1.1. Introduction

Earth-moist concrete, mortar or dry-concrete are multiple names used to describe basically the same product. This product, originating around rammed concrete, was traditionally based around the three central concrete components water, cement and fine aggregate, which still are the central components today [24]. For the purpose of simplification, any further reference of this product will be named by the shorthand EMC.

EMC is a specialized concrete variant that is used, because of its ability for quick and large-scale productions, in the production of paving stones, paving blocks, curbs stones and other concrete products in and around the precast industry [25]. While the construction concrete business is heavily regulated with hundreds of international, European and national standards, this is not the case concerning precast EMC products. Where the standard concrete industry is regulated based on the principles of the imaginable consequences of failures, the EMC products are “regulated” mainly on the principles of market forces and the technology available [24]. Ultimately the final buyer of the products will only purchase products of a certain quality, which puts pressure on the distributor of these products, which finally puts pressure on the producer of them. Nobody wants concrete water main lines that can’t survive frost and nobody wants paving stones that can’t handle the abrasion of repeated traffic. This has made the demands for strength, density, abrasion resistance, freeze/thaw resistance, production accuracy and appearance high and ever growing [24].

3.1.2. Earth-moist concrete design

It was mentioned earlier that the main components in EMC are water, cement and fine aggregates. Because of the noted lack of regulations surrounding EMC, the exact design, and the steps taken to optimize the mixture, are largely left up to the individual producer [24]. This has turned most, if not all, EMC into a mixture of five components. Admixtures and additives have become a central part in EMC, which allows for much more variety and recipe design [24]. This has made the process of enhancing the workability and hardened properties much, much simpler.

Water, cement, fine aggregates, admixtures and additives are basically 5 of the 6 ingredients in standard concrete, so it might be hard to differentiate, but EMC separates itself on a few crucial points. The first of these points are a much lower water/cement ratio. Whereas a standard concrete can vary from as high as 0.8, for weaker privately mixed concrete, to 0.4, in stronger construction concrete, the case is different in EMC. The w/c-ratio of EMC can also theoretically vary slightly [24], but it should be as close to 0.4 as possible [25] without exceeding it.

Another crucial characteristic of EMC is a high cement content. The cement content can in some instances be under 300 kg/m^3 concrete [24], but most often the number will be in the range of 350-400 kg/m^3 [25]. With this much cement and so little water, the resulting amount of cement paste is minimal. As little as 210-240 litre paste per m^3 fresh concrete [24] is what is available to provide lubrication and moisture to the aggregates. This creates a very thick and stiff concrete, that unlike "standard" concrete, which will almost always spread some on its own, will not compact at all without external help.

There is a lot of different factors, not counting the cement and water mixture, that are responsible for the significant strength development in EMC, despite the overabundance of finer and "weaker" particles and lack of coarse aggregates. One of the biggest factors is the method of compaction [24] and the ability to compact [25]. This is again dependant on the particles granular structure, how they interlock with each other and the friction between them when they move around each other [24]. The low water content is responsible for a low degree of hydration in the cement, which provides another positive effect on the compaction. Post-reactions with the free cement can after some time fill in the capillary pores in the EMC, which creates an even denser and stronger product [25]. Cement mixed with fly-ash are already in use [13] to reduce the CO_2 emissions from EMC and this is possible to carry on with the use of other "pozzolanic fillers" [25], such as possibly SiGS. Because of the limited regulations concerning EMC and EMC products, there is great possibilities for experimenting with these areas.

3.1.3. Earth-moist concrete production

In order to produce the large quantities of EMC products, at the pace that is expected, it is a necessity to also produce the EMC at the same concrete works [24]. The entire explanation of how this functions at Aaltvedt Betong, which is the manufacturer connected to this thesis, can be read in chapter 7.1.2 of the pre-project report [13]. This is obviously not 100% the same as for other manufacturers, but on the larger scale this process is the same at all of them and the differences are mainly cosmetic.

3.2. Cement and Supplementary Cementitious Materials (SCMs)

Cement is the product name of a mixture of primarily limestone and clay that acts as the central element in any concrete, including EMC, that when mixed with water acts like a binding agent between the other particles in the concrete. The history behind Ordinary Portland Cement (OPC) and an explanation of the production process behind it are covered by chapter 3.2.1 and 3.2.2 in the pre-project report [13], in appendix 1, and is not as relevant to reiterate in this chapter. Only the sections that are relevant to the main topics of this paper, cement emissions and supplementary cementitious materials, will be covered here.

Cement has an immense carbon footprint. During the entire calcination process, where the limestone and clay are increasingly heated to around 1450°C [6] and broken down/melted into clinker, up to 1 tonne CO_2 is released per tonne clinker produced [4]. As has been mentioned a few times already, cement has a large negative environmental impact. The optimal way to negate as much of this impact as possible is to substitute parts of this cement with materials commonly known as supplementary cementitious materials or SCMs [6, 26]. The most commonly used SCMs in the cement and concrete industry are by-products, waste products or residues left over from other industrial processes. There do exist more natural SCMs, but they are much less commonly used [3, 6, 13, 26]. In order to exhibit the necessary properties, similar to cement, the materials are ground down to powders and either used to replace the clinker in the production of cement or to partly replace the Portland cement in the concrete mixtures themselves [6]. When in their powdered form, the materials are soluble, like cement, with a primary component of either siliceous, calcium aluminosiliceous or aluminosiliceous elements [3, 6, 13, 26]. Depending on their properties and reactivity, any SCMs can be put into any one of two categories. These are latent hydraulic materials and pozzolanic materials, sometimes known as pozzolans. In their original form, or as separate self-contained substances, most SCMs will either react poorly with water or not show any reactions of any value comparable to cement [3, 26]. This is the challenge that is mostly negated by grinding the materials to fine powder [3, 6, 13, 26].

The most important attribute about cement, which has been alluded to, is its ability to chemically react with water in the process of hydration [27]. Hydration is represented by the two reaction:

$$2C_3S + 6H = C_3S_2H_3 + 3CH$$
$$2C_2S + 4H = C_3S_2H_3 + CH$$

These notations are in reality much more complicated, but have been simplified for simplicity's sake. In reality calcium silicate hydrate ($C_3S_2H_3$), or C-S-H as it is often even more shortened to, have the actual formula (3CaO · 2SiO2 · 3H2O) and calcium hydroxide (CH) have the actual notation (Ca[OH]2) [6]. The process of constructing the optimal concrete and the process of limiting the environmental impact will depend on factors such as material composition, material structure and the production process, but much of it will depend on the careful and correct use of SCMs.

SCMs is not only the primary contributor in helping reduce the CO_2-emissions associated with cement, but luckily enough they also have many other positive effects on the fresh and cured concrete [6, 26]. They can help create more compact concrete products, which again can help increase the strength development of said products [3, 6, 13, 26].

The materials known as latent hydraulic materials are SCMs known for a few special qualities. The main quality, that is a requisite for most of the others, are a high calcium content [6, 26]. A high calcium content is the driving factor behind the use of limestone in cement production, which then results in latent hydraulic materials being able to also produce semi-hydraulic reactions, even in the total absence of OPC [6, 26]. This reaction is quite slow and does require a significant PH-value in the mixture. This reaction will not create a material close to the strength and endurance of OPC and that is why it is only used to substitute parts of the cement [3, 6, 13, 26].

On the other hand, are pozzolanic material compounds that do not react with water alone. They will, as a powder, instead chemically react with calcium hydroxide ($Ca(OH)_2$), in what is known as the pozzolanic reaction. As was explained earlier, calcium hydroxide is one of the two resulting products from the chemical reaction between water and cement and it has no positive impact on the strength development of concrete [6]. The only positive effect ($Ca(OH)_2$) can have on concrete is to provide some rust protection [6] to the rebar inside the concrete. The other resultant, calcium silicate hydrate (C-S-H), is the compound that positively contributes to the strength development of concrete. The relation between the amount of each resultant can vary from case to case, but a rough estimate estimates 20-30% ($Ca(OH)_2$) and 70-80% C-S-H) [6, 13]. With the ($Ca(OH)_2$) being such an integral part to the pozzolanic reaction, it is clear that some hydraulic reactions in the cement have to exist first. This means that the pozzolanic reactions are slow to begin, but it is also temperature dependent [6]. As the cement hydration increases the temperature, the pozzolanic reactions pick up pace. This will increase the temperature even more and the total temperature is higher than it would have been with only OPC [3, 6, 13, 26].

SCMs has through time become a primary tool for the reduction of CO_2-emissions from concrete, but specifically cement [3]. The exact numbers are difficult to calculate, and can vary from paper to paper, but it seems like there is a possibility of achieving a reduction in emissions of upwards of 30 % [26]. Which is attainable with little to no significant performance, durability or cost differences [26]. In the concrete business of today, there are three SCMs that stand out as being mostly preferred [6]. These are fly-ash, Silica fume/Microsilica and ground granulated blast-furnace slag.

3.2.1. Fly-ash

Fly-ash is the most commonly utilized SCM in the world and it has been for many decades [3]. Juenger, Snellings and Bernal [3] estimates in table 1 of their paper that about 330-400 million tonnes of fly-ash are used as an SCM every year and that a total of 700-1100 Mt are used every year. When comparing fly-ash to the other common SCMs, silica fume and GGBFS, it is easy to see that the world uses about 1.2 times as much fly-ash as GGBFS and 330 to 800 times as much as silica fume [3]. This total amount includes the fly-ash that are used directly into other products, such as the blended FA cements from Norcem AS, that was introduced in 1982 and became normalized in the early 2000s [6].

Fly-ash is a by-product from the combustions inside power plants, but only from those using coal combustion to drive their energy [6]. The fly-ash residue is collected as the smoke fumes rises upward, through special filters, and the dust settles inside those filters. Not all coal power plants can produce fly-ash that has enough of the needed properties for using it as an SCM [6]. Even if Norway has a coal-fired power plant, on Svalbard, this has never been able to produce fly-ash, because that depends both on the individual coal properties and the equipment used to burn the coal [6]. This has resulted in large amounts of fly-ash having to be imported from other European nations [6], which obviously impacts the total emissions.

The coal properties and equipment used will not only decide if the power plant can produce fly-ash, but also what kind of fly-ash is produced. There are two primary types of fly-ash available on the European market today, calcium based ash and silicate based ash [6]. In Norway the easiest one to get a hold of is the silicate based one, so that is the one in use here.

The compound that makes fly-ash such an "environmentally friendly" item in the cement industry is also what is ultimately going to be the downfall of it. As has been mentioned, and what is one of the reasons behind the research project this thesis is a part of, fly-ash availability is going down. The push for green energy and the continuous march towards renewable energy sources have led to Norway already promising to shut down their Svalbard power plant in 2 to 5 years [28], the rest of Europe are planning to shut all theirs down by 2030 and the US have shut down 40% of theirs already [26]. That means the shortage of fly-ash will only increase and the need for new SCMs will also only increase.

3.2.2. Silica fume/Microsilica

Silica fume, or Microsilica as it is just as well-known as, is the least used of the three major SCMs [3]. As estimated in table 1 of Juenger, Snellings and Bernal [3] there is only consumed about 1-2.5 Mt/y of Silica fume and only between 0.5 and 1 Mt of this is used strictly as an SCM. This might be counterintuitive, since Silica fume is the most reactive and "strongest SCM" [6], but because of decline availability and corresponding increasing price [6], silica fume is today only used in higher quality and high performance concrete [3].

3.2.3. Ground granulated blast-furnace slag (GGBFS)

GGBFS is the third of the three big SCMs. Differently to the other two, GGBFS is the only one of the three that are a latent hydraulic instead of a pozzolan [6]. Table 1 of Juenger, Snellings and Bernal [3] estimates that somewhere between 300 and 360 Mt GGBFS are used every year and that about 300 Mt are used just as an SCM. This is a great way to show that where fly-ash and silica fumes have some other uses, just about all GGBFS are fully used as an SCM.

3.3. Fine aggregates

Chapter 3.1.2 mentions how coarse and fine aggregates are a central component in “standard” concrete, but that only fine aggregates are used in EMC. Since this thesis is only looking at the EMC in concrete paving stones, then only fine aggregates are of an interest. For a more broad look at aggregates as a whole, chapter 3.3 of the pre-project report [13], in appendix 1, covers the theme much more extensively.

Aggregate has different meanings in different sciences, but in material science *construction aggregate* is a collective name for materials used in construction. These materials included gravel, sand, crushed stone, recycled crushed concrete and slag [6]. Fine aggregates specifically are generally classified as aggregates with grain sizes of less than 4mm, which then comes down to the natural aggregate sand and finely grained crushed aggregates. It can be seen in the concrete mix recipe in table 3 in the pre-project report [13], in appendix 1, that fine aggregates can make up ¾ of any standard EMC mixture. This means that much of how the fresh EMC behaves and much of the final EMC properties are governed by the particle relationships internally in the aggregates and externally in the aggregates with the cement glue [6].

It is not the case that all the natural aggregates are actually usable as aggregates for construction. Only some deposits made over tens of thousands of years, by glacial movements, are really optimal for especially concrete [6] and as a consequence of these time periods, the deposits are starting to dry up. Some deposits will not have particles with a good enough spread in grain sizes and some will be full of minerals that negatively affect the final products [6]. This has then been the governing factor for where quarries have been located, in order to capitalize on the great resources and not waste time and money on processing bad resources. Continuous industrialization has made it so that the demand for aggregates have emptied the best deposits and the less than optimal ones have had to be used. The less optimal ones have then seen an increase in production costs, as a consequence of increased material washing, sieving, crushing and combining materials, with specific particle size distributions, with materials from other sites that also have different PSDs [6]. When it comes to natural aggregates, fine aggregates will almost never exist in a totally natural form. 0/8 mm is the lowest of the natural grain size ranges made in Norway [6]. This means that it has to be processed again to reach 0/4 mm.

The lack of consistent sources of natural aggregates has been one of the major reasons behind the rise in the need for crushed aggregates and crushed recycled aggregates. Crushed aggregates has for a long time been prominent in asphalt and road construction [6], but has up until, in the historical perspective, quite recently not been a major factor in concrete production. This has changed and today somewhere between 20% and 30% of concrete aggregates [6] can be crushed/machined. Recycled aggregates on the other hand have become a staple in countries with a serious shortage on aggregates and is often crushed treated and recycled old concrete, that is reused in new areas. Because of the variety of uses crushed aggregates can have, the grain size varieties are also larger. 0/2, 0/4 and 2/5 mm are quite common fine crushed aggregates and is often made to be mixed with the natural smoother particles in natural aggregates [6], which have been smoothed by the earlier mentioned glaciers. These smoother particles help lower particle movement resistance, which help them compact closer together, creating a stronger concrete [6].

3.4. SiGS

Silica Green Stone, or SiGS as it will be known as from this point, is a product name given to the waste/by-product from the silicomanganese alloy industry, silicomanganese slag (SiMn) [7], which is a major alloy used in the steel industry. Norway alone produced about 2% of the global SiMn alloy in 2018 [29], and with a total global output that year of around 16 million tonnes it is estimated around 320 000 tonnes was produced in Norway that year [29]. Not only is the steel-industry ever growing, but the SiMn alloy consumption, per tonne steel, is also growing. This led to a rise in SiMn production globally of 16% [29] from 2017 to 2018.

With 2% of the global SiMn production, it is reasonable to assume Norway is also responsible for about 2% of the total SiGS production in the world. Eramet Norway, the largest Mn alloy producer in the country, estimates that they each year produces 300 000 tonnes of SiGS, across different factories [7]. As the introductory sections of this paper have mentioned, SiGS seems to exhibit similarities with other SCMs and should those indications turn out to make SiGS usable as an SCM permanently, the impacts are massive. With these smelting plants located in multiple areas of Norway, it would be easy to set up storage and delivery to most of southern Norway. Should this also turn out to be profitable, both monetary and environmentally, the entire process would also be able to be spread out to other major Eramet locations in 5 different continents [7]. This could potentially have positive environmental possibilities that are difficult to comprehend at this early stage.

3.4.1. Current situation of SiGS

Throughout history, and in current times, SiGS have potentially been highly underutilized, but Eramet have always been on the lookout for better uses for the by-product. What started out as products being driven straight to “landfills” [7], has slowly started to find value elsewhere. These landfills can become huge sores in the landscape, so reducing the use of those is another added environmental benefit. One of the uses already found for SiGS is as a filling material on land and in the sea [7], which again reduces some of the need for digging out gravel and stone in quarry’s. This would again save on machinery and fuel consumption in digging and crushing this gravel/stone.

There are multiple potential uses for SiGS that are being researched almost simultaneously. These are in road construction, as a supporting base layer under the asphalt, as a “soil enhancer”, to reduce plant weakness/sickness, and as a potential cement replacement [7]. It is this last section that is interesting for this thesis to look at. This replacement can come as a directly added material in the cement production, which it with a high amount of limestone already has shown promise as [7], but that is not relevant for this thesis. The other possibility is as an SCM added to the cement when making concrete and that is a still more untested subject.

3.4.2. Chemical and structural appearance

The reason why SiGS are a great possibility as an SCM is because of its structural and chemical composition. During the production process, the furnaces used can reach as much as 1600 degrees, which “burns off” the harmful particles and separates the manganese ore from the rest of the raw mined material [7]. This leaves a stable, natural and clean mineral by-product made up of mainly calcium and silicon, which are two of the primary parts of both cement and other SCMs [6]. As figure 3.1 below shows, the SiGS has a significant green hue and in that particular state it is quite durable

[7]. The SiGS seems to exhibit none of the potentially concrete damaging traits, such as low chloride/sulfate content, and with no environmentally damaging materials, such as asbestos, the effect of using SiGS seems to only be positive [7].

Figure 3.1 Original SiGS rocks [7]

SiGS can be "produced" in two different varieties, depending on how they are cooled from the earlier mentioned 1600 degrees and how fast those two cooling effects happen. The chemical composition will obviously slightly vary from place to place, depending on where the original materials were mined, but structurally it depends on either air-cooling or water-quenching/granulating the material. When dropping the molten material straight into jets of cold water, granulating it, the material will rapidly cool [30]. This process gives the SiO in the SiGS an amorphous structure, which has better reactivity then other structures, and gives the SiGS tiny glassy bubbles in the inside structure [10]. The other method, air-cooling, slowly cools the slag in air, which gives it time to develop crystalline phases instead [10]. The air cools the surface first, but the inside structure has loads of time to gradually crystalize. The rapid nature of granulation has so much internal energy related to it that the material will break apart into smaller and brittle parts. Combining this with the smoother and slicker surface on the glassy bubbles, the granulated SiGS should be easier to grind down to powder [30]. This should also benefit the final powder with higher reactivity, but here the total behaviour, after short and long-term, are still unknown. These are some areas that increasing research will look at.

At present Eramet Norway cools their SiGS using the air-cooled method, but internationally, and especially at their headquarters in Dunkirk, the granulation is the standard method. Since this research project is also investigating if there are any differences between the methods, should granulation turn out to be better, then Eramet Norway is ready to invest money into beginning to granulate their own SiGS.

SCMs are divided into two categories of reactivity, depending on their chemical makeup, microstructure, particle size, surface structure and particle size distribution in the total material used [6]. These two, pozzolanic materials and latent hydraulic materials, are better explained in chapter 3.2. Being a slag, SiGS should in theory share more similarities with the latent hydraulic materials GGBFS, but that might not be the case. Miniggio, Nærland and Aaserud [12] showed in their thesis a chemical analysis, represented in figure 3.2, that SiGS actually can have as much 20% less CaO then GGBFS. Combining this with the high values of SiO_2 and Al_2O_3 it is quite likely to say that SiGS is more pozzolanic, with a similar chemistry to fly-ash, then latent hydraulic. This statement is already supported by a growing amount of research papers [8-13]. There is still a need to research this subject, but the themes are showing promise so far. Looking further into figure 3.2 it is easy to see that SiGS. GGBFS and cement are not too different on the grander scale. They all contain the most of the four compounds SiO_2, Al_2O_3, CaO and MgO, but just in different amounts. This difference is one main reason for the difference in reactivity. SiGS also has a significant percentage of MnO, which is what was needed for use in SiMn production in the first place. SiGS contains around 89% of these four main parts, which is much better than the average for other SiMn-slags, which is about 70% [12]. When talking about microstructure and particle size, it is the fact that cement and other SCMs will react better with a larger surface area to weight ratio and such seems to be the case with SiGS as well. SiGS are therefore ground down to powder of a cement particle size, but here there are still questions of cost/benefit, both environmental and monetary [11-13], with the grinding process.

wt%	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	Alk	MnO	Mn-Calc	SO_3
Air Cooled SiMn-Slag	44,28	15,69	1,78	25,52	7,98	0,84	0,27	0,82	7,27(2)	-	-
Granulated SiMn-Slag	40,3	18,20	0,18(1)	21,15	8,7	1,29	0,37	-	8,35	6,45	-
GBFS	35,06	11,02	0,76	41,69	8,47	0,45	0,32	-	-	-	1,38
Cement Clinker	20,50	5,50	3,25	63,50	3,00	0,85(3)		-	-	-	2,00

(1) Chemical component is measured in FeO for granulated SiMn-slag
(2) Chemical component is measured in Mn_2O_3 for air cooled SiMn-slag
(3) The values for K_2O and Na_2O are combined from the original source
Chemical components $\leq 0,2$ wt% are not included in the table

Figure 3.2 Chemical comparisons of cement, SiGS and GGBFS [12]

It was mentioned earlier that SiGS has two main ways it can be used. One of these is as a direct addition to the limestone, early on in the cement production process. This is something that is not as relevant to this thesis, but more information on the subject can be found in chapter 3.6.3 of the pre-project report [13], in appendix 1. This is very interesting for the overarching research project, but just not here. The second major usage for SiGS is when added to the cement after the cement has been produced.

This second possibility can also be divided into two "sections". The first of these two is mixing it in with the cement right after production and selling it as one product. This is done in Norway today with fly-ash, as *FA cement*, and internationally with slag as *slag cement*. This is a process that will have to include many more companies and a lot more regulations and is not something that will be easily done at the moment. There will also be a need for more extensive research into large amounts of substitution in all situations, before that becomes a reality. Even if research so far [8-13] are showing promise, the consequences for durability and stability after 2, 5 or 10 years are very much up in the air. The second of these two are using the SiGS as an SCM in the concrete mixture. This means adding smaller amounts of SiGS directly into the mixture to both reduce cement use and increase some specific properties. When added to cement afterwards the SiGS will have the benefit of still being amorphous and not having been melted down together with the limestone in the kilns. This is positive both for surface reactivity and long-term properties.

3.5. Concrete paving stones

Concrete paving stones as a material are a low maintenance, strong and cheap alternative to the much more expensive decking materials asphalt and standard concrete. When correctly laid in interlocking patterns they are flexible enough to move with the surfaces, independently from each other, and are therefore easily able to handle the repeated downwards forces of vehicles, machinery or foot traffic [31]. Should the foundation of the surface be properly drained, such as not to completely fall apart, these stones can technically survive any forces, in any direction, just by moving and shifting their positions slightly [31]. Whereas asphalt is flexible, but will slowly deteriorate, and concrete is durable, but cracks under bending forces, the concrete paving stones combine these properties and is therefore used in everything from parking lots to drive ways all over the world [31]. Paving stones are made using the EMC mentioned in chapter 3.1 and in giant nearly automated facilities [13].

3.5.1. Today's areas of use

Concrete paving stones are used in so many different areas of society, that it is difficult to understand all of them. It is so much easier to lay these stones yourself, in your own driveway, then to go through the hassle of organizing, getting delivery of enough and to correctly lay asphalt, that paving stones are the staple product in the majority of Norwegian homes [31]. Going from that through the square miles of parking lots and all the way to industrial sites, it is easy to see how many tonnes of stones are actually produced each year. For a much more extensive look at all the areas paving stones are currently used, it can be found in chapter 3.5.2 of the pre-project report [13], in appendix 1. It was important to document that there were reasons for choosing paving stones as the area of research for cement replacement, but now that paving stones are being researched it is less important.

3.5.2. Appearance, composition and dimensions

There are hundreds of shapes, sizes and colours that it is possible to make a paving stone [31]. Figure 3.3 shows a sampling of what is produced at the largest Norwegian paving stone producer, Aaltvedt Betong. All stones are either locking stones, partly locking stones or non-locking stones and as all these again are made to fit an overarching pattern, the shape possibilities are endless [31]. When you add in the possibility of "artificial" colouring, weathering textures, layering and different base materials you end up with a lot of possible outcomes.

Figure 3.3 products available at Aaltvedt Betong [13]

Historical trends and not too many Norwegian producers have kept the varieties slightly limited in this country, but this is gradually changing to match the rest of the world [31].

Standard

Concrete paving stones are governed by one particular standard, NS-EN 1338:2003 [32]. This standard covers a few specific rules when discussing what can and cannot be called a paving stone. This does obviously not include specially fitted end/corner pieces, but these general rules are:

- The maximum length of a stone has to be less than or equal to four times the maximum thickness [31, 32].
- 50 mm from all stone edges, the cross-section, in all directions, cannot have a horizontal dimension smaller than 50 mm [31, 32].

Paving stones that exceed those limitations are then called paving slabs and are immediately covered by another standard.

3.6. International, European and Norwegian standards

The practice of regulating and documenting technical specification in Standards are the most important work having been done to negate miscommunications and misinformation in the technical world. This uniform design is optimal for sharing of production methods, regulation rules and documentation between countries, independent of language or continents. Most countries, and a few continents/unions, have their own organizations which governs standards specialized for them. Above that again is the international organization that helps all the national organizations work together properly, The International Organization for Standardization, best known just as ISO.

There did exist international standards organizations before the ISO, but in 1947 ISO was created to bring these together into a stronger one [33]. By 2018 the membership numbers had reached 162 countries, and with a base in Switzerland the organization is strategically placed to support their subcommittees all around the world [33]. These subcommittees are set up to create standards covering equipment, management systems, products, processes, symbols, quality of goods and unit names. ISO has not covered every single subject, but in 2018 they passed 22000 different standards [33].

Another organization, like ISO, that is heavily involved in standards Norway takes as their own is the Comité Européen de Normalisation, or CEN. CEN works within the Brussels EU/EFTA system as the official European standardization organization and is the governing body for maintaining/updating existing European standards and for creating new ones [34]. CEN has since the beginning in 1961 governed all areas of technical specifications, except telecommunications and electrical engineering, and reached 34 membership countries in 2017 [34].

As was said earlier, most countries have their own national organizations that translate and customize international standards to fit in with individual peculiarities. The ISO and CEN member that do such a job for Norway are Standard Norway [35]. Standard Norway is the private and independent organization that makes sure that for instance standards made with tropical climates in mind, will also work in the permafrost of Svalbard [35]. Standard Norway does not, similar to ISO and CEN, cover telecommunications and electrical engineering, but unlike ISO and CEN Standard Norway also does not cover the postal service.

The standards used in this thesis are:

- **NS-EN 1338:2003 – Belegningsstein av betong – Krav og prøvingsmetoder – (innbefattet rettelsesblad AC:2006) [32]**
    - NS-EN 1338:2003 is a standard, based on the European EN 1338, that has little to nothing to do with other concrete standards, but is specially aimed at concrete paving stones. Moving through the different sections of paving stone production that the standard covers, it starts by regulating what materials are allowed to be used and what quality that material has to have. Then it specifies surface qualities/textures, before moving over to the mechanical properties; splitting tensile strength, frost resistance, slipping/gliding resistance, wear and tear resistance and fire resistance properties, before ending with visual aspects and colour choices [32]. At the end of the standard are annexes that lists what kinds of testing that has to be done on the stones, inside the factory and in laboratories, and how to perform and document them correctly.

- **NS-EN 197-1:2011 – Sement – Del 1: Sammensetning, krav og samsvarskriterier for ordinære sementtyper [36]**
    - NS-EN 197-1 is a standard, based on the European EN 197-1, that regulates and classifies cement. NS-EN 197-1 classifies 27 kinds of standard cement types and 7 kinds of sulfate resistance cements, but it does not regulate special cements, such as supersulfated cements [36]. It covers everything that is allowed to be used in the making of the cement and every material that is allowed added after production [36]. This covers both the ways which SiGS are being investigated for use and is therefore the hurdle SiGS will have to climb before entering mass use.

4. Research question

Concrete, especially the cement aspect of it, is an industry with environmental challenges. The industry itself has developed supplementary cementitious materials (SCMs) to partly replace the cement in concrete. Environmental and societal changes have constantly led to the need for new such materials and the purpose of this master's thesis is to research if one specific by-product, Silica Green Stone (SIGS), from the concern Eramet Holding Manganese can serve that purpose. As a consequence of significantly less regulations to consider, it was decided to start the research in the dry-concrete and concrete paving stones business, which led to this research question:

- **How would changes in the solidification method and substitution level of SiGS, when used as an SCM, influence the quality of concrete paving stones?**

In order to provide a satisfactory answer to this question and at the same instance lay the groundworks for getting SiGS approved by the regulations, these points will be researched:

- **Properties of fresh concrete**
    - **Compressibility, density and experience in full-scale production**
- **Quality of final products**
    - **Strength development as a function of time**
    - **Durability (Development of resistance towards freeze-thaw deterioration)**
    - **Geometric stability**
    - **Visual appearance**

4.1. Limitations and restrictions

Under the circumstances laid upon this project by the set structure of a school semester and Covid-19, concerning set delivery dates, workspace access and available man-hours, some limitations and restrictions had to be set on the project.

- Only a standard earth-moist/dry concrete recipe, used at Aaltvedt Betong, will be researched in this thesis, used in all stone production and be the base in all the laboratory work mentioned.
- Only the air-cooled SiGS from Kvinesdal and the granulated SiGS from Dunkirk will be included in this thesis.
- The tensile splitting strength tests on the paving stones will only be performed at 1, 3, 7, 14, 28 and 77 days.
- The rest of the tests will be done as close to the given dates in the standard, but when that is not possible an explanation will be given there.
- Tensile splitting strength is the only mechanical property that will be tested in this thesis.
- The rest of the properties that are mentioned in the paving stones standard, or the different concrete standards, will not be researched here. This as a result of the time/work constraints.

5. Case/Materials

5.1. Case

It would have been possible to investigate the use of SiGS as an SCM in all kinds of areas and all kinds of ways. Using it directly in the production of cement is an area that has been and is being researched by Norcem AS themselves directly. This has shown a lot of promise, but the positive developments have plateaued [8] and the outside involvement at this point would have minimal effect. The second angle of attack, that the research could take, was to research adding the SiGS in with the cement after production and using it as an SCM. This would be easy enough to conduct experiments on and different researchers could conduct independent research before the results were collected in the central project.

Using SCMs mixed into cement, when producing concrete, is an exact science. Not only does the standardization system have standards specifically for cement, what can be mixed into cement and properties the cement has to have, but it also has standards specifically for how the SCMs used in the cement can behave. These standards both regulate the compositions of the SCMs and the properties that the SCMs has to have. These properties have to be tested according to carefully researched methods that also are given in these standards.

It is also important to think about the secondary regulations, regulations on the concrete itself, that is impacting the cement composition and SCMs usage. For a lot of concrete, especially concrete used for situations with a huge potential for massive catastrophe, the regulations are extremely strict. Concrete that could, if it does not perform what it is supposed to, potentially be responsible for the loss of thousands of lives, or billions of dollars, have to be made exactly to standard. The development of these regulations has been ongoing for decades and decades, and the process of getting a new product approved in that system, from scratch, would take time and money this project doesn’t have.

With the addition of Aaltvedt Betong as a collaborator in the research project it was decided that approaching from another angle would be quicker and potentially a little simpler in the long run. Aaltvedt Betong, as the largest paving stone producer in Norway, produces a product that not only is known for using an extra amount of cement pr. m^3 concrete, but also for making these products with concrete that has almost no regulations to control it. This means that should this project be able to prove that SiGS concrete can pass the regulations that are in the few paving stone standards that exist, then the road from there into full production with SiGS is short. To do that, this project has made one type of paving stone, with different kinds and amounts of SiGS, in order to perform all the regulation testing and then compare these results with the standard results. There will still be some potential negative effects that will not become apparent until long after this thesis is finished, but this thesis will look at a good number of them. The standards for paving stones are almost exclusively geared towards the results after 28 days, but this thesis will look at results after that also, because all information is invaluable for a new subject.

5.2. Materials

Research into and production of any concrete related mixtures is a process that requires a wide variety of products and materials. This chapter will attempt to structure, explain and describe these in an orderly and detailed fashion.

5.2.1. Silica Green Stone (SiGS)

SiGS is the product name given to the by-product silicomanganese slag, which is the by-product of the silicomanganese alloy production at the Norwegian branch of Eramet Holding Manganese, Eramet Norway A/S. An introductory explanation of SiGS can be found in chapter 5.2 of the pre-project report [13] in appendix 1. The just mentioned chapter separated SiGS into two SiGS types used there and the same was used in this thesis as well. These two are still air-cooled and granulated and are very similar, but differ in a few crucial ways.

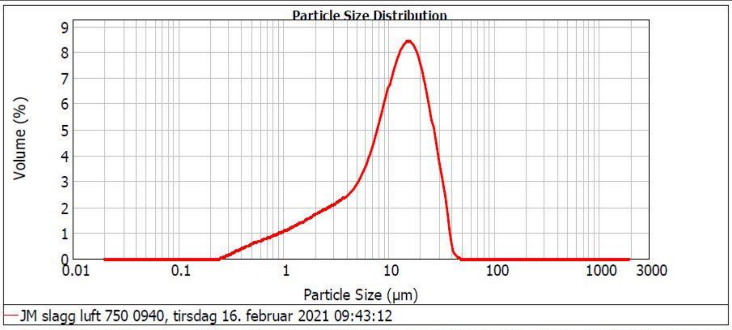
Air-cooled SiGS

The first type of SiGS used in this thesis was air-cooled SiGS from Eramet Kvinesdal. Eramet Kvinesdal has, as of now, only the equipment available to "produce" the air-cooled SiGS, so only air-cooled SiGS was taken from there. Almost 1 tonne of the original stone slag was sent from Kvinesdal to ReSiTec AS in Kristiansand where the slag was ground down to powder. As can be seen in the centre of the three pictures in figure 5.1 below, the material was ground down to about d_{50} = 12 µm using a jet mill. This was done in order to create a similar size as cement, in order to make the later comparisons easier to handle. This way created less variables and an easier time comparing SiGS types with standard cement and cement with fly-ash. Around 700kg of the grey dust powder, seen in figure 5.1, was eventually collected and shipped to the paving stones facility at Aaltvedt Betong using the big bag also seen in the figure below.

Figure 5.1 Delivery bag of SiGS and the air-cooled powder product

It was mentioned in the previous chapter that the air-cooled SiGS was ground down to about d_{50} = 12 µm. The process and the equipment used to produce this powder was not well tested on SiGS material, so in order to test the quality of the grinding a PSD analysis was performed on the material. The results of the analysis, and the connected graph, can be seen in figure 5.2 below and the entire rapport can be seen in appendix 3 at the end of this thesis. The analysis was performed using a Mastersizer 2000 at the ReSiTec facility and shows a d_{50} of 11.351 µm.

d(0.1): 1.830 um d(0.5): 11.351 um d(0.9): 25.063 um



Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %
0.010	0.00	0.105	0.00	1.096	1.06	11.482	7.05	120.226	0.00	1258.925	0.00
0.011	0.00	0.120	0.00	1.259	1.17	13.183	7.50	138.038	0.00	1445.440	0.00
0.013	0.00	0.138	0.00	1.445	1.30	15.136	7.58	158.489	0.00	1659.587	0.00
0.015	0.00	0.158	0.00	1.660	1.42	17.378	7.23	181.970	0.00	1905.461	0.00
0.017	0.00	0.182	0.00	1.905	1.55	19.953	6.46	208.930	0.00	2187.762	0.00
0.020	0.00	0.209	0.00	2.188	1.67	22.909	5.36	239.883	0.00	2511.886	0.00
0.023	0.00	0.240	0.02	2.512	1.79	26.303	4.04	275.423	0.00	2884.032	0.00
0.026	0.00	0.275	0.10	2.884	1.91	30.200	2.77	316.228	0.00	3311.311	0.00
0.030	0.00	0.316	0.21	3.311	2.04	34.674	1.29	363.078	0.00	3801.894	0.00
0.035	0.00	0.363	0.31	3.802	2.21	39.811	0.16	416.869	0.00	4365.158	0.00
0.040	0.00	0.417	0.42	4.365	2.45	45.709	0.00	478.630	0.00	5011.872	0.00
0.046	0.00	0.479	0.51	5.012	2.80	52.481	0.00	549.541	0.00	5754.399	0.00
0.052	0.00	0.550	0.61	5.754	3.28	60.256	0.00	630.957	0.00	6606.934	0.00
0.060	0.00	0.631	0.69	6.607	3.91	69.183	0.00	724.436	0.00	7585.776	0.00
0.069	0.00	0.724	0.78	7.586	4.67	79.433	0.00	831.764	0.00	8709.636	0.00
0.079	0.00	0.832	0.86	8.710	5.51	91.201	0.00	954.993	0.00	10000.000	
0.091	0.00	0.955	0.96	10.000	6.35	104.713	0.00	1096.478	0.00		
0.105		1.096		11.482		120.226		1258.925			

Figure 5.2 PSD analysis of air-cooled SiGS

At the same time as the PSD analysis, an XRF analysis was also performed by ReSiTec on the air-cooled SiGS. This is an analysis of the material composition of the SiGS and is given here in figure 5.3 and appendix 4. This was an attempt to, at the same time as keeping control of possible irregularities in the material, to compare it with earlier studies. This is a way to see if it is possible to reliably assume similar compositions and similar behaviour in future situations. Comparing with the air-cooled results in figure 3.2, we can see that the amount does slightly differ. For instance, the SiO_2 changes from 44.28 to 44.9 and the CaO from 25.52 to 23.8. These are not the biggest changes and might just be because of the small sample size of 16.2g, but they are important to keep in mind. It is also relevant to say that the numbers in figure 3.2 were on material with a much larger particle size and might therefore possibly be less accurate.

PANalytical
Results on-line

Type:	Routine
Archive:	Slagg LC&SiMn x
Application:	Slagg LC&SiMn x
Sample:	SIMN LUFTKJOLT SLG-OVN1 SM200
Sum (%):	99.8000
Init weight:	15 g
Flux weight:	1.200001 g
Final weight:	16.2 g
Norm.factor:	0.9723

Compound	Value	Unit	Status
Mn-Calc	5.0	NONE	
SiO2	44.9	%	
Al2O3	14.8	%	
CaO	23.8	%	
MgO	7.4	%	
K2O	0.70	%	
FeO	0.28	%	
B/A	0.94	NONE	
TiO2	0.128	%	
VISK	13.1	NONE	
BaO	0.65	%	
Na2O	0.33	%	
S	0.36	%	
MnO	6.5	%	

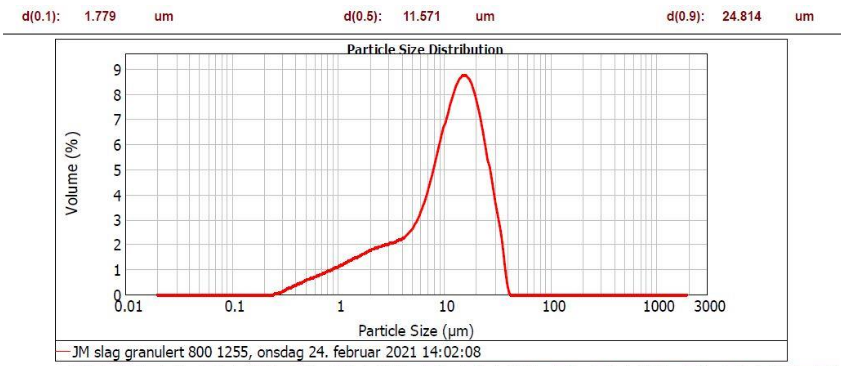
Figure 5.3 XRF analysis of air-cooled SiGS

Granulated SiGS

The second type of SiGS used in this thesis was granulated SiGS from an Eramet facility in Dunkerque, France. The reason for this chosen location, to extract our sample product, was that they had one of the closest granulation facilities to Norway and that the chemistry between Kvinesdal SiGS and Dunkerque SiGS turned out to be relatively similar. This meant that the variable of chemical difference, when comparing it with air-cooled SiGS, could be given less relevance than other sources for errors. In this case, as well as with the air-cooled SiGS, about 1 tonne of material was delivered to ReSiTec AS in Kristiansand. This was also ground down to about D_{50} = 12 µm using the same or a similar jet mill. The choice of size was again deliberate, in order to compare this granulated SiGS with the other materials mentioned in the air-cooled section. As figure 5.4 below shows, around 730kg of granulated SiGS was collected and shipped using the same big bag as with the air-cooled SiGS. The colours of the two SiGS variants seems from figure 5.1 and 5.4 to be almost indistinguishable from each other, but in practicality the granulated SiGS has a slightly brighter tone to it.

Figure 5.4 Delivery bag of SiGS and the granulated powder product

As with the air-cooled a PSD analysis was performed with the granulated SiGS using the same Mastersizer 2000. This is below in figure 5.5, and in appendix 3, and shows a d_{50} of 11.571 µm.



Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %
0.010	0.00	0.105	0.00	1.096	1.12	11.482	7.27	120.226	0.00	1258.925	0.00
0.011	0.00	0.120	0.00	1.259	1.24	13.183	7.78	138.038	0.00	1445.440	0.00
0.013	0.00	0.138	0.00	1.445	1.37	15.136	7.88	158.489	0.00	1659.587	0.00
0.015	0.00	0.158	0.00	1.660	1.49	17.378	7.49	181.970	0.00	1905.461	0.00
0.017	0.00	0.182	0.00	1.905	1.59	19.953	6.65	208.930	0.00	2187.762	0.00
0.020	0.00	0.209	0.00	2.188	1.68	22.909	5.46	239.883	0.00	2511.886	0.00
0.023	0.00	0.240	0.01	2.512	1.76	26.303	4.04	275.423	0.00	2884.032	0.00
0.026	0.00	0.275	0.09	2.884	1.82	30.200	2.71	316.228	0.00	3311.311	0.00
0.030	0.00	0.316	0.20	3.311	1.89	34.674	1.11	363.078	0.00	3801.894	0.00
0.035	0.00	0.363	0.30	3.802	2.01	39.811	0.00	416.869	0.00	4365.158	0.00
0.040	0.00	0.417	0.40	4.365	2.22	45.709	0.00	478.630	0.00	5011.872	0.00
0.046	0.00	0.479	0.51	5.012	2.55	52.481	0.00	549.541	0.00	5754.399	0.00
0.052	0.00	0.550	0.61	5.754	3.05	60.256	0.00	630.957	0.00	6606.934	0.00
0.060	0.00	0.631	0.70	6.607	3.72	69.183	0.00	724.436	0.00	7585.776	0.00
0.069	0.00	0.724	0.80	7.586	4.58	79.433	0.00	831.764	0.00	8709.636	0.00
0.079	0.00	0.832	0.90	8.710	5.52	91.201	0.00	954.993	0.00	10000.000	
0.091	0.00	0.955	1.01	10.000	6.47	104.713	0.00	1096.478	0.00		
0.105		1.096		11.482		120.226		1258.925			

Figure 5.5 PSD analysis of granulated SiGS

The same XRF test performed on the air-cooled SiGS was also performed on the granulated SiGS. This is given in figure 5.6 and shows much the same as with the air-cooled SiGS. Also, in this material there is some difference from the values in figure 3.2. The same possible explanations of small sample size and different particle size is possible as an explanation here, but in the end, it is difficult to say.

PANalytical
Results on-line

Type:	Routine
Archive:	Slagg LC&SiMn x
Application:	Slagg LC&SiMn x
Sample:	SIMN VANNKJOLT SLG-OVN1 SM200
Sum (%):	99.8000
Init weight:	15 g
Flux weight:	1.200001 g
Final weight:	16.2 g
Norm.factor:	1.0027

Compound	Value	Unit	Status
Mn-Calc	7.8	NONE	
SiO2	41.6	%	
Al2O3	17.8	%	
CaO	18.3	%	
MgO	8.5	%	
K2O	1.52	%	
FeO	0.20	%	
B/A	0.99	NONE	
TiO2	0.135	%	
VISK	11.3	NONE	
BaO	0.71	%	
Na2O	0.36	%	
S	0.59	%	
MnO	10.1	%	

Figure 5.6 XRF analysis of granulated SiGS

5.2.2. Cement

As a consequence of factors explained in other sections of this thesis, two kinds of cement were used for the production of concrete paving stones used for this research. These two were *Portland cement EN 197-1 – CEM I 52,5 R – Brevik* and *Portland-composite cement EN 197-1 – CEM II/B-M 42,5 R – Brevik*.

Portland cement EN 197-1 – CEM I 52,5 R – Brevik (*Norcem Industrisement*)
Portland cement EN 197-1 – CEM I 52,5 R – Brevik or *Norcem Industrisement [37]*, as it is better known as in Norwegian, is a cement produced at the Norcem AS facility at Brevik. This cement is a specially designed cement that is engineered for the harsh Norwegian winter climate. It has been designed to resist the negative effects cold temperatures have on concrete development and with a high early strength, it can be perfect for concrete products such as paving stones [37]. The cement can be delivered in small bags, big bags and, as is the case with Aaltvedt, in large bulk. From the product data sheet, in appendix 5, it can be seen that this cement is a very clean cement-type with a clinker percent of 96. In the case of this thesis, the cement was stored in large silos at the Aaltvedt facility before being transported and used according to the production methods described in chapter 7.1 of the pre-project report [13] in appendix 1.

Portland-composite cement EN 197-1 – CEM II/B-M 42,5 R – Brevik (*Norcem Standardsement FA*)
Portland-composite cement EN 197-1 – CEM II/B-M 42,5 R – Brevik or *Norcem Standardsement FA* [38], as it is better known as in Norwegian, is also a type of cement produced at the Norcem AS facility at Brevik. This is a much less specially engineered cement, but it is still constructed in a way such as to be able to function in all exposal-, durability- and strength classes, under all Norwegian climates [38]. With only 78% clinker and about 18% fly ash, taken from the product data sheet in appendix 6, CEM II has a much slower strength development then CEM I. The CEM II cement has the same delivery options as CEM I cement and is stored in silos next to the other cement at Aaltvedt Betong. The transport and use of CEM II cement in this thesis have also followed the same procedure as for the CEM I cement.

5.2.3. Sand

The production of concrete paving stones is a delicate and carefully researched process. In order to achieve the compression and properties necessary a wide variety of sand fractions and qualities are used. As can be seen in the concrete mix in figure 6.1 there are 6 “different” sand types/qualities involved in the process of producing standard concrete paving stones at Aaltvedt Betong. In reality, that is actually a small “fallacy” and is not the completed truth. Chapter 7.1 of the pre-project report [13], in appendix 1, shows that during the site visit to Aaltvedt Betong it was explained that sand is stored in silos. This is done in order to both protect the sand from weather and to have enough sand easily available quick enough. It is also the fact that the mixtures use different amounts of sand and therefore a lot more of some sand. This means that some silos have the same sand in them, which is the case at Aaltvedt. 0-8 LUNDE, 2-5 ncc and GSG 0-1 are separate sand types/qualities, but the other three are not. GSG Sand T6, T3 and T4 are the same type of GSG 0-4 sand and the different T numbers are just the numbers of the silos it came from.

0-8 LUNDE

The 0-8 LUNDE sand is sand taken from a local producer at a quarry near Lunde. This is a sand with no measured oversized grains, but with grain sizes between 0mm and 8mm. Any measurement of the sand used in this thesis was taken on the 4th of march, just a few days before the sand was used and it was performed at the Aaltvedt facility by the Aaltvedt laboratory.

The concrete mix in figure 6.1 shows that 208kg of this sand was used for a full batch production and that by the time of use it had a moisture content of 4.0%. The full grain distribution, PSD graph and measured moisture content is given in appendix 7. This shows a moisture content in that part of the sand of 4.9%, which also shows how different parts of the same sand can have different moisture, at the same time.

2-5 ncc

The 2-5 ncc sand is a sand from the NCC company that produces and delivers large amounts of sands around Norway. The sand has grain sizes between 2mm and 5mm, with a slight percentage of oversize/undersize. This sand was delivered from a quarry at Hedrum, which is a place outside the large city of Larvik. The measurements on this sand were performed by NCC themselves at the time the sand was extracted, 5th of January.

The concrete mix shows that 508kg of this sand was used to produce 1 full batch. The PSD report in appendix 7, shows a moisture content in the sand at delivery of 0.3%, but the concrete mix shows a moisture content of 1,5%. This shows the impact the environment has on the sand constantly. A full PSD rapport, with the connected graph, is also given in appendix 7.

GSG 0-1

The GSG 0-1 sand is sand collected from a local quarry quite near the Aaltvedt facility. The sand has mostly grain sizes in the range of 0mm to 1mm, but with a slight percentage of oversized grains. When talking about this sand, the measurements were also performed at the Aaltvedt facility by the Aaltvedt laboratory. This sand was measured on the 5th of march, a few days after the first experiments were performed, but before the second round of production.

For this sand the concrete mix used 153kg, in order to produce a full batch of concrete. The moisture content taken from sand in the concrete mix was 2.0%, but when testing the sand at Aaltvedt the PSD in appendix 7, shows a measured moisture of 4.5%. The full PSD rapport, with the full PSD graph for this sand is also given in appendix 7.

GSG 0-4

The GSG 0-4 sand is a sand also collected from the local quarries near Aaltvedt Betong. The sand is in essence the same as the 0-1 sand, but the grain sizes here are in the range 0mm to 4mm. This sand does not have any percentage of oversized material and was measured at the same time as the 0-1 sand.

Since this was the sand that was used in three different silos, a lot was used. 1180kg was used in total with a moisture content of either 3% or 4%. The testing of the sand at Aaltvedt showed a moisture content of 4.2%, which again is visible in appendix 7, and the full PSD rapport/graph can once again be found there.

5.2.4. Additives

With such little water in the EMC, it is often a challenge to still keep all the wanted abilities of the mixture, without making a runny, sticky and wet mass. The way to solve this is, as with other types of concrete, with the help of additives. There are a lot of additives to choose from and they all provide different degrees of assistance, with different tasks. Most of these are not relevant for this thesis, but this chapter will present the one that is used at Aaltvedt Betong. From the concrete mix recipe in figure 6.1, it can be seen that this material is called Aktiv Colour at Aaltvedt.

Aktiv Colour is a material with the full name COLORaktiv 2000 SR (LP) and is according to the standard EN 934-2: T5 classified as an *Sedimentation-reducing air-entraining agent* [39]. This is a material that produces a lot of effect that greatly improves the concrete. These are [39]:

- Reduction in efflorescence
- Stabilizing the mixture
- Improvement in the freeze-thaw resistance
- Intensifying the effect of artificially added colour
- Helping the EMC not stick to either the ramming construction or the molds

The material is suggested to be added in at an amount of 0.2-0.4 ml/kg cement [39], but this can vary with material quality and wanted effect. Figure 6.1 shows that Aaltvedt calculated with 2.00 kg of material and with a density of 1.01-1.05 g/ml [39], this is about 1905-1981 ml used. With the given amount of cement of 340kg, then it is evident that 5.6-5.8 ml/kg is well above the baseline recommendation. These are numbers that have been tested and reviewed together with the manufacturer, so even if it is well above, it is within the needed numbers in this situation. The full product information can be found in appendix 8.

6. Method

A master's thesis is a final report of an independent school project that is heavily based in the theories and practices of scientific research. It is a logical, precise and verifiable presentation of the problem being investigated, the solutions applied, the results achieved and all the work that was needed to do so. The research project is required to be grounded in a subject area that holds a central position in the overarching master's programme. As it is a requisite to pass certain subjects, including the pre-project that preceded this subject, it is natural to use the knowledge and working tools gathered there as assistance when continuing the work into this specific thesis. All the different kinds of research methods that can be used to execute a master's research project, and write the ensuing thesis, will slightly change depending on the study programme and the master's subject. This chapter, with all its following sub-chapters, will outline the methods this thesis is built upon and how they, by their function, helps the research move forward.

6.1. Literature study and literature review

6.1.1. Introduction

It has been explained a few times already that a pre-project is one of the subjects required to have been passed in order to continue on to writing this thesis. This means that anything learned, studied and produced in that subject is in many ways background literature to help the writing of the thesis itself. This specific literature study builds further upon the literature study method explained and learned in chapter 6.1.1 of the pre-project report [13] which has been provided in appendix 1 of this thesis.

6.1.2. Literature search for background theory and introductory knowledge

As is being repeated often, this thesis builds upon the work done in the pre-project report in appendix 1. This means that the primary topic of the thesis has long been agreed upon and compiled research on. The first searches of literature and the first literature study will therefore not be into new topics but it will be into the topics already written about in the pre-project report [13], in order to either see if information has been updated or if there is now available additional information to supplement the exciting sources from that report.

The first searches of this literature study, that can be seen in the aforementioned log-book in appendix 2, were systematic literature searches into the personal documentation about SiGS, that was acquired through the pre-project timeline, and additional information about cement and EMC. The first procedure in the log-book was to establish the limitations for this entire literature study. As the main facets of the study were already established, the next point was to find all search terms, abbreviations, synonyms and phrases, in multiple languages, that could help facilitate acceptable results. In order to limit the number of words in each individual search it was important to group the words in blocks, so that similar terms for one item were not used in the same block and the same search. Considering this is a continuation of the literature study from the pre-project report [13] it is natural to set the starting yearly limit at the same as in that one, 2015. This chapter has also stated that one of the purposes is to find updated information, so the limit should obviously not be older than 2015. The upper limitations have been set to 2021, as that is the year this thesis is being written, even though the probability of finding scientific research only weeks old is limited. Scientific articles can be challenging to read in non-native languages, so the selection of language limitations was set to those well known, Norwegian, Danish, Swedish and English. This is a research project started primarily by the subsidiary of Eramet, Eramet Norway AS together with the University of Agder, SINTEF Helgeland AS, Norcem AS and other companies interested in Norwegian concrete development. This means that the geographical limitations of this literature study will start with Norway, but as the project has the potential to have greater potential, the limitations will reflect that by moving outwards towards Europe. The more general knowledge about slag, cement and EMC is often found in tertiary sources, industry websites and educational websites, so that had to be included in the limit for the informational academic level. The most updated facts, numbers and figures are found in peer-reviewed scientific articles, so whenever possible, that was set as the primary limitations and criteria for selection. Articles and information found on open web-share sites was on the other hand deemed a criterion for rejection.

The methods of searching used had to change depending on the time of searching and what was being searched for. Since most of the searches in this literature study are building further on specific searches from earlier reports, those searches were systematic literature searches. The other search method was random literature searches, when the need for more searches became apparent. Both of these search methods are explained in chapter 6.1.1 of the pre-project report [13] in Appendix 1. The random literature searches were almost exclusively done through google.com, since they are the best alternative for finding educational websites and specific company websites. The systematic literature searches were on the other hand done through scientific databases, or the internal project fileshare, considering they are much better at finding articles then just google.com. When talking about the time-period the search was carried out in, that had to be separated into multiple stages. The first searches were completed on the first day of the semester, 4th of January 2021. Then the follow up searches were carried out on the 8th of January, the 29th of January and the 3rd of march. The search terms did not change significantly during this study, since they were copied almost directly from the pre-project report [13], which kept them consistent.

The first searches, done on the 4th of January, were searches into this writer's own files and the internal project file share system, in order to find all the documentation used from there in the pre-project report [13] and all new reports written since these searches were done for that report initially. Which obviously included the pre-project report [13] in appendix 1 and the search terms and reasoning behind the choices for the previously accepted reports can be found in chapter 6.1.2 there [13]. When searches for new documents in the file share system were carried out on the 8th of January a few results appeared. These searches were random literature searches and as the log-book in appendix 2 shows, the search terms were identical. The total number of hits was slightly higher the last time and of these new results two was seen as interesting. These were written by a senior employee of SINTEF and are therefore reliable for use here.

One of the first searches of the pre-project [13], right after being informed about the project subject, was into "Eramet slagg" and "Eramet product". This created the two resulting products *Grønn høyteknologi i verdenstoppen* [40] and *GRØNT BIPRODUKT Silica Green Stone* [7], which was immediately promoted to be included in this paper. The reasoning behind the selections and an explanation of them can be found in chapter 6.1.2 of the pre-project report [13] in appendix 1. The last two search were directed searches for specific values needed in the thesis.

6.1.3. Literature search for thesis and research specific topics

The consequence of already having written a pre-project report [13] was that even if the precise research question for this thesis was not immediately clear, all general themes and areas of investigation were so. This meant that the first literature search into research specific topics could be undertaken right away. Appendix 9 shows how this literature search was logged in its own log-book, which kept track of all the different searches and made it easier to make sure all areas had been searched on.

Since the research question was not fully articulated the entire process of finding facets, search terms, synonyms, phrases, language variations, abbreviations and blocking those together had to be split into sections. All of this developed in time with the wording of the research questions and the searches being needed. The limitations on the other hand could be established right away, since they were highly unlikely to change. As with the last chapter the starting year of the timeframe was kept consistent with the year from the corresponding search in chapter 6.1.3 of the pre-project report [13] in appendix 1. Even if the chance of finding 2021 dated reports is minimal, it is always best to just choose the current year as the end of the timeframe. This gave 1995-2020 as the timeframe for these searches. The languages and geographical limitations were set consistent with the previous chapter, Norwegian, Swedish, Danish, English, Norway and Europe. Since the pre-project report [13] showed research on Mn-slag has happened more outside of Europe, than inside, it was decided to also include the world. The listing of first Norway, then Europe and finally the world was also in line with the corresponding search from the pre-project report [13]. The final section of limitations that had to be documented was academic level and criteria of selection/rejection. The easiest way to get approval for a concrete with new materials, would probably be to pass the concrete testing that is already widely in use and academically accepted. These tests are generally always found in standards from organizations for standardization, like ISO, Standard Norge and CEN, so that was the first level of academia the searches were aimed at. The second level of interest was peer-reviewed primary scientific literature before the last academic level was educational material and official product information. Finally, all documentation on open file-share websites, badly referenced articles and articles with completely unknown authors were rejected.

This entire literature search was carried out using multiple search methods. These methods will be named in the place they were used and for an explanation of them, it can be found in chapter 6.1.1 of the pre-project report [13] in appendix 1. The searches have different strengths and weaknesses, so they were carried out through varying search engines. Searches for specific websites, direct product information, direct test information and more randomized information are only accessible through the general search engines Google.com, google scholar and then the standards of Standards Norway, so those searches were carried out there. When moving on to the search for scientific articles, that was done in article databases such as Web of Science, Brage, AGRIS, Google scholar and Oria. These engines are better at unearthing the most updated research that can be relevant to this thesis. These searches were as well executed in many stages, throughout the writing process. The first round of searches happened on the 12th of January 2021 and the last happened 25th of April 2021. These constantly evolving searches meant that search terms evolved along with it.

The first searches on the 12th of January were random literature searches, using google.com. The initial two searches where in reality the same search in two languages, using the terms “Alkali-Silica reaction in concrete, laboratory test methods” and “Alkali-Silika reaksjon i betong, laboratorietester”. The need for these searches came from the wish of the project research group to find a way to understand if the introduction of SiGS could have an effect on these possible reactions. When carrying out the searches in English the resulting number of hits where 1.35 million. This is obviously way too many to attempt to look through, but when switching to the Norwegian searches it only resulted in 239 hits. Out of these hits 2 where interesting enough to include in the source material for this thesis. While they did not give an exact answer to the part of the search about laboratory test methods, they provided a good explanation about the reaction itself and the theory surrounding it. One result was a report from 2013 from the Norwegian Public Roads Administration and the second was an even more recent presentation from the same company. This is one of the most trusted and well-informed researchers into concrete, in Norway, so any information from them is trustworthy.

After this time there was little need for additional searches for a long time. This was because the themes were discussed and decided on by the research group as a whole and the needed information for that was already well known.

The next search on 19th of April was this time a systematic literature search, using Google.com. The search was performed using the name “Schleibinger Geräte Teubert u. Greim GmbH” in presumably the German language. This search was necessary not only for finding data on and about that specific apparatus, but also the freeze-thaw testing process itself. The search itself generated 3330 hits, but luckily the company site, and by that the user manual were not hard to find. Most of the information that the search was looking for were easily found in the user manual and the rest were a matter of trying to use the machine itself. This user manual is made by the producer of the machine, so there are not any more reliable sources than that.

A final supplementary search was performed on the 25th of march. This was a random literature search, using google.com, in order to double check a few pieces of information about earth-moist concrete. The search term “Earth-moist concrete” was used and the hope was to get confirmation on a few numbers related to the mixing of EMC. The number of hits did reach 6.98 million, but after a little look at that, an article from the Concrete Plant International was found. They were well referenced as a company and therefore seemed reliable. The article was from 2012, but on the background of its well-presented and well-argued information it was decided that this was not too old.

6.2. Production of concrete paving stones

All concrete paving stones talked about and used in this thesis have been produced at the Aaltvedt Betong production facility. This is a highly autonomous facility that has been running for decades. For a more in-depth look at how the production lines function in normal operation, see chapter 6.3, 7.1 and 8.1 of the pre-project report [13] in appendix 1. As a consequence of the thorough explanation there, this chapter will only point out the differences made, in order to make the situation work.

The difference from that standardized production and to this chapter is the introduction and use of SiGS as a cement replacement. In order to be able to run the testing batches, a few changes had to be made to the process and that is what will be explained in this section.

The first difference made was the decision to only run half batches. This decision was made in order to not only conserve SiGS material, but keep the cost as low as possible and to provide the opportunity to run additional production, if some problem should arise. In smaller production facilities this might have been a problem, but as has been mentioned before Aaltvedt has an automated facility. This meant that just by hitting a few buttons the concrete mix, seen in figure 6.1, could be split in half and the new correct amount of each material be mixed together automatically.

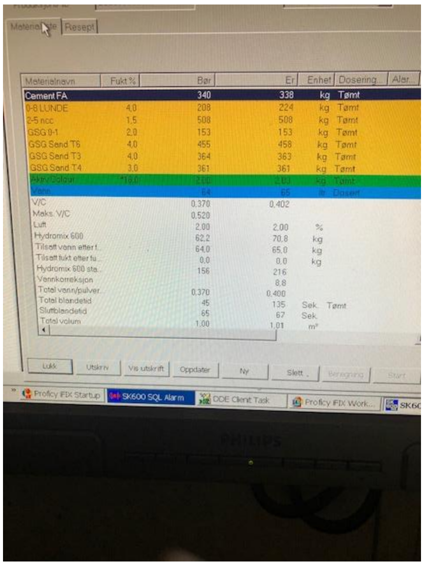


Figure 6.1 Concrete mix of the reference stones in the project

The second difference made was the removal of a certain amount of cement. This was done on the back of collaborative discussions surrounding what kinds of SiGS to cement replacement levels the group felt was best, in order to properly see the effectiveness of the SiGS. After some discussions it was decided that on the first day 20% and 40% replacement, of both SiGS types, would give an interesting spread of levels. This gave the calculations that can be seen in table 6.1, below:

Table 6.1 Cement and SiGS amounts during first production

Cement amount in a full mixing batch	340kg
Cement amount in half a mixing batch	170kg
Cement amount with 20% replacement	136kg
SiGS amount with 20% replacement	34kg

Cement amount with 40% replacement	102kg
SiGS amount with 40% replacement	68kg

The preparation and measurement of these SiGS amounts had to be done by hand. The SiGS was collected in the buckets seen in figure 6.2 below and weighted using the butcher weight in the same figure.

Figure 6.2 weight and bucket

Because of the fluffiness of the powder and the size of the buckets it was decided that no bucket should be filled with more than 12kg of material. An added benefit of this was that the buckets were easier to transport around the facility and to the concrete mixer. After being filled, the buckets were transported to the concrete mixer in another part of the facility. As has been mentioned, the production is nearly automated. In order to then make the testing possible, the production had to be manually stopped. Only then could the inspection hatch on the mixer be opened and the SiGS material added by hand. The process is shown in figure 6.3 below:

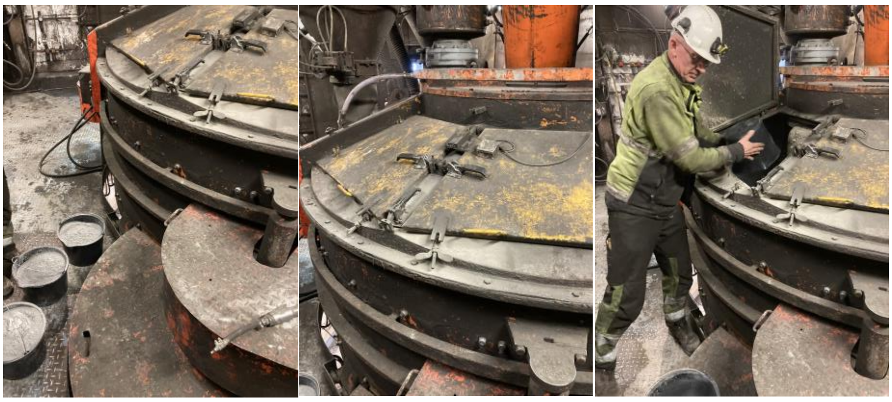


Figure 6.3 SiGS, concrete mixer, inspection hatch and manual operation

At the same time as this was done by one operator the other operators were in charge of monitoring the control room. This was the only way to safely merge the automated system with the new manual elements of it. The decision was ultimately made to not make any additional changes to the concrete mix design. In order to then run these modified batches through the system, the operators had to manually monitor the mixing time, and the added water, so that the mixture was close enough in consistency to the reference mixtures.

The second day it was decided to run additional productions, in order to create additional comparison points on the development graph. It was decided that 30% and 50% was the best alternatives and the SiGS amount calculations for that can be seen in table 6.2 below:

Table 6.2 Cement and SiGS amounts during second production

Cement amount in a full mixing batch	340kg
Cement amount in half a mixing batch	170kg
Cement amount with 30% replacement	119kg
SiGS amount with 30% replacement	51kg
Cement amount with 50% replacement	85kg
SiGS amount with 50% replacement	85kg

The rest of this second production day was run identically to the first day and the first production, in terms of both preparation and execution. This was also in order to create as close of a comparison as was possible, with the existing circumstances.

When summarising and discussing the production that went on over these first days, it was discovered that because of miscommunication the production had used *Norcem Standardsement FA* instead of *Norcem Industrisement*. Since *FA* stands for fly-ash, the cement amount ultimately turned out to be much lower than intended, in these samples. Since this gave unclear numbers and Aaltvedt ultimately also were interested in the possibilities of limiting fly-ash use in parts of their production, it was decided that Aaltvedt themselves would run the exact same production again, using *Norcem Industrisement*. Every part of the already concluded production was copied and followed to the letter, so that the comparison would be as good as possible.

6.2.1. Density and experience in full-scale production

The process the paving stones takes through the production facility, both with and without SiGS, is detailed in chapter 7.1.2 of the pre-project report [13] found in appendix 1. As a consequence of this thesis being as close to the standard production as possible, only the important sections of that process will be further highlighted in this chapter.

One of the most important parameters concerning concrete paving stones is density. Because of this Aaltvedt Betong has their own protocols for testing and controlling the density of their products. This is also mentioned in the same chapter of the pre-project report [13], as just mentioned. Since it was important to keep the production processes identical and to compare as many parameters as possible, the author himself was stationed at this section throughout the production process. The process was done identically for all the variants of stones and was as follows:

After leaving the vibration/compression machine, the trays with stones are moved towards the curing hall on a large conveyor belt. When the first couple of trays had passed, as the first and last trays of a batch always have imperfections, the conveyor belt was stopped. This was done by one of the control room operators, who was in charge of those operations that day. As can be seen in figure 6.4, the density station is situated in the middle of the conveyor belt and after stopping the belt, the operator chose an average representative of each stone batch and brought that over to the density station. That was based on intuition and what looked like a good stone. The stone was first weighted dry before being sunk into water, as can be seen in the last picture of figure 6.4, and then weighted again. Then the density was calculated using:

$$\frac{Dry\ weight}{Dry\ weight - Wet\ weight} * 1000$$

The resulting numbers were added into one of the empty production control forms, seen in appendix 10.

Figure 6.4 Density station and density procedure

A very important question to ask when doing industrial testing is how does it feel to use this new product? To get an understanding of this it is often best to go back to the beginning and to directly ask those closest to the situation.

Why do you do some of the things you do? Often an answer will not be apparent, but sometimes it is because that is how it has always been done. Repetition, experience and intuition is a major part of decision making and such is also the case in the larger industries. In a lot of company positions you can find people who have been working there for multiple decades. These people can often feel if something is wrong immediately and will be important, in order to understand the differences between using SiGS and not. This will indicate how using SiGS in a full-scale operation might be and might shine a light on any problem areas early on in the process.

In order to research this unknown parameter, a few questions had to be asked. These questions were asked in a slightly informal situation, in order to attempt to get the best answers from a live facility where everybody is constantly moving from one concrete batch to the next. The questions asked where:

- How did it go this time?
- Did something feel different?
- Did the material or time usage have to be adjusted, in order for the system to function?
- Did the finished products look different?
- How did the compaction look and was the density higher or lower than normal?

These questions were aimed at as many of the operators that were involved in the process as possible and the common answers were also noted down on the same production control forms as for density.

After every density measurement was taken, for each of the sample batches, the trays of the same paving stone configurations were moved into the same spaces in the curing hall. This was controlled by the facility operators in order to minimize the impact on the regular production pace. The curing hall at Aaltvedt Betong is a carefully controlled system of adding, stacking and removing trays in order to make sure every stone is cured in the correct time frame.

6.3. Laboratory work

The concrete standards, and the standard specifically covering concrete paving stones, defines a number of different tests of concrete properties. They also reference categories where concrete in most instances will experience crucial and critical failures. To research and test all of these crucial properties', laboratory work, both at the Aaltvedt Betong laboratory and the university's laboratory, were performed. In some instances, the testing had to be initiated at the Aaltvedt Betong laboratory and then concluded at the university laboratory. When that was necessary, the reason was tests having to be performed over a long time and then that will be commented on there. There were also instances of Covid-19 related travel and transportation issues, which made keeping with exact time frames difficult. This will also be commented on when it occurred.

Every measurement and every testing done on all of the variants of stones are based around the declared work dimensions of the stones. These form the groundworks from which everything is built around and for these types of paving stones they are:

- Length = 208 mm
- Width = 138 mm
- Thickness = 58 mm

6.3.1. Compressibility

The primary tool for keeping control of compressibility is the automated system already in existence at Aaltvedt Betong. For an in-depth explanation of how this system works, see chapter 6.3 and chapter 7.1.3 of the pre-project report in appendix 1 [13]. If the machinery should disqualify the different concrete paving stone versions, it will be noted in the corresponding results chapter.

The second tool, which can be great for keeping control of compressibility, are the different categories for shape and uniformity in the concrete paving stones standard NS-EN 1338. The literature study and the site visit that led up to the gathering of all knowledge, concerning paving stones and compressibility, can be seen in chapter 6 and 7 also in the pre-project report in appendix 1 [13]. Those chapters show how important compressibility is to the production of concrete paving stones and that the relevant standard, NS-EN 1338, covers the regulations concerning the subject. Concrete paving stones are produced by pouring an optimized earth-moist concrete mixture into moulds, applying pressure and shaking vigorously [31]. Because of this, the standard [32] covers in chapter 5.2 and in appendix C how successfully the machinery has been in compressing the concrete and filling the moulds correctly.

Chapter 5.2 of NS-EN 1338 covers a multitude of measurement deviations, that the finished stones need to stay on the positive side of. All of these deviations are relative to the given work dimensions, which is the dimensions of the stones given by the manufacturer [32]. Chapter 5.2.3 in the standard [32] points out that the stones does not have to be perfectly rectangular, but when that is the case any chased and profiled side faces or stones with a draw or spacer nibs have to have their work dimensions declared. The permissible deviations from these work dimensions are clear and well presented in the ensuing chapters of the standard. Table 1 in chapter 5.2.4 of the standard [32] classifies the permissible length, width and thickness deviations, which is given in table 6.3 here:

Table 6.3 permissible deviations for 2 different total thickness ranges [32]

Wanted thickness of paving stone	Length	Width	Thickness
< 100 mm	± 2 mm	± 2 mm	± 3 mm
≥ 100 mm	± 3 mm	± 3 mm	± 4 mm

In order to account for uneven surfaces on the stones, there is an additional point to table 1. That is that any of a random two numbers of thickness measurements, on a single paving stone, cannot differ with more than 3 mm [32]. A lot of paving stones are not rectangular. Should that be the case, then the manufacturer is responsible for declaring all the deviations, for all the other dimensions [32]. Moving further along in the regulations, there are not only limits for deviations in one direction. There is also a limit on permissible deviation differences between two measurements [32]. This is only relevant when the diagonals of the stone has a length of more than 300 mm and is given in the next table of the standard [32], reproduced in table 6.4 here:

Table 6.4 Permissible differences between diagonals, when diagonals exceed 300 mm [32]

Class of paving stone	Marking on paving stone	Maximum difference between diagonals
1	J	5 mm
2	K	3 mm

There is one final section of permissible measurement deviations, which is for flatness and bow on the upper face of the stone, when that surface is intended to be flat. This is only applicable for any stone that has a maximum dimension, in any direction, that exceeds 300 mm [32]. When that is the case, the permissible deviations are given in the next table of the standard, shown in table 6.5 below:

Table 6.5 Permissible deviations on flatness and bow measurements [32]

Length of gauge	Maximum convex	Maximum concave
300 mm	1,5 mm	1,0 mm
400 mm	2,0 mm	1,5 mm

If paving stones are supposed to be made with dimensions outside of the "standardized" sizes, or used in specialized areas, then the permissible deviations are allowed to be requested tougher. The way to perform these measurements are, according to the standard, to follow annex C of NS-EN 1338 [32], so all the deviation testing was performed according to that. The exact procedure used in this thesis is explained in table 6.6 below. In accordance with the standard 8 stones were chosen in each series of paving stones. The total groups of paving stones were 14, with 12 SiGS groups and 2 control groups, which made 112 total stones used for these measurements.

Table 6.6 Preparation and measurement procedure [32]

1.	Clean all paving stones, chosen for measuring, of all flashings and burrs.
2.	Find and use measuring equipment with a minimum of 0,5 mm accuracy.
3.	For each relevant work dimension, measure in two different places and measure to the nearest whole millimetre.
4.	Measure the diagonal of the paving stone and see if it exceeds 300 mm.
5.	If it does, measure both and note down the difference between them.

6.	Measure the thickness, to the nearest millimetre, of the paving stones at four different points, at least 20 mm in from the stone edge.
7.	Note down the measurements, find the mean thickness, also to the nearest millimetre and find the largest difference between any measurements, to the nearest millimetre.
8.	Measure the maximum dimension of the stone and see if it exceeds 300 mm
9.	If that is the case, then use measuring equipment with a minimum of 0,1 mm accuracy to measure the largest convex and concave deviations on the upper face along both diagonal axes.
10.	Measure to the nearest 0,1 mm and record all results.

All the stones measured in this chapter were then immediately used in the next procedure: *6.3.2. Test of tensile splitting strength.*

6.3.2. Test of tensile splitting strength

The standard way of controlling and testing the strength parameters of a concrete paving stone is to perform the test for tensile splitting strength. This is a testing method documented in chapter 5.3.3 of the standard, which mentions that the testing has to be done according to appendix F, of the European standard EN 1338 and the Norwegian standard NS-EN 1338 [32]. Since every production control system, in every production facility, has to follow the guidelines in that standard, those pages will not be reprinted here. What will be touched on here is the specific machinery used at the facilities used in this thesis and any slight adjustments having to be done in order to fit within the parameters of a working factory.

Chapter 5.3.3 of NS-EN 1338 is one of the smallest chapters in the standard, but it summarizes and highlights the most important regulations on the subject [32]. The chapter detail the 3 important strength parameters that each of the performed testing procedures has to satisfy, which is:

- The average characteristic tensile splitting strength, of 4 test results, T cannot be lower than 3,6 MPa [32].
- None of the individual 4 test results can be lower than 2,9 MPa [32].
- None of those 4 individual results can have a lower failure load than 250 N/mm of the splitting length [32].

Moving on to appendix F of the standard, F.1 deals with the particularities of the machine apparatus. The machine used at Aaltvedt Betong is a *Teksam aps* from Denmark, which was controlled and approved the last time by *Kontrollrådet* at 01.03.21. *Kontrollrådet* is a privately based organization that is responsible for the yearly control of technical building industry equipment. The main part of the machine can be seen in figure 6.5 below.

Figure 6.5 Tensile splitting strength machine at Aaltvedt Betong

The machine satisfies the demands of:

- Having a scale with accuracy of ± 3%, over the range of test loads, and capabilities of specific increasing rates in the load forces [32].

- Having two rigid bearers with a contact surface, that has a radius of 75mm ± 5mm [32].
- Both bearers being held in an equal vertical plane, with an misalignment tolerance of ± 1mm at both ends of the bearers, and the upper mounted bearer has to be able to rotate along its own transverse axis [32].

The standard specifies two pieces of wood, *packing pieces*, that need to be kept between the bearers and the paving stones during testing. Two such pieces, at the Aaltvedt facility, can be seen on the right of the two pictures in figure 6.5. At Aaltvedt Betong these pieces of wood are cut from a larger wood sheet, in order to satisfy the regulations of:

- Being 15mm (± 1mm) wide, 4mm (± 1mm) thick and reaching a minimum of 10mm past the expected fracture plane [32].
- Meeting the hardness criteria listed in the standard [32], which is satisfied by the plywood used at Aaltvedt Betong.

Moving on to chapter F.2 of the standard [32] comes the preparation face of the test. In the case of this thesis and the amount of stone samples, the procedure of finding all the samples, choosing a reference number of stones and preparing those became quite convoluted. The system used in this research was that the stones were removed from the curing hall after 1 day, in accordance with the standard production system at Aaltvedt. Then the first and last few trays of stones were thrown away, in order to end up with 3-5 trays of good quality reference stones, for that SiGS configuration. The stones were then stacked with the stacking robot, visible in figure 6.6. The robot stacks the stones in interlocking switching patterns, on specialized pallets, in order to keep stability when the stacks get very large. These pallets were then transported around the facility and placed outside the laboratory facility. As is visible from figure 6.6, the necessary number of stones were taken out of the stacks and moved into the laboratory. 4 and 4 stones were taken out of the stacks, in alternating patterns, in order to make sure each set of 4 stones, for each testing time interval, were taken from the same position from 4 different trays. This is the normal procedure at Aaltvedt Betong, so the decision was made to stick to that.

Figure 6.6 Stacking machine, pallets and pallets of cured SiGS paving stones

After entering the laboratory, each set of 4 stones were marked with the SiGS type, replacement amount and a letter to indicate the time interval they should be tested at. Then they were placed on shelves in a climate and temperature-controlled room, where they were kept until the time of testing. Chapter F.2 of the standard [32] does mention that the preferred way of preparing stones is by keeping them in about 20 °C water for about 24 hours, but it also allows for different methods used. In the case of Aaltvedt they have been approved by *Kontrollrådet* to keep their stones in a temperature and climate control room for the entirety of the preparation time instead, so that is the method that was used in this thesis.

The procedure used during the actual testing was pretty simple, since the produced blocks were rectangular in form. This meant that with a distance from the splitting section to the side faces of 69mm, which is far above 0,5 times the thickness of 58mm [32], section a) of chapter F.3 were easily followed. The resulting numbers were noted down in a binder, that can be seen in figure 6.7 below, before being entered into the excel-sheets, in appendix 11-20.

Figure 6.7 Note taking and calculation of test results

The testing was performed at 1, 3, 7, 14 and 28 days, in order to observe the standard concrete strength development and to be able to create a basis for understanding how much SiGS are safe to use in which situation. With 2 reference batches, 12 SiGS batches and 5 different time intervals, the test of tensile splitting strength was ultimately performed 70 times with a total of 280 stones being split.

Extra round of testing

One of the primary goals of this research project was to investigate the long-term effects of SiGS. It was therefore decided to perform another round of testing for tensile splitting strength at the latest available point. This was obviously dictated by the time of production and time of thesis delivery. This ended up being 77 days after production. These tests were performed at the UiA facility and as a consequence of this, they had to be performed a little differently.

First of the differences were the preparation of stones. It was explained a few paragraphs earlier that Aaltvedt has been allowed the procedure of not immersing the samples in water for 24h before testing. This was then also done for the additional testing at UiA. The difference is that while the 1d, 3d, 7d, 14d and 28d tested stones were kept in a climate-controlled room, this was not the exact case now. Not only had the stones been through a journey of stacking, moving and transportation from Aaltvedt Betong to UiA, but after arrival they were kept inside the main concrete laboratory at UiA. This room is generally temperature controlled, but much less accurate than the smaller facility at Aaltvedt. This would in many ways simulate the natural journey of any sold standard stone anyway.

The second difference came from the testing machine itself. As figure 6.10 shows, the machine at Aaltvedt were specially designed for the performance of tensile splitting strength testing. This was not the case at UiA where the machine available was a newer machine designed for the primary use of testing 100x100 cubes. To solve this problem, two rigid bearers were made in accordance with chapter F.1 and figure F.1 of the standard [32]. The bearers would not be able, when fitted to the machine, to move in the way the same parts of the standard dictated, but they ensured a similar spreading and increasing of load. Figure 6.8 shows these bearers after they were produced.

Figure 6.8 pictures of the rigid bearers

The third, but much smaller, difference was in the production of packing pieces. Aaltvedt Betong used a certain type of plywood that they had been approved to use. This had to satisfy the demands of chapter F.1 of the standard [32], concerning strength values. It was not deemed a feasible use of time to check if the plywood available at UiA also satisfied this, so it was decided to use a standard plywood, in figure 6.9. The assumption was that this would in all likelihood be more than enough.

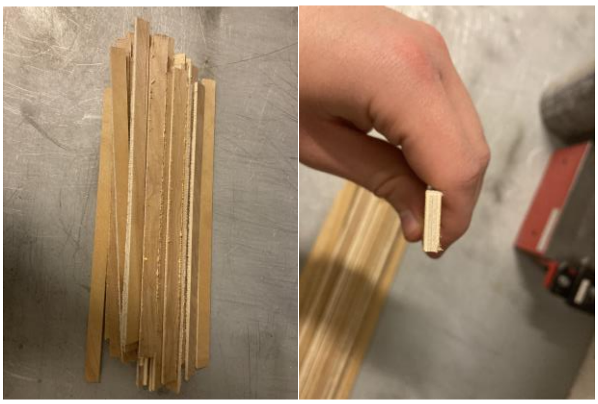


Figure 6.9 The plywood at UiA

The last difference came in the actual performance of the test and was a consequence of the second difference. Since the machine at UiA were set up for testing of cubes, it became impossible to fasten the rigid bearers to the machine structure. This meant that the insertion and centring of these had to be done by slight measurements and the eye test. Since these were loose, then the balancing and centring of the packing piece, then the stone, the other packing piece and finally the other bearer became impossible to get completely correct. Figure 6.10 shows how this was done inside the UiA machine, before each test was performed.

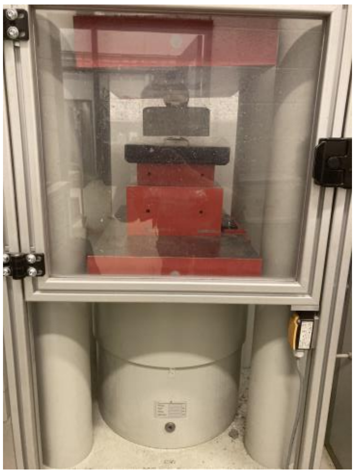


Figure 6.10 The setup in the UiA machine of the test of tensile splitting strength

The tests were run using a program in the machine for a different sized paving stone. These dimensions were impossible to change, but since the calculations of total MPa would be done using the Aaltvedt Excel system, and all that was needed were the breaking load in kN, this was deemed a less relevant concern. In order to find the correct load increase on the machine, a few preliminary tests were run. The full setup of these tests can be seen in figure 6.11.

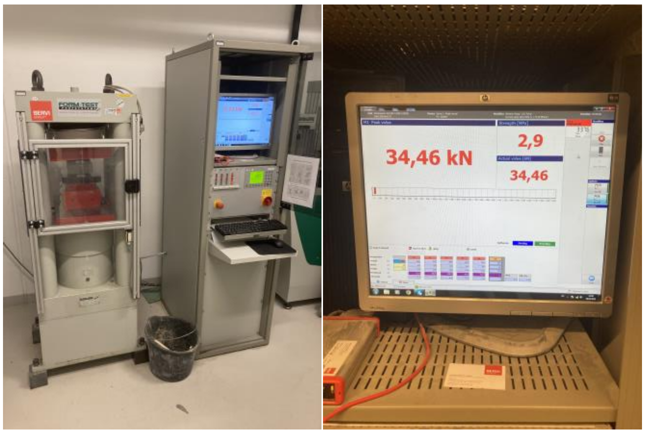


Figure 6.11 The total test setup with the machine

Appendix 21 shows a comment from Aaltvedt Betong that says that they are aiming for a test to last around 45 seconds. To attempt to reach this, firstly the machine was set to 0,13 MPa/s. When tested on a 20% air-cooled stone, this resulted in a break after 65 seconds. This was too long, so the setting was adjusted again to 0,18 MPa/s. This resulted in a break after 38 seconds on a G50 stone, 43 seconds on a G30 stone and 35 seconds on a G20 stone. This seemed close enough to the testing procedure at Aaltvedt Betong and was deemed acceptable. After this the stones were tested in the natural groups of 4, using the same procedure as with the preliminary test stones.

Each result was noted down on paper, before being entered into the same Excel document, in appendix 22, as was used to calculate the total results at Aaltvedt.

6.3.3. Test of water absorption

Aaltvedt Betong uses two main sections of laboratory testing, to perform regular product testing. One of these is the test of tensile splitting strength, shown in the last chapter, and the other is the test of water absorption. The test of water absorption is a subsection of the larger frost resistance chapter in NS-EN 1338, chapter 5.3.2 [32]. The second part of the section, about freeze-thaw deterioration, will be the subject of the next chapter, but half of the chapter and annex E is about water absorption and will be the subject in this chapter. The test of water absorption is simply a test of measuring the percentage loss in mass between a stone soaked to constant mass and the same stone dried to constant mass.

NS-EN 1338 divides frost-resistance into 3 classes [32], that a stone can receive. Class 1 is the lowest class and has therefore no regulated limits for frost resistance [32]. This is obviously a class that is only relevant in places where frost is not a concern and not here in this thesis. Jumping over to class 3, that is the class for freeze-thaw deterioration and will come in chapter 6.3.4. This leaves just class 2, which is connected to water absorption. Chapter NA 5.3.2 in NS-EN 1338 does specify that class 3 is the class that shall be used in Norway [32], but since Aaltvedt does use the water absorption test as a reliable and consistent indicator of quality, and much more rarely the more time-consuming and expensive freeze-thaw test, it was decided that they would perform water absorption at their facility anyway. This would provide another point of comparison between non-SiGS and SiGS stones and was therefore more information that will come in handy moving forward.

The actual regulation demand of class 2 frost resistance is given in table 4.1 in chapter 5.3.2.2 of NS-EN 1338 [32] and is:

- The average result of all stones tested has to be less than 6% of the mass [32]

Table 7 of NS-EN 1338 gives the factory control number of 3 stones for every test of water absorption [32]. With 2 reference stone batches and 12 different SiGS variants the total number of water absorption tests performed was 14, with a total of 42 stones tested.

Chapter E.2 of the standard specifies that no stone tested can weigh more than 5kg [32]. This could have required a need for cutting out sample stones, but since the stones were less than 5kg, whole stones were tested at the same time. It is also defined in chapter E.5 of the standard the importance of ensuring a temperature of 20°C (± 5°C) in the stones before the testing can begin [32]. This was solved by making sure that all the stones were kept in the same temperature-controlled room as the stones used for the test of splitting strength, before they were used for this test. Moving on from there, all stones were cleaned and brushed, with a stiff brush, before being lowered into a 20 °C water bath [32]. The stones were placed on a level grate in a large industry basin, that were more than big enough to satisfy the size demands in the standard [32], before being left there until 2 weightings with 24h between them showed a mass difference of less than 0.1% [32]. In order to avoid involving and calculating any excess water all the stones were wiped off with a moist cloth until the concrete stopped having the shine of excess water. After the weighing became accurate enough, each stone was placed in the ventilated drying oven, in figure 6.12, at the Aaltvedt laboratory, with the required distance of 15mm [32] between each of the stones.

Figure 6.12 The ventilated drying oven at Aaltvedt Betong

As different production dates and large production volumes made the process of starting and ending all tests simultaneously a logistical nightmare, some adjustments had to be made. The 3 and 3 stones that were connected, from the same production batch, were obviously tested at the same time. It was also the case that the first stones produced were put into the oven and dried as soon as possible to the 1d curing time, but as the stones kept coming some had to wait on others being removed from the oven, before being put in themselves. After the minimum of three days [32] in the oven and the stones passed another cycle of 24h spaced measurements, the stones were cooled and weighed the final time.

The results were entered into the same excel sheets as with the previous chapter, which can be found in appendix 11-20. The calculations done in those excel documents are according to the formula in chapter E.7 [32] of the standard.

6.3.4. Test of resistance towards freeze-thaw deterioration

One of the bigger tests of a specific paving stone property is the *Determination of freeze/thaw resistance with de-icing salt* [32]. This is a testing method in the standard NS-EN 1338 that is fundamental for determining the long-term effects of using the specific stone in everyday situations, but as a consequence of high cost and little possibility of changes of results within the same concrete mix, is rarely performed. Since SiGS stones have such a large uncertainty concerning creating changes in the material reactions, it was determined that this was a necessary testing method to perform. The requirements for an acceptable freeze-thaw resistance are given in table 4.2 of the standard as:

- No single result in a test over 1.5kg/m^2 and an average result under 1.0kg/m^2 [32]

The method used in this chapter is a replica of Annex D of the standard [32] and this chapter will consequently not copy all aspects from that annex. As has been the case with other chapters in this thesis, this chapter will merely attempt to comment on how well this method is staying within the limits of the standard and where this thesis might differentiate, in order to be practically possible.

Determination of freeze/thaw resistance with de-icing salt [32] is one of the longest and most time-consuming testing methods found in Annex D of NS-EN 1338. As chapter D.1 of the annex describes, the test is a method with the principle where 3 concrete paving stones, for each test, are preconditioned before the surfaces are covered with a 3% NaCl solution and the stones are run through 28 freeze thaw cycles [32]. Any materials that have scaled off after 28 days are then collected, weighed and expressed in kg/m^2. Since this is a test that can be performed on all kinds of different paving stones, it is important to calculate the test surface that is being used and to make sure the test surface is within the limits given in the standard. In chapter 6.3 of this thesis, it is given that the length and width of one paving stone are 208x138mm, which gives a surface of 28704mm^2. This is outside the limits of 7500-25000mm^2 [32], which means that the specimens have to be taken out of the larger stones/blocks. The standard mentions that the stones have to be at least 20 days old, in order to be cut to fit the given limits, so that is something any stones used in this thesis were well within. The equipment used to cut the specimens to size were a *Tyrolit hydrostress* concrete saw that is situated at the laboratory at UIA. The saw is visible on figure 6.13 and is regularly controlled.

Figure 6.13 Concrete saw at the University of Agder

This is in line with chapter D.4 of the standard and is therefore more than appropriate. The decision was made to perform cutting of at least one stone, of each kind, before the cutting of the sample stones. Since there still exists uncertainties surrounding the packing and density of the SiGS paving stones this was a way to see if the cutting would produce unwanted cracking or other irregular effects. Each of the stones that were cut before the sample stones themselves, were examined thoroughly and measured at least three times in each direction. After a few attempts at finding the optimal way of cutting the paving stone it was decided that because of the ridges and corners of the stone, it would be better to have some supportive help to keep the stones in place and somewhat level. This was accomplished with the metal disc and clamp shown in figure 6.14, which made the cutting significantly more repeatable.

Figure 6.14 Clamp and metal disc for edge support

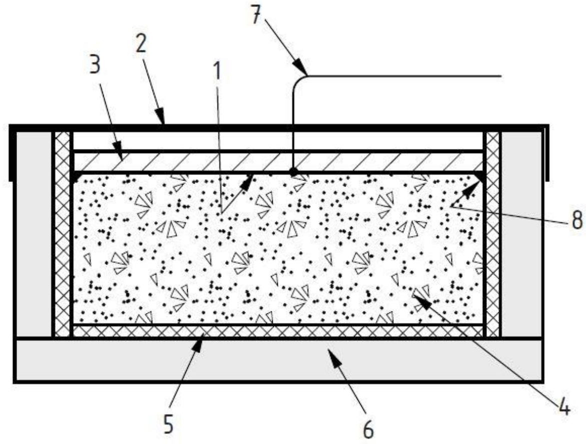
After that had produced the satisfactory results, 3 paving stones of each of the 7 *Industrisement* types, with and without SiGS, were cut in a similar pattern. These 21 cut stones were now going to be used as the official freeze/thaw samples. These official test samples were also examined for irregularities [32], before being set aside for *preparation of test specimens*. The standard specifies, in table 7, the need for 3 stones for each test being performed [32]. With 14 different kinds of stones produced in chapter 6.2 of this thesis, this would normally mean 14 tests and 42 stones. The two reasons 7 tests were deemed optimal were time and available space. The machine that is able to control the free-thaw cycles has limited space. This meant that there would never be enough space to do the full number of tests and therefore something had to be prioritized. Since Aaltvedt Betong is mostly interested in using the SiGS with *Industrisement* that was then prioritized.

Moving on to the *preparation of specimens* [32], a few adjustments had to be made for practical purposes. After finally having been the recipient, at the UiA laboratory, of the produced paving stones it became clear that to get enough of the necessary rubber sheets, in points D.4.3 [32], was difficult and time-consuming. It was then decided that in order to reach the delivery time limits an alternative had to be made. After discussions with the supervisors and external experts from UIT it was decided that replacing the rubber with a thick enough layer of Tec7 sealant could provide close to the same functions. This meant that the climate chamber mentioned in point D.5 of the standard [32] would not be used to help strengthen the seal between the rubber sheets and the concrete and was therefore a little less critical.

Another adjustment needed was the timeframe for when to start the test itself. The preparation chapter says that the test has to start between 28 and 35 days [32] after the stones are produced. This would turn out to not be possible, since Covid-19 regulations at the university made it impossible to freely work at the necessary pace and an unfortunately placed easter holiday, shut the whole school building down. As was mentioned a few paragraphs earlier, the *Industrisement* stones were prioritized for this test. This had the fortunate side effect of being the stones that were produced last, which again became the closest to 35 days as was possible to come. The *Industrisement* stones were produced on the 08th of march and by the time they were finally placed inside the machine, on the 20th of April, 43 days had passed. This is 8 days after the recommendation, but some reasons for this not being the biggest problem will be discussed in the discussion chapter for the results of this test.

Chapter D.5 of the standard [32] mentions that the stones have to spend 168h in a climate chamber curing with the previously mentioned rubber sheets. A few paragraphs ago it was mentioned that without the rubber sheets this was less relevant, but there was still an attempt made to replicate this as closely as possible with Tec7. Therefore, instead of being kept in an actual climate chamber, the samples were kept for the 8 extra mentioned days in a room where the standard temperature is 20° and the relative humidity is controlled by an air-condition system to be at a normal level between 55% and 75%. This meant that the stones could cure and the Tec7 could harden as much as needed.

Then came the actual preparation of testing samples for this thesis. Figure 6.15 shows an example of how an optimal specimen should look, according to the standard [32] and that is the basis from where all adjustments were done from. The figure shows the rubber, which it was decided to replace with Tec7, all-encompassing the concrete before the thermal insulation surrounded that again. The many times mentioned chapter D.5 in the standard mentions that a silicon rubber/sealant has to provide a complete seal between the rubber and the concrete [32]. The Tec7 is in itself such a sealant, so by careful construction the Tec7 should satisfy this requirement.



Key

1 Test surface	5 Rubber sheet
2 Polyethylene sheet	6 Thermal insulation
3 Freezing medium (salted water)	7 Temperature measuring device
4 Specimen	8 Sealant string

Figure 6.15 An example of the optimal setup of a test specimen (the cross-section) [32]

As luck would have it the laboratory at UIA already had something that would perfectly cover the area of thermal insulation. A former student project at the university investigated the use of polystyrene boxes for the production of concrete cubes, instead of standard steel constructions. These boxes had sides of 20mm polystyrene, which was the size recommended by point D.4.4 of the standard [32] and as figure 6.16 shows, only small adjustments would make them perfectly usable.

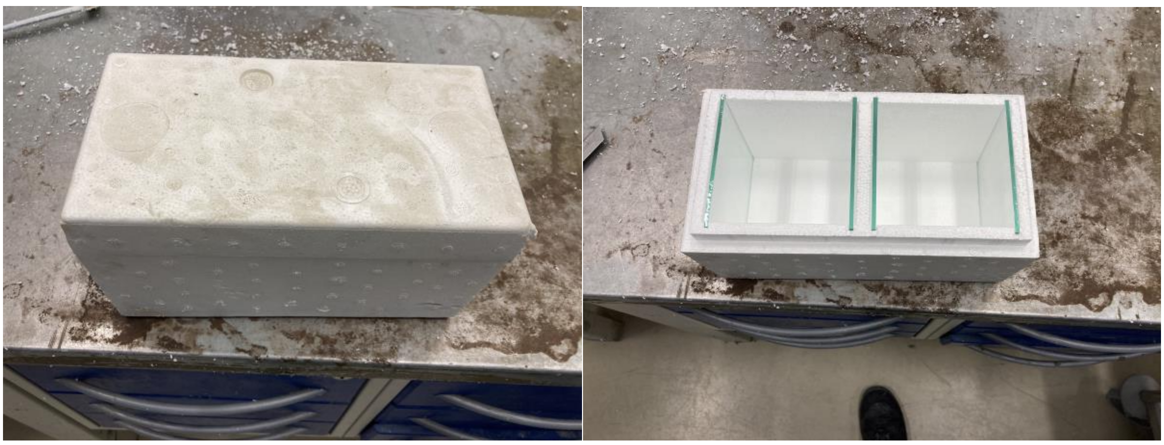


Figure 6.16 Polystyrene box with 20mm edges

Firstly, the boxes were made for the production of two cubes. This had the unfortunate side effect of only giving the separating polystyrene piece a thickness of 10mm. The way to solve this was to cut the box on one side of the divider. Then to cut off an edge of the leftover piece and glue/tape that onto the previously cut side of the main box. This is illustrated from left to right in figure 6.17.

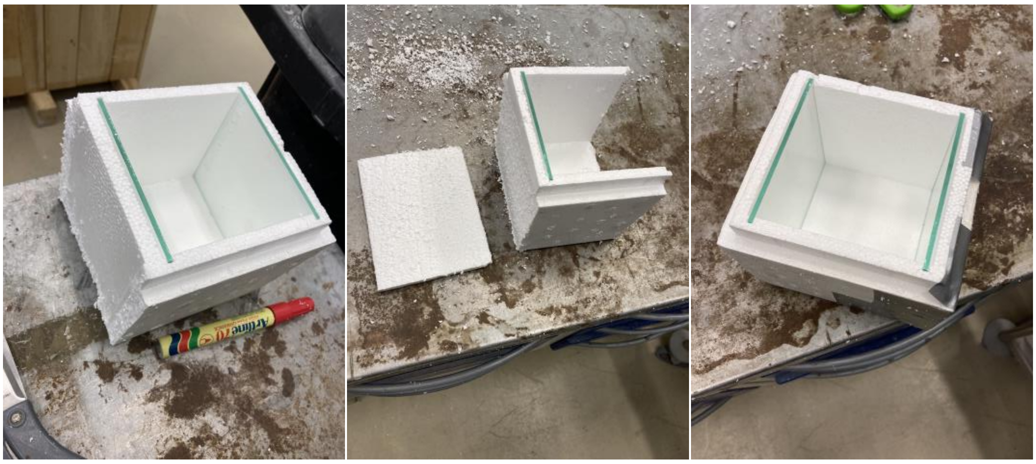


Figure 6.17 Cutting and adjusting the box dimensions

After the construction of the boxes, the actual insertion of the paving stones, and sealing of the edges, could begin. As figure 6.18 shows, The Tec7 was filled into the box and then smeared out into all areas of the box. Then the stones were lowered into the box and the edges were sealed with a 2,5mm line of Tec7 sealant.

Figure 6.18 Tec7 and the fitting of the paving stones

After the stones had been sealed in, the boxes were filled with 5mm of distilled water, holding room temperature of 20°. According to the standard, the water was supposed to be held on the stones for 70-74h [32], but once again time ran away from the project. In order to still have enough time on the backend of the experiment, both for the rest of the work on this and at the rest of the thesis, it was decided that 24h would have to be enough. This was also the timeframe listed on the Tec7 sealant for that to fully cure. Thermally insulating the samples are supposed to happen during this timeframe [32], but that had already happened, so the samples were left in peace for 24h.

In preparation for the following day, some substances had to be prepared. 30min before placing the samples into the freezing chamber, the water was replaced with a 3% NaCl solution [32]. This solution was made, as shown in figure 6.19, with a standard chemical NaCl, distilled water and a laboratory weight. The solution was therefore made according to weight percent. During the 30min, after the NaCl solution was added, the time was right for starting up and calibrating the freezing chamber.

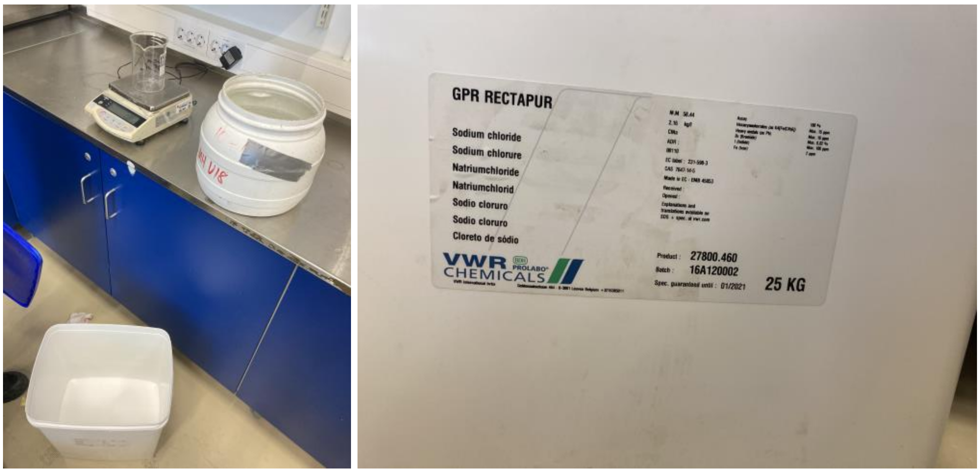


Figure 6.19 NaCl and the mixing process

The freezing chamber used at UIA was a *Schleibinger Ger¨ate Teubert u. Greim GmbH* Schleibinger Slabtester. This is a Freeze Thaw Tester that is capable of many functions, but in this thesis was only used for freezing and thawing in air [41]. This machine is capable of performing tests according to 22 different standards [41], where the EN 1338 family of standards are one of those. The machine and the documentation for this specific one can be seen in figure 6.20.

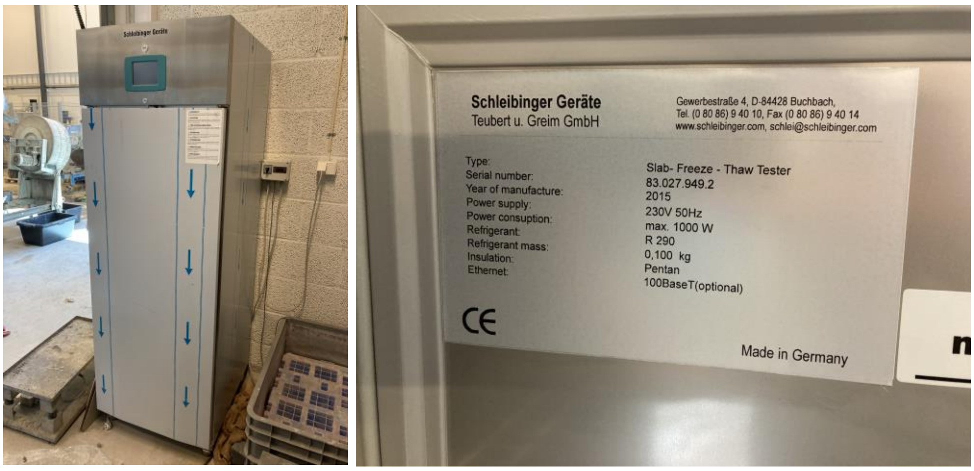


Figure 6.20 Freezing chamber at UIA

When finally finding the manual for the machine it became time to set up the testing procedure properly. The machine was switched on near the main plug with the activate switch [42] and after booting up for 20-30 sec, the machine was operating and the main menu, in the first picture of figure 6.21, appeared. After that the *setup* button was pressed, which is in the middle of figure 6.21. Then from that the *profile inp.* tab was hit and the choices in the last picture of figure 6.21 appeared. There were a lot of choices there, but the EN 1338 was an already added option, so that was chosen. Since this is an automated setting, the machine will follow the temperature profile from said standard [32]. This temperature profile is then run for 28 cycles, which is 28 days.

Figure 6.21 Menu of the freezing chamber

From there each of the samples were covered by a polyethylene sheet, stretched in such a way as not to touch the water, and placed inside the chamber [32]. It was assumable that the automated EN 1338 setting follows the settings in chapter D.6 of the standard [32], concerning time and temperature ranges, so that was not double checked. The temperature in the chamber was measured with both the integrated sensors and with an additional temperature measuring device. This way, there were 6 temperatures being measured instead of just 2. The test had to be run concurrently with another student project, but as figure 6.22 shows, everything was spread out in the chamber and the machine started.

Figure 6.22 Placement inside chamber and starting details

When 7 and 14 cycles had passed, and while the samples were thawing, a little extra NaCl solution was added to the samples [32]. This was needed for keeping the level at the earlier specified 3-7mm layer.

When 28 days/cycles had passed, the machine program was stopped and the door was opened. When opening the machine, it became apparent that the machine had been started at the wrong point in a temperature cycle. This was because as figure 6.23 shows, the surface moisture was still frozen. Unfamiliarity with the machine setup had led to problems starting it, but it was assumed to be alright. This was wrong.

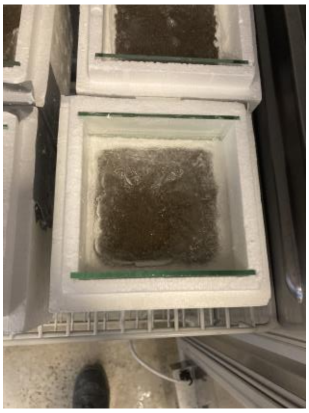


Figure 6.23 Frozen surface of a freeze-thaw sample

As a consequence of this, the samples were left in the machine, with the door open, overnight to thaw. The next day, each sample where removed, rinsed with a spray bottle, brushed with a soft brush and poured into filter paper. This is in accordance with chapter D.6 of the standard [32]. Figure 6.24 shows all of the materials used for this collection process.

Figure 6.24 Filter paper, spray bottle and brush used to collect the scaled of material

The materials and filter were then dried using a standard drying cupboard, that can be seen in figure 6.25. This was set to 75°C and left for 4 hours.

Figure 6.25 Drying cupboard and materials drying inside it

When the materials were dry, they were moved to the area pictured in figure 6.26 and finally weighed using a standard laboratory scale. The results were noted down on paper, before being calculated and added to the results as first total g over total mm^2, then g/mm^2 and finally converted to kg/m^2.

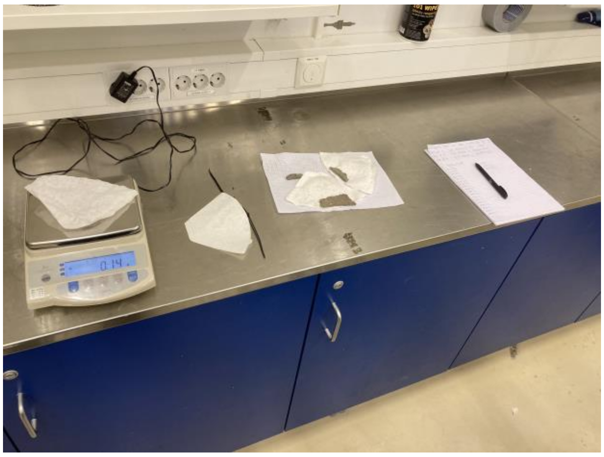


Figure 6.26 weighting scaled of materials

6.3.5. Geometric stability, measurements and visual appearance

When investigating new materials in any concrete mixture it is important to look at the possibilities of the reactions that have the possibility to completely ruin a concrete. Such possible reactions as the alkali-silica reactions and delayed ettringite reactions are two such possibilities that could have serious consequences for the lifespan and properties of a concrete. To properly look at those themes, there would be a need for deep and long-lasting chemical analysis of not only individual materials, but also the EMC as a whole. This is not something this thesis has either the time to properly follow up on or the knowledge to see through to the needed degree. As a consequence of this, chapter 6.1.3 has looked at some of this in a simple literature study, in order to see if there is a big need for in depth study on the subject.

There are a few other things that are possible to investigate in this thesis, by using some already established methods in combination with each other. This last method will therefore use a mixture of what the standard NS-EN 1338 calls *Verification of visual aspects* [32] and *Measurement of the dimensions of a single block* [32] to do so. These chapters are a way of using the best equipment available, the human eyesight, to firstly spot imperfections and irregularities and then using precise measuring equipment to document those. The hope is that not only will this discover the superficial discoloration/unevenness, it will also discover more serious cracking/flaking, that then might need further investigation for possible connection to shrinkage or expanding forces.

The theme of visual aspects is firstly covered in chapter 5.4 of NS-EN 1338. This chapter specifies how, when examined according to annex J of the standard, the stones can have no sign of cracking, flacking, delamination/separation, and a good texture consistency and colour consistency [32]. The same chapter also mentions some irregularities that do not have an impact on the performance of them and some that are avoidable if they occur. These are things like efflorescence and variations in colour/textures as a cause of variations in raw materials. Because of this they are normally overlocked in standard production testing. Since this is a completely new mixture, with a new material, it is important to include these, and any other small changes, also into the observations. With more data will then come the possibility of ruling out different things, but in the beginning stages everything should be included.

The procedure for annex J *Verification of visual aspects* is very simple in its theory and was therefore simple to replicate in this case. This procedure is listed in table 6.7 below.

Table 6.7 The procedure done in order to document the visual aspects of the stones according to NS-EN 1338

Number in the list of procedures	Procedures that verify and documents visual aspects about the concrete paving stones
1	Pick out 20 stones1) of the reference batch and do a preliminary check of each stones for cracking, flacking, delamination, texture conformity and colour conformity [32]
2	Take the 20!) stones and lay them down outside in an approximately square interlocking pattern [32]

3	Repeat number 1 and 2 in the list with 20[1)] stones from one of the SiGS batches
4	Stand at a distance of 2m from each side of the stone squares and record any visible imperfections [32]
5	Compare cracks, flaking, texture and colour [32]
6	Measure and record imperfections.
7	Switch out the SiGS stones with 20[1)] stones from another SiGS batch and repeat step 3-6 with those stones
[1)] The standard says 20 stones, but because of limited delivery, some not being usable because of transportation conditions and time constraint, 20 stones would not be possible. It was decided that 8 stones would be a good compromise.	

This procedure was supposed to be performed on both cement variants, but because of time-constraints, and a primary interest in looking at long time effects, it was decided to only look at the stones with longest curing. These were the *Standardsement FA* stones.

After an initial assessment, seen in figure 6.27, it was decided that the surface of some stones, like the one on the left of the picture, looked "moist". In order to remove the possibility of limited ability to properly cure and dry, while being stacked in transport, it was decided that 4 stones, of each 7 variants, should be dried out in a standard drying cabinet. This cabinet is shown in figure 6.28.

Figure 6.27 Initial assessment of texture and colour

Figure 6.28 Standard drying cabinet at UiA

After spending 4-5 hours in up to 70°C another check of texture and colour was made and this can be seen in figure 6.29. The stone with the writing has been dried, the one in the bottom right is a similar undried stone and the two on the left are reference stones.

Figure 6.29 Comparison of extra dried and not dried stones

After the process of drying 4 and 4 stones, 8 stones of each type were laid in a square pattern. 4 of these were numbered and dried, and 4 were not. Then the rest of the procedure in table 6.7 was followed.

When it comes to *Measurement of the dimensions of a single block* this is something that has already been covered in chapter *6.3.1 Compressibility.* This section of this method will follow that chapter closely, especially table 6.3 and the procedure in table 6.6. 4 random stones were picked out of the earlier 8 stones, for each of the 7 stone variants.

After each of the 7x4 stones had been measured and documented, these were then moved over for the second test of tensile splitting strength. It was supposed to be 8 stones of each for measurements, but it was decided to "combine" the two tests, and just measure those used for tensile splitting strength.

All the results were noted down on paper and then entered into the thesis.

7. Results

As a consequence of this being a research project that is attempting to investigate multiple facets of possibly using SiGS for concrete paving stone production, it was necessary to give the reader a structured and understandable way of moving through the thesis. Therefore, each result chapter is split into and listed in the same order as the corresponding method chapter.

7.1. Literature study and literature review

Concrete, or any special kinds of concrete, is a material that is always very open to potential damaging effects. To either make sure those effects never happen or to combat them when they do, only certain tested materials can be used in concrete. Since this thesis is looking at a completely new material, it is vital to keep these things in mind. One of these effects, that will gradually lead to more and more damage, is the alkali-silica reaction (ASR).

ASR is the chemical reaction inside the concrete where the silica materials inside a lot of common aggregates will react with the alkali hydroxide, which comes from the cement [43]. This will break the silica somewhat apart to form a gel like substance. This gel is highly absorbent and will not only absorb the water from the cement paste surrounding it, but also free water from the environment. This makes the gel expand, which again often subjects vulnerable sections of the concrete to expansive pressure [43]. Concrete is often designed for compression, so these expansions can rip sections of the concrete apart from the inside. Normally the ASR itself will only result in random map cracking or spalled concrete, but in serious cases this could lead to even worse effects. This could jeopardize both the density and the strength of the concrete [43], which again creates more vicious cycles of negative consequences, such as limited frost resistance and corrosion. The cracking/spalling from ASR are especially common in areas where there is a steady supply of moisture. This would mean in spots with flat unprotected concrete, close to the ground and generally areas subjected to much weather.

There does exist some division among experts about which of the parts that has the largest effect on ASR, but the subject is a difficult one to fully understand [43]. Since there are three parts necessary for the ASR to function, the optimal way to limit ASR is to eliminate one of them. The first possible solution is to rigorously test the aggregate to make sure that it does not contain the potentially dangerous silica. The second is to limit the amount of alkali in the concrete and the third is to limit the moisture available to the concrete. The first and second of these are problems that have to be solved before the concrete is made and the third way is something that can be helped along greatly even after the concrete has been laid.

The aggregate at Aaltvedt Betong has already been tested for ASR possibilities and shows little to no danger of that, but then the problem comes with cement. A way to solve that has been with the use of some SCMs, since they will partly react with some alkaline hydroxide and form C-S-H instead of ASR [6]. This leaves only the problem of moisture, which can be helped by carefully constructing the mix recipe to not use too much water and by covering the concrete so that external moisture does not enter into the situation.

7.2. Production of concrete paving stones

The presented results in this chapter are deeply connected with the results in the next three sub-chapters. Those chapters are related to experiences and comments made of the productions, so that will not be repeated here. Figure 7.1 is a picture taken of standard reference stones taken on the first day of production. Following from that is figure 7.2-7.4, which is pictures taken of the SiGS stones in order of when they were produced, starting with both 20% mixes and ending with the 50% granulated mix.

Figure 7.1 Fresh reference stones

Figure 7.2 Fresh 20% air-cooled and granulated SiGS

Figure 7.3 Fresh 40% air-cooled and granulated SiGS

Figure 7.4 Fresh 30% and 50% granulated

Both to minimize the impact on the normal factory production and as a consequence of the process, the production was done over 3 days, with different cement used and with different SiGS amounts mixed in. Table 7.1 is a matrix that shows an overview of this process and explains what was done, with what material on each day.

Table 7.1 Matrix of production days, cement usage and SiGS usage

Production date	Cement material	SiGS material	SiGS substitution level	Production code
03.03.21	*Norcem Standardsement FA*	None	0%	0303-FA-N0
03.03.21	*Norcem Standardsement FA*	Air-cooled	20%	0303-FA-A20
03.03.21	*Norcem Standardsement FA*	Granulated	20%	0303-FA-G20
03.03.21	*Norcem Standardsement FA*	Air-cooled	40%	0303-FA-A40
03.03.21	*Norcem Standardsement FA*	Granulated	40%	0303-FA-G40
04.03.21	*Norcem Standardsement FA*	None	0%	0403-FA-N0
04.03.21	*Norcem Standardsement FA*	Granulated	30%	0403-FA-G30
04.03.21	*Norcem Standardsement FA*	Granulated	50%	0403-FA-G50

08.03.21	*Norcem Industrisement*	None	0%	0803-IN-N0
08.03.21	*Norcem Industrisement*	Air-cooled	20%	0803-IN-A20
08.03.21	*Norcem Industrisement*	Granulated	20%	0803-IN-G20
08.03.21	*Norcem Industrisement*	Granulated	30%	0803-IN-G30
08.03.21	*Norcem Industrisement*	Air-cooled	40%	0803-IN-A40
08.03.21	*Norcem Industrisement*	Granulated	40%	0803-IN-G40
08.03.21	*Norcem Industrisement*	Granulated	50%	0803-IN-G50

These codes will appear in different iterations in all of the tests, but only when the chapter specifically mentions it were the same stones used for multiple results. If not mentioned then different stones were used.

7.2.1. Density and experience in full-scale production on 03.03.2021

The results in this chapter are the height and density measurements taken of every different kind of stone produced in the testing time frame, on the first project day. It also includes comments from the technical experts/operators at the facility and any peculiarities related to the different productions. The results are listed in table 7.2-7.4 in the order of how they were produced, which means that all stones in this chapter used the *Norcem Standardsement FA*.

Table 7.2 Overview of density measurements and production notes for day 0 of the reference batch

Code	Height	Density	Comments about the production and testing of the stones
0303-FA-N0	58mm	2269kg/m^3	Standard production without any problems, taken by the operators at 07.00
0303-FA-N0	58,5mm	2224kg/m^3	Standard production without any problems, taken by the operators at 08.00
0303-FA-N0	58mm	2272kg/m^3	Standard production without any problems, taken by the operators at 08.45
0303-FA-N0	59mm	2250kg/m^3	Standard production without any problems, taken by the operators at 12.10

Table 7.3 Overview of density measurements and production notes for day 0 of the 20% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0303-FA-A20	Air-cooled	58mm	2278kg/m^3	36 L. water and HDMI = 200 (surface was nice and smooth, density was inside the limits and every expert involved from Aaltvedt was positive. It took some time to get a homogenized mixture in the concrete mixer)
0303-FA-G20	Granulated	59mm	2276kg/m^3	35 L. water and HDMI = 200 (surface was nice and smooth, density was inside the limits and the difference from the air-cooled density is inside margins of errors. Every expert involved from Aaltvedt was also positive about the results of these fresh stones. It took some time to get a homogenized mixture in the concrete mixer)

Table 7.4 Overview of density measurements and production notes for day 0 of the 40% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0303-FA-A40	Air-cooled	59mm	2228kg/m^3	31 L. water and HDMI = 195 (surface was nice and smooth, density was outside the limits of the charts and slightly lower than wanted. The height was the same, but the operator in the control room would have wanted to increase the water slightly to get a better mixture and an easier mixing time)
0303-FA-G40	Granulated	59mm	2226kg/m^3	32 L. water and HDMI = 195 (surface was nice and smooth, density was outside the limits of the charts and slightly lower than wanted. The height was the same, but the operator in the control room would have wanted to increase

				the water slightly to get a better mixture and an easier mixing time)

7.2.2. Density and experience in full-scale production on 04.03.2021

The results in this chapter are similar to the previous chapter. Here the height and density measurements, from the second project day, are presented for each of the different stone types produced, as was the case in chapter 7.2.1. There were only 3 batches mixed on this day, instead of 5 the previous, but a second stone was measured in the 50% batch. There are also here included the interesting comments from the machine operators. The results are listed in table 7.5-7.7 in production order here as well. These stones in this chapter used the *Norcem Standardsement FA* as well.

Table 7.5 Overview of density measurements and production notes for day 0 of the reference batch

Code	Height	Density	Comments about the production and testing of the stones
0403-FA-N0	58mm	2264kg/m^3	Standard production without any problems, taken by the operators at 07.00
0403-FA-N0	58mm	2280kg/m^3	Standard production without any problems, taken by the operators at 08.00
0403-FA-N0	58mm	2279kg/m^3	Standard production without any problems, taken by the operators at 09.00

Table 7.6 Overview of density measurements and production notes for day 0 of the 30% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0403-FA-G30	Granulated	58mm	2250kg/m^3	33 L. water and HDMI = 202 (surface was nice and smooth, density was outside the limits of the charts and slightly lower than wanted. The height was the same)

Table 7.7 Overview measurements and production notes for day 0 of the 50% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0403-FA-G50	Granulated	58mm	2307kg/m^3	31 L. water and HDMI = 200 (surface was nice and smooth, density was outside the limits of the charts and slightly lower than wanted. The height was the same, but the density was so high that it was decided to take another measurement as a reference)
0403-FA-G50	Granulated		2252kg/m^3	Now the density was much lower than the other stone

7.2.3. Density and experience in full-scale production on 08.03.2021

The results in this chapter are once again presented in a similar fashion as with the previous chapter/chapters. The documentation of height, density and experiences were noted down by Aaltvedt themselves, during the production day they had on their own. This is a similar production to the two previous ones put together, so the results are therefore much more expansive. In this production, there were some irregularities with 20% granulated SiGS, so Aaltvedt made the decision to produce another batch and run the entire test again. This is explained in table 7.9. The results are again listed in table 7.8-7.12 below in production order, but in this case all stones in this chapter used the *Norcem Industrisement*.

Table 7.8 Overview of density measurements and production notes for day 0 of the second production of a reference batch

Code	Height	Density	Comments about the production and testing of the stones
0803-IN-N0	59mm	2303kg/m^3	Standard production recipe, but with normal cement (in order to have another comparison). 33 L. water and HDMI = 208. The products were normal out of the machine

Table 7.9 Overview of density measurements and production notes for day 0 of the second production of 20% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0803-IN-A20	Air-cooled	59mm	2238kg/m^3	33 L. water and HDMI = 204 (no notes were given about this test production, so it was deemed ok) density is a little lower than wanted
0803-IN-G20	Granulated	60mm	2235kg/m^3	34 L. water and HDMI = 210 (the operators said that as a consequence of machine trouble, the mixture became much less viscous and much less compacted. This meant that they did not have good enough representative stones, so the decision was made to run the test again)
0803-IN-G20	Granulated	58mm	2251kg/m^3	32 L. water and HDMI = 202 (this time everything was normal with the production) density is a little lower than wanted

Table 7.10 Overview of density measurements and production notes for day 0 of the second production of 30% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0803-IN-G30	Granulated	59mm	2231kg/m^3	32 L. water and HDMI = 202 (no notes were given about this test production, so it was deemed ok) density is a little lower than wanted

Table 7.11 Overview of density measurements and production notes for day 0 of the second production of 40% SiGS batch

Code	SiGS type	Height	Density	Comments about the production and testing of the stones
0803-IN-A40	Air-cooled	59mm	2236kg/m^3	32 L. water and HDMI = 204 (no notes were given about this test production, so it was deemed ok) density is a little lower than wanted
0803-IN-G40	Granulated	59mm	2196kg/m^3	32 L. water and HDMI = 197 (no notes were given about this test production, so it was deemed ok) density is a little lower than wanted

Table 7.12 Overview of density measurements and production notes for day 0 of the second production of 50% SiGS batch

Code	**SiGS type**	**Height**	**Density**	**Comments about the production and testing of the stones**
0803-IN-G50	Granulated	58mm	2230kg/m^3	32 L. water and HDMI = 197 (no notes were given about this test production, so it was deemed ok) density is a little lower than wanted

7.3. Laboratory work

The results in this chapter are structured into sub-chapters that correspond with their respective method sub-chapters under the larger methods chapter, chapter 6.3.

7.3.1. Compressibility

The results presented in table 7.13-7.37, below, are the results of measurements taken of four and four stones, at certain time intervals, right before further testing and of all the different SiGS iterations. The measurements were made on stones from all three production dates on the same four stones that were going to then be used for testing of splitting strength. These measurements were made at Aaltvedt Betong, by themselves, and they did not feel it necessary to measure lengths and widths, since the stones are made in a standard size mould.

Table 7.13 Overview of measurements made on 1d curing with the reference batch

Code	Production date	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-N0-1	03.03.21	58mm	208mm	138mm	59mm	250mm
0303-FA-N0-2	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-3	03.03.21	58mm	208mm	138mm	59mm	250mm
0303-FA-N0-4	03.03.21	58mm	208mm	138mm	58mm	250mm
0803-IN-N0-1	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-2	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-3	08.03.21	58mm	208mm	138mm	61mm	250mm
0803-IN-N0-4	08.03.21	58mm	208mm	138mm	60mm	250mm

Table 7.14 Overview of measurements made on 3d curing with the reference batch

Code	Production date	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-N0-1	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-2	03.03.21	58mm	208mm	138mm	59mm	250mm
0303-FA-N0-3	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-4	03.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-1	08.03.21	58mm	208mm	138mm	61mm	250mm
0803-IN-N0-2	08.03.21	58mm	208mm	138mm	60mm	250mm
0803-IN-N0-3	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-4	08.03.21	58mm	208mm	138mm	59mm	250mm

Table 7.15 Overview of measurements made on 7d curing with the reference batch

Code	Production date	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-N0-1	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-2	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-3	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-4	03.03.21	58mm	208mm	138mm	58mm	250mm
0803-IN-N0-1	08.03.21	58mm	208mm	138mm	60mm	250mm
0803-IN-N0-2	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-3	08.03.21	58mm	208mm	138mm	59mm	250mm

0803-IN-N0-4	08.03.21	58mm	208mm	138mm	60mm	250mm

Table 7.16 Overview of measurements made on 14d curing with the reference batch

Code	**Production date**	**wanted thickness**	**Length**	**Width**	**Thickness**	**Diagonal 1 & 2**
0303-FA-N0-1	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-2	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-3	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-4	03.03.21	58mm	208mm	138mm	60mm	250mm
0803-IN-N0-1	08.03.21	58mm	208mm	138mm	60mm	250mm
0803-IN-N0-2	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-3	08.03.21	58mm	208mm	138mm	60mm	250mm
0803-IN-N0-4	08.03.21	58mm	208mm	138mm	61mm	250mm

Table 7.17 Overview of measurements made on 28d curing with the reference batch

Code	**Production date**	**wanted thickness**	**Length**	**Width**	**Thickness**	**Diagonal 1 & 2**
0303-FA-N0-1	03.03.21	58mm	208mm	138mm	59mm	250mm
0303-FA-N0-2	03.03.21	58mm	208mm	138mm	59mm	250mm
0303-FA-N0-3	03.03.21	58mm	208mm	138mm	58mm	250mm
0303-FA-N0-4	03.03.21	58mm	208mm	138mm	58mm	250mm
0803-IN-N0-1	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-2	08.03.21	58mm	208mm	138mm	59mm	250mm
0803-IN-N0-3	08.03.21	58mm	208mm	138mm	60mm	250mm
0803-IN-N0-3	08.03.21	58mm	208mm	138mm	60mm	250mm

Table 7.18 Overview of measurements made on 1d curing with the 20% SiGS batch

Code	**Production date**	**SiGS type**	**wanted thickness**	**Length**	**Width**	**Thickness**	**Diagonal 1 & 2**
0303-FA-G20-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-2	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-4	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-1	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-2	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G20-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G20-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-2	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A20-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-4	08.03.21	A	58mm	208mm	138mm	60mm	250mm

Table 7.19 Overview of measurements made on 3d curing with the 20% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G20-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-2	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-4	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-1	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-2	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G20-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-3	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-4	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-A20-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-2	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A20-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-4	08.03.21	A	58mm	208mm	138mm	60mm	250mm

Table 7.20 Overview of measurements made on 7d curing with the 20% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G20-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-2	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G20-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-4	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-1	03.03.21	A	58mm	208mm	138mm	61mm	250mm
0303-FA-A20-2	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-3	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-4	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-1	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-2	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-4	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-A20-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-2	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-3	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A20-4	08.03.21	A	58mm	208mm	138mm	59mm	250mm

Table 7.21 Overview of measurements made on 14d curing with the 20% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G20-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-2	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-4	03.03.21	G	58mm	208mm	138mm	60mm	250mm

0303-FA-A20-1	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-2	03.03.21	A	58mm	208mm	138mm	61mm	250mm
0303-FA-A20-3	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G20-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-4	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-A20-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-2	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-4	08.03.21	A	58mm	208mm	138mm	59mm	250mm

Table 7.22 Overview of measurements made on 28d curing with the 20% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G20-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-2	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G20-4	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-1	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-2	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A20-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A20-4	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-G20-1	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-2	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G20-4	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-A20-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-2	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A20-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A20-4	08.03.21	A	58mm	208mm	138mm	60mm	250mm

Table 7.23 Overview of measurements made on 1d curing with the 30% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G30-1	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-2	04.03.21	G	58mm	208mm	138mm	59mm	250mm
0403-FA-G30-3	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-4	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-1	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-2	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm

Table 7.24 Overview of measurements made on 3d curing with the 30% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G30-1	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-2	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-3	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-4	04.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G30-1	08.03.21	G	58mm	208mm	138mm	61mm	250mm
0803-IN-G30-2	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-4	08.03.21	G	58mm	208mm	138mm	61mm	250mm

Table 7.25 Overview of measurements made on 7d curing with the 30% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G30-1	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-2	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-3	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-4	04.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G30-1	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G30-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm

Table 7.26 Overview of measurements made on 14d curing with the 30% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G30-1	04.03.21	G	58mm	208mm	138mm	59mm	250mm
0403-FA-G30-2	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-3	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-4	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-1	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-2	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm

Table 7.27 Overview of measurements made on 28d curing with the 30% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G30-1	04.03.21	G	58mm	208mm	138mm	59mm	250mm
0403-FA-G30-2	04.03.21	G	58mm	208mm	138mm	61mm	250mm
0403-FA-G30-3	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0403-FA-G30-4	04.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G30-2	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G30-3	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G30-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm

Table 7.28 Overview of measurements made on 1d curing with the 40% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G40-1	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-2	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-3	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-4	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-A40-1	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A40-2	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G40-2	08.03.21	G	58mm	208mm	138mm	61mm	250mm
0803-IN-G40-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-1	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-2	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-4	08.03.21	A	58mm	208mm	138mm	60mm	250mm

Table 7.29 Overview of measurements made on 3d curing with the 40% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G40-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G40-2	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G40-3	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-4	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-A40-1	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-2	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-1	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-2	08.03.21	G	58mm	208mm	138mm	61mm	250mm
0803-IN-G40-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-2	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-4	08.03.21	A	58mm	208mm	138mm	59mm	250mm

Table 7.30 Overview of measurements made on 7d curing with the 40% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G40-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G40-2	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G40-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm

0303-FA-G40-4	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-1	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-2	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G40-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G40-3	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G40-4	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-1	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-2	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-3	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-4	08.03.21	A	58mm	208mm	138mm	59mm	250mm

Table 7.31 Overview of measurements made on 14d curing with the 40% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G40-1	03.03.21	G	58mm	208mm	138mm	62mm	250mm
0303-FA-G40-2	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-3	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-4	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-A40-1	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-2	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-3	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G40-2	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-4	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-1	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-2	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-3	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-4	08.03.21	A	58mm	208mm	138mm	60mm	250mm

Table 7.32 Overview of measurements made on 28d curing with the 40% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0303-FA-G40-1	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G40-2	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-G40-3	03.03.21	G	58mm	208mm	138mm	60mm	250mm
0303-FA-G40-4	03.03.21	G	58mm	208mm	138mm	61mm	250mm
0303-FA-A40-1	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0303-FA-A40-2	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A40-3	03.03.21	A	58mm	208mm	138mm	59mm	250mm
0303-FA-A40-4	03.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G40-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm

0803-IN-G40-3	08.03.21	G	58mm	208mm	138mm	60mm	250mm
0803-IN-G40-4	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-1	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-2	08.03.21	A	58mm	208mm	138mm	60mm	250mm
0803-IN-A40-3	08.03.21	A	58mm	208mm	138mm	59mm	250mm
0803-IN-A40-4	08.03.21	A	58mm	208mm	138mm	59mm	250mm

Table 7.33 Overview of measurements made on 1d curing with the 50% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G50-1	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-2	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-3	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-4	04.03.21	G	58mm	208mm	138mm	55mm	250mm
0803-IN-G50-1	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G50-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-4	08.03.21	G	58mm	208mm	138mm	59mm	250mm

Table 7.34 Overview of measurements made on 3d curing with the 50% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G50-1	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-2	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-3	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-4	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0803-IN-G50-1	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G50-2	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-4	08.03.21	G	58mm	208mm	138mm	58mm	250mm

Table 7.35 Overview of measurements made on 7d curing with the 50% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G50-1	04.03.21	G	58mm	208mm	138mm	56mm	250mm
0403-FA-G50-2	04.03.21	G	58mm	208mm	138mm	56mm	250mm
0403-FA-G50-3	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-4	04.03.21	G	58mm	208mm	138mm	56mm	250mm
0803-IN-G50-1	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-2	08.03.21	G	58mm	208mm	138mm	57mm	250mm
0803-IN-G50-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-4	08.03.21	G	58mm	208mm	138mm	58mm	250mm

Table 7.36 Overview of measurements made on 14d curing with the 50% SiGS batch

Code	Production date	SiGS type	wanted thickness	Length	Width	Thickness	Diagonal 1 & 2
0403-FA-G50-1	04.03.21	G	58mm	208mm	138mm	57mm	250mm

0403-FA-G50-2	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-3	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-4	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0803-IN-G50-1	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-2	08.03.21	G	58mm	208mm	138mm	59mm	250mm
0803-IN-G50-3	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-4	08.03.21	G	58mm	208mm	138mm	58mm	250mm

Table 7.37 Overview of measurements made on 28d curing with the 50% SiGS batch

Code	**Production date**	**SiGS type**	**wanted thickness**	**Length**	**Width**	**Thickness**	**Diagonal 1 & 2**
0403-FA-G50-1	04.03.21	G	58mm	208mm	138mm	56mm	250mm
0403-FA-G50-2	04.03.21	G	58mm	208mm	138mm	57mm	250mm
0403-FA-G50-3	04.03.21	G	58mm	208mm	138mm	56mm	250mm
0403-FA-G50-4	04.03.21	G	58mm	208mm	138mm	56mm	250mm
0803-IN-G50-1	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-2	08.03.21	G	58mm	208mm	138mm	58mm	250mm
0803-IN-G50-3	08.03.21	G	58mm	208mm	138mm	57mm	250mm
0803-IN-G50-4	08.03.21	G	58mm	208mm	138mm	58mm	250mm

With diagonals of much less than 300mm and no maximum dimension exceeding 300mm it was deemed, according to table 6.4 and table 6.5, not necessary to measure anymore on the stones.

7.3.2. Test of tensile splitting strength

Presented in this chapter are the results from a multitude of tensile splitting strength tests. All 14 stone variants were tested at 1, 3, 7, 14 and 28 days. The results in table 7.38 are sorted in rising order of SiGS percentage, from 0% all the way to 50%, and each type is sorted internally in rising order from 1 day to 28 days. This means that the production dates are not completely in order. It has been said in the method chapter that 4 and 4 stones are tested together, so those 4 are always grouped together. A final note is that each note of *days of curing* is related to the production date given on the same line of text.

Table 7.38 Splitting test results first and second production

Production code	SiGS type	Date	SiGS level	Days of curing	Height deviation	Strength	Failure load
0303-FA-N0-1-1d	No SiGS	03.03.2021	0%	1-day	1	4.2 MPa	
0303-FA-N0-2-1d	No SiGS	03.03.2021	0%	1-day	0	4.7 MPa	
0303-FA-N0-3-1d	No SiGS	03.03.2021	0%	1-day	1	4.2 MPa	
0303-FA-N0-4-1d	No SiGS	03.03.2021	0%	1-day	0	4.3 MPa	
0303-FA-N0-1-3d	No SiGS	03.03.2021	0%	3-day	0	4.1 MPa	
0303-FA-N0-2-3d	No SiGS	03.03.2021	0%	3-day	1	4.7 MPa	
0303-FA-N0-3-3d	No SiGS	03.03.2021	0%	3-day	0	3.8 MPa	
0303-FA-N0-4-3d	No SiGS	03.03.2021	0%	3-day	1	4.1 MPa	
0303-FA-N0-1-7d	No SiGS	03.03.2021	0%	7-day	0	3.9 MPa	
0303-FA-N0-2-7d	No SiGS	03.03.2021	0%	7-day	0	3.7 MPa	
0303-FA-N0-3-7d	No SiGS	03.03.2021	0%	7-day	0	3.7 MPa	
0303-FA-N0-4-7d	No SiGS	03.03.2021	0%	7-day	0	3.8 MPa	
0303-FA-N0-1-14d	No SiGS	03.03.2021	0%	14-day	0	4.1 MPa	
0303-FA-N0-2-14d	No SiGS	03.03.2021	0%	14-day	0	4.0 MPa	
0303-FA-N0-3-14d	No SiGS	03.03.2021	0%	14-day	0	4.2 MPa	
0303-FA-N0-4-14d	No SiGS	03.03.2021	0%	14-day	2	4.0 MPa	
0303-FA-N0-1-28d	No SiGS	03.03.2021	0%	28-day	1	4.7 MPa	507 N/mm
0303-FA-N0-2-28d	No SiGS	03.03.2021	0%	28-day	1	4.6 MPa	490 N/mm
0303-FA-N0-3-28d	No SiGS	03.03.2021	0%	28-day	0	5.2 MPa	552 N/mm
0303-FA-N0-4-28d	No SiGS	03.03.2021	0%	28-day	0	4.9 MPa	521 N/mm
0303-FA-N0-1-77d	No SiGS	03.03.2021	0%	77-day	0	5.2 MPa	
0303-FA-N0-1-77d	No SiGS	03.03.2021	0%	77-day	0	5.0 MPa	
0303-FA-N0-1-77d	No SiGS	03.03.2021	0%	77-day	0	5.3 MPa	
0303-FA-N0-1-77d	No SiGS	03.03.2021	0%	77-day	0	5.6 MPa	
0803-IN-N0-1-1d	No SiGS	08.03.2021	0%	1-day	1	4.5 MPa	
0803-IN-N0-2-1d	No SiGS	08.03.2021	0%	1-day	1	4.7 MPa	
0803-IN-N0-3-1d	No SiGS	08.03.2021	0%	1-day	3	4.2 MPa	
0803-IN-N0-4-1d	No SiGS	08.03.2021	0%	1-day	2	4.0 MPa	
0803-IN-N0-1-3d	No SiGS	08.03.2021	0%	3-day	3	4.7 MPa	
0803-IN-N0-2-3d	No SiGS	08.03.2021	0%	3-day	2	4.8 MPa	
0803-IN-N0-3-3d	No SiGS	08.03.2021	0%	3-day	1	4.8 MPa	
0803-IN-N0-4-3d	No SiGS	08.03.2021	0%	3-day	1	4.8 MPa	
0803-IN-N0-1-7d	No SiGS	08.03.2021	0%	7-day	2	4.6 MPa	
0803-IN-N0-2-7d	No SiGS	08.03.2021	0%	7-day	1	4.6 MPa	
0803-IN-N0-3-7d	No SiGS	08.03.2021	0%	7-day	1	4.9 MPa	

0803-IN-N0-4-7d	No SiGS	08.03.2021	0%	7-day	2	5.4 MPa	
0803-IN-N0-1-14d	No SiGS	08.03.2021	0%	14-day	2	4.8 MPa	
0803-IN-N0-2-14d	No SiGS	08.03.2021	0%	14-day	1	5.1 MPa	
0803-IN-N0-3-14d	No SiGS	08.03.2021	0%	14-day	2	5.2 MPa	
0803-IN-N0-4-14d	No SiGS	08.03.2021	0%	14-day	3	4.9 MPa	
0803-IN-N0-1-28d	No SiGS	08.03.2021	0%	28-day	1	5.8 MPa	623 N/mm
0803-IN-N0-2-28d	No SiGS	08.03.2021	0%	28-day	1	5.3 MPa	573 N/mm
0803-IN-N0-3-28d	No SiGS	08.03.2021	0%	28-day	2	5.8 MPa	623 N/mm
0803-IN-N0-4-28d	No SiGS	08.03.2021	0%	28-day	2	5.6 MPa	602 N/mm
0303-FA-A20-1-1d	Air-cooled	03.03.2021	20%	1-day	1	2.0 MPa	
0303-FA-A20-2-1d	Air-cooled	03.03.2021	20%	1-day	2	2.3 MPa	
0303-FA-A20-3-1d	Air-cooled	03.03.2021	20%	1-day	2	1.9 MPa	
0303-FA-A20-4-1d	Air-cooled	03.03.2021	20%	1-day	2	2.1 MPa	
0303-FA-A20-1-3d	Air-cooled	03.03.2021	20%	3-day	1	3.8 MPa	
0303-FA-A20-2-3d	Air-cooled	03.03.2021	20%	3-day	2	3.1 MPa	
0303-FA-A20-3-3d	Air-cooled	03.03.2021	20%	3-day	2	3.0 MPa	
0303-FA-A20-4-3d	Air-cooled	03.03.2021	20%	3-day	2	3.1 MPa	
0303-FA-A20-1-7d	Air-cooled	03.03.2021	20%	7-day	3	3.6 MPa	
0303-FA-A20-2-7d	Air-cooled	03.03.2021	20%	7-day	1	3.4 MPa	
0303-FA-A20-3-7d	Air-cooled	03.03.2021	20%	7-day	1	3.9 MPa	
0303-FA-A20-4-7d	Air-cooled	03.03.2021	20%	7-day	1	3.7 MPa	
0303-FA-A20-1-14d	Air-cooled	03.03.2021	20%	14-day	2	3.8 MPa	
0303-FA-A20-2-14d	Air-cooled	03.03.2021	20%	14-day	3	4.2 MPa	
0303-FA-A20-3-14d	Air-cooled	03.03.2021	20%	14-day	1	4.4 MPa	
0303-FA-A20-4-14d	Air-cooled	03.03.2021	20%	14-day	2	4.0 MPa	
0303-FA-A20-1-28d	Air-cooled	03.03.2021	20%	28-day	1	3.9 MPa	417 N/mm
0303-FA-A20-2-28d	Air-cooled	03.03.2021	20%	28-day	1	4.3 MPa	463 N/mm
0303-FA-A20-3-28d	Air-cooled	03.03.2021	20%	28-day	2	4.7 MPa	508 N/mm
0303-FA-A20-4-28d	Air-cooled	03.03.2021	20%	28-day	1	4.7 MPa	503 N/mm
0303-FA-A20-1-77d	Air-cooled	03.03.2021	20%	77-day	2	4.8 MPa	
0303-FA-A20-2-77d	Air-cooled	03.03.2021	20%	77-day	2	4.1 MPa	
0303-FA-A20-3-77d	Air-cooled	03.03.2021	20%	77-day	2	3.9 MPa	
0303-FA-A20-4-77d	Air-cooled	03.03.2021	20%	77-day	2	4.8 MPa	
0303-FA-G20-1-1d	Granulated	03.03.2021	20%	1-day	2	2.3 MPa	
0303-FA-G20-2-1d	Granulated	03.03.2021	20%	1-day	2	2.0 MPa	
0303-FA-G20-3-1d	Granulated	03.03.2021	20%	1-day	2	2.0 MPa	
0303-FA-G20-4-1d	Granulated	03.03.2021	20%	1-day	2	1.9 MPa	
0303-FA-G20-1-3d	Granulated	03.03.2021	20%	3-day	2	3.3 MPa	
0303-FA-G20-2-3d	Granulated	03.03.2021	20%	3-day	2	3.3 MPa	
0303-FA-G20-3-3d	Granulated	03.03.2021	20%	3-day	2	3.4 MPa	
0303-FA-G20-4-3d	Granulated	03.03.2021	20%	3-day	2	3.4 MPa	
0303-FA-G20-1-7d	Granulated	03.03.2021	20%	7-day	2	3.8 MPa	
0303-FA-G20-2-7d	Granulated	03.03.2021	20%	7-day	3	3.8 MPa	
0303-FA-G20-3-7d	Granulated	03.03.2021	20%	7-day	2	3.7 MPa	
0303-FA-G20-4-7d	Granulated	03.03.2021	20%	7-day	2	3.9 MPa	
0303-FA-G20-1-14d	Granulated	03.03.2021	20%	14-day	2	4.0 MPa	
0303-FA-G20-2-14d	Granulated	03.03.2021	20%	14-day	2	4.6 MPa	

0303-FA-G20-3-14d	Granulated	03.03.2021	20%	14-day	2	4.6 MPa	
0303-FA-G20-4-14d	Granulated	03.03.2021	20%	14-day	2	4.3 MPa	
0303-FA-G20-1-28d	Granulated	03.03.2021	20%	28-day	2	4.1 MPa	445 N/mm
0303-FA-G20-2-28d	Granulated	03.03.2021	20%	28-day	2	4.1 MPa	444 N/mm
0303-FA-G20-3-28d	Granulated	03.03.2021	20%	28-day	2	4.3 MPa	462 N/mm
0303-FA-G20-4-28d	Granulated	03.03.2021	20%	28-day	2	4.2 MPa	458 N/mm
0303-FA-G20-1-77d	Granulated	03.03.2021	20%	77-day	2	4.4 MPa	
0303-FA-G20-2-77d	Granulated	03.03.2021	20%	77-day	2	4.1 MPa	
0303-FA-G20-3-77d	Granulated	03.03.2021	20%	77-day	2	4.1 MPa	
0303-FA-G20-4-77d	Granulated	03.03.2021	20%	77-day	2	4.9 MPa	
0803-IN-G20-1-1d	Granulated	08.03.2021	20%	1-day	1	3.0 MPa	
0803-IN-G20-2-1d	Granulated	08.03.2021	20%	1-day	1	2.9 MPa	
0803-IN-G20-3-1d	Granulated	08.03.2021	20%	1-day	2	3.0 MPa	
0803-IN-G20-4-1d	Granulated	08.03.2021	20%	1-day	2	3.3 MPa	
0803-IN-G20-1-3d	Granulated	08.03.2021	20%	3-day	1	3.7 MPa	
0803-IN-G20-2-3d	Granulated	08.03.2021	20%	3-day	1	3.4 MPa	
0803-IN-G20-3-3d	Granulated	08.03.2021	20%	3-day	1	3.7 MPa	
0803-IN-G20-4-3d	Granulated	08.03.2021	20%	3-day	1	3.7 MPa	
0803-IN-G20-1-7d	Granulated	08.03.2021	20%	7-day	0	4.2 MPa	
0803-IN-G20-2-7d	Granulated	08.03.2021	20%	7-day	0	3.6 MPa	
0803-IN-G20-3-7d	Granulated	08.03.2021	20%	7-day	0	4.1 MPa	
0803-IN-G20-4-7d	Granulated	08.03.2021	20%	7-day	0	4.5 MPa	
0803-IN-G20-1-14d	Granulated	08.03.2021	20%	14-day	1	4.0 MPa	
0803-IN-G20-2-14d	Granulated	08.03.2021	20%	14-day	1	3.9 MPa	
0803-IN-G20-3-14d	Granulated	08.03.2021	20%	14-day	0	4.3 MPa	
0803-IN-G20-4-14d	Granulated	08.03.2021	20%	14-day	1	4.1 MPa	
0803-IN-G20-1-28d	Granulated	08.03.2021	20%	28-day	0	4.9 MPa	527 N/mm
0803-IN-G20-2-28d	Granulated	08.03.2021	20%	28-day	0	4.6 MPa	494 N/mm
0803-IN-G20-3-28d	Granulated	08.03.2021	20%	28-day	0	4.8 MPa	512 N/mm
0803-IN-G20-4-28d	Granulated	08.03.2021	20%	28-day	0	4.8 MPa	511 N/mm
0803-IN-A20-1-1d	Air-cooled	08.03.2021	20%	1-day	2	3.5 MPa	
0803-IN-A20-2-1d	Air-cooled	08.03.2021	20%	1-day	1	3.2 MPa	
0803-IN-A20-3-1d	Air-cooled	08.03.2021	20%	1-day	2	3.1 MPa	
0803-IN-A20-4-1d	Air-cooled	08.03.2021	20%	1-day	2	3.2 MPa	
0803-IN-A20-1-3d	Air-cooled	08.03.2021	20%	3-day	2	3.8 MPa	
0803-IN-A20-2-3d	Air-cooled	08.03.2021	20%	3-day	1	3.9 MPa	
0803-IN-A20-3-3d	Air-cooled	08.03.2021	20%	3-day	2	3.8 MPa	
0803-IN-A20-4-3d	Air-cooled	08.03.2021	20%	3-day	2	3.8 MPa	
0803-IN-A20-1-7d	Air-cooled	08.03.2021	20%	7-day	2	3.8 MPa	
0803-IN-A20-2-7d	Air-cooled	08.03.2021	20%	7-day	2	3.9 MPa	
0803-IN-A20-3-7d	Air-cooled	08.03.2021	20%	7-day	1	4.1 MPa	
0803-IN-A20-4-7d	Air-cooled	08.03.2021	20%	7-day	1	3.7 MPa	
0803-IN-A20-1-14d	Air-cooled	08.03.2021	20%	14-day	2	4.4 MPa	
0803-IN-A20-2-14d	Air-cooled	08.03.2021	20%	14-day	2	4.1 MPa	
0803-IN-A20-3-14d	Air-cooled	08.03.2021	20%	14-day	2	4.0 MPa	
0803-IN-A20-4-14d	Air-cooled	08.03.2021	20%	14-day	1	4.2 MPa	
0803-IN-A20-1-28d	Air-cooled	08.03.2021	20%	28-day	2	4.6 MPa	494 N/mm

0803-IN-A20-2-28d	Air-cooled	08.03.2021	20%	28-day	1	4.9 MPa	528 N/mm
0803-IN-A20-3-28d	Air-cooled	08.03.2021	20%	28-day	2	5.0 MPa	543 N/mm
0803-IN-A20-4-28d	Air-cooled	08.03.2021	20%	28-day	2	4.6 MPa	503 N/mm
0403-FA-G30-1-1d	Granulated	04.03.2021	30%	1-day	2	2.0 MPa	
0403-FA-G30-2-1d	Granulated	04.03.2021	30%	1-day	1	1.7 MPa	
0403-FA-G30-3-1d	Granulated	04.03.2021	30%	1-day	2	1.9 MPa	
0403-FA-G30-4-1d	Granulated	04.03.2021	30%	1-day	2	1.8 MPa	
0403-FA-G30-1-3d	Granulated	04.03.2021	30%	3-day	2	2.6 MPa	
0403-FA-G30-2-3d	Granulated	04.03.2021	30%	3-day	2	2.5 MPa	
0403-FA-G30-3-3d	Granulated	04.03.2021	30%	3-day	2	2.2 MPa	
0403-FA-G30-4-3d	Granulated	04.03.2021	30%	3-day	1	2.5 MPa	
0403-FA-G30-1-7d	Granulated	04.03.2021	30%	7-day	2	3.4 MPa	
0403-FA-G30-2-7d	Granulated	04.03.2021	30%	7-day	2	3.3 MPa	
0403-FA-G30-3-7d	Granulated	04.03.2021	30%	7-day	2	3.3 MPa	
0403-FA-G30-4-7d	Granulated	04.03.2021	30%	7-day	1	3.7 MPa	
0403-FA-G30-1-14d	Granulated	04.03.2021	30%	14-day	1	3.9 MPa	
0403-FA-G30-2-14d	Granulated	04.03.2021	30%	14-day	2	3.6 MPa	
0403-FA-G30-3-14d	Granulated	04.03.2021	30%	14-day	2	4.0 MPa	
0403-FA-G30-4-14d	Granulated	04.03.2021	30%	14-day	2	3.6 MPa	
0403-FA-G30-1-28d	Granulated	04.03.2021	30%	28-day	1	4.5 MPa	480 N/mm
0403-FA-G30-2-28d	Granulated	04.03.2021	30%	28-day	3	4.0 MPa	438 N/mm
0403-FA-G30-3-28d	Granulated	04.03.2021	30%	28-day	2	4.4 MPa	474 N/mm
0403-FA-G30-4-28d	Granulated	04.03.2021	30%	28-day	2	4.1 MPa	441 N/mm
0403-FA-G30-1-77d	Granulated	04.03.2021	30%	77-day	2	4.0 MPa	
0403-FA-G30-2-77d	Granulated	04.03.2021	30%	77-day	1	3.0 MPa	
0403-FA-G30-3-77d	Granulated	04.03.2021	30%	77-day	2	4.8 MPa	
0403-FA-G30-4-77d	Granulated	04.03.2021	30%	77-day	1	4.4 MPa	
0803-IN-G30-1-1d	Granulated	08.03.2021	30%	1-day	2	3.1 MPa	
0803-IN-G30-2-1d	Granulated	08.03.2021	30%	1-day	2	3.0 MPa	
0803-IN-G30-3-1d	Granulated	08.03.2021	30%	1-day	2	2.7 MPa	
0803-IN-G30-4-1d	Granulated	08.03.2021	30%	1-day	2	3.1 MPa	
0803-IN-G30-1-3d	Granulated	08.03.2021	30%	3-day	3	3.9 MPa	
0803-IN-G30-2-3d	Granulated	08.03.2021	30%	3-day	2	3.8 MPa	
0803-IN-G30-3-3d	Granulated	08.03.2021	30%	3-day	2	3.5 MPa	
0803-IN-G30-4-3d	Granulated	08.03.2021	30%	3-day	3	3.7 MPa	
0803-IN-G30-1-7d	Granulated	08.03.2021	30%	7-day	2	4.1 MPa	
0803-IN-G30-2-7d	Granulated	08.03.2021	30%	7-day	1	4.0 MPa	
0803-IN-G30-3-7d	Granulated	08.03.2021	30%	7-day	2	4.2 MPa	
0803-IN-G30-4-7d	Granulated	08.03.2021	30%	7-day	2	4.1 MPa	
0803-IN-G30-1-14d	Granulated	08.03.2021	30%	14-day	2	4.2 MPa	
0803-IN-G30-2-14d	Granulated	08.03.2021	30%	14-day	2	4.0 MPa	
0803-IN-G30-3-14d	Granulated	08.03.2021	30%	14-day	2	3.9 MPa	
0803-IN-G30-4-14d	Granulated	08.03.2021	30%	14-day	2	4.1 MPa	
0803-IN-G30-1-28d	Granulated	08.03.2021	30%	28-day	1	5.2 MPa	558 N/mm
0803-IN-G30-2-28d	Granulated	08.03.2021	30%	28-day	2	5.5 MPa	592 N/mm
0803-IN-G30-3-28d	Granulated	08.03.2021	30%	28-day	1	4.9 MPa	524 N/mm
0803-IN-G30-4-28d	Granulated	08.03.2021	30%	28-day	2	4.7 MPa	506 N/mm

0303-FA-A40-1-1d	Air-cooled	03.03.2021	40%	1-day	1	1.2 MPa	
0303-FA-A40-2-1d	Air-cooled	03.03.2021	40%	1-day	2	1.1 MPa	
0303-FA-A40-3-1d	Air-cooled	03.03.2021	40%	1-day	2	1.4 MPa	
0303-FA-A40-4-1d	Air-cooled	03.03.2021	40%	1-day	2	1.1 MPa	
0303-FA-A40-1-3d	Air-cooled	03.03.2021	40%	3-day	2	2.3 MPa	
0303-FA-A40-2-3d	Air-cooled	03.03.2021	40%	3-day	2	2.3 MPa	
0303-FA-A40-3-3d	Air-cooled	03.03.2021	40%	3-day	2	2.3 MPa	
0303-FA-A40-4-3d	Air-cooled	03.03.2021	40%	3-day	2	2.3 MPa	
0303-FA-A40-1-7d	Air-cooled	03.03.2021	40%	7-day	2	2.8 MPa	
0303-FA-A40-2-7d	Air-cooled	03.03.2021	40%	7-day	2	2.9 MPa	
0303-FA-A40-3-7d	Air-cooled	03.03.2021	40%	7-day	2	2.7 MPa	
0303-FA-A40-4-7d	Air-cooled	03.03.2021	40%	7-day	2	2.6 MPa	
0303-FA-A40-1-14d	Air-cooled	03.03.2021	40%	14-day	2	3.3 MPa	
0303-FA-A40-2-14d	Air-cooled	03.03.2021	40%	14-day	2	3.4 MPa	
0303-FA-A40-3-14d	Air-cooled	03.03.2021	40%	14-day	2	3.5 MPa	
0303-FA-A40-4-14d	Air-cooled	03.03.2021	40%	14-day	2	3.6 MPa	
0303-FA-A40-1-28d	Air-cooled	03.03.2021	40%	28-day	2	3.6 MPa	393 N/mm
0303-FA-A40-2-28d	Air-cooled	03.03.2021	40%	28-day	1	3.5 MPa	381 N/mm
0303-FA-A40-3-28d	Air-cooled	03.03.2021	40%	28-day	1	3.6 MPa	386 N/mm
0303-FA-A40-4-28d	Air-cooled	03.03.2021	40%	28-day	2	3.3 MPa	357 N/mm
0303-FA-A40-1-77d	Air-cooled	03.03.2021	40%	77-day	1	3.9 MPa	
0303-FA-A40-2-77d	Air-cooled	03.03.2021	40%	77-day	2	3.8 MPa	
0303-FA-A40-3-77d	Air-cooled	03.03.2021	40%	77-day	2	3.3 MPa	
0303-FA-A40-4-77d	Air-cooled	03.03.2021	40%	77-day	1	4.4 MPa	
0303-FA-G40-1-1d	Granulated	03.03.2021	40%	1-day	3	1.0 MPa	
0303-FA-G40-2-1d	Granulated	03.03.2021	40%	1-day	3	1.1 MPa	
0303-FA-G40-3-1d	Granulated	03.03.2021	40%	1-day	3	1.2 MPa	
0303-FA-G40-4-1d	Granulated	03.03.2021	40%	1-day	3	0.9 MPa	
0303-FA-G40-1-3d	Granulated	03.03.2021	40%	3-day	2	2.4 MPa	
0303-FA-G40-2-3d	Granulated	03.03.2021	40%	3-day	2	2.3 MPa	
0303-FA-G40-3-3d	Granulated	03.03.2021	40%	3-day	3	2.3 MPa	
0303-FA-G40-4-3d	Granulated	03.03.2021	40%	3-day	3	2.0 MPa	
0303-FA-G40-1-7d	Granulated	03.03.2021	40%	7-day	2	3.1 MPa	
0303-FA-G40-2-7d	Granulated	03.03.2021	40%	7-day	2	3.0 MPa	
0303-FA-G40-3-7d	Granulated	03.03.2021	40%	7-day	2	3.0 MPa	
0303-FA-G40-4-7d	Granulated	03.03.2021	40%	7-day	2	2.7 MPa	
0303-FA-G40-1-14d	Granulated	03.03.2021	40%	14-day	4	3.3 MPa	
0303-FA-G40-2-14d	Granulated	03.03.2021	40%	14-day	3	3.8 MPa	
0303-FA-G40-3-14d	Granulated	03.03.2021	40%	14-day	3	3.7 MPa	
0303-FA-G40-4-14d	Granulated	03.03.2021	40%	14-day	3	3.4 MPa	
0303-FA-G40-1-28d	Granulated	03.03.2021	40%	28-day	2	3.3 MPa	355 N/mm
0303-FA-G40-2-28d	Granulated	03.03.2021	40%	28-day	3	4.1 MPa	444 N/mm
0303-FA-G40-3-28d	Granulated	03.03.2021	40%	28-day	2	3.4 MPa	369 N/mm
0303-FA-G40-4-28d	Granulated	03.03.2021	40%	28-day	3	3.9 MPa	424 N/mm
0303-FA-G40-1-77d	Granulated	03.03.2021	40%	77-day	3	4.4 MPa	
0303-FA-G40-2-77d	Granulated	03.03.2021	40%	77-day	3	4.3 MPa	
0303-FA-G40-3-77d	Granulated	03.03.2021	40%	77-day	3	4.0 MPa	

0303-FA-G40-4-77d	Granulated	03.03.2021	40%	77-day	3	3.9 MPa	
0803-IN-G40-1-1d	Granulated	08.03.2021	40%	1-day	1	3.1 MPa	
0803-IN-G40-2-1d	Granulated	08.03.2021	40%	1-day	3	3.0 MPa	
0803-IN-G40-3-1d	Granulated	08.03.2021	40%	1-day	2	2.7 MPa	
0803-IN-G40-4-1d	Granulated	08.03.2021	40%	1-day	2	3.1 MPa	
0803-IN-G40-1-3d	Granulated	08.03.2021	40%	3-day	2	3.6 MPa	
0803-IN-G40-2-3d	Granulated	08.03.2021	40%	3-day	3	3.2 MPa	
0803-IN-G40-3-3d	Granulated	08.03.2021	40%	3-day	2	2.8 MPa	
0803-IN-G40-4-3d	Granulated	08.03.2021	40%	3-day	2	3.4 MPa	
0803-IN-G40-1-7d	Granulated	08.03.2021	40%	7-day	1	3.8 MPa	
0803-IN-G40-2-7d	Granulated	08.03.2021	40%	7-day	1	3.7 MPa	
0803-IN-G40-3-7d	Granulated	08.03.2021	40%	7-day	1	3.6 MPa	
0803-IN-G40-4-7d	Granulated	08.03.2021	40%	7-day	1	3.7 MPa	
0803-IN-G40-1-14d	Granulated	08.03.2021	40%	14-day	1	4.3 MPa	
0803-IN-G40-2-14d	Granulated	08.03.2021	40%	14-day	2	4.1 MPa	
0803-IN-G40-3-14d	Granulated	08.03.2021	40%	14-day	2	3.9 MPa	
0803-IN-G40-4-14d	Granulated	08.03.2021	40%	14-day	2	4.0 MPa	
0803-IN-G40-1-28d	Granulated	08.03.2021	40%	28-day	1	4.9 MPa	525 N/mm
0803-IN-G40-2-28d	Granulated	08.03.2021	40%	28-day	1	5.4 MPa	575 N/mm
0803-IN-G40-3-28d	Granulated	08.03.2021	40%	28-day	2	5.0 MPa	547 N/mm
0803-IN-G40-4-28d	Granulated	08.03.2021	40%	28-day	1	4.5 MPa	484 N/mm
0803-IN-A40-1-1d	Air-cooled	08.03.2021	40%	1-day	1	2.7 MPa	
0803-IN-A40-2-1d	Air-cooled	08.03.2021	40%	1-day	2	2.3 MPa	
0803-IN-A40-3-1d	Air-cooled	08.03.2021	40%	1-day	2	2.4 MPa	
0803-IN-A40-4-1d	Air-cooled	08.03.2021	40%	1-day	2	2.3 MPa	
0803-IN-A40-1-3d	Air-cooled	08.03.2021	40%	3-day	2	3.3 MPa	
0803-IN-A40-2-3d	Air-cooled	08.03.2021	40%	3-day	2	2.8 MPa	
0803-IN-A40-3-3d	Air-cooled	08.03.2021	40%	3-day	2	3.2 MPa	
0803-IN-A40-4-3d	Air-cooled	08.03.2021	40%	3-day	1	3.3 MPa	
0803-IN-A40-1-7d	Air-cooled	08.03.2021	40%	7-day	1	3.2 MPa	
0803-IN-A40-2-7d	Air-cooled	08.03.2021	40%	7-day	1	3.3 MPa	
0803-IN-A40-3-7d	Air-cooled	08.03.2021	40%	7-day	1	3.2 MPa	
0803-IN-A40-4-7d	Air-cooled	08.03.2021	40%	7-day	1	3.2 MPa	
0803-IN-A40-1-14d	Air-cooled	08.03.2021	40%	14-day	2	2.8 MPa	
0803-IN-A40-2-14d	Air-cooled	08.03.2021	40%	14-day	1	3.6 MPa	
0803-IN-A40-3-14d	Air-cooled	08.03.2021	40%	14-day	2	3.5 MPa	
0803-IN-A40-4-14d	Air-cooled	08.03.2021	40%	14-day	2	3.6 MPa	
0803-IN-A40-1-28d	Air-cooled	08.03.2021	40%	28-day	1	4.4 MPa	475 N/mm
0803-IN-A40-2-28d	Air-cooled	08.03.2021	40%	28-day	2	4.4 MPa	477 N/mm
0803-IN-A40-3-28d	Air-cooled	08.03.2021	40%	28-day	1	4.0 MPa	428 N/mm
0803-IN-A40-4-28d	Air-cooled	08.03.2021	40%	28-day	1	4.2 MPa	451 N/mm
0403-FA-G50-1-1d	Granulated	04.03.2021	50%	1-day	-1	1.9 MPa	
0403-FA-G50-2-1d	Granulated	04.03.2021	50%	1-day	-1	1.8 MPa	
0403-FA-G50-3-1d	Granulated	04.03.2021	50%	1-day	-1	2.0 MPa	
0403-FA-G50-4-1d	Granulated	04.03.2021	50%	1-day	-3	1.8 MPa	
0403-FA-G50-1-3d	Granulated	04.03.2021	50%	3-day	-1	2.9 MPa	
0403-FA-G50-2-3d	Granulated	04.03.2021	50%	3-day	-1	2.9 MPa	

0403-FA-G50-3-3d	Granulated	04.03.2021	50%	3-day	-1	2.9 MPa	
0403-FA-G50-4-3d	Granulated	04.03.2021	50%	3-day	-1	2.9 MPa	
0403-FA-G50-1-7d	Granulated	04.03.2021	50%	7-day	-2	4.0 MPa	
0403-FA-G50-2-7d	Granulated	04.03.2021	50%	7-day	-2	4.0 MPa	
0403-FA-G50-3-7d	Granulated	04.03.2021	50%	7-day	-1	3.9 MPa	
0403-FA-G50-4-7d	Granulated	04.03.2021	50%	7-day	-2	3.8 MPa	
0403-FA-G50-1-14d	Granulated	04.03.2021	50%	14-day	-1	5.2 MPa	
0403-FA-G50-2-14d	Granulated	04.03.2021	50%	14-day	-1	4.7 MPa	
0403-FA-G50-3-14d	Granulated	04.03.2021	50%	14-day	-1	4.9 MPa	
0403-FA-G50-4-14d	Granulated	04.03.2021	50%	14-day	-1	4.8 MPa	
0403-FA-G50-1-28d	Granulated	04.03.2021	50%	28-day	-2	4.3 MPa	447 N/mm
0403-FA-G50-2-28d	Granulated	04.03.2021	50%	28-day	-1	5.0 MPa	534 N/mm
0403-FA-G50-3-28d	Granulated	04.03.2021	50%	28-day	-2	5.1 MPa	537 N/mm
0403-FA-G50-4-28d	Granulated	04.03.2021	50%	28-day	-2	5.1 MPa	533 N/mm
0403-FA-G50-1-77d	Granulated	04.03.2021	50%	77-day	-1	5.5 MPa	
0403-FA-G50-2-77d	Granulated	04.03.2021	50%	77-day	-1	4.9 MPa	
0403-FA-G50-3-77d	Granulated	04.03.2021	50%	77-day	-2	5.0 MPa	
0403-FA-G50-4-77d	Granulated	04.03.2021	50%	77-day	-1	5.6 MPa	
0803-IN-G50-1-1d	Granulated	08.03.2021	50%	1-day	0	2.3 MPa	
0803-IN-G50-2-1d	Granulated	08.03.2021	50%	1-day	1	2.3 MPa	
0803-IN-G50-3-1d	Granulated	08.03.2021	50%	1-day	0	2.5 MPa	
0803-IN-G50-4-1d	Granulated	08.03.2021	50%	1-day	1	2.4 MPa	
0803-IN-G50-1-3d	Granulated	08.03.2021	50%	3-day	1	3.4 MPa	
0803-IN-G50-2-3d	Granulated	08.03.2021	50%	3-day	0	3.4 MPa	
0803-IN-G50-3-3d	Granulated	08.03.2021	50%	3-day	0	3.4 MPa	
0803-IN-G50-4-3d	Granulated	08.03.2021	50%	3-day	0	3.2 MPa	
0803-IN-G50-1-7d	Granulated	08.03.2021	50%	7-day	0	4.3 MPa	
0803-IN-G50-2-7d	Granulated	08.03.2021	50%	7-day	-1	3.6 MPa	
0803-IN-G50-3-7d	Granulated	08.03.2021	50%	7-day	0	4.0 MPa	
0803-IN-G50-4-7d	Granulated	08.03.2021	50%	7-day	0	4.1 MPa	
0803-IN-G50-1-14d	Granulated	08.03.2021	50%	14-day	0	4.6 MPa	
0803-IN-G50-2-14d	Granulated	08.03.2021	50%	14-day	1	3.6 MPa	
0803-IN-G50-3-14d	Granulated	08.03.2021	50%	14-day	0	4.3 MPa	
0803-IN-G50-4-14d	Granulated	08.03.2021	50%	14-day	0	4.4 MPa	
0803-IN-G50-1-28d	Granulated	08.03.2021	50%	28-day	0	4.8 MPa	508 N/mm
0803-IN-G50-2-28d	Granulated	08.03.2021	50%	28-day	0	4.8 MPa	512 N/mm
0803-IN-G50-3-28d	Granulated	08.03.2021	50%	28-day	-1	5.0 MPa	533 N/mm
0803-IN-G50-4-28d	Granulated	08.03.2021	50%	28-day	0	4.8 MPa	507 N/mm

7.3.3. Test of water absorption

After following the method detailed in chapter 6.3.3 of this thesis, the results of those tests are given in table 7.39 below. Each water absorption test was done on 3 and 3 stones, so those are listed together. Then an average of those 3 results are given. The results are listed according to SiGS content firstly and inside that, according to production date. This means that for each SiGS level the first listed results are always the *Norcem Standardsement FA*.

Table 7.39 water absorption results for the first and second production

Production code	SiGS substitution	Production date	Weight 1	Weight 2	Water absorption	Average of 1-3
0303-FA-N0-1	None	03.03.21	3665g	3565g	2.8%	
0303-FA-N0-2	None	03.03.21	3735g	3635g	2.8%	
0303-FA-N0-3	None	03.03.21	3770g	3615g	4.3%	3.3%
0803-IN-N0-1	None	08.03.21	3895g	3790g	2.8%	
0803-IN-N0-2	None	08.03.21	3870g	3805g	1.7%	
0803-IN-N0-3	None	08.03.21	3845g	3780g	1.7%	2.1%
0303-FA-G20-1	20% granulated	03.03.21	3705g	3540g	4.7%	
0303-FA-G20-2	20% granulated	03.03.21	3765g	3640g	3.4%	
0303-FA-G20-3	20% granulated	03.03.21	3755g	3630g	3.4%	3.8%
0803-IN-G20-1	20% granulated	08.03.21	3835g	3655g	4.9%	
0803-IN-G20-2	20% granulated	08.03.21	3800g	3610g	5.3%	
0803-IN-G20-3	20% granulated	08.03.21	3865g	3665g	5.5%	5.2%
0303-FA-A20-1	20% air-cooled	03.03.21	3735g	3660g	2.0%	
0303-FA-A20-2	20% air-cooled	03.03.21	3875g	3765g	2.9%	
0303-FA-A20-3	20% air-cooled	03.03.21	3800g	3700g	2.7%	2.6%
0803-IN-A20-1	20% air-cooled	08.03.21	3785g	3620g	4.6%	
0803-IN-A20-2	20% air-cooled	08.03.21	3855g	3700g	4.2%	
0803-IN-A20-3	20% air-cooled	08.03.21	3860g	3695g	4.5%	4.4%
0403-FA-G30-1	30% granulated	04.03.21	3770g	3685g	2.3%	
0403-FA-G30-2	30% granulated	04.03.21	3790g	3665g	3.4%	
0403-FA-G30-3	30% granulated	04.03.21	3810g	3685g	3.4%	3.0%
0803-IN-G30-1	30% granulated	08.03.21	3800g	3645g	4.3%	
0803-IN-G30-2	30% granulated	08.03.21	3810g	3640g	4.7%	
0803-IN-G30-3	30% granulated	08.03.21	3750g	3625g	3.4%	4.1%
0303-FA-G40-1	40% granulated	03.03.21	3855g	3695g	4.3%	
0303-FA-G40-2	40% granulated	03.03.21	3770g	3605g	4.6%	
0303-FA-G40-3	40% granulated	03.03.21	3905g	3705g	5.4%	4.8%
0803-IN-G40-1	40% granulated	08.03.21	3830g	3655g	4.8%	
0803-IN-G40-2	40% granulated	08.03.21	3790g	3595g	5.4%	
0803-IN-G40-3	40% granulated	08.03.21	3870g	3670g	5.4%	5.2%
0303-FA-A40-1	40% air-cooled	03.03.21	3775g	3570g	5.7%	
0303-FA-A40-2	40% air-cooled	03.03.21	3735g	3515g	6.3%	
0303-FA-A40-3	40% air-cooled	03.03.21	3705g	3515g	5.4%	5.8%
0803-IN-A40-1	40% air-cooled	08.03.21	3760g	3580g	5.0%	
0803-IN-A40-2	40% air-cooled	08.03.21	3770g	3595g	4.9%	
0803-IN-A40-3	40% air-cooled	08.03.21	3760g	3565g	5.5%	5.1%
0403-FA-G50-1	50% granulated	04.03.21	3620g	3565g	1.5%	

0403-FA-G50-2	50% granulated	04.03.21	3605g	3530g	2.1%	
0403-FA-G50-3	50% granulated	04.03.21	3605g	3540g	1.8%	1.8%
0803-IN-G50-1	50% granulated	08.03.21	3730g	3550g	5.1%	
0803-IN-G50-2	50% granulated	08.03.21	3770g	3600g	4.7%	
0803-IN-G50-3	50% granulated	08.03.21	3700g	3525g	5.0%	4.9%

7.3.4. Test of resistance towards freeze-thaw deterioration

The results in this chapter details all facets of the entire process surrounding the test. They are structured according to when they occurred, from beginning, through preparing samples and all the way to finishing the tests.

The first table of results, table 7.40, is the measurements made of a standard stone before and after two cuttings of the stone. The cuts were made to attempt to get the stone as close to 100x100mm as possible and were trial and error cuts, in order to find the optimal way of doing the process. Each dimension measured was measured in three different places along the stone and the pattern of cutting can be seen in figure 7.5 below.

Figure 7.5 Pattern of cutting chosen after some testing

Table 7.40 dimensions after test cutting 1 paving stone with the concrete saw

Width 1 before cutting	**Width 2 before cutting**	**Width 3 before cutting**	**Length 1 before cutting**	**Length 2 before cutting**	**Length 3 before cutting**
138mm	138mm	138mm	208mm	208mm	208mm
Width 1 after cut 1 & 2	**Width 2 after cut 1 & 2**	**Width 3 after cut 1 & 2**	**Length 1 after cut 1 & 2**	**Length 2 after cut 1 & 2**	**Length 3 after cut 1 & 2**
99mm	98mm	97mm	96mm	96mm	96mm
Width 1 of remaining pieces	**Width 2 of remaining pieces**	**Width 3 of remaining pieces**	**Length 1 of remaining pieces**	**Length 1 of remaining pieces**	**Length 1 of remaining pieces**
36mm	37mm	37mm	108mm	107mm	108mm
Lost material	**Lost material**	**Lost material**	**Lost material**	**Lost material**	**Lost material**
3mm	3mm	4mm	4mm	5mm	4mm

After the trail stones had been cut and measured, some points that needed attention became obvious. As figure 7.6 shows, the surface of the cut revealed a significant amount of “free cement”. This could obviously also be SiGS, but the point is that this powder made the cut “slippery” and therefore, as figure 7.6 shows, it was impossible to make the entire cut flush. This was only a problem at the bottom of the stones and not at the top layer of the stones.

Figure 7.6 "free cement" and uneven cutting

The next results, in table 7.41, are the measurements taken of the official stones that were chosen for the testing itself. 3 of each 7 stone variants were cut and measured before being stored until further testing could commence. Each stone was marked with either G, for granulert (granulated), or L for luftkjølt (air-cooled). They were also marked with the number representing percentage of SiGS and the number 1-3 for easier control of results. Each cut stone was turned with the natural corner to the upper left and every first measurement, in both directions, started closest to that corner. After the stones were sealed into the polystyrene boxes with the 2,5mm thick line of sealant, the measurements were adjusted and the new adjusted areas are found to the far right in the table.

Table 7.41 measurements of surface area of the cut actual test stones

Code	1. measure	2. measure	3. measure	Average result	Adjusted result	Area	Adjusted area
0803-IN-N0-1	$Length_1$ = 98.5mm	$Length_2$ = 97.5mm	$Length_3$ = 96.5mm	Length = 97.5mm	Length = 97.0mm	9506.25 mm^2	9409.00 mm^2
	$Width_1$ = 97mm	$Width_2$ = 97.5mm	$Width_3$ = 98mm	Width = 97.5mm	Width = 97.0mm		
0803-IN-N0-2	$Length_1$ = 99mm	$Length_2$ = 99mm	$Length_3$ = 98.5mm	Length = 98.8mm	Length = 98.3mm	9583.60 mm^2	9485.95 mm^2
	$Width_1$ = 96.5mm	$Width_2$ = 97mm	$Width_3$ = 97.5mm	Width = 97mm	Width = 96.5mm		
0803-IN-N0-3	$Length_1$ = 99mm	$Length_2$ = 98.5mm	$Length_3$ = 98mm	Length = 98.5mm	Length = 98mm	9554.50 mm^2	9457.00 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-G20-1	$Length_1$ = 97mm	$Length_2$ = 97mm	$Length_3$ = 96.5mm	Length = 96.8mm	Length = 96.3mm	9418.64 mm^2	9321.84 mm^2

	$Width_1$ = 97mm	$Width_2$ = 97.5mm	$Width_3$ = 97.5mm	Width = 97.3mm	Width = 96.8mm		
0803-IN-G20-2	$Length_1$ = 97.5mm	$Length_2$ = 97mm	$Length_3$ = 97mm	Length = 97.2mm	Length = 96.7mm	9496.44 mm^2	9399.24 mm^2
	$Width_1$ = 97mm	$Width_2$ = 98mm	$Width_3$ = 98mm	Width = 97.7mm	Width = 97.2mm		
0803-IN-G20-3	$Length_1$ = 96.5mm	$Length_2$ = 96.5mm	$Length_3$ = 96mm	Length = 96.3mm	Length = 95.8mm	9389.25 mm^2	9292.60 mm^2
	$Width_1$ = 97mm	$Width_2$ = 97.5mm	$Width_3$ = 98mm	Width = 97.5mm	Width = 97mm		
0803-IN-A20-1	$Length_1$ = 96mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96mm	Length = 95.5mm	9312.00 mm^2	9215.75 mm^2
	$Width_1$ = 97mm	$Width_2$ = 97mm	$Width_3$ = 97mm	Width = 97mm	Width = 96.5mm		
0803-IN-A20-2	$Length_1$ = 96mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96mm	Length = 95.5mm	9340.80 mm^2	9244.40 mm^2
	$Width_1$ = 97mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97.3mm	Width = 96.8mm		
0803-IN-A20-3	$Length_1$ = 96mm	$Length_2$ = 96mm	$Length_3$ = 95.5mm	Length = 95.8mm	Length = 95.3mm	9263.86 mm^2	9167.86 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 97mm	Width = 96.7mm	Width = 96.2mm		
0803-IN-G30-1	$Length_1$ = 96mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96mm	Length = 95.5mm	9312.00 mm^2	9215.75 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-G30-2	$Length_1$ = 97mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96.3mm	Length = 95.8mm	9341.10 mm^2	9244.70 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-G30-3	$Length_1$ = 96mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96mm	Length = 95.5mm	9312.00 mm^2	9215.75 mm^2
	$Width_1$ = 96.5mm	$Width_2$ = 97mm	$Width_3$ = 97.5mm	Width = 97mm	Width = 96.5mm		
0803-IN-G40-1	$Length_1$ = 96.5mm	$Length_2$ = 96.5mm	$Length_3$ = 96mm	Length = 96.3mm	Length = 95.8mm	9389.25 mm^2	9292.60 mm^2
	$Width_1$ = 97mm	$Width_2$ = 97.5mm	$Width_3$ = 98mm	Width = 97.5mm	Width = 97mm		
0803-IN-G40-2	$Length_1$ = 96.5mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96.2mm	Length = 95.7mm	9331.40 mm^2	9235.05 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-G40-3	$Length_1$ = 97mm	$Length_2$ = 97mm	$Length_3$ = 96.5mm	Length = 96.8mm	Length = 96.3mm	9389.60 mm^2	9292.95 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-A40-1	$Length_1$ = 97.5mm	$Length_2$ = 97mm	$Length_3$ = 97mm	Length = 97.2mm	Length = 96.7mm	9302.04 mm^2	9205.84 mm^2

	$Width_1$ = 96mm	$Width_2$ = 95.5mm	$Width_3$ = 95.5mm	Width = 95.7mm	Width = 95.2mm		
0803-IN-A40-2	$Length_1$ = 96mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96mm	Length = 95.5mm	9331.20 mm^2	9234.85 mm^2
	$Width_1$ = 96.5mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97.2mm	Width = 96.7mm		
0803-IN-A40-3	$Length_1$ = 97mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96.3mm	Length = 95.8mm	9341.10 mm^2	9234.85 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-G50-1	$Length_1$ = 97mm	$Length_2$ = 96.5mm	$Length_3$ = 96mm	Length = 96.5mm	Length = 96mm	9360.50 mm^2	9264.00 mm^2
	$Width_1$ = 96mm	$Width_2$ = 97mm	$Width_3$ = 98mm	Width = 97mm	Width = 96.5mm		
0803-IN-G50-2	$Length_1$ = 98mm	$Length_2$ = 97mm	$Length_3$ = 96mm	Length = 97mm	Length = 96.5mm	9438.10 mm^2	9341.2 mm^2
	$Width_1$ = 96.5mm	$Width_2$ = 97.5mm	$Width_3$ = 98mm	Width = 97.3mm	Width = 96.8mm		
0803-IN-G50-3	$Length_1$ = 97mm	$Length_2$ = 96mm	$Length_3$ = 96mm	Length = 96.3mm	Length = 95.8mm	9437.40 mm^2	9340.50 mm^2
	$Width_1$ = 97mm	$Width_2$ = 98mm	$Width_3$ = 99mm	Width = 98mm	Width = 97.5mm		

Appendix 23 gives the temperature readings from the machine over time and Table 7.42 below is the results from the testing of all the samples in table 7.41. The codes are matched to that table and the results are presented in both actual weighed material, g/mm^2 and the total kg/m^2.

Table 7.42 Final results of the freeze-thaw testing

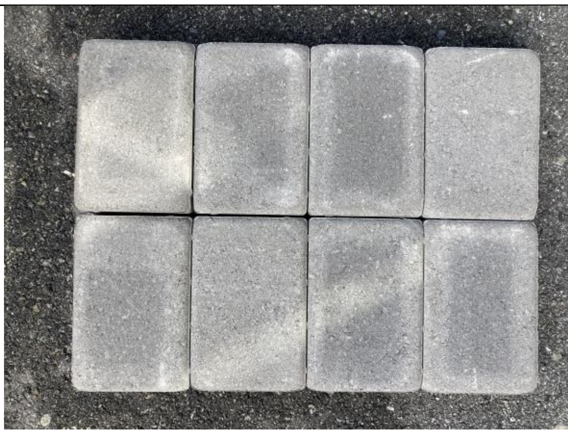
Code	Weight of scaled of material	Results in g/mm^2	Result in kg/m^2
0803-IN-N0-1	0.17g	0.0000181	0.0181
0803-IN-N0-2	0.16g	0.0000169	0.0169
0803-IN-N0-3	0.14g	0.0000148	0.0148
0803-IN-G20-1	3.69g	0.000396	0.396
0803-IN-G20-2	0.63g	0.0000670	0.0670
0803-IN-G20-3	0.71g	0.0000764	0.0764
0803-IN-A20-1	6.15g	0.000667	0.667
0803-IN-A20-2	3.62g	0.000392	0.392
0803-IN-A20-3	0.01g	0.00000109	0.00109
0803-IN-G30-1	12.07g	0.001310	1.310
0803-IN-G30-2	1.62g	0.000175	0.175
0803-IN-G30-3	2.47g	0.000268	0.268
0803-IN-G40-1	11.59g	0.001247	1.247
0803-IN-G40-2	4.44g	0.000481	0.481
0803-IN-G40-3	0.94g	0.000101	0.101
0803-IN-A40-1	15.58g	0.001692	1.692
0803-IN-A40-2	10.47g	0.001134	1.134

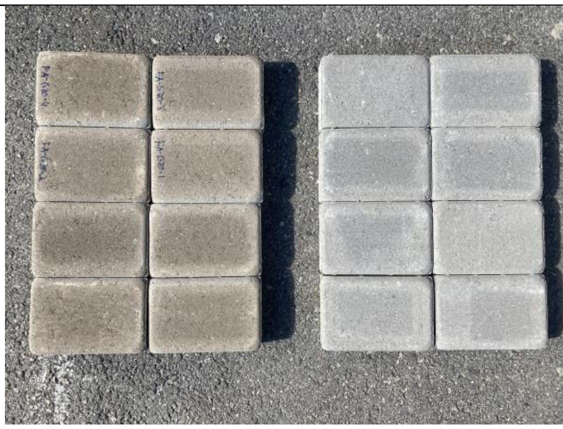
0803-IN-A40-3	6.85g	0.000742	0.742
0803-IN-G50-1	19.58g	0.002114	2.114
0803-IN-G50-2	6.58g	0.000704	0.704
0803-IN-G50-3	15.92g	0.001704	1.704

7.3.5. Geometric stability, measurements and visual appearance

The first section of chapter 6.3.5, the method chapter this is related to, starts with the visual inspections of the paving stones. Therefore, these results are laid out in a pattern, where the pictures, figure 7.7-7.19, taken of each stone sort inspected is placed together with the comments about those stones next to them. These are given in table 7.43.

Table 7.43 Inspection of 7 different stone variants

Code	Picture of stones	Comments
0303-FA-N0-(1-8)	 *Figure 7.7 Picture of surface development of 8 reference stones*	Colour and texture appear ok. Slight white/grey stripes that can easily be wiped off. Slight discolouration in the centre of some stones that laid at under other stones during storage and transportation.
0303-FA-G20-(1-8)	 *Figure 7.8 Picture of surface development of 8 G20 stones*	Quite an alright surface texture, with no apparent cracks or marks. Slight brown/red tint to especially the surfaces of the stones. Also, slightly darker in the middle of the stones that were on the bottom of the stacks of stones.
Comparison of N0 and G20 stones	 *Figure 7.9 Comparison of the surfaces of N0 and G20 stones*	The surface textures are indistinguishable from each other with the naked eye. The colour differences are not huge, but it appears like the G20 stones have a brown/red sheen to them

0303-FA-A20-(1-8)	 *Figure 7.10 Picture of surface development of 8 A20 stones*	The surface texture in these is completely normal as well. The grey colour is slightly darker, but still based in grey. The same darker tint in the centre of some stones is present here as well
Comparison of N0 and A20 stones	 *Figure 7.11 Comparison of the surfaces of N0 and A20 stones*	The surface textures are basically indistinguishable from each other with the naked eye. The colour differences are tiny, but it appears like the A20 stones have a slightly darker grey sheen to them.
0403-FA-G30-(1-8)	 *Figure 7.12 Picture of surface development of 8 G30 stones*	At 2m distance there is not possible to see any difference in surface texture, just as the others. Slight brown/red tint to especially the surfaces of the stones. Also, slightly darker in the middle of the stones that were on the bottom of the stacks of stones.
Comparison of N0 and G30 stones	 *Figure 7.13 Comparison of the surfaces of N0 and G30 stones*	At the 2m distance it is impossible to separate the texture of them, but close up the G30 might have slightly more pores. The G30 stones have a brown/red tint that is even stronger than for the G20 stones

0303-FA-G40-(1-8)	 *Figure 7.14 Picture of surface development of 8 G40 stones*	Close by the surface texture is a little rougher, but at a distance of 2m there is still no difference. The brown/red tint is even clearer than on the G20 and G30 stones. Also, a darker part in the middle of some stones.
Comparison of N0 and G40 stones	 *Figure 7.15 Comparison of the surfaces of N0 and G40 stones*	Close by it is visible that the texture on the G40 stones have some more pores. The colour on the G40 stones is clearly redder/ browner and visible at a distance.
0303-FA-A40-(1-8)	 *Figure 7.16 Pictures of surface development of 8 A40 stones*	The surface texture in these is completely normal at 2m as well. The same as with the G40, the pores are bigger close up. The grey colour is slightly darker, but still grey. The same darker tint in the centre of some stones is present here as well.
Comparison of N0 and A40 stones	 *Figure 7.17 Comparison of the surfaces of N0 and A40 stones*	Close by it is visible that the texture on the A40 stones have some more pores. At 2m distance it is impossible to see. The colour on the A40 stones is clearly darker grey.

0403-FA-G50-(1-8)	 Figure 7.18 Pictures of surface development of 8 G50 stones	This time the rougher surface is visible at a little further distance. Even at 2m you can see that something is up. The red/brown colour tint is just as strong as with the G40 stones.
Comparison of N0 and G540 stones	 Figure 7.19 Comparison of the surfaces of N0 and G50 stones	The difference in surface texture is visible at 2m, but you have to stare properly to see it. The colour is visibly different at much further distance. And clearly red/brown

After the visual inspection came the measurements of the stones. This is given in table 7.44-7.48 and is based around the earlier stated production dimensions of:

Length = 208mm, width = 138mm, thickness = 58mm and diagonals = 250mm

Table 7.44 Overview of measurements made on day 76 of curing with the reference batches

Code	Production date	Length	Width	Thickness	Diagonal 1	Diagonal 2
0303-FA-N0-1	03.03.21	208mm	138mm	58mm	250mm	250mm
0303-FA-N0-2	03.03.21	208mm	138mm	58mm	250mm	250mm
0303-FA-N0-3	03.03.21	208mm	138mm	58mm	250mm	250mm
0303-FA-N0-4	03.03.21	208mm	138mm	58mm	250mm	250mm

Table 7.45 Overview of measurements made on day 76 of curing with the 20% SiGS batch

Code	Production date	SiGS type	Length	Width	Thickness	Diagonal 1	Diagonal 2
0303-FA-G20-1	03.03.21	G	208mm	138mm	60mm	250mm	250mm
0303-FA-G20-2	03.03.21	G	208mm	138mm	60mm	250mm	250mm
0303-FA-G20-3	03.03.21	G	208mm	138mm	60mm	250mm	250mm
0303-FA-G20-4	03.03.21	G	208mm	138mm	60mm	250mm	250mm
0303-FA-A20-1	03.03.21	A	208mm	138mm	60mm	250mm	250mm
0303-FA-A20-2	03.03.21	A	208mm	138mm	60mm	250mm	250mm

0303-FA-A20-3	03.03.21	A	208mm	138mm	60mm	250mm	250mm
0303-FA-A20-4	03.03.21	A	208mm	138mm	60mm	250mm	250mm

Table 7.46 Overview of measurements made on day 75 with the 30% SiGS batch

Code	Production date	SiGS type	Length	Width	Thickness	Diagonal 1	Diagonal 2
0403-FA-G30-1	04.03.21	G	208mm	138mm	60mm	250mm	250mm
0403-FA-G30-2	04.03.21	G	208mm	138mm	59mm	250mm	250mm
0403-FA-G30-3	04.03.21	G	208mm	138mm	60mm	250mm	250mm
0403-FA-G30-4	04.03.21	G	208mm	138mm	59mm	250mm	250mm

Table 7.47 Overview of measurements made on day 76 with the 40% SiGS batch

Code	Production date	SiGS type	Length	Width	Thickness	Diagonal 1	Diagonal 2
0303-FA-G40-1	03.03.21	G	208mm	138mm	61mm	250mm	250mm
0303-FA-G40-2	03.03.21	G	208mm	138mm	61mm	250mm	250mm
0303-FA-G40-3	03.03.21	G	208mm	138mm	61mm	250mm	250mm
0303-FA-G40-4	03.03.21	G	208mm	138mm	61mm	250mm	250mm
0303-FA-A40-1	03.03.21	A	208mm	138mm	59mm	250mm	250mm
0303-FA-A40-2	03.03.21	A	208mm	138mm	60mm	250mm	250mm
0303-FA-A40-3	03.03.21	A	208mm	138mm	60mm	250mm	250mm
0303-FA-A40-4	03.03.21	A	208mm	138mm	59mm	250mm	250mm

Table 7.48 Overview of measurements made on day 75 with the 50% SiGS batch

Code	Production date	SiGS type	Length	Width	Thickness	Diagonal 1	Diagonal 2
0403-FA-G50-1	04.03.21	G	208mm	138mm	57mm	250mm	250mm
0403-FA-G50-2	04.03.21	G	208mm	138mm	57mm	250mm	250mm
0403-FA-G50-3	04.03.21	G	208mm	138mm	56mm	250mm	250mm
0403-FA-G50-4	04.03.21	G	208mm	138mm	57mm	250mm	250mm

8. Discussion

Every discussion in a thesis is based on the results collected with the outlined methods in the same thesis. Since this is the case each discussion chapter is corresponding with the result chapter in the same way as those corresponds with method chapter. In some instances, there will be chapters that follow up on each other or chapters that rethread parts of other chapters. When that is the case, it is to connect the results and try to discuss what they might mean for each other.

8.1. Literature study and literature review

EMC, and with that concrete paving stones, does have the characteristics that separates it from standard concrete. This would also influence the possibilities of ASR, at least in theory. With only small aggregates the possibility of ASR, if the aggregates were predisposed to it, would increase, because of the larger surface area to weight ratio. Luckily there is very little of the dangerous aggregates in Norway and everything used at Aaltvedt has already been tested for these compounds.

It was discussed in chapter 7.1 how the SCMs being in use today are already helping limit the possibility of ASR in concrete. SCMs are already being used in paving stones, since fly-ash is a natural added part of most cement sold in Norway. The problem obviously would be the fact that in essence this project is trying not only to replace cement, but also partly “replace” fly-ash as an SCM. Luckily SiGS has already shown many signs of being a pozzolanic material, so by introducing SiGS some of the alkali hydroxide should bind with the SiGS as well to form more C-S-H.

The last potential problem is moisture. Paving stones are produced with a deficit of water. This would leave little water accessible for the ASR. On the other hand, a problem is the use of paving stones and where it is laid down. Normally paving stones are used outside on “flat” ground with little protection. This would leave it in contact with a lot of water. Since paving stones basically are made of EMC this water would over time seep into the stones and instead of reacting with free cement it would react in the ASR. This is luckily not much of a problem, since the other two categories negate any possibility of ASR.

These are the reasons behind not looking at ASR closely in this thesis. Nothing is indicating this to be any problem, so on a list of things that needs investigating this comes at the bottom.

8.2. Production of concrete paving stones

The results of chapter 7.2 are heavily connected to the results of chapter 7.2.1-7.2.3, which is the results that chapter 8.2.1 is based around. Because of this there are some things that will not be touched in this chapter, but will be examined closer in the next chapter. What is interesting in this chapter is the pictures in figure 7.1-7.4. These pictures show that it is quite hard to see any visual difference on the surface of any of these stones, in their fresh state. With the writer's limited experience in the paving stones business there is very little apparent difference in the visual pores, on the surfaces, and there were no clear colour differences.

8.2.1. Density and experience in full-scale production on 03.03, 04.03 and 08.03

Continuing from the previous chapter and looking further into the stone surfaces, it is important to also connect that with the experiences in full-scale production, that chapter 7.2.1-7.2.3 partly focuses on. Looking through table 7.3-7.4, table 7.6-7.7 and table 7.9-7.12 there is no negative comment from anyone involved in the production process, specifically about the surface quality. This means that those that have seen hundreds of thousands of paving stones pass through the facility could not see any apparent differences in the fresh stone surfaces.

In Table 7.2 there is an interesting point that is important to keep in mind for the rest of the density discussions. During the full day of operation, 03.03.21, the density of these regular reference paving stones varied between at least 2224kg/m^3 at the minimum and at least 2272kg/m^3 at the most. It is unwise to state facts based only on small samples, but these were average stones, at random points in time and during an average production day of 5h. It is therefore not totally impossible to say that even during normal production, the density can vary with at least 48kg/m^3 and possibly more. Chapter 6.2.1 mentions how the paving stones were chosen from random production trays, just not the first or last few trays, and that on those trays they were chosen from different locations. This indicates that there are a lot more factors involved when the density is achieved.

When trying to compare this with the results in table 7.5, in order to disprove anomalies, the results there also show some of the similar traits. In this table, with results from 04.03.21, the lowest density measured were 2264kg/m^3 and the highest 2280kg/m^3. This is a lower result spread, only 16kg/m^3, but these results are 3 measurements over 2h instead of 4 measurements over 5h. It is also a fact that none of the values from these two first tables are the same. Even if the spread is closer to an assumable margin of error, the most interesting result in this table is actually the maximum result of 2280kg/m^3. For all intents and purposes, both the products in table 7.2 and in table 7.5 were produced with the same materials, by the same machinery, by the same automated system and by the same operators. This should mean that the product differences between these days should be almost identical. If you then take the minimum value from the first day and the maximum value from the second day, the difference can be assumed to be 56kg/m^3 instead of 48kg/m^3.

The last measurement on reference stones, in table 7.8, were done on stones with a different cement and on an "forced" extra production batch, in order to have the comparable reference there as well. This makes this not really comparable in this instance, but trying to compare the numbers we see that the numbers in table 7.8 is 2303kg/m^3. This is a little higher than the earlier mentioned 2280kg/m^3. It is also only 1 measurement, so it is impossible to know if other stones with

Industrisement will have results consistent with that, if 2303 is in a higher place on a range or if it is in a lower spot on a range. The most important point to take from this is that on 7 different measurements, on basically the same premise, 7 completely different results were achieved. Also, with the spread of 56kg/m^3 it is possible to say that there are other factors involved then just the material composition, when it comes to density of concrete paving stones.

Moving on to attempting to compare the two different kinds of SiGS with each other, a few points are important to point out. Starting from the left in figure 8.1 we can see that with 20% SiGS and *Standardsement FA* they are almost identical. All the bars with lines in the figure are *FA,* the fully coloured ones are *Industrisement*, the blue colours are granulated SiGS and the red are air-cooled. Looking further at those numbers, in table 7.3, we can see that the air-cooled SiGS had a density of 2kg/m^3 more, which is miniscule. Looking at the right side of that table, we can see that the HDMI number is the same. This is the number that indicates how moist the mixture is. Even if there was slightly more water in the air-cooled mixture, this is probably a consequence of material taken from different sections in a silo having different water content, at different times. The height measured on the stones shows that the stone with slightly worse density also had 1mm more of height. This does make sense, since the less the EMC can be compacted into the mould, the less dense it should be.

Going from 20% *FA* to 40% *FA*, we simply move to the next two bars in figure 8.1. These two are also nearly identical, with the air-cooled density again being slightly higher. In table 7.4 this time we can see that also here there is only 2kg/m^3 separating the two. Again, the HDMI values are identical, but this time it is the granulated SiGS that got 1l more of water, instead of the air-cooled in the last paragraph. This might be an indicator that the total amount of water added will have little impact on the density, since more water resulted in both a higher and lower density. This time the heights measured were identical. It is difficult to know if this is just a difference in where on the stones that were measured or if the air-cooled SiGS actually got less compacted this time.

Moving into the *Industrisement* we start with the first two fully coloured bars in figure 8.1. These are again for the 20% SiGS variants. From there it can seem like the results again are extremely similar, but looking at the connected table 7.9, the numbers deserve more explanation. The air-cooled sample ended up with a density of 2238kg/m^3, a HDMI of 204 and a height of 59mm, which was deemed quite normal. The problem then came with the granulated samples. The first batch got a comparable density of 2235, but the height this time was 60mm and the HDMI had gone up to 210. This was also commented on by the machine operators as a batch that did not compact to their standards, so another mixture was run. This time the height was even better than the air-cooled with 58mm and the HDMI was closer to the 204, with 202. This produced a density of 2251kg/m^3, which was significantly higher than both the air-cooled batch and the first granulated batch. With a result of a lower density with more height and more HDMI, and higher density with a lower height and lower HDMI, it was decided to average out those results to find somewhere in the middle. 2243 was now the density in figure 8.1, which is slightly higher than the 2238 of the air-cooled. This again indicates that the lower the height, the better density. This is intuitive, but it also might indicate that there is a sweet spot, when it comes to the HDMI value and going with a too moist mixture is bad for the density.

Finally looking at the last two bars, with 40% SiGS, we suddenly have a massive difference in figure 8.1. This is out of the norm from the other results, so it is important to find out what that might be because of. Looking at table 7.11, we see that the density differed by 40kg/m^3, but that the height was identical. As we also see, the HDMI numbers were widely different. Granulated SiGS, which had lower density, also had 7 less HDMI. It seemed from the previous paragraph, that a lower HDMI was good for the density, but with these numbers saying the opposite, it is assumed that going too low is also not a good thing.

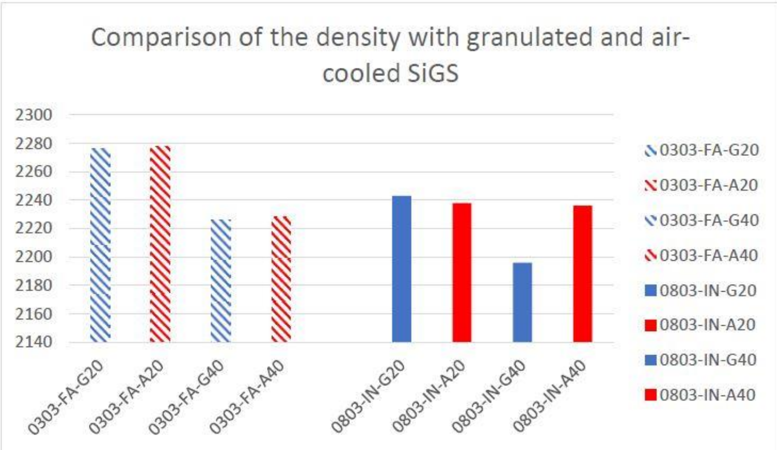


Figure 8.1 Comparison of density with G-SiGS and A-SiGS

Finally looking at the entire figure 8.1 we can try and see if there is any difference between the A-SiGS and G-SiGS. Strictly looking at the *FA*, since this had fewest production irregularities it might be the case that air-cooled is slightly easier to work with, when looking just at density. Since both of the *Industrisement* had some problems with the granulated SiGS it is difficult to say if this is related to the granulation or if it is a reaction between the cement and SiSG.

If we now make an attempt to see if the increasing amounts of SiGS has any effect on the density, we can see some interesting results on figure 8.2. On this figure the bars with red lines are standard *Standardsement FA,* the blue lines are standard *Industrisement,* the red colour are FA-G-SiGS, the yellow are FA-A-SiGS, the blue are IN-G-SiGS and the green are IN-A-SiGS.

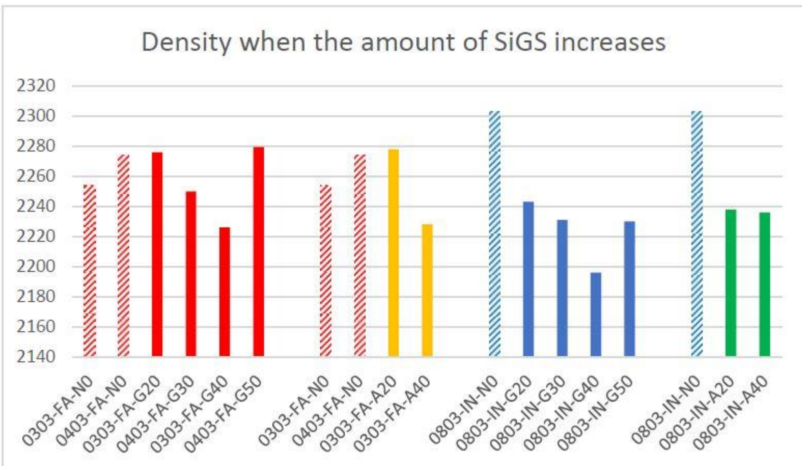


Figure 8.2 Density of regular stones compared to stones with increasing SiGS amounts

Initially looking at just the transition from 0% SiGS to 20% SiGS we can see some inconsistent results. Starting at the *FA* we see that the density actually slightly increases both with the 20% G-SiGS and the 20% A-SiGS. Then from there the density gradually drops off down to the 40% variants. We can see from the chart that the 50% granulated value suddenly shoots back up, even above the 20%. This is actually, when referencing table 7.7, an average of two different values measured. The first measurement was so much higher than the norm, so a decision was made to do a follow up measurement. That was 55kg/m^3 lower, which is significant. This is almost as much as the measurement range that was talked about in the start of this chapter. The second result was still much higher than expected, so the average still ended up much higher than the rest. Both the 30% and 40% results, in table 7.4 and 7.6, had higher HDMI results and lower density and lower HDMI with lower density. This might again indicate that there is a sweet spot for density that is closer related to the HDMI than anything else.

Moving over to the *Industrisement,* we see the exact same trend with a drop off in density, the more SiGS is added. The differences seem to be slightly lower, but this is again difficult to say for certain. We get another look at the confusing 50% granulated result, which is a sharp increase from the 40% one. It is much more in line with the 40% air-cooled result, since the drop off from there is only slight. The confusing part is really that the only difference between this 40% and 50% granulated is the 1mm in height. The water and HDMI are identical. It is therefore hard to conclude anything from it.

Finally, attempting to compare the density results from the two different cements with each other, we get figure 8.3. With the *FA* on the left and the *IN* on the right it shows that while the *FA* seems to slightly worsen with more and more SiGS, except the outlier at 50%, the *IN* starts much higher before having a massive drop of. Then the *IN* seems to be much more stable, except the outlier at G40, but here again the irregularities in measurements and conditions were worse than for the *FA*, so it is possible those results are more true.

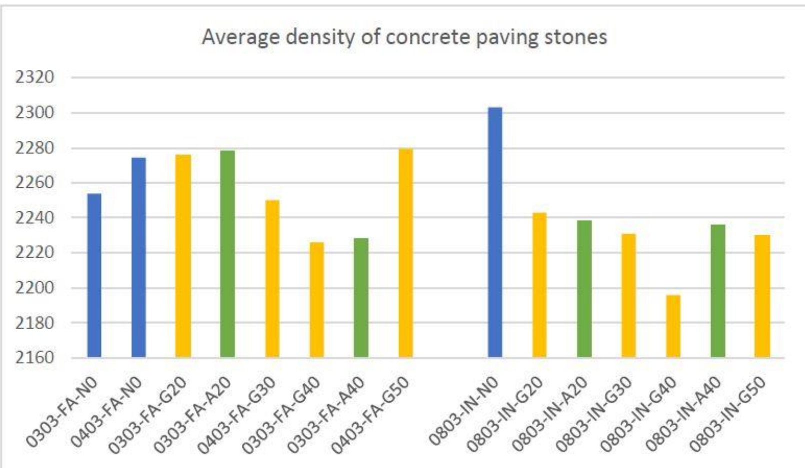


Figure 8.3 Comparison of FA sement and Industrisement

After all this back and forth, there are still questions with this section of the research. The data is limited, with one or two measurements, the conditions in a live factory makes the details impossible to keep consistent and with this many people involved the possibility for human error is increased.

8.3. Laboratory work

Whereas the two previous chapters were deeply connected, and therefore intermixed quite a lot, these next chapters are structured according to each connected result chapter. There will be some connection between some chapters, and even some chapters that connect back with the density chapter. When that occurs, it is for specific reasons and will be highlighted and explained then.

8.3.1. Compressibility

The results in chapter 7.3.2 can primarily be seen as three things. Firstly, as they are taken on stones that are going to be tested for tensile splitting strength, they are a much better indicator on how consistent the compression is then just the single measurements taken in the density chapters. The second is also a better indication, but this time on the differences in compression on *FA* vs *IN,* granulated vs air-cooled and on the increasing SiGS percentages. The last is as a helping hand to the later chapter of geometric stability. Do the stones increase or shrink in height over time or are there no clear indication of expansion?

There are a lot of tables connected to this chapter, table 7.13-7.37, so in order to create an extra point of reference, the table of average values, table 8.1, was made. The table is ordered in such a way as to follow the original tables. This means that it is mainly ordered from 0% to 50% SiGS before internally on each of them, the *FA* comes first. Then finally again ordered with the granulated values first.

Table 8.1 Average thickness measurement deviations for all stone productions and all intervals

Production code	SiGS type	Production date	Days of curing	Average height	Average deviation
0303-FA-N0-(1-4)	None	03.03.21	1	58.5mm	0.5mm
0303-FA-N0-(1-4)	None	03.03.21	3	58.5mm	0.5mm
0303-FA-N0-(1-4)	None	03.03.21	7	58.0mm	0.0mm
0303-FA-N0-(1-4)	None	03.03.21	14	58.5mm	0.5mm
0303-FA-N0-(1-4)	None	03.03.21	28	58.5mm	0.5mm
0803-IN-N0-(1-4)	None	08.03.21	1	59.8mm	1.8mm
0803-IN-N0-(1-4)	None	08.03.21	3	59.8mm	1.8mm
0803-IN-N0-(1-4)	None	08.03.21	7	59.5mm	1.5mm
0803-IN-N0-(1-4)	None	08.03.21	14	60.0mm	2.0mm
0803-IN-N0-(1-4)	None	08.03.21	28	59.5mm	1.5mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	1	60.0mm	2.0mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	3	60.0mm	2.0mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	7	60.3mm	2.3mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	14	60.0mm	2.0mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	28	60.0mm	2.0mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	1	59.8mm	1.8mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	3	59.8mm	1.8mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	7	59.5mm	1.5mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	14	60.0mm	2.0mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	28	59.3mm	1.3mm
0803-IN-G20-(1-4)	20% Granulated	08.03.21	1	59.5mm	1.5mm
0803-IN-G20-(1-4)	20% Granulated	08.03.21	3	59.0mm	1.0mm

0803-IN-G20-(1-4)	20% Granulated	08.03.21	7	58.0mm	0.0mm
0803-IN-G20-(1-4)	20% Granulated	08.03.21	14	58.8mm	0.8mm
0803-IN-G20-(1-4)	20% Granulated	08.03.21	28	58.0mm	0.0mm
0803-IN-A20-(1-4)	20% Air-cooled	08.03.21	1	59.8mm	1.8mm
0803-IN-A20-(1-4)	20% Air-cooled	08.03.21	3	59.8mm	1.8mm
0803-IN-A20-(1-4)	20% Air-cooled	08.03.21	7	59.5mm	1.5mm
0803-IN-A20-(1-4)	20% Air-cooled	08.03.21	14	59.8mm	1.8mm
0803-IN-A20-(1-4)	20% Air-cooled	08.03.21	28	59.8mm	1.8mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	1	59.8mm	1.8mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	3	59.8mm	1.8mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	7	59.8mm	1.8mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	14	59.8mm	1.8mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	28	60.0mm	2.0mm
0803-IN-G30-(1-4)	30% Granulated	08.03.21	1	60.0mm	2.0mm
0803-IN-G30-(1-4)	30% Granulated	08.03.21	3	60.5mm	2.5mm
0803-IN-G30-(1-4)	30% Granulated	08.03.21	7	59.8mm	1.8mm
0803-IN-G30-(1-4)	30% Granulated	08.03.21	14	60.0mm	2.0mm
0803-IN-G30-(1-4)	30% Granulated	08.03.21	28	59.5mm	1.5mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	1	61.0mm	3.0mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	3	60.5mm	2.5mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	7	60.0mm	2.0mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	14	61.3mm	3.3mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	28	60.5mm	2.5mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	1	59.8mm	1.8mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	3	60.0mm	2.0mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	7	60.0mm	2.0mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	14	60.0mm	2.0mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	28	59.5mm	1.5mm
0803-IN-G40-(1-4)	40% Granulated	08.03.21	1	60.0mm	2.0mm
0803-IN-G40-(1-4)	40% Granulated	08.03.21	3	60.3mm	2.3mm
0803-IN-G40-(1-4)	40% Granulated	08.03.21	7	59.0mm	1.0mm
0803-IN-G40-(1-4)	40% Granulated	08.03.21	14	59.8mm	1.8mm
0803-IN-G40-(1-4)	40% Granulated	08.03.21	28	59.3mm	1.3mm
0803-IN-A40-(1-4)	40% Air-cooled	08.03.21	1	59.8mm	1.8mm
0803-IN-A40-(1-4)	40% Air-cooled	08.03.21	3	59.8mm	1.8mm
0803-IN-A40-(1-4)	40% Air-cooled	08.03.21	7	59.0mm	1.0mm
0803-IN-A40-(1-4)	40% Air-cooled	08.03.21	14	59.8mm	1.8mm
0803-IN-A40-(1-4)	40% Air-cooled	08.03.21	28	59.3mm	1.3mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	1	56.5mm	-1.5mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	3	57.0mm	-1.0mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	7	56.3mm	-1.7mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	14	57.0mm	-1.0mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	28	56.3mm	-1.7mm
0803-IN-G50-(1-4)	50% Granulated	08.03.21	1	58.5mm	0.5mm
0803-IN-G50-(1-4)	50% Granulated	08.03.21	3	58.3mm	0.3mm
0803-IN-G50-(1-4)	50% Granulated	08.03.21	7	57.8mm	-0.2mm
0803-IN-G50-(1-4)	50% Granulated	08.03.21	14	58.3mm	0.3mm

0803-IN-G50-(1-4)	50% Granulated	08.03.21	28	57.8mm	-0.2mm

Spread between measurements in individual time intervals
Starting with the *FA* values, we see from table 7.13-7.17 and 8.1, that the 0% values are extremely consistent. For all 5 time-intervals the average deviation is 0mm or 0,5mm, which is not much. Looking at each of the time-intervals the only place with an outlier is in table 7.16, where one measurement is 2mm above the other 3.

Moving into the 20% granulated SIGS, in table 7.18-7.22 and 8.1, we see even more consistency. The heights measured is much taller, but every measurement is at 60mm, except 1 measurement after 7 days, which was at 61mm. This gave a spread in the average deviations of just 0.25, even better then with 0% SIGS. Moving across to the 20% Air-cooled we see a slightly higher average spread of 0.75mm. Looking at the individual test intervals, we can see that the reason for this slightly larger spread in numbers is that in both table 7.20 and 7.21 there are two measurements that are 2mm apart.

30% granulated SiGS on the other hand is back down to only 0,25mm of an average deviation. The reason for this extra deviation can be seen in table 7.27, where the two first measurements are separated by 2mm. This gave the extra mm for the 0.25 increase.

Now going from 30% granulated to 40% granulated we can see that the average deviations in table 8.1 suddenly increase all the way up to 1.25mm. It has still not reached a point where the average is as much as the maximum difference between two single measurements we have measured, of 2mm, but it is still an average well over the earlier maximum of 0.75mm. Looking at table 7.30 and 7.31 we see that the jump in the average is from 7 to 14 days. Even if the average is very different, on each of the time intervals all 4 individual measurements are very similar. At 7 days all 4 measure 60mm and at 14 days 3 measure 61mm and 1 measure 62mm. Jumping over to air-cooled again we are suddenly back down to an average deviation spread of just 0.5mm. The individual results connected to that have no interesting points to comment on, since the maximal difference on individual days is just 1mm.

Finally in the end of the *FA* section, we have the 50% granulated SiGS. There are interesting points here that will be come back to, but just looking at the average deviations and the consistency of deviations, we see that the maximum spread from lowest to highest average is back up to 0.75mm. The most important thing to comment on here is that for the 1-day measurement, in table 7.33, there is a difference between the highest and lowest number of 2mm.

Transferring over to the *Industrisement* section, we see from the 0% SiGS in table 8.1 that the maximal difference in average deviations is back down to just 0.5mm. This is among the lowest numbers that have been seen, on level with a lot of other values. In three of the five time-intervals, table 7.13-7.14 and 7.16, the spread between maximal and smallest measurement was as much as 2mm. This should have had a larger impact, but the average numbers seemed to even out.

The 20% granulated on the other hand had in this instance a massive difference and the biggest difference to this point, with 1.5mm. Interestingly enough the individual days, table 7.18-7.22, are actually extremely consistent, with only a few days having one or two measurements be 1mm above the rest. Then going over to the 20% air-cooled we are actually back down to the lowest average deviation difference of just 0.25mm. Here as well, all the individual time intervals have consistency between the 4 individual measurements, with only a few being separated by 1mm.

Going to the 30% granulated results, we see from table 8.1 that the average deviation spread is back up to 1mm. There is nothing particularly interesting about the individual measurements, for all the time-intervals, since looking through table 7.23-7.27 there is no more than 1mm between the largest separated values.

Moving up one more time, to 40% granulated SiGS, we are up one more time in table 8.1 to 1.25mm as the largest spread between average deviations. Here we again see individual measurements, in individual time-intervals, that are separated by 2mm. This is the case in both table 7.28 and 7.29, which is 1 and 3 days. Going from there to the 40% air-cooled we are suddenly back down to just 0.75mm between highest and lowest average deviation in table 8.1. The individual time-intervals for the air-cooled SiGS are back to being very consistent. Table 7.28-7.32 is back to just having 1mm being the maximal distance between two individual measurements, so that is again within consistency.

Looking at the final 50% values in table 8.1, we see that the maximal average deviation difference is similar to the previous with 0.75mm. This time the highest and lowest values are on both sides of zero, but this will be commented on later. The maximum difference between individual values in these time-intervals are again just 1mm, so the consistency is back to being quite good.

It is difficult to attempt to make any definite statements about any of the details that have been commented on so far. The statistical samples are really quite small, so if anything can be gleaned from it, it is based heavily on assumptions. Since this project is based around how the SiGS compares with the ordinary samples it is important to see if anything is comparable. From the 14-day testing on 0% SiGS *FA*, 1 day 0% SiGS *Industrisement*, 3 day 0% SiGS *Industrisement* and 14 day 0% SiGS *Industrisement* we can see that it is possible for the standard stones to have as much as 2mm separate 2 out of the 4 measurements. Had this only happened at one instance, then that could much more likely be chance, but at 4 out of 10 time-intervals it is assumed that 2mm is a normal difference. This is again based on little data, but it is at least assumable until disproved.

Based on all these factors it might be possible to say that all the other individual 4 and 4 measurements are within the normal limit, since none exceeded 2mm. It might also be possible to say that neither the SiGS nor the amount of it have much of an impact on the total homogeneousness of the mass, when pressed into all the moulds.

Change in average deviations over time and total deviations

If we now attempt to look at the total average deviations, in relation to the reference stones, and the changes over time, we have some noticeable points to comment on. The first is that according to table 8.1, the *FA* with 0% SiGS are always between 0 and 0.5mm. This might suggest that in order to have the same quality of stones, the SiGS stones should also be at that level. When then looking at the *Industrisement* stone with 0% SiGS we can see that this might not be the case. Here the stones are between 1,5 and 2mm. This is still based on very little data, but when comparing results, it is then maybe possible to say that anything under 2mm is within the standard values at Aaltvedt Betong. With the lowest average, in the 0% SiGS stones, of 0mm and the highest 2mm, we can go through table 8.1 and see if any results are outside those limits.

We find the first result outside of the limit, with 2.25mm, at 7-day testing for the 20% granulated SiGS with *FA.* The next result outside the limit, with 2,5mm, is found at 3-day testing for the 30% granulated SiGS with *Industrisement.* At 40% granulated SiGS with *FA* it is actually the case that all the results, except at 7 days, are above the limit of 2mm. Moving from there to 40% granulated with *Industrisement* we again only find one result, at 3-day testing, which is above 2mm with 2,3mm. At the 50% granulated SiGS with *FA* we can see that all the results are in the negative numbers, so they are all under 0mm. Finally for the 50% SiGS with *Industrisement* we have -0,2mm at both 7 and 28 days.

The most interesting thing about this is that none of the air-cooled SiGS results were outside the limits. With so little data, and no other parameters adjusted then SiGS amount, it is difficult to know if this just chance or an indication of air-cooled being slightly easier to compress. The first interesting point to look at is 40% SiGS with *FA.* It was just said that the air-cooled SiGS at 40% had no outliers, but looking at the numbers we just saw that the granulated SiGS had 4 out of 5. There is nothing in the density measurements in table 7.4 that indicates why this should be, since all the apparent values in that table are pretty much identical. This could then be the best indication that there could be a difference between the types of SiGS.

Connecting this back with the density results in chapter 7.2.1-7.2.3 again, we can see that it is the 50% granulated SiGS results in table 7.7 where the original density measured was so much higher than anything else. The extra measurement was also surprisingly high. This would make sense that the densest stones also had the lowest measurement deviations. Why it went so far into the negative is on the other hand still difficult to say. Maybe the filler effect from the finer inert particles, that was discussed in the density chapter, was so strong that the mixture even “shrunk” a mm or 2 after being compressed into the mould. Comparing the height measurement taken in table 7.7, it is even possible that this process occurred during the curing process. Finally, we can see that both *FA* and *Industrisement* have 3 instances each of these outlier numbers, so it is possible that in this category there is little difference between the cement types.

If we now try to look at how these values change and evolve over time. This is illustrated in figure 8.4. This figure shows how all the tested variants with *FA sement* change over time, from 1 day to 28 days. Firstly, it can be seen that the pale blue line at the bottom, G50-SiGS, moves up and down between -1 and -1,75. Since the values move up and down, there is no sharp movement one way. That would probably rule out any expansion/contraction, since no stone would do both within a few days. The same is the case for the darker blue line above it, where the values stay relatively consistent. Above that is the A20, G20, G30 and A40 lines clumped together a little. All of these move a little bit up and down, but they stay well under 1mm each time they increase/decrease. The last line in the figure is another interesting one. That is the brown G40-SiGS line at the top. This line moves even more then the G50-line, which only moved up and down 0,75mm twice. The G40-line moves down 1mm from 1 to 7 day, before moving back up 1,25mm at 14 days. Then it moves down

0.75mm all the way to 28 days. That means it does not end more than 0.5mm below the initial 1-day value.

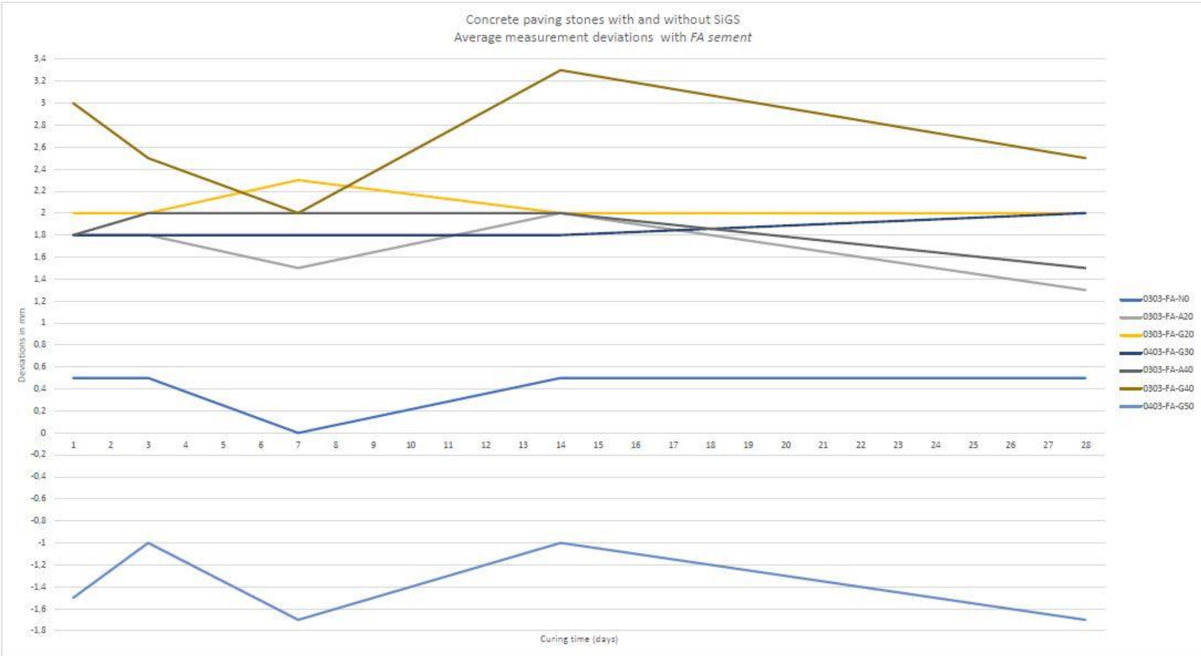


Figure 8.4 Average measurement deviations with FA sement

If we look at a similar figure for *Industrisement*, figure 8.5, we see some of the same trends. All of the variants are going up and down multiple times, just like in figure 8.4, but there are a few of the lines that deserve more comments.

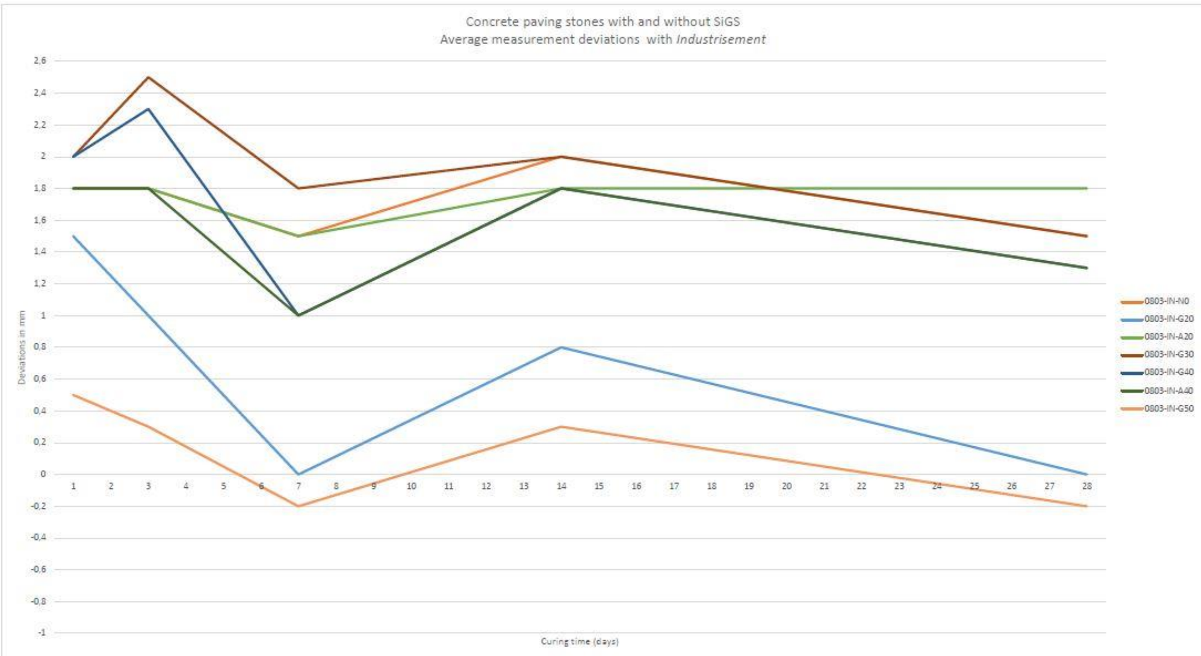


Figure 8.5 Average measurement deviations with industrisement

The first line to look at is the light blue G20 line. This line takes a significant drop off between 1 and 7 days of 1,5mm. then after 14 days it is back up halfway, before dropping back down to the same level as after 7 days. This is one of the batches with production irregularities, but it is difficult to say if that is the reason for such different outcomes, if the increased amount of cement in the *Industrisement* has had some impact on late reactions or if some other outcome has occurred. The last line in this figure to comment on is the G40-line in darker blue. This batch had a very low density, which was difficult to explain. Between 3 and 7 days this line drops of more than 1mm, which was noticeable. On the other hand, this is after having gone up between 1 and 3 and going up a lot between 7 and 14 days, so in the end it is difficult to say what is the cause. Finally, it is worth noticing that 4 out of the 7 variants had a downwards trend between 1 and 28 days. There would be a need for much further testing to conclude if that is just chance or not.

Regulations in the standard and factory demands

The final section of this chapter is about the stated permissible deviations in chapter 6.3.1 and how these tests compare to that. For these stones the permissible deviations were ± 3mm. These 3mm are supposed to be for any stones tested, according to the standard and is even then rarely a problem. Out of 280 stones measured only 1 stone did not pass this limit. This was a 40% granulated SiGS stone with *FA sement* after 14 days. This is a very low failure rate and if looking at the total question of SiGS it is promising. When working on the pre-project report it became clear that Aaltvedt Betong does not actually operate with ±3mm as their limit, but with ±1mm [13]. If we take this as the premise, then the numbers change. Now suddenly 156 of 280 are outside those limits. Fortunately enough this is testing where only the cement/SiGS ratio were adjusted. There are still many adjustments possible and to get SiGS into use at Aaltvedt, then this is just one section where this would be necessary.

8.3.2. Test of tensile splitting strength

The results in chapter 7.3.1 and the subsequent discussion in chapter 8.3.1 were based around the measurements made on paving stones that immediately were then split, using the test of tensile splitting strength. Because of this, the chapters were placed one after the other, to try and connect them, if possible.

Test result consistency

In the same way as was done for compressibility, the first point that should be looked at is the consistency between the 4 results in each individual test. This is presented in table 8.2 below as the largest difference in strength values.

Starting with the reference stones, so that we have the comparison points for later, we see that even though both the FA-N0 and the IN-N0 can be as low as 0,2 and 0,1MPa, they can also both be as high as 0,8 and 0,9MPa. Almost every value in between is also represented in the values. It is difficult and unwise to conclude anything based on limited data, but based on the data available, it might be possible to assume that any normal production will have values that vary significantly. If we then assume that 0,1MPa and 0,9MPa are quite normal difference values to get, then we can use those to make the limits and compare with the rest of the test samples.

Table 8.2 consistency in strength measurements

Production code	SiGS type	Product date	SiGS level	Days of curing	Largest difference between two heights	Largest difference between two strength values
0303-FA-N0-(1-4)-1d	No SiGS	03.03.21	0%	1-day	1 mm	0.5 MPa
0303-FA-N0-(1-4)-3d	No SiGS	03.03.21	0%	3-day	1 mm	0.9 MPa
0303-FA-N0-(1-4)-7d	No SiGS	03.03.21	0%	7-day	0 mm	0.2 MPa
0303-FA-N0-(1-4)-14d	No SiGS	03.03.21	0%	14-day	2 mm	0.2 MPa
0303-FA-N0-(1-4)-28d	No SiGS	03.03.21	0%	28-day	1 mm	0.6 MPa
0303-FA-N0-(1-4)-77d	No SiGS	03.03.21	0%	77-day	0 mm	0.6 MPa
0803-IN-N0-(1-4)-1d	No SiGS	08.03.21	0%	1-day	2 mm	0.7 MPa
0803-IN-N0-(1-4)-3d	No SiGS	08.03.21	0%	3-day	2 mm	0.1 MPa
0803-IN-N0-(1-4)-7d	No SiGS	08.03.21	0%	7-day	1 mm	0.8 MPa
0803-IN-N0-(1-4)-14d	No SiGS	08.03.21	0%	14-day	2 mm	0.4 MPa
0803-IN-N0-(1-4)-28d	No SiGS	08.03.21	0%	28-day	1 mm	0.5 MPa
0303-FA-A20-(1-4)-1d	Air-cooled	03.03.21	20%	1-day	1 mm	0.4 MPa
0303-FA-A20-(1-4)-3d	Air-cooled	03.03.21	20%	3-day	1 mm	0.8 MPa
0303-FA-A20-(1-4)-7d	Air-cooled	03.03.21	20%	7-day	2 mm	0.5 MPa
0303-FA-A20-(1-4)-14d	Air-cooled	03.03.21	20%	14-day	2 mm	0.6 MPa
0303-FA-A20-(1-4)-28d	Air-cooled	03.03.21	20%	28-day	1 mm	0.8 MPa
0303-FA-A20-(1-4)-77d	Air-cooled	03.03.21	20%	77-day	0 mm	0.9 MPa
0303-FA-G20-(1-4)-1d	Granulated	03.03.21	20%	1-day	0 mm	0.4 MPa
0303-FA-G20-(1-4)-3d	Granulated	03.03.21	20%	3-day	0 mm	0.1 MPa
0303-FA-G20-(1-4)-7d	Granulated	03.03.21	20%	7-day	1 mm	0.2 MPa
0303-FA-G20-(1-4)-14d	Granulated	03.03.21	20%	14-day	0 mm	0.6 MPa
0303-FA-G20-(1-4)-28d	Granulated	03.03.21	20%	28-day	0 mm	0.2 MPa

0303-FA-G20-(1-4)-77d	Granulated	03.03.21	20%	77-day	0 mm	0.8 MPa
0803-IN-G20-(1-4)-1d	Granulated	08.03.21	20%	1-day	1 mm	0.4 MPa
0803-IN-G20-(1-4)-3d	Granulated	08.03.21	20%	3-day	0 mm	0.3 MPa
0803-IN-G20-(1-4)-7d	Granulated	08.03.21	20%	7-day	0 mm	0.9 MPa
0803-IN-G20-(1-4)-14d	Granulated	08.03.21	20%	14-day	1 mm	0.4 MPa
0803-IN-G20-(1-4)-28d	Granulated	08.03.21	20%	28-day	0 mm	0.3 MPa
0803-IN-A20-(1-4)-1d	Air-cooled	08.03.21	20%	1-day	1 mm	0.4 MPa
0803-IN-A20-(1-4)-3d	Air-cooled	08.03.21	20%	3-day	1 mm	0.1 MPa
0803-IN-A20-(1-4)-7d	Air-cooled	08.03.21	20%	7-day	1 mm	0.4 MPa
0803-IN-A20-(1-4)-14d	Air-cooled	08.03.21	20%	14-day	1 mm	0.4 MPa
0803-IN-A20-(1-4)-28d	Air-cooled	08.03.21	20%	28-day	1 mm	0.4 MPa
0403-FA-G30-(1-4)-1d	Granulated	04.03.21	30%	1-day	1 mm	0.3 MPa
0403-FA-G30-(1-4)-3d	Granulated	04.03.21	30%	3-day	1 mm	0.4 MPa
0403-FA-G30-(1-4)-7d	Granulated	04.03.21	30%	7-day	1 mm	0.4 MPa
0403-FA-G30-(1-4)-14d	Granulated	04.03.21	30%	14-day	1 mm	0.4 MPa
0403-FA-G30-(1-4)-28d	Granulated	04.03.21	30%	28-day	2 mm	0.5 MPa
0403-FA-G30-(1-4)-77d	Granulated	04.03.21	30%	77-day	1 mm	1.8 MPa
0803-IN-G30-(1-4)-1d	Granulated	08.03.21	30%	1-day	0 mm	0.4 MPa
0803-IN-G30-(1-4)-3d	Granulated	08.03.21	30%	3-day	1 mm	0.4 MPa
0803-IN-G30-(1-4)-7d	Granulated	08.03.21	30%	7-day	1 mm	0.2 MPa
0803-IN-G30-(1-4)-14d	Granulated	08.03.21	30%	14-day	0 mm	0.3 MPa
0803-IN-G30-(1-4)-28d	Granulated	08.03.21	30%	28-day	1 mm	0.8 MPa
0303-FA-A40-(1-4)-1d	Air-cooled	03.03.21	40%	1-day	1 mm	0.3 MPa
0303-FA-A40-(1-4)-3d	Air-cooled	03.03.21	40%	3-day	0 mm	0.0 MPa
0303-FA-A40-(1-4)-7d	Air-cooled	03.03.21	40%	7-day	0 mm	0.3 MPa
0303-FA-A40-(1-4)-14d	Air-cooled	03.03.21	40%	14-day	0 mm	0.3 MPa
0303-FA-A40-(1-4)-28d	Air-cooled	03.03.21	40%	28-day	1 mm	0.3 MPa
0303-FA-A40-(1-4)-77d	Air-cooled	03.03.21	40%	77-day	1 mm	1.1 MPa
0303-FA-G40-(1-4)-1d	Granulated	03.03.21	40%	1-day	0 mm	0.3 MPa
0303-FA-G40-(1-4)-3d	Granulated	03.03.21	40%	3-day	1 mm	0.4 MPa
0303-FA-G40-(1-4)-7d	Granulated	03.03.21	40%	7-day	0 mm	0.4 MPa
0303-FA-G40-(1-4)-14d	Granulated	03.03.21	40%	14-day	1 mm	0.5 MPa
0303-FA-G40-(1-4)-28d	Granulated	03.03.21	40%	28-day	1 mm	0.8 MPa
0303-FA-G40-(1-4)-77d	Granulated	03.03.21	40%	77-day	0 mm	0.5 MPa
0803-IN-G40-(1-4)-1d	Granulated	08.03.21	40%	1-day	2 mm	0.4 MPa
0803-IN-G40-(1-4)-3d	Granulated	08.03.21	40%	3-day	1 mm	0.8 MPa
0803-IN-G40-(1-4)-7d	Granulated	08.03.21	40%	7-day	0 mm	0.2 MPa
0803-IN-G40-(1-4)-14d	Granulated	08.03.21	40%	14-day	1 mm	0.4 MPa
0803-IN-G40-(1-4)-28d	Granulated	08.03.21	40%	28-day	1 mm	0.9 MPa
0803-IN-A40-(1-4)-1d	Air-cooled	08.03.21	40%	1-day	1 mm	0.4 MPa
0803-IN-A40-(1-4)-3d	Air-cooled	08.03.21	40%	3-day	1 mm	0.5 MPa
0803-IN-A40-(1-4)-7d	Air-cooled	08.03.21	40%	7-day	0 mm	0.1 MPa
0803-IN-A40-(1-4)-14d	Air-cooled	08.03.21	40%	14-day	1 mm	0.8 MPa
0803-IN-A40-(1-4)-28d	Air-cooled	08.03.21	40%	28-day	1 mm	0.4 MPa
0403-FA-G50-(1-4)-1d	Granulated	04.03.21	50%	1-day	2 mm	0.2 MPa
0403-FA-G50-(1-4)-3d	Granulated	04.03.21	50%	3-day	0 mm	0.0 MPa
0403-FA-G50-(1-4)-7d	Granulated	04.03.21	50%	7-day	1 mm	0.2 MPa

0403-FA-G50-(1-4)-14d	Granulated	04.03.21	50%	14-day	0 mm	0.5 MPa
0403-FA-G50-(1-4)-28d	Granulated	04.03.21	50%	28-day	1 mm	0.8 MPa
0403-FA-G50-(1-4)-77d	Granulated	04.03.21	50%	77-day	1 mm	0.7 MPa
0803-IN-G50-(1-4)-1d	Granulated	08.03.21	50%	1-day	1 mm	0.2 MPa
0803-IN-G50-(1-4)-3d	Granulated	08.03.21	50%	3-day	1 mm	0.2 MPa
0803-IN-G50-(1-4)-7d	Granulated	08.03.21	50%	7-day	1 mm	0.7 MPa
0803-IN-G50-(1-4)-14d	Granulated	08.03.21	50%	14-day	1 mm	1.0 MPa
0803-IN-G50-(1-4)-28d	Granulated	08.03.21	50%	28-day	1 mm	0.2 MPa

If we start by doing what we did with the measurements and see how many of each of the 4 stone groups are outside the limits, we see something interesting. Out of the total of 60 measurements of 4 stones each, only 1 is above 0,9 MPa. This is for the *Industrisement* with 50% granulated after 14 days. That specific value is only above with 0,1 MPa, so it is not exactly a strong case for any kind of reasoning. If we look at values under the 0,1 then we come up with only two. One is after 3 days with the FA-A40 stones and one is after 3 days with the FA-G50 stones.

It is possible that these 3 instances are extreme outliers and therefore it would be good to check how many of the values are actually right on the limits. Going through the table it shows that a total of 3 values are at 0,1 and 2 values are at 0,9. If we decrease to one value inside the limits, then we find 14 instances. This means that 38 values, almost 60%, are spread out well inside the limits. It is still difficult to conclude anything, but it seems like, just as with compressibility, there might not be anything in the SiGS that affects the even distribution of properties in the mixture. By that it means that it is not likely for the SiGS to heavily "clump" together or only react in certain sections of the initial mixture.

Results compared to the standard

Chapter 6.3.2 discussed the three central demands in the standard, when talking about the tensile splitting strength. These were:

- Not an average strength lower than 3,6 MPa
- No individual strength lower than 2,9 MPa
- No individual failure load lower than 250 N/mm

All of those are set to the timeline of 28 days, so with the results of those three categories collected in table 8.3 we can see which stone variant that passes and which fails. If we start with the average strength, we can see that only the 40 % air-cooled SiGS with *FA* did not manage to get above 3,6. It ended at 3,5 MPa. Looking through individual strength values, we can see that no values were under the limit of 2,9 MPa. We can see that both FA-A40 and FA-G40 have 1 strength value at 3,3 MPa, but that is the closest. If we also look at the failure load, then we can see that none of those are even close to 250 N/mm. One of the just mentioned 3,3 MPa results were the closest, with 355 N/mm.

Table 8.3 results from tensile splitting strength relevant to the standard

Production code	SiGS type	Date	SiGS level	Strength	Average strength	Failure load
0303-FA-N0-1-28d	No SiGS	03.03.2021	0%	4.7 MPa		507 N/mm

0303-FA-N0-2-28d	No SiGS	03.03.2021	0%	4.6 MPa		490 N/mm
0303-FA-N0-3-28d	No SiGS	03.03.2021	0%	5.2 MPa		552 N/mm
0303-FA-N0-4-28d	No SiGS	03.03.2021	0%	4.9 MPa	4.85 MPa	521 N/mm
0803-IN-N0-1-28d	No SiGS	08.03.2021	0%	5.8 MPa		623 N/mm
0803-IN-N0-2-28d	No SiGS	08.03.2021	0%	5.3 MPa		573 N/mm
0803-IN-N0-3-28d	No SiGS	08.03.2021	0%	5.8 MPa		623 N/mm
0803-IN-N0-4-28d	No SiGS	08.03.2021	0%	5.6 MPa	5.63 MPa	602 N/mm
0303-FA-A20-1-28d	Air-cooled	03.03.2021	20%	3.9 MPa		417 N/mm
0303-FA-A20-2-28d	Air-cooled	03.03.2021	20%	4.3 MPa		463 N/mm
0303-FA-A20-3-28d	Air-cooled	03.03.2021	20%	4.7 MPa		508 N/mm
0303-FA-A20-4-28d	Air-cooled	03.03.2021	20%	4.7 MPa	4.40 MPa	503 N/mm
0303-FA-G20-1-28d	Granulated	03.03.2021	20%	4.1 MPa		445 N/mm
0303-FA-G20-2-28d	Granulated	03.03.2021	20%	4.1 MPa		444 N/mm
0303-FA-G20-3-28d	Granulated	03.03.2021	20%	4.3 MPa		462 N/mm
0303-FA-G20-4-28d	Granulated	03.03.2021	20%	4.2 MPa	4.18 MPa	458 N/mm
0803-IN-G20-1-28d	Granulated	08.03.2021	20%	4.9 MPa		527 N/mm
0803-IN-G20-2-28d	Granulated	08.03.2021	20%	4.6 MPa		494 N/mm
0803-IN-G20-3-28d	Granulated	08.03.2021	20%	4.8 MPa		512 N/mm
0803-IN-G20-4-28d	Granulated	08.03.2021	20%	4.8 MPa	4.78 MPa	511 N/mm
0803-IN-A20-1-28d	Air-cooled	08.03.2021	20%	4.6 MPa		494 N/mm
0803-IN-A20-2-28d	Air-cooled	08.03.2021	20%	4.9 MPa		528 N/mm
0803-IN-A20-3-28d	Air-cooled	08.03.2021	20%	5.0 MPa		543 N/mm
0803-IN-A20-4-28d	Air-cooled	08.03.2021	20%	4.6 MPa	4.78 MPa	503 N/mm
0403-FA-G30-1-28d	Granulated	04.03.2021	30%	4.5 MPa		480 N/mm
0403-FA-G30-2-28d	Granulated	04.03.2021	30%	4.0 MPa		438 N/mm
0403-FA-G30-3-28d	Granulated	04.03.2021	30%	4.4 MPa		474 N/mm
0403-FA-G30-4-28d	Granulated	04.03.2021	30%	4.1 MPa	4.25 MPa	441 N/mm
0803-IN-G30-1-28d	Granulated	08.03.2021	30%	5.2 MPa		558 N/mm
0803-IN-G30-2-28d	Granulated	08.03.2021	30%	5.5 MPa		592 N/mm
0803-IN-G30-3-28d	Granulated	08.03.2021	30%	4.9 MPa		524 N/mm
0803-IN-G30-4-28d	Granulated	08.03.2021	30%	4.7 MPa	5.08 MPa	506 N/mm
0303-FA-A40-1-28d	Air-cooled	03.03.2021	40%	3.6 MPa		393 N/mm
0303-FA-A40-2-28d	Air-cooled	03.03.2021	40%	3.5 MPa		381 N/mm
0303-FA-A40-3-28d	Air-cooled	03.03.2021	40%	3.6 MPa		386 N/mm
0303-FA-A40-4-28d	Air-cooled	03.03.2021	40%	3.3 MPa	3.50 MPa	357 N/mm
0303-FA-G40-1-28d	Granulated	03.03.2021	40%	3.3 MPa		355 N/mm
0303-FA-G40-2-28d	Granulated	03.03.2021	40%	4.1 MPa		444 N/mm
0303-FA-G40-3-28d	Granulated	03.03.2021	40%	3.4 MPa		369 N/mm
0303-FA-G40-4-28d	Granulated	03.03.2021	40%	3.9 MPa	3.68 MPa	424 N/mm
0803-IN-G40-1-28d	Granulated	08.03.2021	40%	4.9 MPa		525 N/mm
0803-IN-G40-2-28d	Granulated	08.03.2021	40%	5.4 MPa		575 N/mm
0803-IN-G40-3-28d	Granulated	08.03.2021	40%	5.0 MPa		547 N/mm
0803-IN-G40-4-28d	Granulated	08.03.2021	40%	4.5 MPa	4.95 MPa	484 N/mm
0803-IN-A40-1-28d	Air-cooled	08.03.2021	40%	4.4 MPa		475 N/mm
0803-IN-A40-2-28d	Air-cooled	08.03.2021	40%	4.4 MPa		477 N/mm
0803-IN-A40-3-28d	Air-cooled	08.03.2021	40%	4.0 MPa		428 N/mm
0803-IN-A40-4-28d	Air-cooled	08.03.2021	40%	4.2 MPa	4.25 MPa	451 N/mm

0403-FA-G50-1-28d	Granulated	04.03.2021	50%	4.3 MPa		447 N/mm
0403-FA-G50-2-28d	Granulated	04.03.2021	50%	5.0 MPa		534 N/mm
0403-FA-G50-3-28d	Granulated	04.03.2021	50%	5.1 MPa		537 N/mm
0403-FA-G50-4-28d	Granulated	04.03.2021	50%	5.1 MPa	4.88 MPa	533 N/mm
0803-IN-G50-1-28d	Granulated	08.03.2021	50%	4.8 MPa		508 N/mm
0803-IN-G50-2-28d	Granulated	08.03.2021	50%	4.8 MPa		512 N/mm
0803-IN-G50-3-28d	Granulated	08.03.2021	50%	5.0 MPa		533 N/mm
0803-IN-G50-4-28d	Granulated	08.03.2021	50%	4.8 MPa	4.85 MPa	507 N/mm

Since both of the 50% batches and the other 40% ones passed the regulations quite easily, it would probably be smart to perform further testing on the one that did not pass. This would verify if that was just chance or if something happens specifically at that mixture of components and amounts. Based on just these numbers, then there does not seem to be anything about SiGS itself that should make it unusable by the standards of the law. The only road blocks in the strength category would then be what Aaltvedt Betong would be comfortable with as a result and what improvements might be possible by optimizing the mixtures in other ways.

Average results of strength development

When attempting to look at the development of strength over time periods it would be extremely difficult and confusing to look at all the individual results. In order to make the results a little simpler to read, all the results of 4 and 4 stones were averaged out in table 8.4 below. The results are sorted according to SiGS amounts, just like the original results were.

Table 8.4 Average splitting test results for all time intervals for both productions

Production code	SiGS type	Production date	SiGS level	Days of curing	Strength
0303-FA-N0-(1-4)-1d	No SiGS	03.03.2021	0%	1-day	4.35 MPa
0303-FA-N0-(1-4)-3d	No SiGS	03.03.2021	0%	3-day	4.18 MPa
0303-FA-N0-(1-4)-7d	No SiGS	03.03.2021	0%	7-day	3.78 MPa
0303-FA-N0-(1-4)-14d	No SiGS	03.03.2021	0%	14-day	4.08 MPa
0303-FA-N0-(1-4)-28d	No SiGS	03.03.2021	0%	28-day	4.85 MPa
0803-IN-N0-(1-4)-1d	No SiGS	08.03.2021	0%	1-day	4.35 MPa
0803-IN-N0-(1-4)-3d	No SiGS	08.03.2021	0%	3-day	4.78 MPa
0803-IN-N0-(1-4)-7d	No SiGS	08.03.2021	0%	7-day	4.88 MPa
0803-IN-N0-(1-4)-14d	No SiGS	08.03.2021	0%	14-day	5.00 MPa
0803-IN-N0-(1-4)-28d	No SiGS	08.03.2021	0%	28-day	5.63 MPa
0303-FA-A20-(1-4)-1d	Air-cooled	03.03.2021	20%	1-day	2.08 MPa
0303-FA-A20-(1-4)-3d	Air-cooled	03.03.2021	20%	3-day	3.25 MPa
0303-FA-A20-(1-4)-7d	Air-cooled	03.03.2021	20%	7-day	3.65 MPa
0303-FA-A20-(1-4)-14d	Air-cooled	03.03.2021	20%	14-day	4.10 MPa
0303-FA-A20-(1-4)-28d	Air-cooled	03.03.2021	20%	28-day	4.40 MPa
0303-FA-G20-(1-4)-1d	Granulated	03.03.2021	20%	1-day	2.05 MPa
0303-FA-G20-(1-4)-3d	Granulated	03.03.2021	20%	3-day	3.35 MPa
0303-FA-G20-(1-4)-7d	Granulated	03.03.2021	20%	7-day	3.80 MPa
0303-FA-G20-(1-4)-14d	Granulated	03.03.2021	20%	14-day	4.38 MPa
0303-FA-G20-(1-4)-28d	Granulated	03.03.2021	20%	28-day	4.18 MPa

0803-IN-G20-(1-4)-1d	Granulated	08.03.2021	20%	1-day	3.05 MPa
0803-IN-G20-(1-4)-3d	Granulated	08.03.2021	20%	3-day	3.63 MPa
0803-IN-G20-(1-4)-7d	Granulated	08.03.2021	20%	7-day	4.10 MPa
0803-IN-G20-(1-4)-14d	Granulated	08.03.2021	20%	14-day	4.08 MPa
0803-IN-G20-(1-4)-28d	Granulated	08.03.2021	20%	28-day	4.78 MPa
0803-IN-A20-(1-4)-1d	Air-cooled	08.03.2021	20%	1-day	3.25 MPa
0803-IN-A20-(1-4)-3d	Air-cooled	08.03.2021	20%	3-day	3.83 MPa
0803-IN-A20-(1-4)-7d	Air-cooled	08.03.2021	20%	7-day	3.88 MPa
0803-IN-A20-(1-4)-14d	Air-cooled	08.03.2021	20%	14-day	4.18 MPa
0803-IN-A20-(1-4)-28d	Air-cooled	08.03.2021	20%	28-day	4.78 MPa
0403-FA-G30-(1-4)-1d	Granulated	04.03.2021	30%	1-day	1.85 MPa
0403-FA-G30-(1-4)-3d	Granulated	04.03.2021	30%	3-day	2.45 MPa
0403-FA-G30-(1-4)-7d	Granulated	04.03.2021	30%	7-day	3.43 MPa
0403-FA-G30-(1-4)-14d	Granulated	04.03.2021	30%	14-day	3.78 MPa
0403-FA-G30-(1-4)-28d	Granulated	04.03.2021	30%	28-day	4.25 MPa
0803-IN-G30-(1-4)-1d	Granulated	08.03.2021	30%	1-day	2.98 MPa
0803-IN-G30-(1-4)-3d	Granulated	08.03.2021	30%	3-day	3.73 MPa
0803-IN-G30-(1-4)-7d	Granulated	08.03.2021	30%	7-day	4.10 MPa
0803-IN-G30-(1-4)-14d	Granulated	08.03.2021	30%	14-day	4.05 MPa
0803-IN-G30-(1-4)-28d	Granulated	08.03.2021	30%	28-day	5.08 MPa
0303-FA-A40-(1-4)-1d	Air-cooled	03.03.2021	40%	1-day	1.20 MPa
0303-FA-A40-(1-4)-3d	Air-cooled	03.03.2021	40%	3-day	2.30 MPa
0303-FA-A40-(1-4)-7d	Air-cooled	03.03.2021	40%	7-day	2.75 MPa
0303-FA-A40-(1-4)-14d	Air-cooled	03.03.2021	40%	14-day	3.45 MPa
0303-FA-A40-(1-4)-28d	Air-cooled	03.03.2021	40%	28-day	3.50 MPa
0303-FA-G40-(1-4)-1d	Granulated	03.03.2021	40%	1-day	1.05 MPa
0303-FA-G40-(1-4)-3d	Granulated	03.03.2021	40%	3-day	2.25 MPa
0303-FA-G40-(1-4)-7d	Granulated	03.03.2021	40%	7-day	2.95 MPa
0303-FA-G40-(1-4)-14d	Granulated	03.03.2021	40%	14-day	3.55 MPa
0303-FA-G40-(1-4)-28d	Granulated	03.03.2021	40%	28-day	3.68 MPa
0803-IN-G40-(1-4)-1d	Granulated	08.03.2021	40%	1-day	2.98 MPa
0803-IN-G40-(1-4)-3d	Granulated	08.03.2021	40%	3-day	3.25 MPa
0803-IN-G40-(1-4)-7d	Granulated	08.03.2021	40%	7-day	3.70 MPa
0803-IN-G40-(1-4)-14d	Granulated	08.03.2021	40%	14-day	4.08 MPa
0803-IN-G40-(1-4)-28d	Granulated	08.03.2021	40%	28-day	4.95 MPa
0803-IN-A40-(1-4)-1d	Air-cooled	08.03.2021	40%	1-day	2.43 MPa
0803-IN-A40-(1-4)-3d	Air-cooled	08.03.2021	40%	3-day	3.15 MPa
0803-IN-A40-(1-4)-7d	Air-cooled	08.03.2021	40%	7-day	3.23 MPa
0803-IN-A40-(1-4)-14d	Air-cooled	08.03.2021	40%	14-day	3.38 MPa
0803-IN-A40-(1-4)-28d	Air-cooled	08.03.2021	40%	28-day	4.25 MPa
0403-FA-G50-(1-4)-1d	Granulated	04.03.2021	50%	1-day	1.88 MPa
0403-FA-G50-(1-4)-3d	Granulated	04.03.2021	50%	3-day	2.90 MPa
0403-FA-G50-(1-4)-7d	Granulated	04.03.2021	50%	7-day	3.93 MPa
0403-FA-G50-(1-4)-14d	Granulated	04.03.2021	50%	14-day	4.90 MPa
0403-FA-G50-(1-4)-28d	Granulated	04.03.2021	50%	28-day	4.88 MPa
0803-IN-G50-(1-4)-1d	Granulated	08.03.2021	50%	1-day	2.38 MPa
0803-IN-G50-(1-4)-3d	Granulated	08.03.2021	50%	3-day	3.35 MPa

0803-IN-G50-(1-4)-7d	Granulated	08.03.2021	50%	7-day	4.00 MPa
0803-IN-G50-(1-4)-14d	Granulated	08.03.2021	50%	14-day	4.23 MPa
0803-IN-G50-(1-4)-28d	Granulated	08.03.2021	50%	28-day	4.85 MPa

To attempt to compare and contrast these results in a graphical way is challenging. The best way to solve this is to split the results into “sub-categories” that then can be internally compared. The first category are air-cooled vs granulated SiGS.

Comparison of air-cooled and granulated SiGS

The comparison of both 20% air-cooled vs 20% granulated SiGS and 40% air-cooled vs 40% granulated SiGS is shown in figure 8.6 below. This figure shows the 20% comparisons on the left side of each time-interval and 40% on the right. It also shows the air-cooled variants as striped colours and the granulated variants as solid colours. Finally, it is such that each pair of two bars represent the same cement variant for both of them.

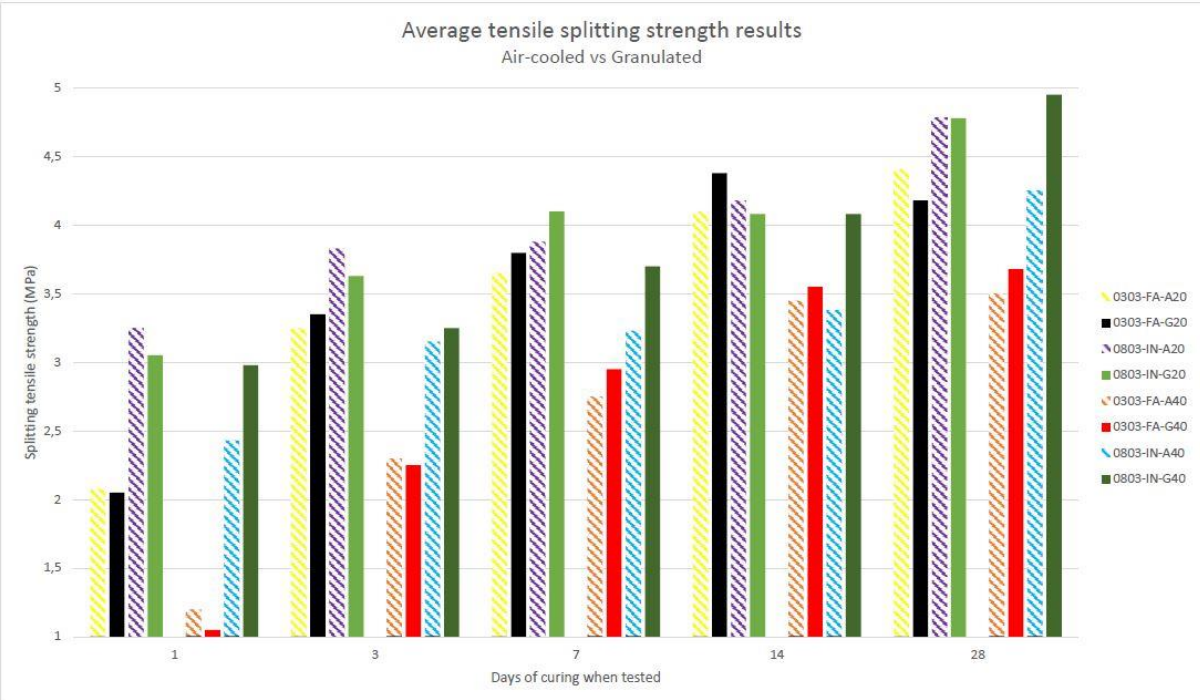


Figure 8.6 Comparison of tensile splitting strength for air-cooled and granulated SiGS

The first point to comment on is the “score” for the total number of comparisons. As the figure shows, in 7 of the 20 comparisons the air-cooled SiGS has the highest value. In 1 of them the result is identical and in the remaining 12 comparisons it is the granulated SiGS that comes out on top. This is in line with the assumptions made in chapter 3.4.2, that granulation produces structures with better reactivity in the SiGS. This is still not an overwhelming and conclusive case. When only working with single datasets it is possible that every one of these should be the opposite instead. It is possible that running the experiments a 1000 times would produce exactly the same results or that they would average out sharply in one direction. It is interesting to see that the only comparison where after 28 days the air-cooled SiGS is winning, which is for the FA 20% mixtures, the granulated sample is seeing a noticeable drop-off from 14 days. Some of the results do appear at times to flatten out, but this is the only one were the result drops. Looking through the individual 4 results for that sample, in table 7.38, we can see that those are quite even across the four of them. This means there is not an obvious "mistake" that drags the average result down. This could just be the case of the factories production just not being even enough across their production, and those four were from a weaker stone tray, or it could be some other effect weakening the results. The fact that the FA samples are consistently producing the weaker results id not a shocking revelation, since that cement already has up to 20% fly-ash.

Development over time

If the effort now is made to look at how both of these sample series develop over time, we get firstly figure 8.7. This is a representation of the *Standardsement FA* samples and shows their development from 1 to 28 days.

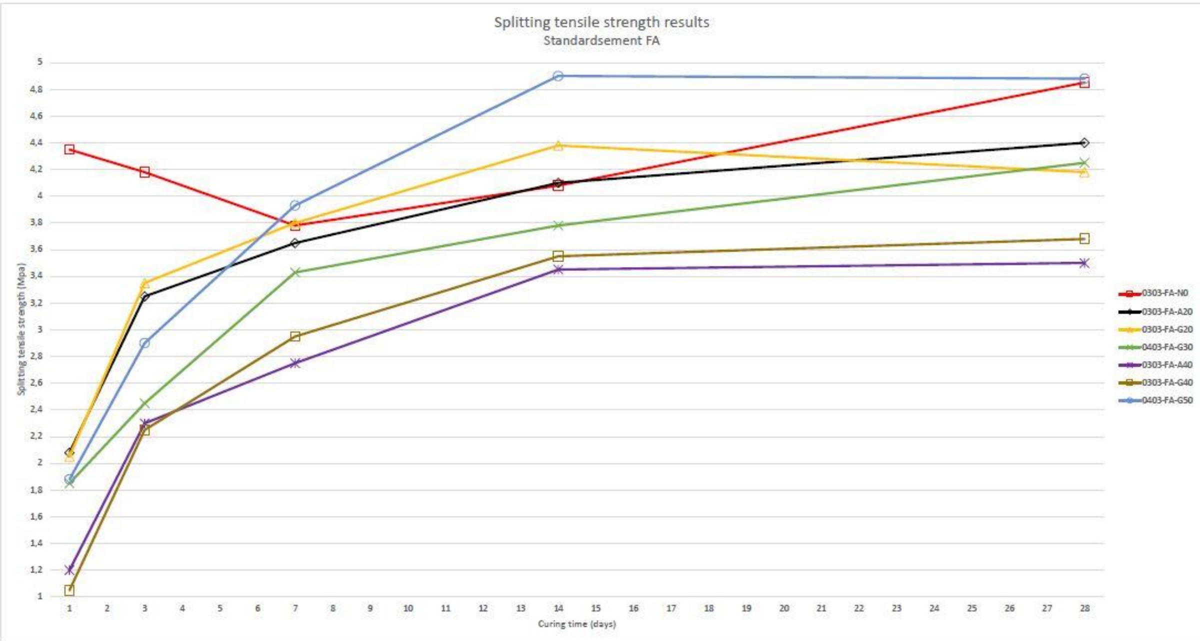


Figure 8.7 Splitting tensile strength results for the Standardsement FA samples

The first point to look at is the reference sample line in red. This shows how the results for this standard sample without any SiGS fell significantly from 1 to 7 days. Looking at table 8.4, we see that it actually fell from 4.35 MPa to 3.78 MPa in this timeframe. This was an occurrence that according to Aaltvedt themselves had never happened for any of their standard stones. They attempted to investigate this, to see if some production error had occurred, but the reasoning behind it could never be found.

The next interesting topic is the timeframe from 1 to 7 days, for all the other samples. As the figure shows, the 1-day results start much, much lower than the reference stones. Then after sharp increases in strength at 3 days, most of the SiGS stones have already cut that gap in half. This increasing value continues to 7 days, where two of the categories, FA-G20 and FA-G50, have already surpassed the reference stones. Even if every category, including the reference stones, climb in strength between 7 and 14 days, the gap between the FA-G50 and the reference stones widens significantly.

In the time from 14 to 28 days it is actually the reference stones that climb the most in strength. This is counterintuitive since the stones with clearly the most cement, should have the most increase at the start. This is probably related to the decreasing values the reference stones had in the beginning, since looking at 1 day and 28-day values for all the variants it is obvious that the reference stones have the smallest increase. This is as it should be, since chapter 3.2 explains how the reactions in SCMs is much slower than the cement reaction. Therefore, the most cement should have the smallest increase over time. Looking at the timeframe between 14 and 28 days we see how most of the values either slows its growth significantly or flattens out. The exception is the FA-N0, which increases, and the FA-G20, which decreases. Both of these phenomenon's has been talked about already and is difficult to explain.

There is not an obvious connection between the amount of SiGS in a sample and which place on the graph that sample has, but there are indications. Both of the 40% tests are across the board at the bottom of the graph and above that is the G30% samples. As was just said in the last paragraph, the G20% results fall slightly from 14 to 28 days. This is enough to make it drop under the G30% results at 28 days, but from 1 to 14 days both of the 20% samples are above the 30% one.

The last two inconsistent results which do not fit in with this are the reference stones and the G50 once. Not only does the G50 samples start in the middle of the pack, instead of at the bottom, but after just 7 days it has clearly reached the highest strength of all the seven. This is a place it keeps all the way to 28 days. An attempt has been made to explain this great result from the G50 stones in both chapter 8.2.1 and chapter 8.3.1. This could probably all be connected, since the assumed increasing filler effect, and with that the increased density and compressibility, would then lead to a higher strength value as well.

Moving over to the *Industrisement* samples in figure 8.8, it is a much clearer picture. The reference stone starts as the significantly largest strength value and every single of the 7 values rises sharply to 3 days. Comparing it to figure 8.7 we see that the increase from 1 to 3 days is much slower for the *Industrisement* than the *Standardsement FA.* This occurrence is related to two factors. Comparing the two figures we see that every SiGS value starts much higher after 1 day with the *Industrisement.* This is most likely related to two connected factors. First is the amount of cement. *Industrisement* has a much higher amount of cement, so the quick cement reaction would mean a higher early strength. The *Standardsement FA* already has 20% fly-ash, which through the pozzolanic reaction takes a little longer to properly come into effect.

We can see that all the samples with *Industrisement* gradually increase in strength between 3 and 14 days, but that some of them have slight plateaus in different sections. Both G20 and G30 do actually drop slightly off between 7 and 14 days, but it is at the most 0.05 MPa, so that is just as likely to be just a coincidence. From 14 to 28 days the situation is back to being a general increase in strength for all 7 variants.

Looking at this figure as well, to see what combination has the highest and lowest strengths, we see some of the same inconsistencies as with the *Standardsement FA.* This time the clearly strongest stones are the reference stones with 100% cement. This is the expected occurrence and is in line with the general idea of how EMC and paving stones work. After 1 day it is actually the case that both the 20% SiGS samples have the next highest strength. Then below that does come the 30% one, then both of the 40% once and finally the 50% at the bottom. Some of these are just separated by decimals, but the strengths do actually decrease with the rising SiGS amount.

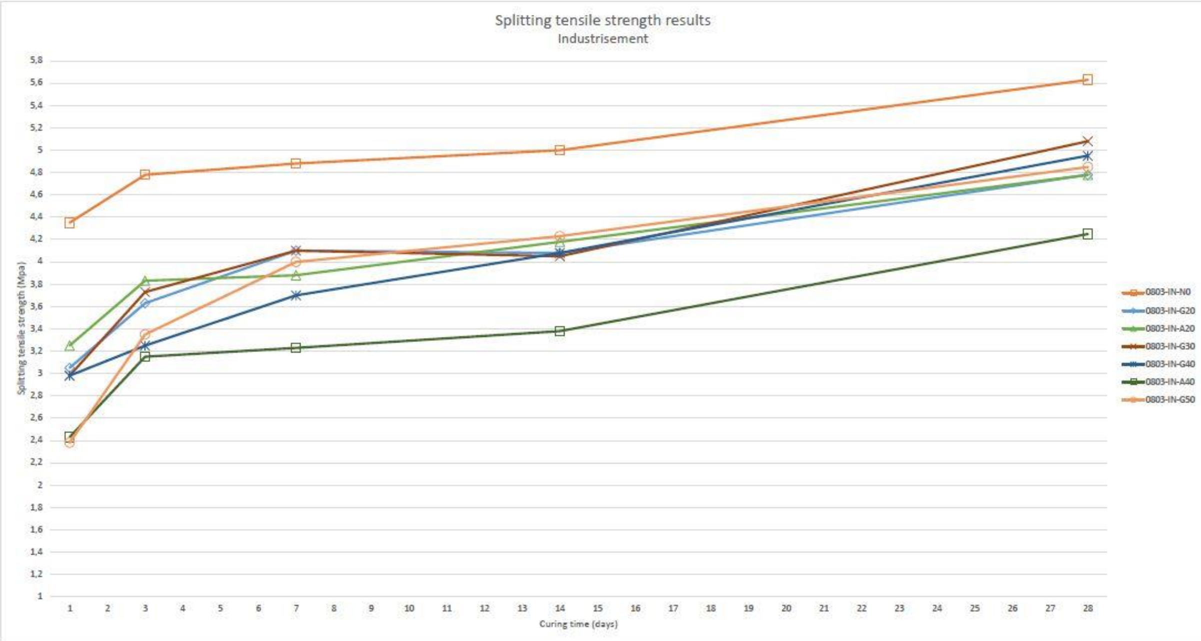


Figure 8.8 Splitting tensile strength results for the Industrisement samples

When coming up to 3 days is when the situation starts to change and become more inconsistent, in line with the *Standardsement FA* graph. By this point the 50% have passed both the 40% once and the 30% have passed one of the 20% once. This continues again towards 7 days, where suddenly the 30% sample is up to the 2nd highest strength and the 50% is in 4th place. This changes again at 14 days, where the 50% samples are up to 2nd and the 30% have dropped down to 6th. At 14 days 5 of the 7 results are very clustered together, so it is a possibility that some of the changes happening there are just chance.

Finally at 28 days, everything has switched around again. Now it is actually the G30 that is number 2, then G40, then G50, then both with 20% and finally the A40. Not only does this not make any clear sense internally for each cement type, when trying to compare across the cement types it also makes little clear sense. The only shared statement after 28 days is that in both cases it is the air-cooled 40% that has the lowest strength. This would in theory be expected, since the air-cooled SiGS should be less reactive and the more SiGS added, the less strength should develop after 28 days. Since the rest of the results are not conclusive at all, then this would however not be enough to state either that granulated is better or that 40% is the worst.

Extra round of testing

As was explained at the end of chapter 6.3.2, an extra round of testing was done on the oldest stones. This was done to attempt to see the development after a really long time and to see if any major changes could be found then. If we look at the results from the result consistency of those tests, in table 8.2 at the beginning of this chapter, we see a few problems. Since the initial tests, after 1, 3, 7, 14 and 28 days, were done in a totally different setup, and by a different person, it is important to compare the quality of test results. The two categories with very spread results after 77 days appear to be for the G30 and A40 samples. The maximum spread between highest and lowest single result in one test for the G30 was 0,5 MPa. After 77 days this had shot up to 1,8 MPa. For the A40 one, the numbers were 0,3 MPa and 1,1 MPa after 77 days. This means that those results are not completely reliable, without additional data to compare to. To try and remove some of these inconsistencies at 77-days is unwise, so the paper will therefore only use the average results. There is not a need to see the entire time-period, so to make it a little easier only 1, 28 and 77 days will be looked at.

Table 8.5 shows the collected average results from the *Standardsement FA* testing and is a collection of the already introduced 1- and 28-days results and the new average results from the 77-day testing.

Table 8.5 Average results from the 77-day testing compared to the 1- and 28-day testing

Production code	**SiGS type**	**Production date**	**SiGS level**	**Days of curing**	**Strength**
0303-FA-N0-(1-4)-1d	No SiGS	03.03.2021	0%	1-day	4.35 MPa
0303-FA-N0-(1-4)-28d	No SiGS	03.03.2021	0%	28-day	4.85 MPa
0303-FA-N0-(1-4)-77d	No SiGS	03.03.2021	0%	77-day	5.28 MPa
0303-FA-A20-(1-4)-1d	Air-cooled	03.03.2021	20%	1-day	2.08 MPa
0303-FA-A20-(1-4)-28d	Air-cooled	03.03.2021	20%	28-day	4.40 MPa
0303-FA-A20-(1-4)-77d	Air-cooled	03.03.2021	20%	77-day	4.40 MPa
0303-FA-G20-(1-4)-1d	Granulated	03.03.2021	20%	1-day	2.05 MPa
0303-FA-G20-(1-4)-28d	Granulated	03.03.2021	20%	28-day	4.18 MPa
0303-FA-G20-(1-4)-77d	Granulated	03.03.2021	20%	77-day	4.38 MPa
0403-FA-G30-(1-4)-1d	Granulated	04.03.2021	30%	1-day	1.85 MPa
0403-FA-G30-(1-4)-28d	Granulated	04.03.2021	30%	28-day	4.25 MPa
0403-FA-G30-(1-4)-77d	Granulated	04.03.2021	30%	77-day	4.05 MPa
0303-FA-A40-(1-4)-1d	Air-cooled	03.03.2021	40%	1-day	1.20 MPa
0303-FA-A40-(1-4)-28d	Air-cooled	03.03.2021	40%	28-day	3.50 MPa
0303-FA-A40-(1-4)-77d	Air-cooled	03.03.2021	40%	77-day	3.85 MPa
0303-FA-G40-(1-4)-1d	Granulated	03.03.2021	40%	1-day	1.05 MPa
0303-FA-G40-(1-4)-28d	Granulated	03.03.2021	40%	28-day	3.68 MPa
0303-FA-G40-(1-4)-77d	Granulated	03.03.2021	40%	77-day	4.15 MPa
0403-FA-G50-(1-4)-1d	Granulated	04.03.2021	50%	1-day	1.88 MPa
0403-FA-G50-(1-4)-28d	Granulated	04.03.2021	50%	28-day	4.88 MPa
0403-FA-G50-(1-4)-77d	Granulated	04.03.2021	50%	77-day	5.25 MPa

These results in table 8.5 are graphically represented in figure 8.9, where the results are separated into groups of bars after the total number of days curing. Just as the table increases in SiGS amount when moving downwards, the bar chart increases in SiGS amount when moving from left to right in it. The striped colours are the air-cooled results.

The figure and the table firstly show how the A20 numbers do not change anything from 28 to 77-days. This is not one of the categories where the distance between the smallest and largest number is much higher than it was at 28 days, but it is a difference of 0,1 MPa. This is probably related to the unknown factors of the secondary round of testing, but since the difference is so small, then it is also possibly just the way it should be. The second result to comment on is for the G30 results. In figure 66 it is easy to see that the strength drops between 28 and 77 days. This is the category with the largest spread between highest and lowest ever recorded and a 1,3 MPa larger spread then at 28 days. This is such a difference that at least some of that is probably related to testing errors as a consequence of a different and untested method. Looking at the individual results in table 7.38 we see that especially one result, at 3,0 MPa, is very low. If this result is then counted as a mistake or adjusted towards the other results, then the average after 77-days would be either on level or surpass the 28-day average. This can obviously not outright be done, without being certain that the particular test actually was an error.

Looking at the last sample after 77-days with some inconsistencies, we have the A40 stones. It was the only other 77-day test with more than 1 MPa between the highest and lowest value. This means that even though the actual average strength does rise from 28 to 77 days, in contrast to G30 which dropped, it is just as possible that this is a failed result. Going through the individual results in table 7.38 for this as well, we do not see the one result standing out as obviously different. In this case there is a high result and a low result, that together create the large difference. This makes it less likely that those are outside the normal and could therefore be accurate.

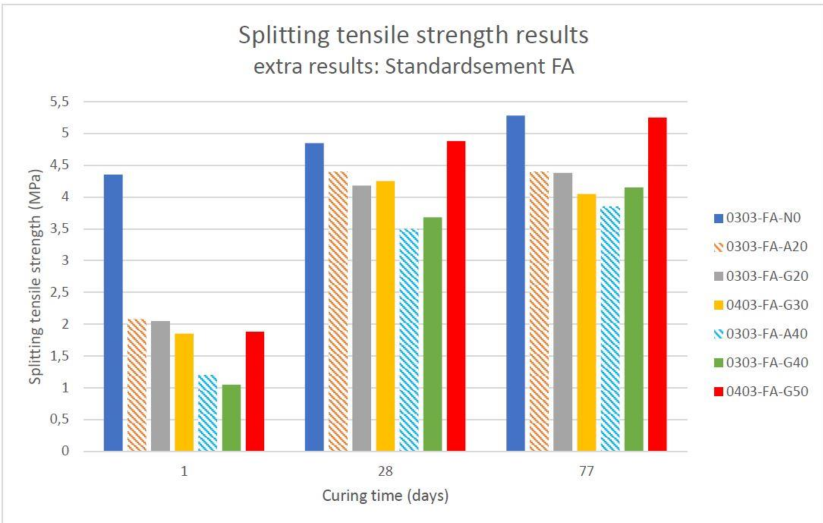


Figure 8.9 Splitting tensile strength results from 1, 28 and 77-day testing for Standardsement FA

8.3.3. Test of water absorption

When looking at the results of chapter 7.3.3 there are 3 main things to check about water absorption alone, before attempting to see if that is connected with any of the other chapters. The first thing is obviously to check how each of the stone variants is looking compared to the minimum level set in the standard. The second is the comparison between 0% SiGS, air-cooled SiGS and granulated SiGS and the last is a comparison of different levels of SiGS.

Since the pore structure, and by that density and strength, is generally important when talking about water absorption, then it would be interesting to try and look at those properties at the end of the chapter. The two tests were not done on the same stones, so the results will not be completely comparable, but it could show some relation.

Results compared to the standard

Chapter 6.3.3 describes the maximum allowable water absorption as no more than 6%. This is supposed to be the average result of all three stones tested, per test performed. Looking at table 8.6 we can see that none of the tests exceeded that limit. The closest were FA-A40 stones with 5,8% and below that IN-G20 and IN-G40 at 5,2%. This means that except for the one 5,8% result the rest were well under the limit. If we look closer at the FA-A40 results in table 7.39 we see that much of the high average can be contributed to one of those three stones having the largest single result of 6,3%.

This would then be more than ok by the "standards of the standard", but as a large company with their own product requirements it is not what Aaltvedt deems ok. If we then compare the SiGS results with the reference stones, then we see a few interesting points. Firstly, the reference stones ended on 2,1% for the IN-N0 stones and 3,3% for the FA-N0 stones. With only one test on each of them, the confidence in the absolute of those results are difficult to have. But if we again make some assumptions, then we assume that for each of the FA/IN batches that are made, then the absorption will be ± a few decimals from those levels as a general rule.

By that assumption we can see in table 8.6 that FA-G20 are noticeable over, FA-A20 are significantly under, FA-G30 are skirting the line, FA-G40 are well over, FA-A40 are significantly over and FA-G50 are well, well under. We can also see that all the IN stones are at the least 2% above the reference stones. This would then result in the presumption that some optimization would have to be done before Aaltvedt would be comfortable with the results.

Table 8.6 Average results of all 14 tests of water absorption

Production code	SiGS substitution	Production date	Average of 1-3
0303-FA-N0-(1-3)	None	03.03.21	3.3%
0803-IN-N0-(1-3)	None	08.03.21	2.1%
0303-FA-G20-(1-3)	20% granulated	03.03.21	3.8%
0803-IN-G20-(1-3)	20% granulated	08.03.21	5.2%
0303-FA-A20-(1-3)	20% air-cooled	03.03.21	2.6%
0803-IN-A20-(1-3)	20% air-cooled	08.03.21	4.4%
0403-FA-G30-(1-3)	30% granulated	04.03.21	3.0%
0803-IN-G30-(1-3)	30% granulated	08.03.21	4.1%

0303-FA-G40-(1-3)	40% granulated	03.03.21	4.8%
0803-IN-G40-(1-3)	40% granulated	08.03.21	5.2%
0303-FA-A40-(1-3)	40% air-cooled	03.03.21	5.8%
0803-IN-A40-(1-3)	40% air-cooled	08.03.21	5.1%
0403-FA-G50-(1-3)	50% granulated	04.03.21	1.8%
0803-IN-G50-(1-3)	50% granulated	08.03.21	4.9%

Comparison of granulated and air-cooled SiGS

As we have discussed multiple times, one of the important things to look at is the comparison of granulated and air-cooled SiGS. This is presented in figure 8.10 and shows the FA based stones in solid colours and the IN based stones in stripes. The air- SiGS clearly had the lowest result in two of the four instances. In one instance the granulated SiGS just as clearly come out on top and the final comparison is basically even. The air-cooled SiGS does win that one as well, but only by 0,1%.

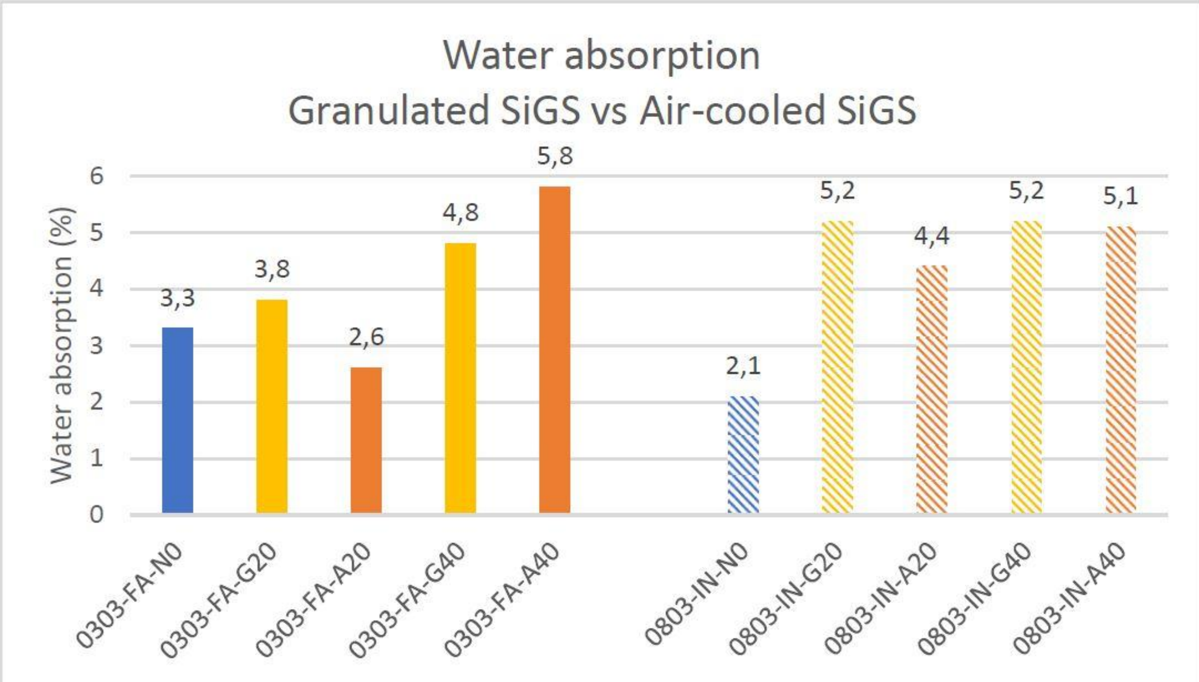


Figure 8.10 Water absorption comparison of granulated and air-cooled SiGS

If we go back to chapter 7.2.3, we see that both the IN-G20 and IN-G40 are the two IN batches with production issues and differentiated density. It is possible that this is part of the reason for why granulated SiGS loses to air-cooled in both of the *Industrisement* examples, but beats air-cooled in the 40% examples. On the other hand, in table 7.3 there is nothing that indicates problems in the FA-G20 or FA-A20 batches. This makes it a possibility that since both FA batches had no production issues, in the 20 and 40% once, those results for water absorption are the actual “correct” ones. It is way too little data available to conclude that and what then is the reason for FA-A20 being so low is difficult to know.

Comparison of different SiGS levels

The final interesting comparison to make in the main section of this chapter is to see how increasing percentages of SiGS influences the result. This is presented in figure 8.11, where once again

Standardsement FA is in solid colours and *Industrisement* in stripes. There are also other colour coordination's, such that blue is the reference stones, yellow is the granulated SiGS and orange is the air-cooled.

This figure shows both some indication and widely inconsistent results. Firstly, by looking at just the air-cooled results we see that in both examples the absorption rises with the increased SiGS. It is evident from chapter 7.2.1 and 7.2.3 that the density difference between FA-A20 and FA-A40 are much larger than the density difference between IN-A20 and INA40. This would then mean more open pores in the concrete and could explain the massive increase in water absorption, compared to the much smaller increase between the *Industrisement* samples.

If we then move over to look at the granulated examples, we see a similar, and at the same time not, trend. Both the *FA* and *Industrisement* samples with granulated SiGS moves up in percentage, when moving from 0% to 20%. From there it goes down at 30%, up at 40% and finally down again at 50%. The rise from 0% to 20% are much higher on the IN side and the fall between 20% and 30% are also larger on the IN side. From there the rise to 40% and fall between 40 and 50% are much larger on the FA side. It is also noted that on one side the FA-G20 are lower than the FA-G40 and on the other they are equal. The final interesting point is that on one side FA-G30 are higher than FA-G50 and on the other they are the opposite.

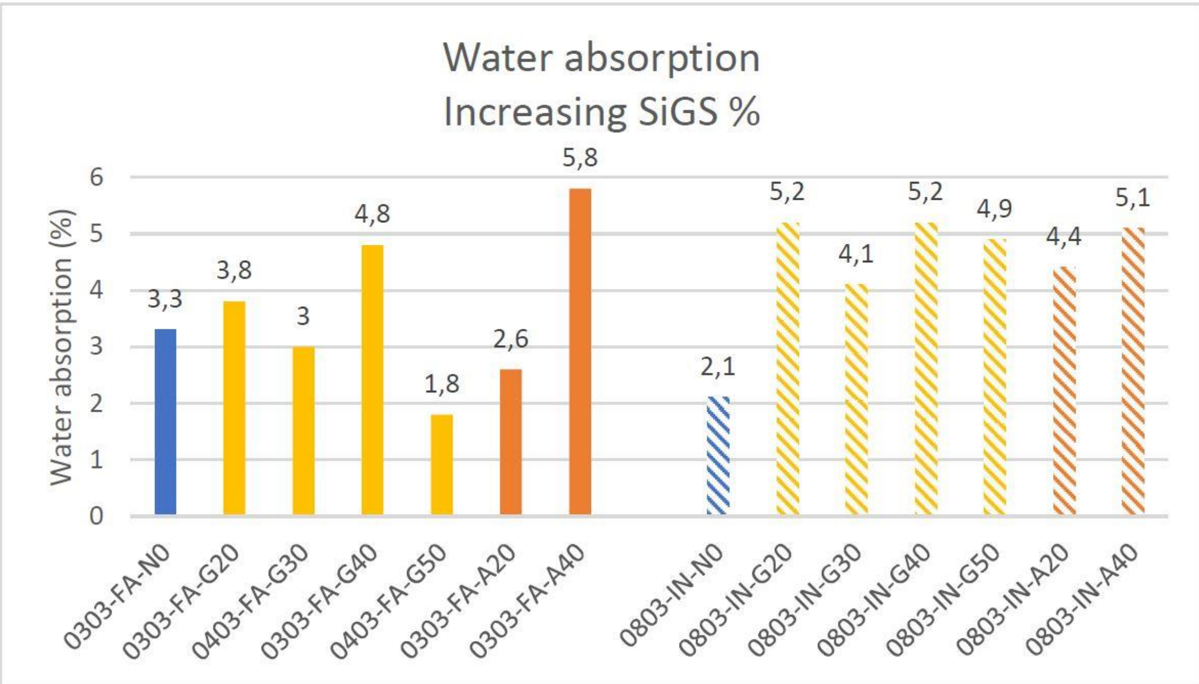


Figure 8.11 Water absorption for all variants with increasing amounts of SiGS

Since the data is quite limited, but the water absorption goes up more than half the time the SiGS amount is increased, then it is a possibility that those factors can relate somewhat. Since most of chapter 8.3.2 shows a lower early strength with increasing SiGS, at the time this test is performed, then it is possible that more reactive powder and more open pores at that time impacts the results. The results have also shown a possible connection with density, but all these questions will be looked at closer in the next section of this chapter.

Water absorption vs Density

There have already in this chapter been made some comments on the possible connection between water absorption and density. To properly look at this subject, figure 8.12 below has been made. These graphs show the water absorption in solid colour, with the connecting y-axis on the left side, and the density in striped pattern, with the y-axis on the right side.

The first thing we see, if we start at the *FA sement* side, is that there might appear to be a possible connection between the properties. Between N0 and G20 both density and water absorption seem to rise at just about the same level. This continues the other way, as between G20 and G30 both properties seem to fall at about the same speed. Why it goes up and then down is difficult to explain.

If we after that look at FA-G30, FA-G40 and FA-G50 then the imagined correlation is suddenly negative. The density from G30 to G40 sinks, but the water absorption increases. Then the opposite happens from G40 to G50. The way that the water absorption sinks with the increasing density, when it increases from G40 to G50, is in theory expected. This also happens between A20 and A40, but this time the movement is again opposite with increasing SiGS amount. All of these clashing results makes it impossible to see a clear correlation, based on just that data.

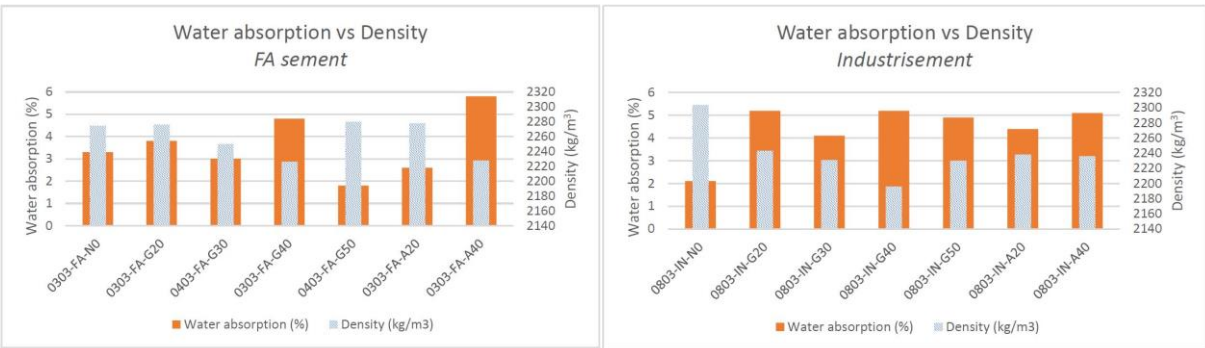


Figure 8.12 Comparison between water absorption and density for both cement types

Moving over to the *Industrisement* side of figure 8.12 we also see no clear correspondence. Compared with the *FA* side we see that the water absorption is higher on the *Industrisement* side in 5 of the 7 categories. While we see that the water absorption is "lower" on the graph in 5 of the 7 categories, on the *FA* side, we see that this is flipped to 1 of 7 on the *Industrisement* side. This means that the relation between the values is not consistent at all. We also see that on the *IN* side, moving from G20 to G50, that both values go down from G20 to G30. Then the density sinks and the water absorption rises, when moving between G30 and G40. Finally, the density increases and the water absorption sinks between G40 and G50.

Both of these values moving in completely different directions, when moving along sections of the figure, makes it impossible to say that there actually is a correlation here. This could, with more data, become a totally different conversation, but without also heavy testing of internal reaction it would be hard to say anything definitive. The last important thing to point out is that these tests were done on the same batches, but completely different stones. This could mean nothing, but it could also mean that this comparison is totally irrelevant.

Water absorption vs Tensile splitting strength

Lastly in the chapter we can attempt a small comparison of the water absorption and the tensile splitting strength. Once again, these tests are done on completely different stones, so the direct comparison is impossible to make. What might be evident are large trends that might appear and that might then be too big for chance. This comparison is presented in figure 8.13, where the solid colour once again is the water absorption.

We see from the *Industrisement* graph that the sample with the clearly largest strength also clearly has the lowest water absorption, but looking at the *FA* side this is not the case there. There the largest strength just has the fourth lowest water absorption.

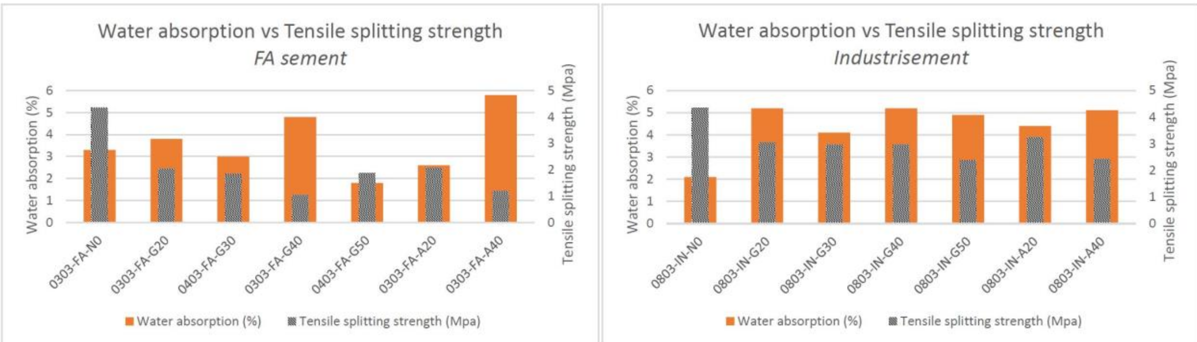


Figure 8.13 Comparison between water absorption and tensile splitting strength for both cement types

Then we see on the *FA* side that the two samples with the lowest strength have clearly the highest water absorption. This is once again not reflected in the other graph, where the lowest strengths have the 3rd and 4th highest water absorption. These are close to the top, but nowhere close to the clear difference in the *FA* graph.

8.3.4. Test of resistance towards freeze-thaw deterioration

How to look at the results from this test is difficult. In its own way they do appear to be quite conclusive, but on the other hand there are enough parameters and caveats here to put enough doubt on it.

Firstly, is the preparation of the test samples. As chapter 6.3.4 mentions, the polystyrene and rubberized protection sheet around the samples had to be switched out. This means that the protection around the samples is not of the same tested quality as with the original standardized test. This means a higher chance for moisture to come in contact with the upper parts of the side wall, instead of just the surface layer. A possible consequence of that is that the NaCl solution would have the opportunity to enter the concrete from multiple sides and expel forces/reactions on the concrete from more than the wanted direction. The effort was made to make the invented solution as secure as possible, but it does differ significantly from the standard solution.

The second problem comes with the freezing chamber. Not only did the concrete laboratory at UiA not have much experience with the machine, there was not a person at the entire school that had any significant experience with it. This made the learning and operating of the machine a difficult process. As appendix 23 shows in column D and E, the temperature in the machine started at the wrong point. Figure D.3 in EN 1338 shows how the temperature should start in the area between 14 and 24°C and as the appendix showed the machine actually started around 10.5°C. This is something that should not happen before an hour or so has passed, according to EN 1338. This would in theory only push the graph an hour or so forwards, but is unclear if this had a negative effect. Running through some of the readings from the appendix it is also clear that at times the numbers are “corrupted” or just wrong. This could be connected to times where the door was opened, to check if more NaCl solution had to be added, but there could also be other mistakes. The last of the problems with the test came when ending it after 28 days. As figure 6.23 shows, the surfaces of the stones were still frozen solid. With the low freezing point of NaCl, and the frozen moisture on the inside of the door, it is probably that the chamber had not reached the top of the temperature it was supposed to.

Because of all these factors, it is difficult to compare the results with anything from previous tests done elsewhere, but it is possible to compare them with each other. All the samples had been through the same process from start to finish, so any difference in results should be because of the materials themselves. Since one of the main requirements for this test in the standard is the average value, the first thing to look at is that. Table 8.7 is a collection of the final individual results from table 7.42 and the average of those results.

Table 8.7 Individual and average results of the freeze-thaw testing

Code	Result in kg/m^2	Average results (kg/m^2)
0803-IN-N0-1	0.0181	
0803-IN-N0-2	0.0169	
0803-IN-N0-3	0.0148	0.0166
0803-IN-G20-1	0.396	
0803-IN-G20-2	0.0670	

0803-IN-G20-3	0.0764	0.1798
0803-IN-A20-1	0.667	
0803-IN-A20-2	0.392	
0803-IN-A20-3	0.00109	0.3534
0803-IN-G30-1	1.310	
0803-IN-G30-2	0.175	
0803-IN-G30-3	0.268	0.5843
0803-IN-G40-1	1.247	
0803-IN-G40-2	0.481	
0803-IN-G40-3	0.101	0.6097
0803-IN-A40-1	1.692	
0803-IN-A40-2	1.134	
0803-IN-A40-3	0.742	1.1893
0803-IN-G50-1	2.114	
0803-IN-G50-2	0.704	
0803-IN-G50-3	1.704	1.5073

The first point to look at is the average results compared to EN 1338. In chapter 6.3.4 of this thesis the requirements are given as firstly no average result over 1.0kg/m^2. Looking through table 8.7 we can see that only the A40 and G50 stones do not meet these requirements.

The second point to look at is the single results. The same requirements in the standard says that no single results over 1.5kg/m^2 is allowed. Going through the single results again we see that even if some results get near 1.5, the only ones going over are single result for the A40 and G50 here as well.

Since we already have explained that the comparisons against standard values are less important, because of test irregularities, what is interesting to look at is the trend for the results. Moving down the table we clearly see that the average result increases as the SiGS amount increases. We also see that the air-cooled values fit perfectly between the value for the same amount of granulated SiGS and the higher granulated value.

The reasons for this increase could be tied to the density. Looking at figure 8.3 we see that the density does decrease from G20 to G40, which means increasing pore structure, easier for the NaCl to break into the concrete and weaker forces keeping it together. But this is quickly offset with the G50 stones having a much higher density than the G40 stones and still having a much higher scaling off result. The A20 stones does have its density fitting in well between the G20 and G30 stones, but the A40 stones also helps to disprove this. With also having a much higher density than the G40 stones, same as with the G50 stones, the scaled off material should be much less.

Where we also do not find a clearer correlation is with the compressibility. Figure 8.5 shows that one of the best compressed stones are the G50 stones, which got clearly the worst results here. The same happens with the splitting tensile strength where high results there also have high results here, which it should not.

All of this makes it difficult to know a reason for sure. It should be connected to the assumed increased reactivity in the granulated SiGS, making that denser over time, but very little results so far clearly support such claims. This leaves the last reason, a chemical occurrence. This is also most likely the reason for some of the discoloration in the next chapter and is difficult to find out for sure. This would need chemical analysis, which is not within the possible timeframe of this thesis.

8.3.5. Geometric stability, measurements and visual appearance

Most of the problematic results that are interesting for this chapter are difficult to find any reason for. First is this apparent "wet" finish on the surface of the stones, which provided a darker square on some stones. The unlikely possibility of there still being some moisture in some of the stones were tested in Figure 6.27-6.29. As they showed, the drying process had little to no effect on the stones. This should be proof that the darker "squares" in the centre of some stone are not the result of stones still being moist.

What those darker areas are a consequence of however is most likely moisture being trapped earlier on in the process. These stones were stacked and stored on EUR-pallets with sides on them. This would heavily limit the ability for the stones to breath and release the last moisture. It is a fact that all paving stones are removed from the trays they are curing in the curing hall on, and then stacked. The difference is probably in how they are stacked. When stacked by the automated robots at Aaltvedt Betong, the stones are firstly rotated in an alternating pattern. Then secondly, they are placed in a slightly overlapping pattern. This makes sure that the centre of one stone is never on top of the centre of another. This would create more cracks between the stones for air to escape. This was not done in the stacking, storing and transporting of the SiGS stones and are probably the reason for this. The reason it is probably independent of the SiGS is because figure 7.7 shows the reference stones to have the exact same problem.

The next thing to comment on is colour. It is again always a possibility of chance being involved, when the data set is small, but since the two air-cooled pictures show the same colour and the granulated pictures show the same colour, then it is most likely related to the SiGS itself.

From chapter 5.2.1 we can see that the air-cooled SiGS is a grey dust. This grey is a little bit darker than cement dust is and is probably the reason why the air-cooled stones are generally a little darker. They were all produced, cured, transported and stored in the same way, so the only possible place that the difference could come from should be the SiGS.

The difficulty comes in explaining the occurrence with the granulated SIGS. Chapter 5.2.1 also shows that the granulated powder is almost indistinguishable from the air-cooled, but that it possibly has a brighter/whiter tone to it. This does not explain the brown/red tint to all the granulated stones pictured in this chapter. As was just said with the air-cooled SiGS, every other factor is basically identical. So, what is the cause of this is probably something chemical. This could be what the standard calls efflorescence or it could be just a natural reaction of the earlier moisture being "trapped" on the stones and then oxidizing on the stones. This is difficult to find out for sure, without extra testing.

Finally, we come to the measurements performed on the stones. table 8.8 shows firstly how there is no noticeable change from 1 day to 28 days, for none of the 7 samples. Then from there it continues to show that even moving all the way up to 75 or 76 days, there is still no clear trend of anything. Some values stay exactly the same all the way, some rise after 28 days and then fall again after 77 and some fall after 28 days and then rise again after 77 days. The largest difference is for the A20 values. At that value there is a rise of 0,75mm from 28 days to 77 days, but this is offset by the value already having sunk 0,5mm from 1 day to 28 days. This means that the 1 to 77 day difference is really only 0,25 at that point.

Table 8.8 Development of stone measurements between 28 and 75/76 days

Production code	SiGS type	Production date	Days of curing	Average height	Average deviation
0303-FA-N0-(1-4)	None	03.03.21	1	58.5mm	0.5mm
0303-FA-N0-(1-4)	None	03.03.21	28	58.5mm	0.5mm
0303-FA-N0-(1-4)	None	03.03.21	76	58.0mm	0.0mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	1	60.0mm	2.0mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	28	60.0mm	2.0mm
0303-FA-G20-(1-4)	20% Granulated	03.03.21	76	60.0mm	2.0mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	1	59.8mm	1.8mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	28	59.3mm	1.3mm
0303-FA-A20-(1-4)	20% Air-cooled	03.03.21	76	60.0mm	2.0mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	1	59.8mm	1.8mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	28	60.0mm	2.0mm
0403-FA-G30-(1-4)	30% Granulated	04.03.21	75	59.5mm	1.5mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	1	61.0mm	3.0mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	28	60.5mm	2.5mm
0303-FA-G40-(1-4)	40% Granulated	03.03.21	76	61.0mm	3.0mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	1	59.8mm	1.8mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	28	59.5mm	1.5mm
0303-FA-A40-(1-4)	40% Air-cooled	03.03.21	76	59.5mm	1.5mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	1	56.5mm	-1.5mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	28	56.3mm	-1.7mm
0403-FA-G50-(1-4)	50% Granulated	04.03.21	75	56.8mm	-1.3mm

Without more data, and chemical analysis, it is impossible to properly say one way or the other. The data that is available however, pictures and measurements, seems to not show any sign of expansion or shrinkage in the paving stones.

9. Conclusion

- ***How would changes in the solidification method and substitution level of SiGS, when used as an SCM, influence the quality of concrete paving stones?***

It seems like, based on the available data, SiGS influences all of the quality categories in very different ways. When only switching out different amounts of cement with SiGS in the concrete mix, and not adjusting anything else, it seems like the effects are mostly negative, but still within the legal requirements.

- ***Properties of fresh concrete: Compressibility, density and experience in full-scale production***

1. It seems like air-cooled SiGS might create a slightly better density then granulated, but some production irregularities and some contradicting results makes it difficult to say.
2. It seems like replacing 20% cement, with fly-ash already in it, with SiGS will have no effect on the density, but replacing 20% *Industrisement* with SiGS will have a massive effect on the density. It seems like the density falls when the replacement increases from 20% to 30 and 40%, but when replacing 50% the density increases again.
3. It seems like air-cooled SiGS might be better against water absorption and that how much cement is replaced is not as important as other factors.
4. There seems to be little direct correlation between SiGS type or substitution level, when talking about ability to compress. That seems to be related to density and moisture.
5. There were a few production errors along the way, but SiGS seemed easy enough to work with within the factory and the workers seemed content with the results.

- ***Quality of final products: Strength development as a function of time***

It seems like all combinations of SiGS create just as consistent results. Only 40% replacement of *Standardsement FA* with air-cooled SiGS did not reach the requirements in the standard. Granulated SiGS performs better in the majority of cases, but not in every case. It is generally the case that increasing SiGS amounts decreases the final strength, but 50% replacement produces better strength then it should.

- ***Quality of final products: Durability (Development of resistance towards freeze-thaw deterioration)***

The data seems to say that air-cooled SiGS has a significantly worse frost resistance and that increasing the substitution also lowers the frost resistance noticeable.

- ***Quality of final products: Geometric stability and visual appearance***

It seems like there is no difference in the size and texture of any of the stones from 1 day to 75/76 days. It appears like the air-cooled SiGS creates a slightly darker finish to the stones and it appears like there is a possibility of some chemical reaction happening in the surfaces of the granulated SiGS stones that creates an unwanted colour.

10. Recommendations

Listed below are some recommendations for areas where there is a need for a lot of study right away and where there is a need for increased study after some time.

- The main recommendation is to run the entirety of the production of stones done in this thesis again. This would hopefully limit the irregularities in that process and make the results easier to conclude with.
- The next recommendation is to perform all the tests done in this thesis again, but also to make sure everything is done as the standard specifies. The available data is too little to be sure of anything, so an increase in data would help that process. By preparing and performing the slightly off tests again, the results from that would be able to compare with earlier results from other research, which would help the research project a lot.
- The final recommendation is to do some chemical analysis on the produced SiGS stones, to look at internal pore structure and potentially dangerous reactions occurring.

Reference list

[1] A. F. a. Y. Leung, "Technology Roadmap Low-Carbon Transition in the Cement Industry," International Energy Agency, International Energy Agency, 05. april 2018 2018. Accessed: 03.02.2021. [Online]. Available: https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Technology-Roadmap-Low-Carbon-Transition-in-the-Cement-Industry

[2] "Key facts & figures: World cement production in 2018 " The European Cement Association. https://cembureau.eu/about-our-industry/key-facts-figures/ (accessed 10.09, 2020).

[3] R. S. Maria C. G. Juenger, Susan A. Bernal, "Supplementary cementitious materials: New sources, characterization, and performance insights," *Cement and Concrete Research,* vol. 122, pp. 257-273, 22 May 2019 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0008884619301693/pdfft?casa_token=1bmKMUMddgAAAAAA:xr_5YxICV_QP3lXp4iBT6xMx0L5jroCzmM5aMhawADvM3f_IzBIiXmUfbXtD7AhAwVFr62J-iSo&md5=17abec1f0d829c5f3293b8be679123bf&pid=1-s2.0-S0008884619301693-main.pdf. 22 May 2019.

[4] "Cement production and emissions." Norcem AS. https://www.norcem.no/en/Cement_and_CCS (accessed 10.09, 2020).

[5] "Energy and Climate Protection." Heidelberg Cement. https://www.heidelbergcement.com/en/energy-and-climate-protection (accessed 08.02, 2021).

[6] M. Maage, *Betong: Regelverk, teknologi og utførelse*, First ed. Byggenæringens Forlag AS: Byggenæringens Forlag AS, 2015.

[7] E. Norway. *GRØNT BIPRODUKT Silica Green Stone*. Bergfald.no: Eramet Norway AS. Accessed: 13.09.2020. [Online]. Available: https://www.bergfald.no/wp-content/uploads/2019/06/Eramet-Green-Stone_infobrosjyre_1.4_ENKELTSIDER.pdf

[8] M. Dåstøl, "Forstudie - utnyttelse av silikomanganslagg fra Eramet Kvinesdal," Styrhuset Vekstskaping, 21.08.2019 2019. Accessed: 13.09.2020.

[9] H. T. S. Jørgensen, "ERAMET SiMn-slagg - Materialkarakterisering og separasjonsforsøk," ReSiTec AS, August 2019 2019. Accessed: 13.09.2020.

[10] E. Bårseth, "Erametslagg som SCM," University of Agder, uia.no, 2019 2019. Accessed: 13.09.2020.

[11] K. J. Tone Buø, Maren Eikill Sæther and Tonje Sætre, "Utilization of silicomanganese slag as a partial cement substitute in mortar," Bachelor Bachelor, University of Agder, uia.no, 2020.

[12] L. N. a. T. I. A. Yvonne-Marie Miniggio, "Environmental Aspects of Utilising Silicomanganese Slag as a Cement Substitute," Bachelor Bachelor, University of Agder, uia.no, 2020.

[13] L. N. Hartz, "Experimentation on the possibilities of partly substituting cement with Silicomanganese slag (SiGS) - Specifically, in the production and use of mortar-based products," University of Agder, Uia.no, 04.01.21 2020. Accessed: 04.01.21.

[14] J. Letman. "Rising seas give island nation a stark choice: relocate or elevate." National Geographic. https://www.nationalgeographic.com/environment/2018/11/rising-seas-force-marshall-islands-relocate-elevate-artificial-islands/ (accessed 27.08, 2020).

[15] J. Podesta. "The climate crisis, migration, and refugees." Brookings Institute. https://www.brookings.edu/research/the-climate-crisis-migration-and-refugees/ (accessed 08.05, 2021).

[16] J. Randen. "Paris-avtalen om klima vedtatt." Klima og miljødepartementet. https://www.regjeringen.no/no/aktuelt/paris-avtalen-om-klima-vedtatt/id2467187/ (accessed 26.08, 2020).

[17] J. Berg. "Norway has ratified the Paris Agreement." Ministry of Climate and Environment. https://www.regjeringen.no/en/aktuelt/norge-har-ratifisert-parisavtalen/id2505365/ (accessed 26.08, 2020).

[18] J. Berg. "Norway steps up 2030 climate goal to at least 50 % towards 55 %." Ministry of Climate and Environment. https://www.regjeringen.no/en/aktuelt/norge-forsterker-klimamalet-for-2030-til-minst-50-prosent-og-opp-mot-55-prosent/id2689679/ (accessed 25.08, 2020).

[19] W. R. Institute. "CAIT Country Greenhouse Gas Emissions Data (1990-2016)." World Resources Institute. https://www.climatewatchdata.org/ghg-emissions?regions=WORLD%2CEUU (accessed 28.08, 2020).

[20] J. L. a. F. Preston, "Making Concrete Change: Innovation in Low-carbon Cement and Concrete," Chatham House, the Royal Institute of International Affairs, chathamhouse.org, June 2018 2018. Accessed: 10.09.2020. [Online]. Available: https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

[21] "Sementproduksjon og CO2." Norcem AS. https://www.norcem.no/no/sementproduksjon-co2 (accessed 11.09, 2020).

[22] Miljødirektoratet. "Tabeller for omregning fra energivare til utslipp." Miljødirektoratet. https://www.miljodirektoratet.no/myndigheter/klimaarbeid/kutte-utslipp-av-klimagasser/klima-og-energiplanlegging/tabeller-for-omregning-fra-energivarer-til-kwh/ (accessed 09.05, 2021).

[23] J. d. B. Sacha Alberici, Irina van der Hoorn, Maarten Staats, "FLY ASH AND BLAST FURNACE SLAG FOR CEMENT MANUFACTURING," Department for Buisness, Energy & Industrial Strategy, www.gov.uk, 7 April 2017 2017. Accessed: 12.09.2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/660888/fly-ash-blast-furnace-slag-cement-manufacturing.pdf

[24] a.-m. GmbH. "EARTH-MOIST CONCRETE –BASIC PRINCIPLES, USE AND OPTIMISATION." ad-media GmbH. https://www.cpi-worldwide.com/journals/artikel/91 (accessed 25.04, 2021).

[25] G. H. a. H. J. H. Brouwers, "A new mix design concept for earth-moist concrete: A theoretical andexperimental study," *Cement and Concrete Research,* vol. 38, no. 10, pp. 1246-1259, October 2008 2008. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0008884608000884.

[26] R. S. Jørgen Skibsted, "Reactivity of supplementary cementitious materials (SCMs) in cement blends," *Cement and Concrete Research,* vol. 124, 09 July 2019 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0008884619302327/pdfft?casa_token=LsMUx09oNVMAAAAA:PMsELx2hTwJMicr21qyGuACZVAFsLAMxs2rVBYHI9vjtDBChi2hSvQtuMNAZn0g1so03b1b7oJ0&md5=2f888082dbe4ff96e28988a947ab7803&pid=1-s2.0-S0008884619302327-main.pdf. 09 July 2019.

[27] Editors. "Portland cement." Britannica Group Inc. https://www.britannica.com/technology/portland-cement (accessed 15.09, 2020).

[28] O. Berthelsen. "Ny energiløsning for Longyearbyen." Olje- og energidepartementet. https://www.regjeringen.no/no/aktuelt/ny-energilosning-for-longyearbyen/id2827886/ (accessed 12.02, 2021).

[29] A. d'Harambure, "IMnI Statistics 2019," INTERNATIONAL MANGANESE INSTITUTE, manganese.org, 2019 2019. Accessed: 24.09.2020. [Online]. Available: https://www.manganese.org/wp-content/uploads/2019/05/IMnI_statistics_2019.pdf

[30] S. K. N. a. S. Kumar, "Evaluation of the suitability of ground granulated silico-manganese slag in Portland slag cement," *Construction and Building Materials,* vol. 125, pp. 127-134, 08.08.20 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950061816312879#.

[31] H. T. A. Svein Bollingberg, Gustav E. Amlie, Knut A. Thorvaldsen og Einar Lund. *Belegningsstein og heller av betong - en veiledning*. (2005). Norsk kommunalteknisk forening: Norsk kommunalteknisk forening. Accessed: 16.09.2020.

[32] ***NS-EN 1338:2003*** *Belegningsstein av betong - Krav of prøvingsmetoder - (innbefattet rettelsesblad AC:2006)*, E. C. f. Standardization, Standard.no, Juli 2003 2006.

[33] T. Holtebekk. "ISO." Store norske leksikon. https://snl.no/ISO (accessed 30.10.2020, 2020).

[34] K. Hofstad. "CEN - Den europeiske standardiseringsorganisasjonen." Store norske leksikon. https://snl.no/CEN_-_Den_europeiske_standardiseringsorganisasjonen (accessed 30.10, 2020).

[35] K. Hofstad. "Standard Norge." Store norske leksikon. https://snl.no/Standard_Norge (accessed 30.10, 2020).

[36] ***NS-EN 197-1:2011*** *Sement - Del 1: Sammensetning, krav og samsvarskriterier for ordinære sementtyper*, E. C. f. Standardization, Standard.no, Desember 2011 2011.

[37] N. AS. "Norcem Industrisement." Norcem AS. https://www.norcem.no/en/industrisement (accessed 18.03, 2021).

[38] N. AS. "Norcem Standardsement FA." Norcem AS. https://www.norcem.no/en/standardsement_fa (accessed 18.03, 2021).

[39] R. B. G. C. KG. *COLORaktiv 2000 SR (LP)*. (2019). remei.com: REMEI Blomberg GmbH & Co. KG. Accessed: 10.05.21. [Online]. Available: https://www.remei.com/product/coloraktiv-2000-sr-lp/

[40] E. Norway. "Grønn høyteknologi i verdenstoppen." Eramet Norway. https://eramet.no/produkt-og-prosess/fremtidsrettet-teknologi/ (accessed 12.09, 2020).

[41] S. G. T. u. G. GmbH. "Slabtester." Schleibinger Geräte Teubert u. Greim GmbH. http://www.schleibinger.com/cmsimple/en/?Durability:Slabtester (accessed 19.04, 2021).

[42] S. G. T. u. G. GmbH. *Schleibinger Slabtester*. (2019). schleibinger.com: Schleibinger Geräte Teubert u. Greim GmbH. Accessed: 19.04.2021. [Online]. Available: http://www.schleibinger.com/cmsimple/en/?Durability:Slabtester

[43] G. G. o. G. Jón and M. Einarsson, "Alkalireaksjoner - Overflatebehandling og andre tiltak," Statens vegvesen, Statens vegvesens rapporter, Nr. 237, Juli 2013 2013. Accessed: 12.01.2021. [Online]. Available: https://vegvesen.brage.unit.no/vegvesen-xmlui/bitstream/handle/11250/2619247/SVV%20rapport%20237%20Alkalireaksjoner%20-%20Overflatebehandling%20og%20andre%20tiltak.pdf?sequence=1&isAllowed=y

Appendices

- **Appendix 1:** Rapport Forprosjekt Lars Normann Hartz
- **Appendix 2:** Log-book background theory and introductory knowledge
- **Appendix 3:** PSD of both kinds of SiGS used in this thesis
- **Appendix 4:** SiGS analyse - SNO-ENK-LAB21042210310
- **Appendix 5:** Productdatasheet CEM I Brevik
- **Appendix 6:** Productdatasheet CEM II Brevik
- **Appendix 7:** PSD of sand types
- **Appendix 8:** COLORaktiv_2000_SR_(LP)-200004010-GB
- **Appendix 9:** Log-book Thesis and research specific topics
- **Appendix 10:** Production control form
- **Appendix 11:** Splitting test 1d first production
- **Appendix 12:** Splitting test 1d second production
- **Appendix 13:** Splitting test 3d first production
- **Appendix 14:** Splitting test 3d second production
- **Appendix 15:** Splitting test 7d first production
- **Appendix 16:** Splitting test 7d second production
- **Appendix 17:** Splitting test 14d first production
- **Appendix 18:** Splitting test 14d second production
- **Appendix 19:** Splitting test 28d first production
- **Appendix 20:** Splitting test 28d second production
- **Appendix 21:** Time of a standard tensile splitting strength test
- **Appendix 22:** Splitting test 77d extra testing
- **Appendix 23:** Data from the freeze-thaw machine
- **Appendix 24:** Control-testing during first production
- **Appendix 25:** Control-testing during second production
- **Appendix 26:** Innledende fremdriftsplan Masteroppgave Lars Normann Hartz
- **Appendix 27:** Referater fra veiledningsmøter
- **Appendix 28:** Referater fra prosjektmøter
- **Appendix 29:** A3poster