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Alexander Åkerlund

Development and validation of a method for determining the amount of water required by natural and manufactured sand in concrete production

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Supervisor: Professor Jari Puttonen
Advisors: M.Sc. Niklas Johansson, Dr. Fahim Al-Neshawy

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

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Author Alexander Åkerlund

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Abstract

The goal of the thesis was to develop a fast, small-scale and easily reproducible method for determining the water requirement of sands in concrete. To enable this, 17 different sands were tested, of which 8 were manufactured, also called crushed, and 9 were natural. The developed method involved the measurement of differences in mortar spread induced by the sands, by utilizing a Hägermann cone. The attained spreads were compared to the amount of superplasticizer needed to produce concretes of similar workability with the different sands. The method was validated by confirming the existence of a linear correlation between the spreads and the amounts of superplasticizer required. The accuracy of the method was analysed with statistical analysis. Apart from testing the sands in concrete and mortar, they were also examined as such for physical properties with standardized tests. Based on the attained results, the method was deemed valid, and its accuracy is improved by comparing sands of the same size fractions, by keeping the mortar spread between 120 and 200 mm, and by using a mortar mixer that can incorporate the full range of particle sizes included in each sand. The manufactured sands generally portrayed a slightly higher water requirement than the natural sands, however there were exceptions to this.

Keywords manufactured sand, crushed sand, natural sand, aggregate water requirement, sand in concrete, sand in mortar, Hägermann cone, mix design, aggregate properties

Aalto University
School of Engineering

Aalto-universitetet, PB 11000, 00076 AALTO
www.aalto.fi

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Abstrakt

Målet med arbetet var att utveckla en snabb, småskalig och lättanvändbar metod för att bestämma vattenkravet för olika typers sand i betong. För att möjliggöra detta testades 17 olika typers sand, varav 8 var krossand och 9 var natursand. Den utvecklade metoden utgick på att med hjälp av en Hägermann-kon mäta skillnader i bruksutflyt, orsakade av sandens vattenkrav. De uppmätta bruksutflyten jämfördes sedan med mängden flyttillsatsmedel som krävdes för att uppnå en viss konsistens för betong innehållande de olika sandtyperna. Metoden validerades genom att bevisa ett linjärt förhållande mellan bruksutflyt och mängden flyttillsatsmedel som krävdes. Metodens noggrannhet analyserades med hjälp av statistisk analys. Förutom bruks- och betongprover gjordes även undersökningar gällande de fysiska egenskaperna för de olika sandtyperna med standardiserade test. Resultaten påvisar att metoden är användbar, och att den ger noggrannare resultat då sandtyper av samma storleksfraktioner jämförs, då brukets utflyt ligger mellan 120 och 200 mm, samt då en bruksblandare som kan inkorporera alla av sandens kornstorlekar används. I regel hade krossanden ett marginellt högre vattenkrav än natursanden, men det förekom undantag till detta.

Nyckelord krossand, natursand, ballastens vattenkrav, sand i betong, sand i bruk, Hägermann-kon, mix design, ballastens egenskaper

Preface

I would like to thank Cementa Research for funding this research, and for allowing me to conduct it at their laboratory on the beautiful island that is Gotland, Sweden. I am especially thankful to my advisor at Cementa Research, Niklas Johansson, who has been instrumental in both the development and execution of this research, and who has helped me tirelessly in hours of need. Furthermore, I would like to extend a thank you to Pentti Koski at Cementa Research, for assisting me with mortar test methods and for guiding me through the process of using and understanding a viscometer. A thank you is also warranted to all of the personnel at Cementa Research, for being immensely welcoming and friendly towards me during my time there.

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Alexander Åkerlund

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Definitions

D_{max}	maximum aggregate size
FM	fineness modulus
ITZ	interfacial transition zone
LRL	linear regression line
R^2	coefficient of determination
SP	superplasticizer
SSD	saturated surface-dry
w/c	water-cement-ratio

Introduction

1.1 Background

The basic components of concrete are water, cement, and aggregate, whereas the aggregate usually consists of a combination of a fine and a coarse aggregate. Traditionally, natural sand mined from fluvial or glacial sources has been the fine aggregate of choice, because of their advantageous particle shape and surface texture gained from wear and tear. However, sources of natural sand are diminishing in many parts of the world, and it is harder than ever to attain permits for sand mining. Additionally, natural sand deposits play an important role in groundwater production, and therefore overmining should be prohibited. In today's global economy the obvious solution to this problem would be to import the products that are in short supply locally. However, importation is not feasible with sand as it would inflate the price heavily due to its low price-to-weight ratio. This is especially true for Nordic countries because of high transportation lengths from locations where sand is in abundance.

Crushed or manufactured sand, hereafter only referred to as manufactured sand, is another solution to the aforementioned problem. Manufactured sand is produced by crushing larger pieces of aggregate into smaller sand-sized particles. These particles usually have properties that vary largely from those of natural sands, attributed to their different origins. The crushing process and the mineralogy of the parent rock have a high influence the crucial attributes of the manufactured sands, and they often end up with an inherent particle shape and surface texture that is worse than that of natural sands. Consequently, manufactured sands often demonstrate a higher water requirement than natural sands when used in concrete production.

The perceived negative impact that manufactured sands have on concrete water requirement has provoked a hesitancy towards the usage of such aggregates in many parts of the concrete industry. Furthermore, the process of changing from one sand to another may seem too tedious for some to surmount. Conventional models and methods for determining the water requirement of sand used in concrete are laborious feats, and the results gained from such models and methods are complicated to convert to practical meaning. Moreover, even if such a conversion is successful the results may still be incorrect, as the number of variables that impact the influence the sand has on water requirement is extensive. Therefore, many rely on trial and error when switching sands, but mixing numerous small batches of concrete is time-consuming and requires special equipment that many concrete producers do not possess. As such, there is an urgent need for a fast, small-scale method that can be utilized to analyse the influence the sand has on water requirement in concrete.

1.2 Purpose and limitations

The goal of this research was to develop and validate a method suitable for determining the water requirement of natural and manufactured sands when used in concrete production. To enable this, Betongindustri provided Cementa Research with 17 different sands, of which both natural and manufactured types were represented. The requirements set on the method were that it had to be simple enough as to not require expensive specialized equipment, and it had to be fast and easily reproducible.

Mortar is similar to concrete as its basic constituents also include water, cement and aggregate. However, mortar excludes the coarse aggregate part that is included in concrete, and as such it sets much lower requirement on mixing equipment. Moreover, as a consequence of the reduced maximum particle size, the produced batch sizes can be significantly smaller than with concrete while still ensuring a uniform mix. Therefore, the methodology proposed in this research revolves around analysing the effect a certain sand has on mortar water requirement, and determining whether this effect is transferred to concrete water requirement.

The water requirement of a concrete is essentially the amount of water needed to achieve a certain workability. Workability of cementitious materials is traditionally determined with slump or flow tests, since they are easy to perform and generate somewhat accurate results. Slump tests measure the vertical decline of a concrete sample, whereas flow tests measure the horizontal spread.

In this research the method developed for evaluating mortar workability involves the measurement of mortar spread by utilizing a Hägermann cone. To provide additional simplicity a Hägermann flow-table, which is often employed alongside the cone, was not used. The mortar spreads attained with the different sands were compared to the effect the sands had on concrete workability, by establishing the amount of superplasticizer needed to reach a certain slump. Apart from the spread and slump tests, the rheology of the materials was established with a viscometer with which viscosities and yield stresses were computed. The method was verified by examining the correlations of the results with statistical analysis.

The sands were also analysed individually with standardized test methods, in order to develop an initial understanding of the differences in their implicit properties, and to enable adequate mix proportioning for the mortars and concretes. However, only the physical properties of the sands were investigated. Therefore, this research does not include any in-depth analysis regarding the mechanical or chemical properties of aggregates. Another substitute to natural aggregates that is gaining popularity is recycled aggregates, however such aggregates were not studied in this research.

2 Concrete Mix Design

2.1 General

Mix design is the process of determining the types and amounts of ingredients needed to attain a concrete with certain preordained properties. Factors regarding both fresh concrete, hardened concrete, and available materials are taken into account. Decisive elements for fresh concrete include: desired initial workability, desired workability retention, transportation time, external temperature, and the amount of reinforcement. The main variable of interest for hardened concrete is usually compressive strength, however other factors such as durability, permeability, creep, elastic modulus, and drying shrinkage may also be significant. Material availability directly affects the range of possibilities for the mix design, and takes into account what types of cement (including blended cements with mineral admixtures such as fly ash, blast furnace slag, limestone and silica fume), aggregate (types and size distributions), and admixtures (such as water reducers and air entraining agents) can be used. (Collepardi et al. 2007.)

In addition to the aforementioned technical properties, mix design also accounts for the economics of concrete. The total cost of concrete is comprised of the cost of all included materials, plant costs and labour expenses. If it is assumed that the plant and labour costs are fixed, which should be the case as long as the fresh concrete workability is adequate, then the fluctuation in expense is mainly a result of price variations between materials. Such variations are primarily caused by the amount of cement in the mixture, as cement prices could be several times that of aggregate. Thereby, in order to reduce cement usage, and consequently costs, the mix design is tasked with producing a concrete with a minimum mean strength that is required for the structure. (Nataraja, 2002.)

2.2 Concrete composition

Concrete composition depends highly on the desired attributes of the concrete in both its plastic and hardened state. The water-cement-ratio (w/c) is often considered the most important factor concerning hardened concrete, as it correlates with concrete strength, permeability, durability, creep, and plastic and drying shrinkage. A decreased w/c increases strength and durability, while it lowers the permeability of the concrete and reduces creep. Additionally, according to Krishna and Kumar (2016), a lower w/c also reduces the drying and plastic shrinkage of concrete. Workability and workability retention for fresh concrete is affected by the w/c, as an increase is gained in both cases with a higher w/c. The w/c is derived by dividing the total mass of water by the total mass of cement (or binder). (Collepardi et al. 2007.)

Aggregate size and type affect the water requirement in order to reach a set workability of the fresh concrete. Manufactured aggregate generally has an increased water requirement when compared to natural aggregate. Furthermore, since manufactured aggregate more often is used for the finer fractions (<4 mm), and since these fractions are crucial for concrete workability, the effect the choice of aggregate type has on workability is enhanced (Göransson, 2015). As for aggregate size, a larger maximum size generally results in a reduced water requirement to reach a certain workability, while also lowering compressive strength (Nataraja, 2002). Consequently, since the water amount is affected, the cement amount is as well for a set w/c. Thereby all of the properties bound to cement content are also indirectly bound to the aggregates. (Collepardi et al. 2007.)

Chemical admixtures are products that alter either the fresh or the hardened concrete, or both, in a desired way. There are several types of admixtures, but the most common ones are: superplasticizers, air-entraining agents, retarders, accelerators and corrosion-inhibitors. Superplasticizers in particular are widely used, and they are polymers composed of different materials that enable great water reductions for increased strength, cheaper concrete mixes since the cement content can be optimised, or higher workabilities when added to a concrete mix. (Mailvaganam and Rixom, 2002)

The total cement or binder content needed, which is highly impactful when it comes to concrete attributes, is mostly a consequence of the desired nominal strength, cement strength class, and a combination of other aforementioned parameters. The strength class of cement can influence both early strength development, which for instance may enable shortened demoulding times during winter, or the final strength of concrete, enabling the creation of high-strength concrete. The cement type is also impactful, especially on the durability of hardened concrete. CEM III, CEM IV and CEM V, which are described in the standard EN 197-1, are for instance clearly superior to other cement types when it comes to protection from sea water, de-icing salts from highways, or sulphate-rich soil in ground works. (Collepardi et al. 2007.)

2.3 Mix Design methods

2.3.1 Types of mixes

Nataraja (2002) presents the following three distinguishable mix types

- Nominal mixes are specified only by the proportions of cement, and fine and coarse aggregate. The amount of water is not given, but is rather added until a desired workability is reached. These mixes provide a very simplistic approach to concrete production, and since the performance and quality of mix ingredients may vary substantially, the margin of procured strength is wide at a certain workability.
- Standard mixes have prescribed compositions in a standard, and are superior to nominal mixes in that they do not allow for under- or over rich mixes in the same capacity. These mixes have a set minimum compressive strength, which makes them more reliable than nominal mixes.
- Designed mixes are created to meet the performance requirements of the concrete set by a designer. The concrete producer designs the concrete composition specifically to meet these requirements, which results in a more or less unique mix that strives to achieve predetermined properties in an economical fashion.

Nataraja further specifies that nominal and standard mixes, where the composition is only defined by the proportions of dry materials and slump, should only be used for minor jobs where the required 28-day strength does not exceed 30 MPa.

2.3.2 Types of mix design

When the concrete composition is designed in order to procure a product with set requirements, the methodology can in general be distinguished into two separate types. The first one being simple mix design, in which the requirements include characteristic strength, workability, class and type of cement, and maximum size of aggregate (whether it be natural or manufactured). The second type is complex mix design, and includes the same data as the first one, the difference being that at least one other parameter is specified from the following: early compressive strength, flexural/tensile strength, durability, or permeability. (Collepardi et al. 2007.)

2.3.2.1 Simple mix design

The process of mix design often begins with establishing a w/c based on strength requirements. This is done by converting the designed minimum characteristic strength of concrete into a mean 28-day compressive strength by either of the following formulas:

$$f_{mc28} \geq f_{ck} + 4 \quad (1)$$
$$f_{mc28} \geq f_{ck} + 1 * 48 * \sigma \quad (2)$$

where f_{mc28} is the mean 28-day compressive strength
f_{ck} is the characteristic strength
σ is the standard deviation.

Once the mean 28-day compressive strength has been established, and the cement type and strength class are determined, it can be converted into a w/c by using Figure 1. (Collepardi et al. 2007.)

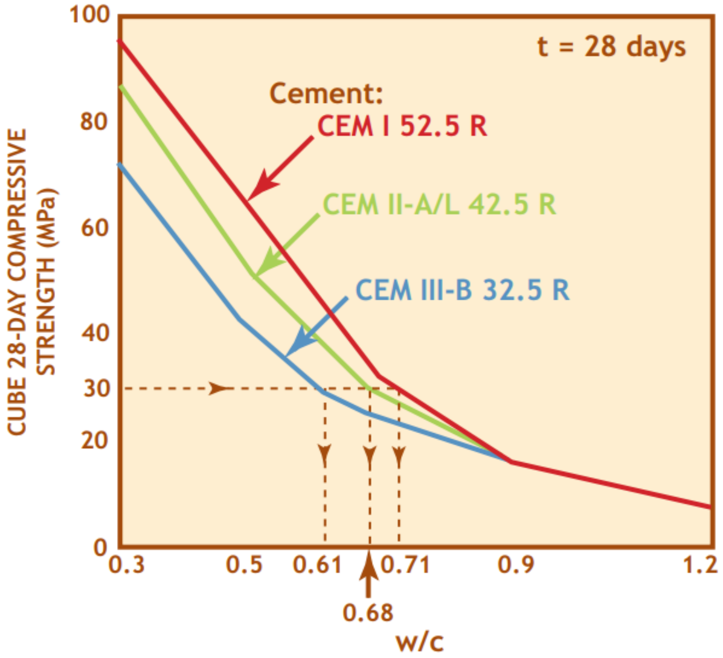

Figure 1. Conversion of mean 28-day compressive strength to w/c when cement type and strength class are known. (Collepardi et al. 2007)

The amount of water required depends highly on the type and maximum size of the aggregate, and once these are known it can be determined based on the desired workability in the form of slump by using Figure 2. When natural aggregate is used the amount of water should be decreased by 10 kg/m^3, and conversely, for the case of manufactured aggregate, increased by 10 kg/m^3. (Collepardi et al. 2007.)

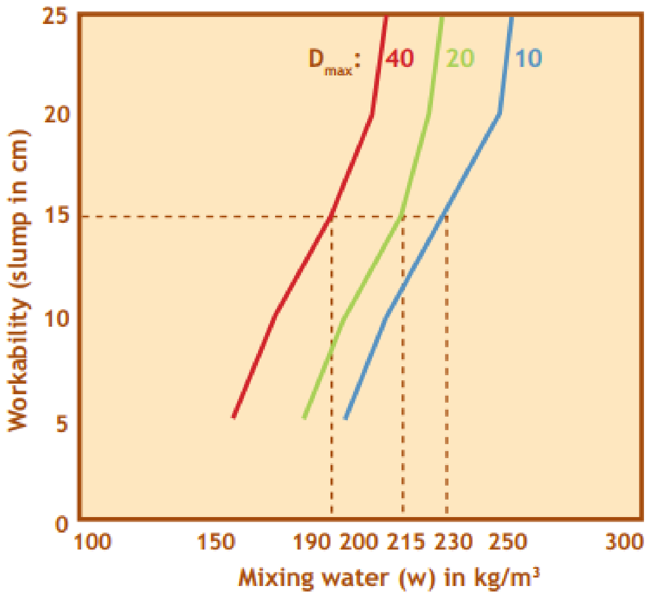

Figure 2. Conversion of workability in the form of slump to water amount when maximum aggregate size and aggregate type are known. (Collepardi et al. 2007)

When the w/c and the water amount are known, the total cement or binder content can be calculated with the following formula:

$$c = \frac{w}{w/c} \tag{3}$$

where c is the cement or binder content
w is the water amount
w/c is the water-cement-ratio.

Aside from influencing the amount of water needed for a certain workability, aggregate size also affects the air content in concrete. Figure 3 displays how the maximum aggregate size can be converted to air content by percentage of concrete volume. (Collepardi et al. 2007.)

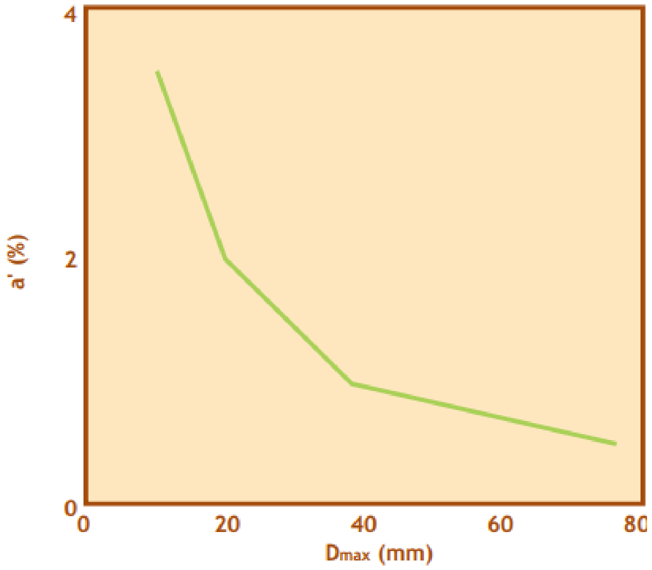

Figure 3. Conversion of maximum aggregate size to air content as percentage of concrete volume (a'). (Collepardi et al. 2007)

Once the amount of cement, water and air in the concrete have been established, it is possible to obtain the total volume of aggregate. This is done by utilizing a volume balance where a 1 m^3 or 1000 L batch is assumed. Therefore, the masses of cement and water have to be converted to volume by their respective densities. Water density is assumed to be 1 kg/L, while cement density usually hovers around 3.15 kg/L. The volume balance used to calculate total aggregate volume is the following: (Collepardi et al. 2007.)

$$V_a = V_{con} - V_c - V_w - V_{a'} = 1000 - \frac{c}{d_c} - w - 10 * a' \tag{4}$$

where V_a is the total aggregate volume
V_{con} is the concrete volume
V_c is the cement or binder volume
V_w is the water volume
$V_{a'}$ is the air volume
c is the cement or binder mass
d_c is the cement or binder density
w is the water mass
a' is the air content as percentage of concrete volume.

The total volume of aggregate is usually a combination of two or more types of aggregate. Sand and gravel are generally the types that combined create the total aggregate profile. As such, the total aggregate volume V_a in equation 4 can be divided into V_G and V_S, which are the volumes of gravel and sand, respectively. Depending on the gradings of these individual aggregate types, they should be combined proportionally to create an aggregate profile that is as close to ideal as possible. However, the ideal aggregate does not have a fixed size distribution, as it varies depending on the desired concrete attributes. For high-strength and durable concrete with low permeability the ideal aggregate would have an increased amount of fines and a smaller average aggregate size. Conversely, if workability is what needs to be improved, a larger average aggregate size is desirable. For convenience in concrete production, the volumes of the aggregates are converted into weights by multiplying them with the densities of the aggregates. The goal of a mix design is thereby to determine a recipe that includes water, cement, fine and coarse aggregate portrayed in kg/m^3. The complete process is displayed in Figure 4. (Collepardi et al. 2007.)

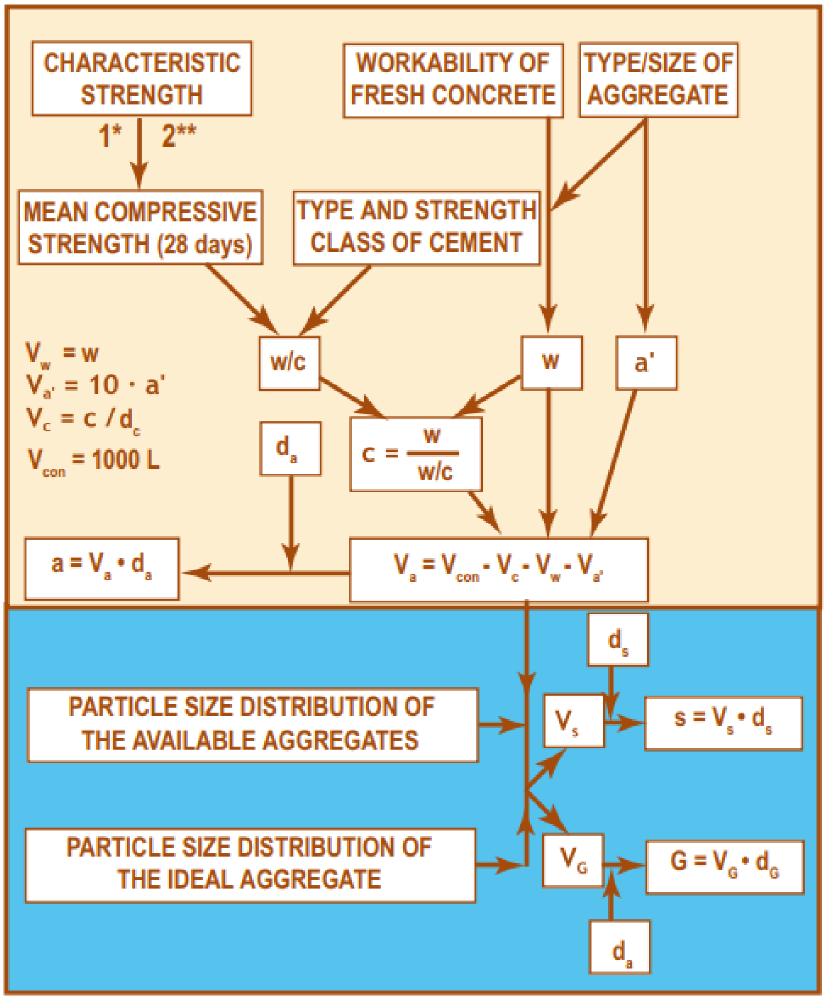

Figure 4. The complete process of a simple mix design. (Collepardi et al. 2007)

2.3.2.2 Complex mix design

As previously mentioned, a mix design becomes complex if it includes the same information as a simple mix design, but it has one or more additional requirements of the following: early compressive strength, flexural/tensile strength, durability, or permeability. Such additional requirements may call for a different w/c than that of the compressive strength. For instance, durability against freeze/thaw attacks of exposure class XF3 sets the maximum w/c to 0.5, as per the SFS-EN 206:2014 + A1:2016 standard. Since a concrete mix can only have one w/c, the lowest w/c is chosen to accommodate all requirements. The additional process that is included in complex mix design cases is depicted in Figure 5. (Collepardi et al. 2007.)

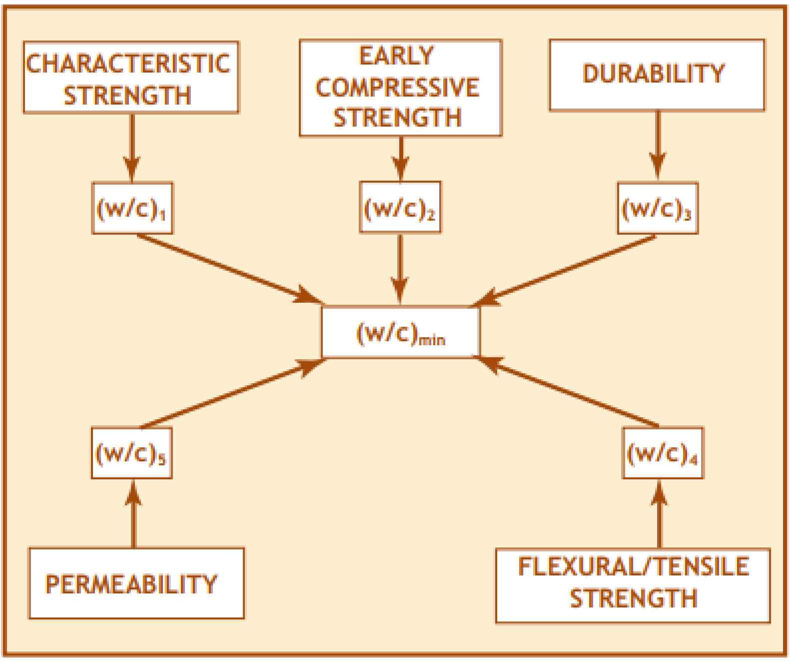

Figure 5. The additional process of a complex mix design, in which several parameters set requirements on the w/c. (Collepardi et al. 2007)

3 Aggregates for concrete production

3.1 General

Aggregates are the most widely used materials in the world apart from soil and water. Depending on economic activity, development and type of construction practiced in a country or a region, the production and consumption of aggregate may vary widely. In Sweden, the total consumption of aggregate increased from 77 million tonnes in 2014 to 84 million tonnes in 2015, of which 13% was used for concrete production (Westrin et al. 2016). Worldwide, an estimated 4.5 billion tonnes of aggregate is used for concrete production annually. In order to compare total aggregate consumption between countries, the average consumption per capita is often adopted. In Europe, the average figure lies at about 5 tonnes per capita, while Swedes on average consume roughly 8.5 tonnes per person. Examples of other countries and their respective aggregate consumption per capita are; UK: 4 tonnes, Finland: 15 tonnes, Norway: 16.5 tonnes, and Spain with only 3 tonnes (European Aggregates Association. 2016). (Alexander and Mindess. 2005.)

Since generally more than 70% of the volume of concrete is occupied by aggregates, it is apparent that they impact the properties of the concrete significantly (Al-Batah et al. 2009). The actual strength of the aggregate usually is of little significance, since the cement paste is normally the weakest part of the concrete. Therefore, it is possible to use most solid materials as aggregate for concrete production, however rock materials are most commonly used due to affordability, suitability and availability. (Lagerblad et al. 2008.)

3.2 Aggregate production

3.2.1 Production of natural aggregates

Natural aggregates are granular materials in the form of sand or gravel that can be processed for usage in concrete with minimal cost and effort. Such materials can be sourced from river beds, pits, beaches, the seabed, terraces, dunes, or other similar deposits. Natural aggregates tend to have certain characteristic mineralogical or physical properties depending on their point of origin. For instance, aggregates from river beds usually have superior particle shapes and surface textures, while aggregates from dunes often have severe deficiencies of fines. The following phases are included in the production of natural aggregate

- reduction phase, where aggregates are reduced in size by crushing if a gravel source has some oversized particles, or if crushing provides technical advantages.
- processing phase, and if there are some superfluous particles a beneficiation phase, in which organic material and unwanted minerals are removed.
- sizing and sorting phase.

Furthermore, aggregates are handled, transported, and stockpiled in preparation for use in concrete production, and in order to guarantee a consistent quality these processes must be carefully controlled. (Alexander and Mindess. 2005.)

The environmental strain caused by aggregate production is significant because of the vast amount of aggregates used for concrete production, alongside the fact that most aggregates are some sort of rock material. This is especially true for natural aggregates. Environmental factors that are affected by aggregate production include

- atmospheric factors: constant background noise from machinery and the plant itself, noise from blasting, and dust from moving vehicles, drilling and crushing.

- water factors: natural sand deposits play a key role in groundwater filtering and production, and mining of such deposits may cause modifications in ground water quality. Surface waters may also be affected, since quarries can alter water courses and increase sediment load.
- landscape factors: mainly regarding the visual impact of a quarry.
- natural factors: concerns regarding the effect a quarry may have on flora and fauna.

Moreover, natural aggregates are becoming a scarce resource in many areas. An example of this is south-eastern England where a lack of local aggregate sources has led to aggregates being imported from Ireland. (Alexander and Mindess. 2005.)

Due to environmental concerns as well as diminishing resources, many countries are attempting to reduce the production of natural aggregate. This has mainly been done by taxation, which is true for Sweden where natural aggregate production has been taxed since July 1st 1996 – and as of 2015 corresponds to a flat 15 SEK per one tonne produced (Lag om skatt på naturgrus: 3 §. 2015). As a result of this taxation, alongside encouragement of use of other aggregates, the consumption of natural aggregate in Sweden has decreased from more than 60 million tonnes in 1985, to 10.7 million tonnes in 2015. In terms of share of total aggregate consumption, these figures correlate to 76% of total aggregate consumption in 1985, and only 13% in 2015. However, this reduction has been diminishing in recent years, as the natural aggregate consumption only decreased by one percentage of total aggregate consumption between 2014 and 2015. Another development that is worth noting is the decline in the number of active quarries, and the increase of their productivity. In the year 2000 there were 3165 active quarries in Sweden, with an average annual output of 20000 tonnes per unit. In 2015 the number of active quarries was only 1284, but the average output had increased to 65000 tonnes per unit. (Westrin et al. 2016.)

3.2.2 Production of recycled and manufactured aggregates

As usage of natural sand is reduced, alternative sources of aggregate need to be employed. Such alternatives include recycled aggregate and manufactured aggregate. Recycled aggregate stems from recycled concrete, which is concrete that has been reclaimed from demolished concrete constructions. This recycled concrete is subsequently processed by crushing, removal of contaminations such as reinforcement, and washing and grading. Thus, a recycled coarse aggregate suitable for concrete production is produced. The fine aggregate retained from this process is however often largely contaminated by old cement paste or mortar, and is therefore usually not suitable for reuse in concrete production. (Alexander and Mindess. 2005.)

Manufactured aggregate is created by quarrying and crushing hard rock. The fact that hard rock can be made into concrete aggregates is imperative in certain regions, where it is the only reasonable source of quality aggregate. By crushing hard rock, it is possible to generate both coarse and fine aggregate. The properties of the manufactured aggregate depend highly on a number of factors, including

- the amount of weathering the parent rock has been subjected to,
- the nature of the parent rock, whether it is jointed or solid, fissured or laminated, etc.,
- the methods of extraction, be it mechanical ripping or blasting, and
- the method of crushing used to process the rock. (Alexander and Mindess. 2005.)

The method of crushing appears to be the most important factor regarding properties developed during the production process of manufactured aggregates. Particle shape is particularly prone to variation depending on crushing methods. This is important specifically for the case of manufactured sand, since fine aggregate is more influential on concrete workability than coarse aggregate. The produced particle shape depends somewhat on the type of crushing equipment, of which favourable examples are gyratory crushers and cone crushers. Other types of crushing equipment include jaw crushers, roll crushers, disc crushers, and impact crushers, such as hammer mills. Furthermore, some mineralogical properties of the rock also influence the quality of the crushing product. Such properties include homogeneity, structure (laminar, fine grained, or coarse grained), hardness, fracture toughness, and moisture content. The amount of free quartz in the rock may also be of interest, as it is harder than normal steel and may therefore increase the wear and tear of the crushing equipment. (Alexander and Mindess. 2005.)

When the source of the manufactured aggregate is hard-quarried rock, a series of crushing process stages is needed to reduce the large boulders to sizes suitable for concrete production. These stages are

- primary crushing: first phase where large boulders are reduced to more manageable sizes, usually with gyratory or jaw crushers.
- secondary crushing: rock material is further reduced to be used in concrete production or in preparation of a tertiary stage, usually with impact crushers or cone crushers.
- tertiary crushing: final phase that is only necessary when exceptionally low reduction ratios (meaning the ratio of the size of the input particles to the size of the output particles) are needed, for instance to improve particle shape. This phase uses largely the same equipment as the secondary crushing.

The tertiary crushing stage can be repeated if a continuous grading of the aggregate is desired. However, especially for larger grain sizes, a gap grading is sometimes favourable for concrete workability since manufactured aggregate tends to have a higher amount of interparticle friction than natural aggregate. This friction is caused by the angular shape and rougher texture of the particles. (Alexander and Mindess. 2005.)

The particles of manufactured sand have a tendency of being flaky and elongated, but this tendency can be reduced by proper crushing techniques. Such proper crushing techniques include

- removal of fines and chips in the primary crushing stage,
- choke feeding (meaning that the feeder chamber is full and that there is material above to keep it full),
- close-circuit feeding,
- usage of crushing surfaces that are corrugated, and
- low reduction ratios, except for the case of impact crushers which can produce a well-shaped aggregate even with high reduction ratios.

However, some rock types inherently produce excessively flaky particles and are therefore simply not suitable for the purpose. For instance, schists and slates, with their marked cleavage planes and laminated structures, are notoriously hard to produce adequate manufactured aggregate with. (Alexander and Mindess. 2005.)

There is still some hesitation in the concrete business about manufactured sand, partly because of long traditions of natural sand usage, and partly because of ignorance and misinformation. Nevertheless, both production and consumption are on the rise, and there are some advantages to manufactured sand that may not always be obvious. One of these is that modern crushing methods and equipment can generate particle shapes that are equivalent or even better than those of some natural sands. Therefore, although manufactured sand usually increases the water requirement of concrete, it is possible, with proper production methods, to attain a material with comparable or even lower water requirement than some natural sands. Furthermore, since the methodology for production of manufactured sand can be kept identical, and conditions can be controlled, the consistency of manufactured sand can be better than that of natural sand. This is primarily seen as the biggest advantage of the material for modern concrete plants. Moreover, contaminations in the form of minerals and organic materials is less likely to be found in manufactured sand than in natural sand. (Alexander and Mindess. 2005.)

3.3 Aggregate properties

Many properties of an aggregate, such as strength, stiffness, hardness, relative density, pore structure, permeability, and mineral and chemical composition, are influenced by the type of its parent rock. Rocks from earth can be regarded as either igneous, sedimentary or metamorphic depending on their origin. All rock material stems from igneous rocks, which are developed when molten material that exists under the crustal zone of the earth is solidified. These igneous rocks are formed as either intrusive rocks, meaning rocks of larger grain-sizes that solidify slowly under the crust, or extrusive rocks, meaning rocks with smaller grain-sizes that rise to the surface and solidify much faster. Sedimentary rocks are formed when pre-existing igneous rocks are broken down either mechanically or chemically. Sedimentary rocks are of high variety, since their properties depend highly on the breakdown process. Metamorphic rocks are created when igneous or sedimentary rocks are altered by high temperature and pressure. This alteration can weaken a rock by forming undesirable minerals in it such as alkali-reactive silicates, or strengthen a rock by for instance converting sandstone into quartzite. Furthermore, any of these primary rock types can undergo alteration, resulting in a rock with different properties than what it originally possessed. Since rocks by default can inhabit a wide variety of properties, and since aggregate production methodology in itself may influence the properties in various ways, the total variance of properties found in concrete-ready aggregates is extensive. (Alexander and Mindess. 2005.)

The properties of an aggregate heavily influence the concrete in which it is used. Concrete science must understand and apply the effects that aggregate properties have on concrete, in order fully utilize the vast spectrum and keep up with the developments in other fields of engineering. Aggregate properties can be divided into three groups, physical, chemical or mechanical. This research will mainly focus on the physical properties, as the chemical and mechanical ones generally have a lesser impact on concrete, and are harder to determine. Mechanical properties not discussed in detail include strength, hardness, abrasion and wear resistance, and elastic properties, while chemical properties not analysed include chemistry, mineralogy, aggregate reactions, sulphate soundness, and freeze-thaw soundness. (Alexander and Mindess. 2005.)

In order to properly be able to describe the effect aggregate properties have on concrete properties, one particular term, the interfacial transition zone, or ITZ, needs to be explained. Traditionally, concrete has been considered a composite material with two phases, namely the aggregates and a uniform matrix of hydrated cement paste in which they are embedded. This model provides an accuracy sufficient for normal engineering purposes, however it is a substantial oversimplification. When the concrete is formed, a thin zone surrounds the aggregate particles in which the cement paste is structurally different from the general body of the paste. This zone is what is referred to as the ITZ, and it is typically 20-40 µm thick. The structural differences that distinguish this zone from the bulk part of the cement paste is that it includes less hydrated cement, it has a higher porosity and generally larger pores, there is less C-S-H (calcium silicate hydrate, which is the main product of Portland cement hydration and the primary source of strength for cement paste), there are large crystals of calcium hydroxide, and there is usually a higher concentration of ettringite. These distinctions cause the ITZ to have less crack resistance than the rest of the paste or the aggregates, which in turn means that the ITZ often is the weakest part of the concrete. (Mindess et al. 2003.)

Porosity, p, is the measure of the internal pore volume of a solid compared to its total volume. Most aggregates available for concrete production have a measurable porosity, which is defined by the following equation:

$$p = \frac{V_p}{V_T} \tag{5}$$

where p is the porosity in %
V_p is the volume of internal pores
V_T is the total volume of the aggregate.

Porosity has a direct relation to aggregate density, and as such it also indirectly affects concrete strength. The volume of internal pores used in equation 5 includes all pores, however with standard tests it is only possible to measure the volume of pores interconnected to the surface. Therefore, the measured porosity is what is called an apparent porosity. This means that there are impermeable pores unaccounted for, which may affect the density and subsequently the strength of an aggregate. Moreover, porous aggregates can absorb water, which means that if they are not fully saturated at the time of concrete mixing, they can withdraw water from the mixture. This results in a more porous ITZ and hence a weakened paste-aggregate bond. However, aggregate porosity can also be advantageous, especially for high strength concrete production. In these cases, an increased porosity of aggregates, and thus an increased water absorption, can be utilized as a delayed source of moisture for the hydrating matrix. Thereby, strength development is improved and autogenous shrinkage reduced after the initial hardening phase. Furthermore, aggregate porosity can assist in limiting the disruptive expansion caused by alkali-aggregate reactivity (Collins and Bareham. 1987). Therefore, an increased porosity is not always a negative property and does not necessarily entail a decreased concrete durability or strength. (Alexander and Mindess. 2005.)

Aggregate absorption depends on their porosity, and it is measured in a similar fashion. The aggregates are oven-dried, after which they are allowed to absorb moisture so that they reach a saturated surface-dry (SSD) state, as per standard EN 1097-6. The SSD state is defined as when aggregates are internally moisture saturated and dry on the surface, while the oven-dry state is defined as when the aggregate has reached a constant mass after being dried in a ventilated oven at a temperature of 110 ± 5 ºC. The percental difference in mass between the oven-dried aggregate and the SSD aggregate is the absorption of the aggregate. If the absorption exceeds 2 or 3 percentage, the aggregates could for instance contribute to a higher drying shrinkage, and thus their effect on concrete should be analysed. Apart from the oven dry and SSD states, aggregates can also come in other moisture states, namely as air dry or wet. Air dry aggregates possess some moisture, and have reached an equilibrium in that there is no moisture movement between the aggregates and the surrounding air. Wet aggregates are internally moisture saturated, with excess free moisture on the surface. (Alexander and Mindess. 2005.)

The moisture state of an aggregate impacts its density. Aggregate density is usually measured in the controllable oven-dry and/or SSD states, which results in what is called apparent density. The SSD state is of particular interest, since aggregates in that state do not withdraw water from, or deliver additional water to a concrete mixture. The apparent density includes the volume of the impermeable internal pores, but not the one of those that are interconnected to the surface and thereby permeable. This density is an important value in concrete technology, as it is what is used in mix design to determine the mass required of an aggregate to make up a set volume. Furthermore, aggregate density has a high impact on concrete density, which carries over to the self-weight a structure has to withstand, and to the pressures that formworks must endure during casting. The construction of dams and structures used for radiation protection are examples of when high-density aggregates can be utilized to create high-density concrete. (Alexander and Mindess. 2005.)

Aggregates used for concrete production are never perfectly shaped and graded, which means that there are voids left between them. This void volume does not include the pores in the aggregates, but rather only the external voids between the particles. For concrete production, the void volume is important as it needs to be filled with cement paste in order to create a coherent compound. A consequence of this void volume is the adoption of the term loose bulk density ρ_b. The loose bulk density describes the density of an aggregate that has been loosely tipped in place, and it is defined in EN 1097-3. Based on the loose bulk density and the dry density of an aggregate, the percentage of voids can be calculated. The loose bulk density and percentage of voids are inversely related to each other, and they depend on the surface texture, particle shape, and grading of an aggregate. A lower percentage of voids translates into a lower amount of cement paste needed, and consequently into a more economic concrete. Furthermore, some technical properties of a hardened concrete, as well as the workability of a plastic concrete may be influenced by the percentage of voids. (Alexander and Mindess. 2005.)

It has previously been determined that aggregate particle shape depends highly on the source of the aggregate, whereas natural aggregates tend to have a better shape than manufactured ones. Figure 6 and 7 portray this tendency with pictures taken with a scanning electron microscope of both natural and manufactured sands of different size fractions. When discussing particle shape, it is usually flakiness, sphericity and roundness that are the main points of interest. Flakiness is often declared in percentages as a flakiness index. This factor is defined as the percentage of a certain size fraction that will pass through a bar sieve with a narrower width of slot than what the minimum diameter for that said fraction is. Sphericity describes how close a particle comes to a spherical shape, while roundness portrays how sharp the edges and corners of a particle are. The flakiness index test is defined in EN 933-3, however it should only be used with aggregates that have a minimum diameter of 4 mm. Another standardized test regarding these properties is the shape index test described in EN 933-4, however this test requires the user to assess the ratio between length and thickness of each particle using a particle slide gauge, which makes it unsuitable for use with sand. Despite the lack of standardized testing for sand materials, it is for the finer size fractions that particle shape is particularly important when surveying concrete properties. It is the single most influential factor regarding workability and water requirement, whereas spherical, rounded particles contribute to a more workable mix as they can roll or slide over each other with less resistance. The same goes for concrete compaction, as a poor particle shape may cause interlocking. The percentage of voids in aggregates is also influenced by particle shape, with more angularity and lower sphericity resulting in a higher percentage. However, a poor particle shape may also have positive consequences, in particular for hardened concrete. For instance, strength may be increased with more angular particles, since they tend to have a higher internal friction. Additionally, if cracking occurs the cracks are forced to take a more complex path around the irregular aggregates, often resulting in smaller, less damaging cracks. (Alexander and Mindess. 2005.)

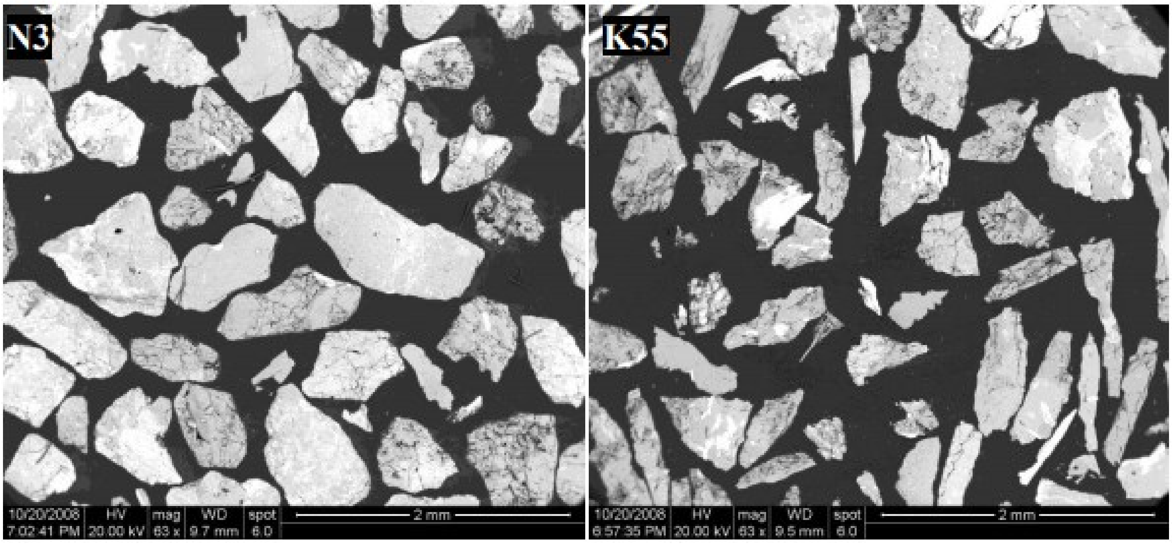

Figure 6. SEM-pictures in backscatter mode of natural (N3) and manufactured (K55) sand particles of size fractions 0.5 – 1 mm. (Lagerblad et al. 2008.)

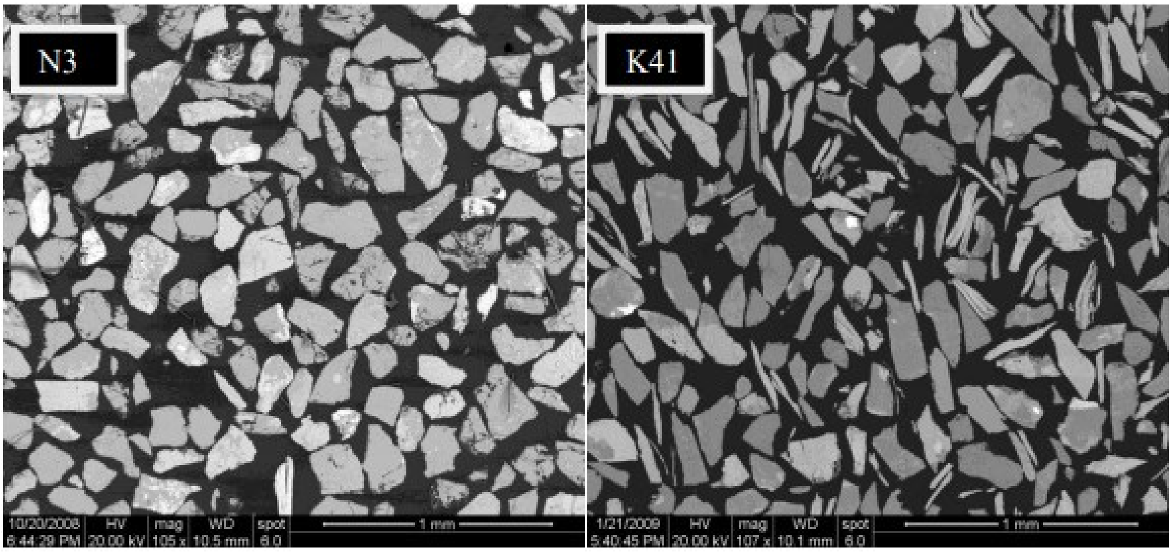

Figure 7. SEM-pictures in backscatter mode of natural (N3) and manufactured (K41) sand particles of size fractions 0.125 – 0.25 mm. (Lagerblad et al. 2008.)

Particle surface texture is another physical property of aggregates that has an impact on plastic and hardened concrete. As is the case for particle shape, surface texture depends highly on the production of the aggregate. Natural aggregates that have been subjected to abrasion tend to have a smoother surface, while manufactured aggregates usually have a rougher surface texture, depending on the composition and mineralogy of the parent rock. Surface texture can be hard to define specifically, however two interconnected properties can be used to describe it: the roughness of the surface, which is the magnitude of relief, and the actual surface area present per unit of projected area. A flow coefficient, which is defined in EN 933-6, can be used to describe surface characteristics of aggregates. As for the effect that the aggregate surface texture has on concrete, a rough surface leads to heightened interparticle-friction, and consequentially a harsher mix that may require additional water in order to compact properly. However, similarly as with particle size, some mechanical properties of the concrete may be improved due to the enhanced interparticle bonding caused by a rough aggregate surface texture. (Alexander and Mindess. 2005.)

The surface area for a set mass of aggregates increases with a decreased aggregate size, which is why the total surface area of a complete array of aggregates is mainly decided by the finer size fractions. The term specific surface, which is the ratio of an aggregates surface area compared to the volume or mass of the particles, is often used. However, it is very hard to calculate the true specific surface on an aggregate, and it has therefore found little practical use. Nevertheless, it is known that the rougher the surface texture and the less spherical the particle, the bigger its specific surface. An increased specific surface results in a larger amount of water needed to wet the surface of the aggregate, and therefore in an increased water requirement for the concrete mix. (Alexander and Mindess. 2005.)

The size distribution of aggregates, also called the grading of aggregates, has many implications on the properties of concrete. The grading of an aggregate is attained by a sieve analysis, where a sample of aggregate is passed through a series of standard sieves. The method is explained in detail in EN 933-1. In order to portray the results a grading curve is often produced, in which the y-axis depicts the cumulative percentage of aggregate passing through the sieves, and the x-axis shows the different aperture sizes of the sieves on a logarithmic scale (Figure 8 and 9). Proper grading cannot however be determined in isolation, but should rather be determined in combination with aggregate shape and surface texture. Together they govern the percentage of voids and the surface area of aggregates that needs to be filled and coated with cement paste, as well as the friction between aggregate particles. Therefore, these factors are largely responsible for the plastic properties of the concrete.

One important goal of mix design is to create a cohesive concrete with adequate workability, given the amount of cement and water that is to be used. If all other variables are constant, it may be necessary to combine aggregates with different gradings to produce an aggregate with acceptable overall grading. The size distributions of an acceptable grading may vary largely depending on circumstances, however traditionally a continuous grading such as the one shown in figure 8 is considered close to optimal. With a continuous grading the spaces between coarser aggregates are filled with finer aggregates, which results in an economical mix with lower mortar requirement. Such gradings generally counteract segregation and provide workable mixes with aggregates that have good particle shapes and surface textures. However, if this is not the case and particle interference (which is when the space between larger aggregates is too narrow for smaller aggregates to pass through, thus worsening flow characteristics) becomes a problem, gap grading where one or more problematic size fractions are excluded may be an appropriate solution. Gap grading is represented by a close to horizontal line in a grading curve, which can be seen in figure 9. Maximum aggregate size D_{max} also has an influence on concrete properties, in that a larger maximum usually reduces water requirement and improves workability. (Alexander and Mindess. 2005.)

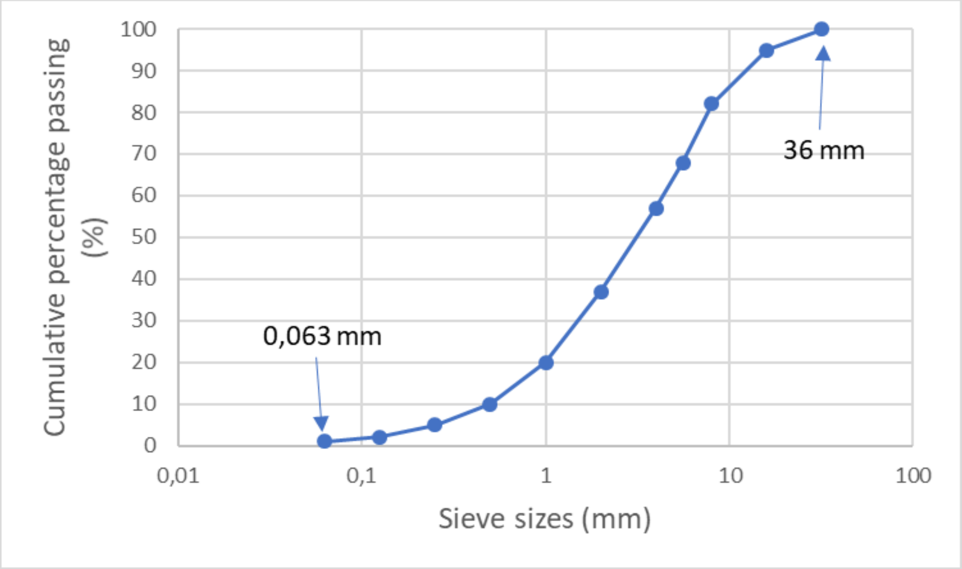

Figure 8. Example of a continuously graded curve.

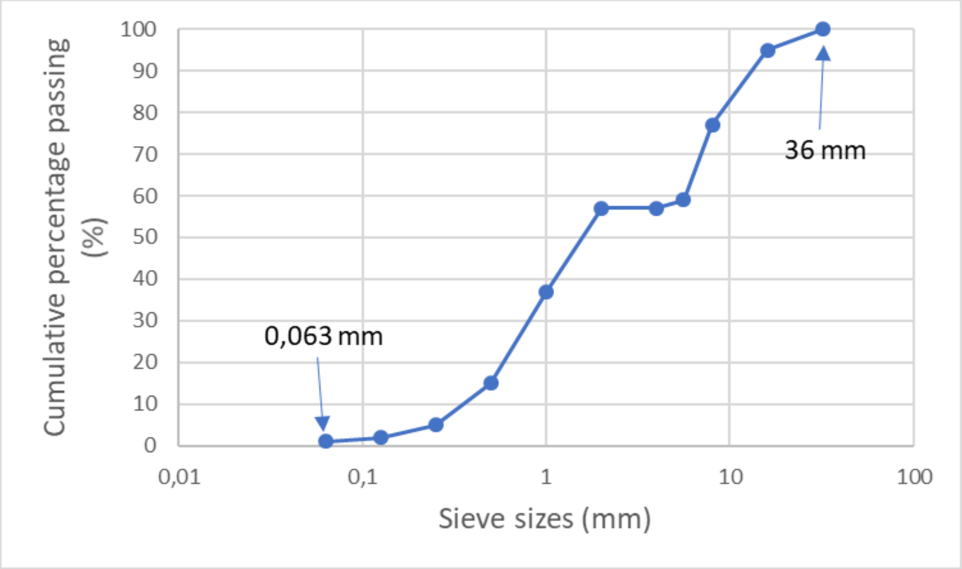

Figure 9. Example of a gap graded curve.

3.4 Aggregate classification

To enable adequate concrete proportioning all factors concerning aggregates that influence workability must be determined. The grading curve needs to be assessed by taking into account the properties the aggregate has at all particle sizes. Therefore, the different particle sizes need to be characterized and classified in order to assess how they will affect the fresh concrete individually. Such a petrographic analysis can be done in detail with microscopy and image processing, or by utilizing different petrological tests. The procedure and terminology for a simplified petrographic description of an aggregate is defined in EN 932-3.

Such methods require specialized equipment and are often very tedious, and therefore practically impossible to use in a production setting. Thus, simpler, more convenient methods have to be utilized instead. (Lagerblad et al. 2008.)

The European standard includes several tests that can be utilized as placeholders for more advanced microscopical or petrological methods. Such tests include, with their respective standards

- EN 933-1 sieving method for determining particle size distribution,
- EN 933-3 flakiness index for determining particle shape, not recommended for use with sand,
- EN 933-4 shape index for determining particle shape, not applicable for fine aggregates, as it requires manual analysis of individual aggregates,
- EN 933-6 flow coefficient for assessing surface characteristics,
- EN 933-8+A1 sand equivalent test for assessment of fines,
- EN 933-9+A1 methylene blue test for assessment of fines,
- EN 933-10 air jet sieving of filler aggregates for assessment of fines,
- EN 1097-3 determination of loose bulk density and voids, and
- EN 1097-6 determination of particle density and water absorption.

The European standard (EN 12620:2002+A1 Aggregates for concrete) defines the following size fractions and their requirements

- coarse aggregate:
    - larger aggregate sizes with a minimum diameter of 4 mm, while the presence of some particles having a minimum diameter of 2 mm is acceptable.
- fine aggregate:
    - finer aggregate sizes with a maximum diameter of 4 mm.
- fines;
    - particle size fraction of an aggregate that passes a 0.063 mm sieve.
- filler aggregate:
    - aggregate of which most passes a 0.063 mm sieve that can be added to construction materials to provide certain properties.
- natural graded 0/8 mm aggregate:
    - aggregate of glacial and/or fluvial origin with a maximum diameter of 8 mm.

The standard also accepts the notion of All-in aggregate. All-in aggregate is a mixture of fine and coarse aggregate, where the minimum diameter is 0 mm and the maximum 45 mm. Such aggregate mixtures shall comply with the general grading requirements presented in the standard. Moreover, a guidance on the description of the coarseness or fineness of sands is included in Annex B of EN 12620. Two methods regarding this are described, whereas sands are characterized as either having a coarse fineness, medium fineness, or fine fineness. The first method utilizes the amount of sand in percentage that passes a 0.5 mm sieve. If the amount passing is 5-45 %, the sand has a coarse fineness, if the amount is 30-70 %, the sand has a medium fineness, and if the amount is 55-100 %, the sand has a fine fineness. The second method described in the standard is the fineness modulus FM, which usually is calculated by adding the cumulative percentages of mass retained on each standard sieve, ranging from 4 mm to 0.125 mm, and dividing the sum by 100. If the FM is between 4 and 2.4, the sand has a coarse fineness, if it is between 2.8 and 1.5, the sand has a medium fineness, and if it is between 2.1 and 0.6, the sand has a fine fineness. Alexander and Mindess (2005) describe the FM as a measure of logarithmic average particle size.

3.5 Implications on concrete mix design

Aggregate porosity in itself has little impact on the plastic state of concrete. However, the absorptivity of aggregates that depend on their porosity does. Not accounting for this while using oven-dry aggregates results in a mix with a reduced workability and w/c as the aggregates absorb some of the water that is intended to lubricate the mix. This phenomenon can be combatted by compensating for the amount of water the aggregates will absorb with additional mixing water of equal amount added to the concrete. This amount can be calculated by multiplying the absorption percentage with the mass of each aggregate type, and adding them together. Additionally, the ITZ may be weakened because of the absorption of dry aggregates, causing a weaker hardened concrete. Therefore, it is recommendable to use aggregates that are fully saturated for concrete production. Since the SSD is a very precise moisture state, and since it is the minimum humidity for when aggregates are fully moisture saturated, the wet moisture state is the most commonly used one. Aggregates in a wet moisture state have superfluous water on the surface, and the total amount of water brought to the mix by this medium needs to be subtracted from the designed mixing water so as to not influence the w/c. Therefore, frequent or continuous checking of the humidity of aggregates is advisable for concrete production plants (Collepardi et al. 2007).

The density of aggregates has certain implications on mix design. The apparent density of each aggregate used needs to be known in order to ensure proper dosage. Furthermore, as the aggregates make up the majority of the concrete, the aggregate density plays a key role in concrete density design. Depending on the function of the structure for which the concrete is intended, different concrete densities may be required. Alexander and Mindess (2005) define different aggregate densities by their loose bulk densities in the following fashion: lightweight aggregates; 880-1120 kg/m^3, normal weight aggregates; 1200-1760 kg/m^3, heavyweight aggregates; 1760-4640 kg/m^3.

It has been determined that aggregate particle shape and surface texture has a major impact on the workability and compactibility, and consequently on the water requirement of concrete, particularly for the finer aggregate size fractions. As for natural sand, the point of origin has a decisive effect on these properties, whereas natural sand from fluvial or alluvial origins usually have better particle shapes and surface textures than those originating from pit sources. For manufactured sand, the parent rock and crushing methodology play a key role in determining these properties. Furthermore, even though natural sands usually are superior to manufactured sands regarding particle shapes and surface textures, this is not always the case. These sentiments found in the literature appear to contradict the notion presented earlier in part 2.3.2.1, in which the required water amount could be determined from figure 2 based on the desired slump, and 10 kg/m^3 should be added when natural aggregate is used and retracted when manufactured aggregate is used. Such a generalized straightforward approach may suffice for simple concrete works, however for advanced and precise concrete production it seems insufficient. This is due to the many aforementioned factors that influence the water requirement of aggregates. Moreover, manufactured aggregate is often used together with natural aggregate, which the method does not account for whatsoever.

The requirements on aggregate grading vary depending on desired workability of the concrete. For a concrete with low workability requirements, for instance in prefab production, the aggregate grading may not play such a crucial role as long as adequate compaction can be achieved. However, if high workability is desired, such as in an in-situ cast setting where extensive secondary reinforcement is present, aggregate grading will be critical in order to achieve sufficient cohesiveness with low internal friction. An increased water requirement caused by poor aggregate shape and surface texture can be compensated to an extent with proper grading. As the water requirement depends partly on the total surface area of the aggregates, and since the specific surface is higher the smaller the aggregate size, a higher D_{max} will lower the total water requirement. Figure 10 shows a model presented by Collepardi et al. (2007) for the determination of mixing water needed depending on D_{max} for different degrees of workability in the form of slump. Furthermore, in order to assess the fineness of a sand used, its fineness modulus can be calculated. Alexander and Mindess (2005) state that as a rule, sands with the same fineness modulus have a similar water requirement when used in concrete. However, they also state that as for particle size, the water requirement mainly depends on the amount of finer material that have particle sizes of < 0.3 mm, and since the FM excludes the sizes of < 0.063 mm, the parameter may not be reliable. Nevertheless, even though the finer size fractions have an increased specific surface, an argument can be made that workability can be improved with larger amounts of fine aggregates. This is because overfilling the void spaces caused by coarser aggregate with finer aggregate reduces internal friction and allows for greater mobility between aggregates, meanwhile attributing to a denser more economical mix with lesser risk of segregation. Grading is therefore in essence the design of a balance, where aggregate-specific properties are taken into consideration to create a spectrum that accommodates both the plastic and hardened requirements of the concrete, while being as economical as possible. (Alexander and Mindess. 2005.)

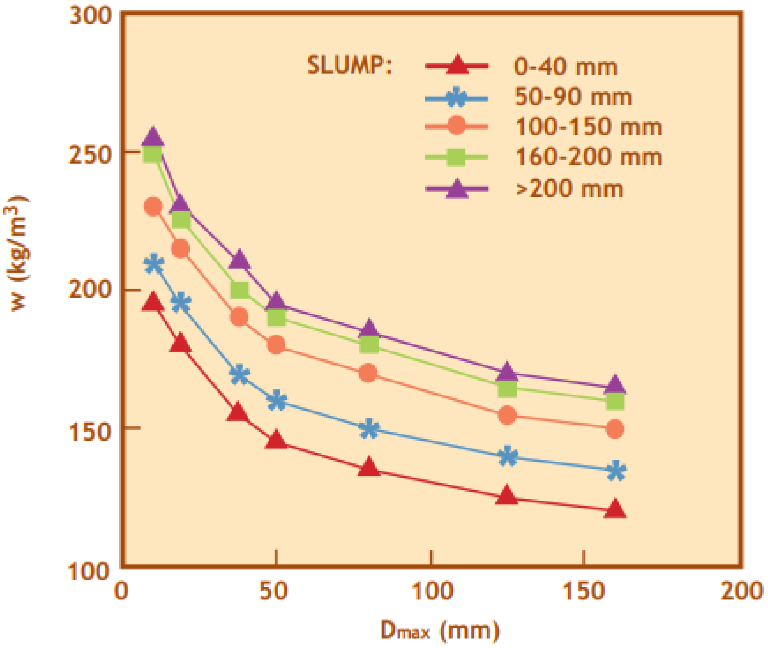

Figure 10. The impact D_{max} has on water requirement for different slumps (Collepardi et al. 2007).

Because of the large amount of properties that define aggregates, and since these properties may have largely varying effects on concrete, especially on its workability, it can be a tedious process to switch from one aggregate to another. There are several models and metrics to assist in this process, although they often require specialized equipment and the results gained can be hard to interpret and may not depict the whole truth. This is especially true for sands, since they are more complicated to analyse than coarse aggregate, and have a higher impact particularly on water requirement when a certain workability is desired. Therefore, the process of switching sands often eventually comes down to trial or error. However, producing a number of different concrete batches solely to examine the effect the sand has on water requirement is strenuous and time-consuming. Moreover, some concrete producers may not have access to laboratory-sized concrete mixers for such a process to be feasible. The goal of this research is therefore to examine whether a sand can be tested in mortar, which is considerably easier to produce than concrete, in order to determine the impact it has on concrete water requirement.

4 Aggregate analysis

4.1 General

In order to enable this research, Betongindustri provided Cementa Research with 17 different sands from various sources in Sweden. Out of the 17, 9 were natural sands and 8 were manufactured. For this report, the sands were given pseudonyms in order to preserve the anonymity of their respective producers. The pseudonyms used were NS 1-NS 9 for the natural sands, and MS 1-MS 8 for the manufactured sands. All of the natural sands had size fractions ranging from 0-8 mm, while the manufactured ones had either 0-2 mm or 0-4 mm. No specific information was provided regarding the origin of the sands, such as the type of parent rock or crushing method used for the manufactured sands, or the source from which the natural sands were attained. However, the assumption can be made that the manufactured sands were crushed from some sort of granite, since it is the most common rock type in Sweden, and since they were all grey in colour. Figure 11 displays the colours of NS 8, NS 3 and MS 6, whereas there is a slight difference between the natural beige sands, while the manufactured sand is clearly different with its grey colour. Before the sands were tested in mortar or concrete, they were analysed individually as such with a number of tests in order to produce an initial understanding of their properties. The complete dataset of results gained from the aggregate analysis is included in appendix 1.

Figure 11. Variations in colour between different sands. The sands pictured from left to right are: NS 8, NS 3, and MS 6.

4.2 Test methods and results

4.2.1 Sieving

All sands were sieved in order to create individual profiles regarding the size distributions of the particles they included. The sieving was done in accordance with EN 933-1. The mass of aggregates tested was approximately 600 g for the natural sands, as their D_{max} was 8 mm, and approximately 200 g for the manufactured sand, since they had a D_{max} of ≤ 4 mm. Each sample was then dried to a constant mass, weighed, washed, dried again, weighed again for the loss of fines, divided into smaller test portions, sieved, and finally weighed again to determine the size distribution. For the washing, a guard sieve with 1 mm aperture size was used to divide the sample into two layers, thus improving water flowability. Sieving was done with the required aperture sizes prescribed in EN 933-2, as well as one additional sieve with an aperture size of 5.6 mm. Once the results had been attained, the total masses of all recorded particle sizes were compared to the total initial mass of the test sample. The recorded differences did not exceed 1%, which is the highest allowed as per EN 933-1. Grading curves were produced based on the results of the sieving process for each of the sands, however since no coarse fractions were included, they were not plotted logarithmically. Figure

12 and 13 show examples of the produced grading curves of two of the sands, one manufactured with size fractions ranging from 0-2 mm, and one natural with size fractions ranging from 0-8 mm. A fineness modulus was also calculated for each sand; however, it was not done exactly the way suggested in EN 126020. Specifically, the size fractions included ranged up to 8 mm as opposed to the 4 mm proposed in the standard. Moreover, the cumulative percentage retained on the 0.125 mm sieve was divided by two in order to reduce its impact on the total FM, thus creating a larger relative disparity between the FMs of the different sands. The final formula used for the FM was the following:

$$FM = \frac{\sum[(>8)+(>5.6)+(>4)+(>2)+(>1)+(>0.5)+(>0.25)+\frac{>0.125}{2}]}{100} \qquad (6)$$

where (>x) is the cumulative percentage of mass retained on a sieve of x aperture size.

Apart from the fineness modulus, a second method for determining the fineness of sands is presented in EN 126020, whereas the amount of sand in percentage by mass that passes a 0.5 mm sieve is compared. Figure 14 and 15 display staple diagrams where the FM and the amount that passed the 0.5 mm sieve in percentage for each sand have been placed in opposite orders of magnitude. This was done since a higher FM should indicate a lower amount passed. The staples for the natural sand have an orange colour, and the ones for manufactured sands have a blue colour.

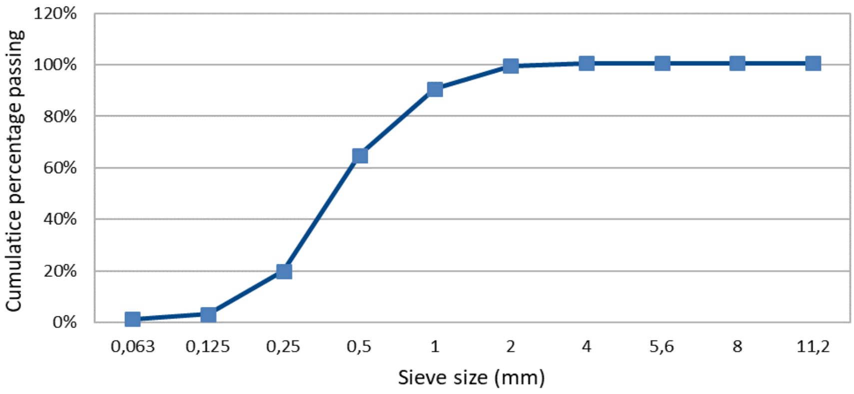

Figure 12. Grading curve of manufactured sand MS 2.

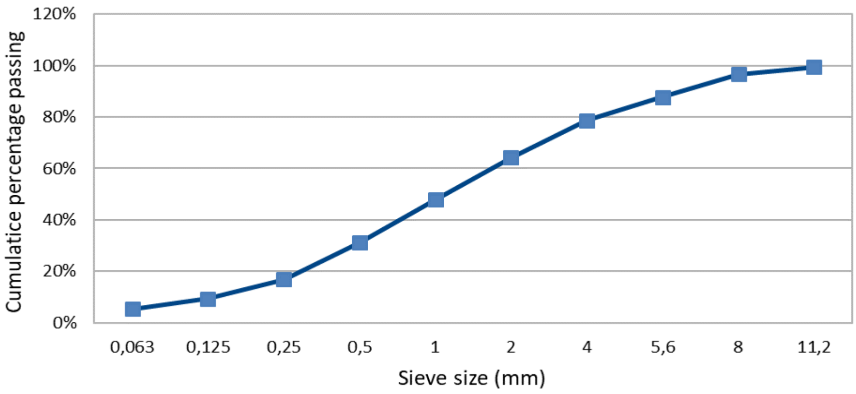

Figure 13. Grading curve of natural sand NS 7.

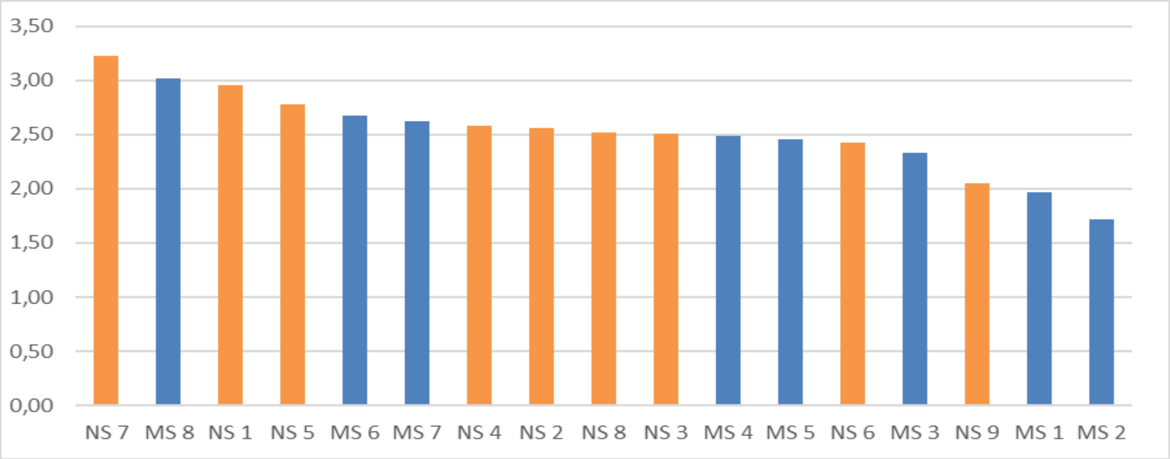

Figure 14. FM calculated with formula 6 of each sand, by order of magnitude.

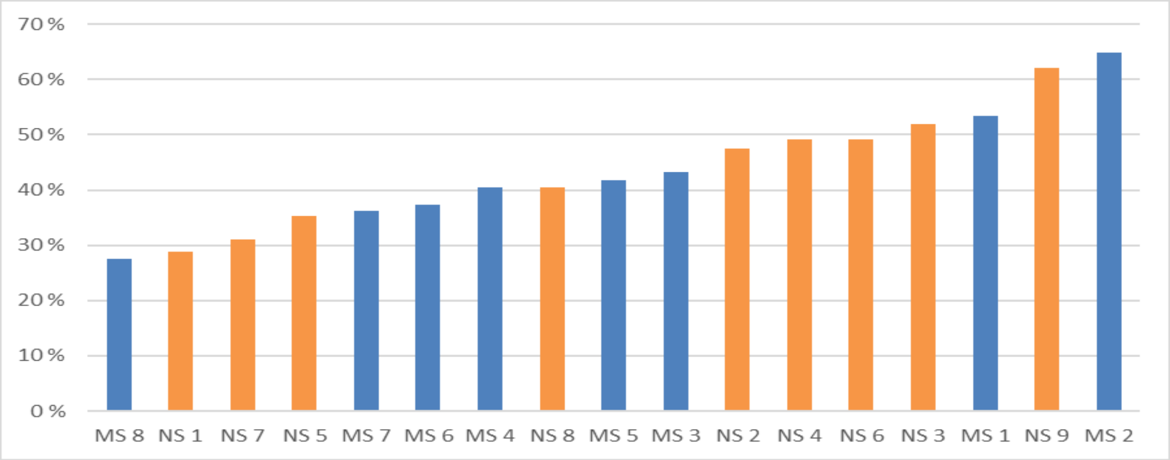

Figure 15. Amount of particles passing the 0.5 mm sieve in percentage, by order of magnitude.

Based on figures 14 and 15, neither of the parameters depicted seem to differentiate on whether a sand is natural or manufactured, even though the natural sands all include larger particle sizes. MS 1 and 2, which are the ones with particle sizes of 0-2 mm, do end up having the lowest FM, however NS 9 ends up between them when the amount passing a 0.5 mm sieve is analysed. Therefore, the conclusion can be drawn that the D_{max} of a sand, and whether the sand is natural or manufactured, do not on their own correlate with its FM, or with the percentile amount of particles passing a 0.5 mm sieve.

4.2.2 Particle density and water absorption

Particle density and water absorption was determined in order to evaluate the differences between the sands, and in order to enable exact dosages for further testing. The test was done with the pycnometer method for aggregate particles passing the 4 mm test sieve and retained on the 0.063 mm test sieve, as prescribed in EN 1097-6:2013, chapter 9. Due to the particle size restrictions of the test, all sands were washed over a 4 mm and a 0.063 mm sieve, and the redundant particles were discarded. The size fractions discarded were assumed to have the same densities and water absorption as those tested for each type of sand. The testing procedure is quite long and includes many elements, but there were no discrepancies to the methodology dictated in the standard for any of the sands, other than that the pycnometers were never immersed in water baths during the 24h waiting period. This part was deemed unnecessary, as the testing was done in a laboratory where the air temperature was kept at 21ºC at all times. Figure 16 shows four of the sand samples in pycnometers during the waiting time. A way to determine when sand is at the SSD state is defined in the standard, whereas after the sand has been exposed to a gentle current of warm air, it is placed in a cone and tamped. The cone is then lifted and the slope of the collapsed sand determines its moisture state. The target slope as defined by the standard, and an example of the achieved slope, are shown in figures 17 and 18.

Figure 16. Sands in pycnometers during the 24h waiting time. From left to right: MS 2, NS 7, NS 1, and NS 8.

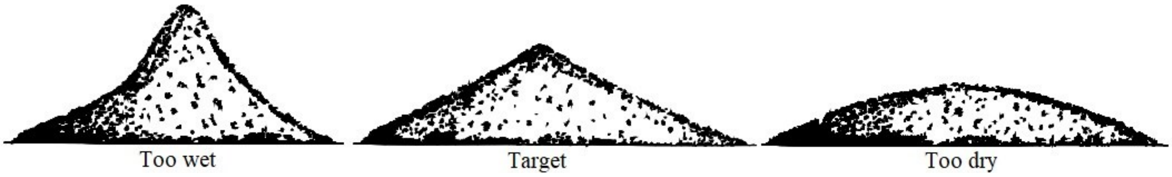

Figure 17. The target slope for an aggregate in the SSD state, and the bordering slopes for too wet and too dry aggregates. (EN 1097-6. 2013.)

Figure 18. The achieved slope during SSD density testing for one of the sands.

The oven-dry and SSD densities and the absorption of the sands were calculated based on the different masses that were measured during the pycnometer testing. The SSD densities and absorptions are shown as diagrams in figure 19 and 20, again by order of magnitude and with different staple colours depending on if the sand is natural or manufactured. Figure 19 shows that the measured densities were very similar, except for two of the manufactured sands that had significantly higher values than the others. The absorptions portrayed in figure 20 however, varied a lot, and the higher values were mostly detected in natural aggregates. Based on these results it would seem that whether a sand is manufactured or not has little impact on its density, however its absorption tends to be higher for natural aggregates.

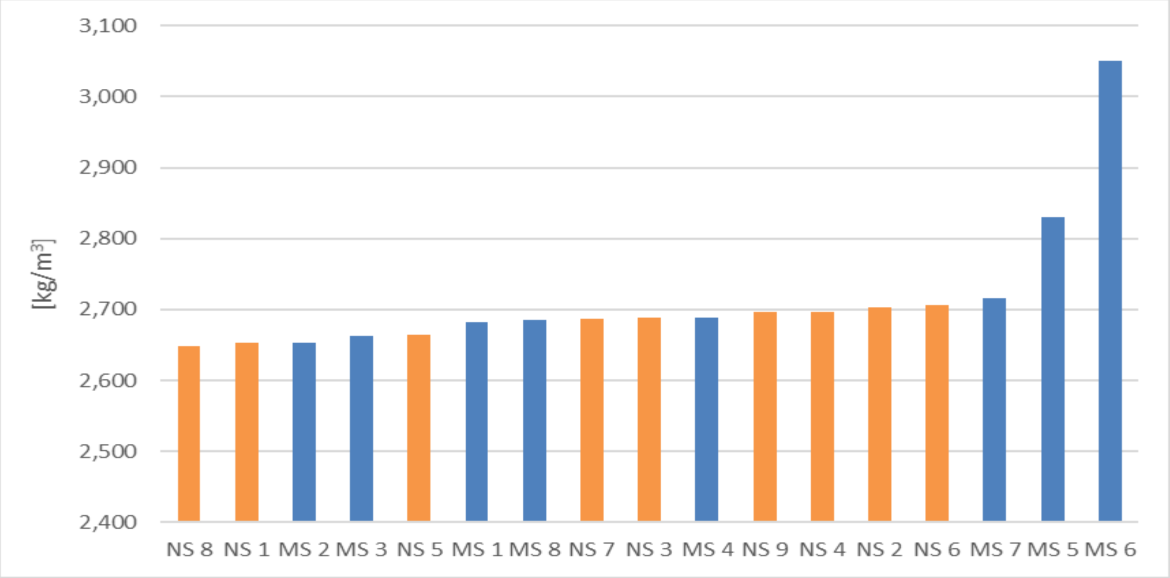

Figure 19. The SSD densities of the different sands, by order of magnitude.

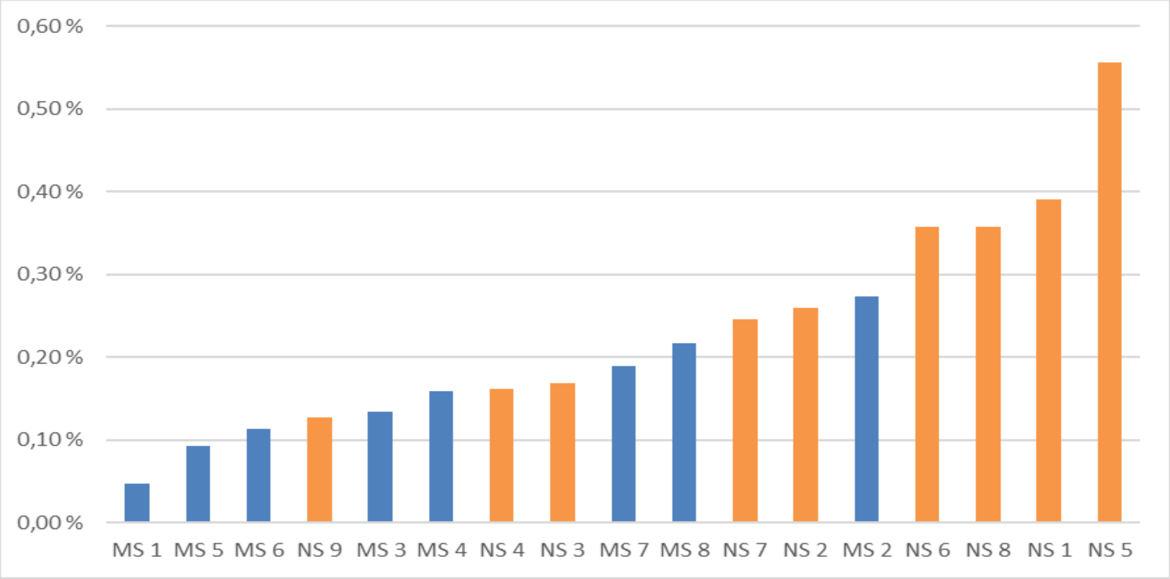

Figure 20. The absorption of the different sands, by order of magnitude.

4.2.3 Flow coefficient

The European standard EN 933-6 defines the flow coefficient as “the time, expressed in seconds, for a specified volume of aggregate to flow through a given opening, under specified conditions using a standard apparatus”. For this research, the described standard apparatus was not available, so alternative equipment, displayed in figure 21, was used as a placeholder. This equipment consisted of a steel feeder cone with a feeder diameter of 1 cm mounted on vertical studs. By clogging the feeder while the test sample was poured into the cone, and only unclogging once all of the sample was in it, the baseline circumstances for each test sequence were identical.

Three different size fractions were tested, namely the 1-2 mm fraction, the 0.25-0.5 mm fraction, and the 0.125-0.25 mm fraction. The exact procedure for the flow coefficient test was the following

- A sample was collected for each sand.
- The sample was washed over a 2 mm and a 0.125 mm sieve, discarding the material passing both sieves and the material retained on the 2 mm sieve.
- The remaining sample was oven-dried to constant mass.
- The sample was divided into 1-2 mm, 0.25-0.5 mm, and 0.125-0.25 mm size fractions by sieving.
- A compact volume of 0.05 dm^3 of each sample was weighed by utilizing the apparent density of the sand measured in the pycnometer tests. The calculated masses ranged from 132.4 g to 152.5 g.
- The weighed volume was poured into the feeder cone while the feeder was clogged.
- Once all of the material was in the feeder cone the feeder was opened, and the timer was started.
- When the last of the sand particles exited the cone, the timer was stopped.
- The time it took for the sample to flow through the feeder was recorded, and the test was repeated five times for each size fraction of every sand.
- The time average of the five repetitions was calculated for each size fraction, formulating the final flow coefficient of the respective fraction.

The standard deviation of the five measured times was calculated for each size fraction of every sand, and the average standard deviation for all sands and fractions was 0.04 seconds. The highest standard deviation as percentage of time recorded was for the 0.125-0.25 size fraction of MS 7, with 1.8 %. Subsequently, as the results gained from the repetitions were very similar, the method was deemed appropriate for attaining flow coefficients of the different sands that could be utilized and compared internally. However, since the methodology used in this research differs completely to the one described in the standard, the produced flow coefficients are not comparable externally to flow coefficients gained in other research. Figure 22 displays a diagram of the three flow coefficients measured for all sands.

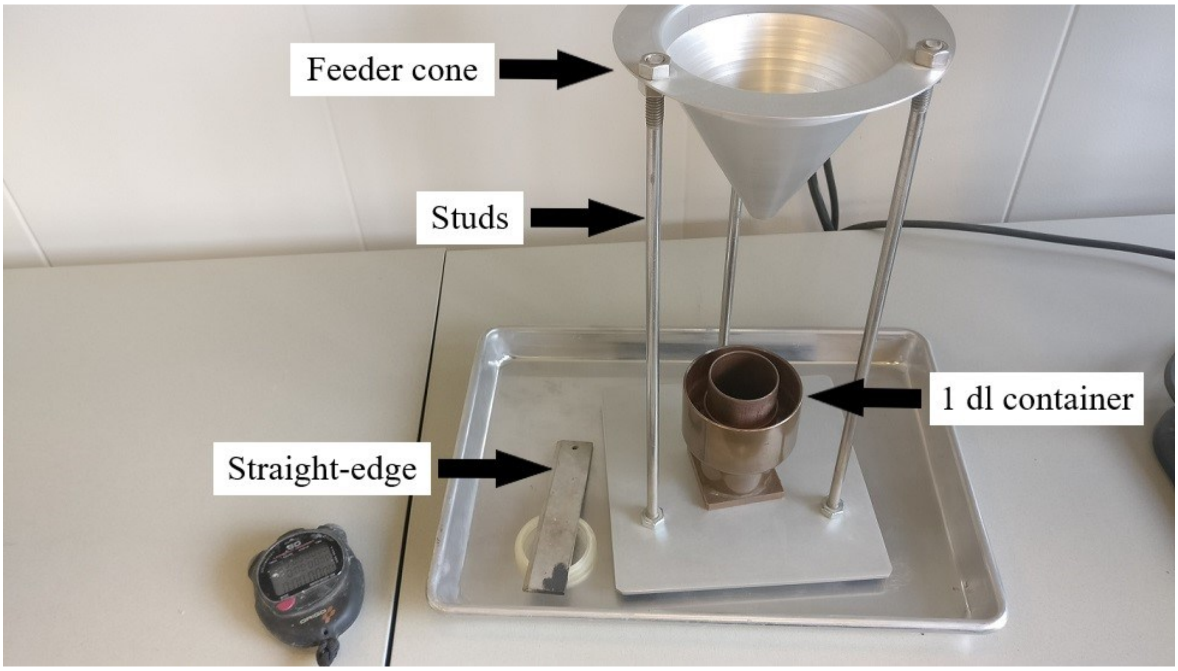

Figure 21. Feeder cone apparatus used in determining both flow coefficient and loose bulk density, and the 1 dl container and straight-edge used for the loose bulk density testing.

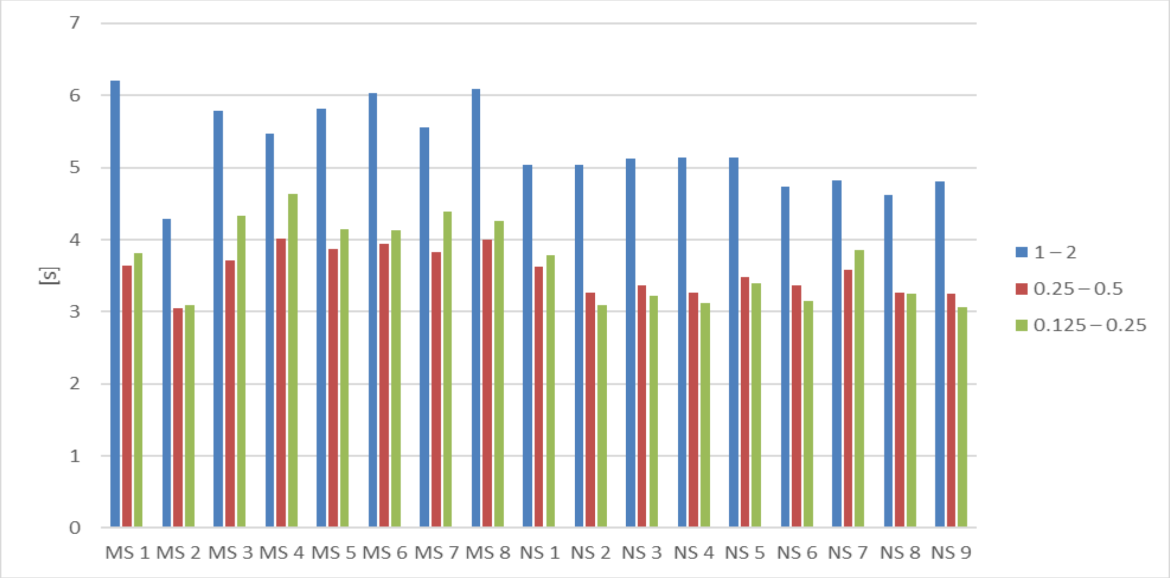

Figure 22. The flow coefficients measured for the different size fractions of all sands.

4.2.4 Loose bulk density and percentage of voids

The test methodology and required equipment to determine the loose bulk density, and subsequently the percentage of voids, for an aggregate is described in EN 1097-3. According to the standard, the required volume of the cylindrical container used to determine the volume of the sample is 1 litre for aggregates with a D_{max} of ≤ 4 mm. However, for this research, such a container was not available so one with a volume of 0.1 litre was used instead. The ratio requirements of the container regarding its inside diameter and depth were however fulfilled. Moreover, the aggregate was not scooped into the container, but was rather poured through the feeder cone in the same manner as with the flow coefficient tests. The feeder cone apparatus, straight-edge and cylindrical container used is pictured in figure 21. The tests samples were, similarly as for the flow coefficient testing, divided into three size fractions of 1-2 mm, 0.25-0.5 mm, and 0.125-0.25 mm. The exact procedure used to determine the loose bulk density was the following

- The 1 dl container was weighed dry and clean, and its mass m_1 was recorded.
- A sample was collected for each sand.
- The sample was washed over a 2 mm and a 0.125 mm sieve, discarding the material passing both sieves and the material retained on the 2 mm sieve.
- The remaining sample was oven-dried to constant mass.
- The sample was divided into 1-2 mm, 0.25-0.5 mm, and 0.125-0.25 mm size fractions by sieving.
- An amount of the sample that would slightly overfill the 1 dl container was poured into the feeder cone while keeping the feeder clogged.
- Once all of the sample was in the feeder cone the feeder was opened, and the sand was allowed to fall into the container.
- The overfilled container was then scraped and levelled with the straight-edge carefully, as to ensure that the sand was not compacted.
- The filled container was weighed and the mass m_2 was recorded.
- This procedure was repeated three times for each size fraction of each sand, and the average of the resulting masses was calculated.

The standard deviation of the three measured masses was calculated for each size fraction of every sand, and the average standard deviation for all sands and fractions was 0.16 g. The highest standard deviation as percentage of mass recorded was for the 1-2 mm size fraction of MS 4, with 0.4 %. Therefore, similarly as with the flow coefficient, the method was deemed appropriate for internal comparison due to the low fluctuation between measurements. Once the average masses had been determined, the loose bulk density could be calculated for every size fraction of each sand by conducting the following equation included in EN 1097-3:

$$\rho_b = \frac{m_2 - m_1}{V} \tag{7}$$

where ρ_b is the loose bulk density
m_2 is the mass of the filled container
m_1 is the mass of the container
V is the volume of the container.

The percentage of voids can be calculated once the loose bulk density and the oven-dry density of an aggregate is known. The oven-dry density of the size fractions studied in this test was assumed to be the same as the one attained for the unreduced sand during the pycnometer tests. EN 1097-3 presents the following formula for calculation of percentage of voids:

$$v = \frac{\rho_p - \rho_b}{\rho_p} * 100 \tag{8}$$

where v is the percentage of voids
ρ_p is the oven-dry density
ρ_b is the loose bulk density.

The values for the percentage of voids gained for the different sands by using this methodology were all between 40 and 60 %, which was deemed reasonable. Figure 23 displays a diagram of the different percentage of voids attained for each size fraction of the sands.

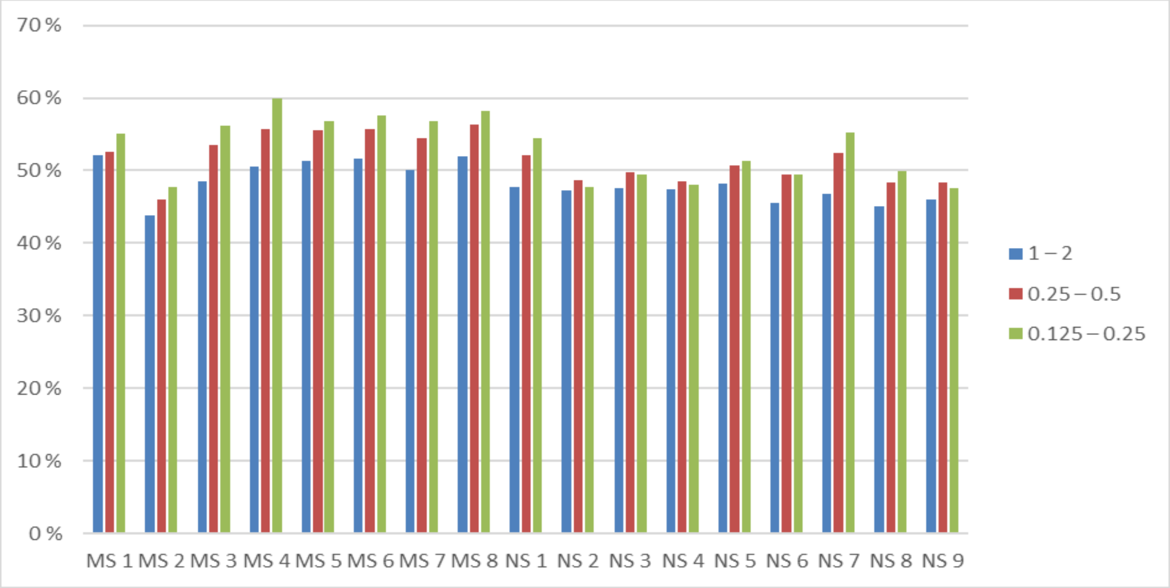

Figure 23. The percentage of voids calculated for the different size fractions of all sands.

4.3 Implications on concrete Mix Design

The flow coefficient and percentage of voids are assumed to depend on the interparticle-friction and how well the particles “fit” together, and thus their magnitude should reflect the particle shape and surface texture of the aggregate. The staples shown in the diagrams of figures 22 and 23 are generally lower for the natural sands on the right than for the manufactured sands on the left, specifically by 14.9 % on average for the flow coefficients, and by 8.2 % for the percentage of voids. Therefore, it seems like natural sands usually have a smoother surface texture, a reduced flakiness, and a rounder and more spherical particle shape. However, as the effect that aggregate properties have on water requirement is enhanced for lower size fractions, they should be analysed independently. Figure 24 shows the flow coefficient for the 0.125-0.25 size fraction of each sand, by order of magnitude and with different colours for natural and manufactured sand.

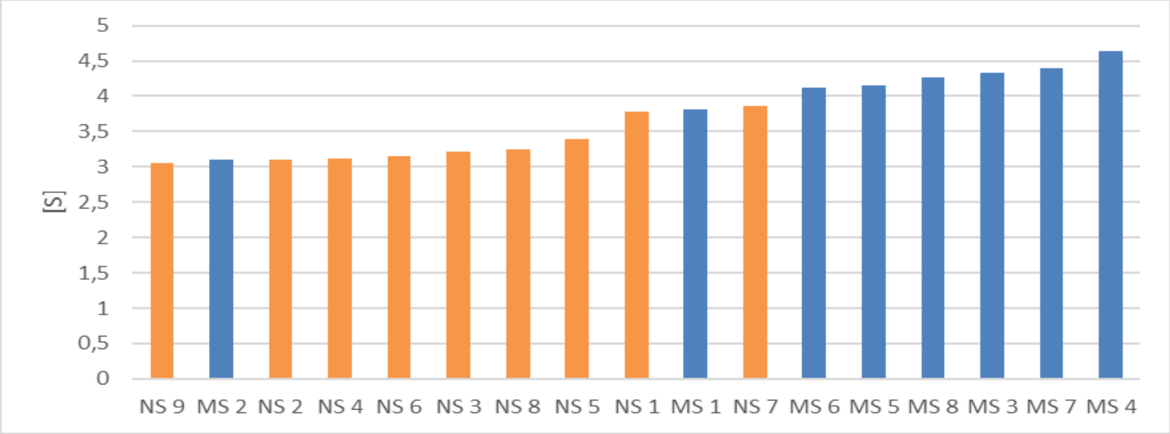

Figure 24. Flow coefficient for the size fraction 0.125 – 0.25 mm of each sand, by order of magnitude.

The differences between the flow coefficients of the manufactured and natural sands displayed in figure 24 are 20.9 % on average, with MS 2 being a clear outlier. This is an increase from the 14.9 % that was observed for the combined fractions in figure 22. Therefore, it is concluded that the water requirement of the manufactured sands on average should be higher than that of the natural sands, as it depends largely on the particle shape and surface texture of the fine aggregate.

As both the flow coefficient and the percentage of voids are said to depend on the same physical properties of the tested aggregate, there should be a correlation between the two. Figures 25, 26 and 27 they display the two parameters plotted against each other for the different size fractions with linear regression lines (LRLs). A LRL is a line created by the observed values of x and y, and it serves as a predictive model of what the dependant y-value should be for an explanatory x-value. The LRL is explained in further detail section 7.1. Since most of the individual plotted points in figures 25-27 are on the LRL, or very close to it, the assumption of correlation is confirmed.

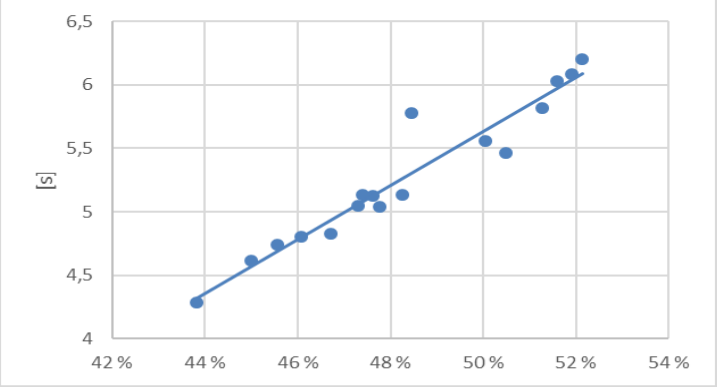

Figure 25. Flow coefficient vs void content, 1-2 mm.

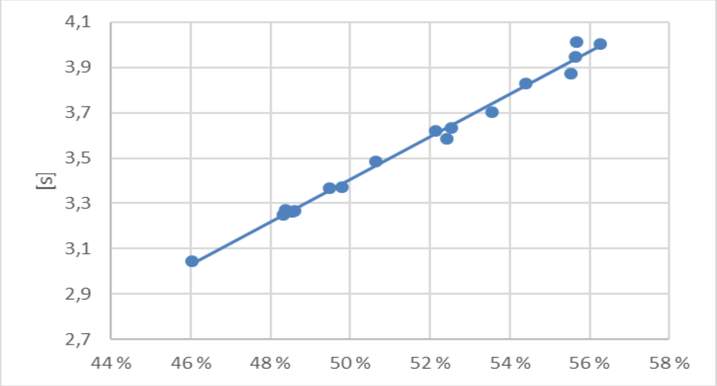

Figure 26. Flow coefficient vs void content, 0.25-0.5 mm.

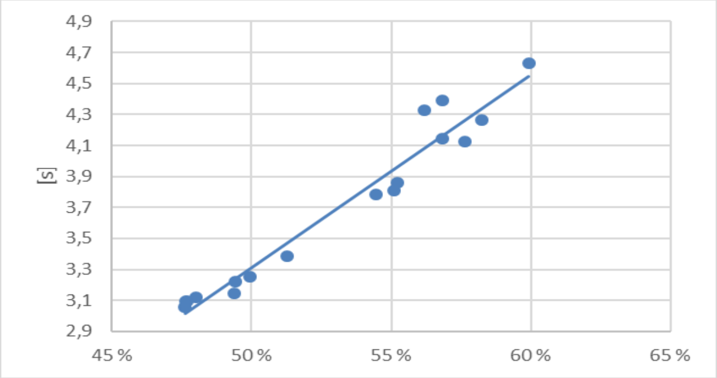

Figure 27. Flow coefficient vs void content, 0.125-0.25 mm.

5 Mortar analysis

5.1 General

The goal of the mortar analysis was to determine the effect that the different sands had on mortar rheology. This was done by testing the mortars for spread by using a Hägermann cone, while the only varying factor in the mortar recipe was the type of sand. The results gained were then compared to the void contents and flow coefficients gained in the aggregate analysis, to examine whether these properties impacted the mortar rheology as expected. The rheology of the mortars produced were furthermore tested by determining their yield stresses and viscosities, by the use of a viscometer. The complete dataset of results gained from the mortar tests is included in appendix 2.

The yield stress and viscosity were tested since fresh cementitious materials can be considered as fluids, and the two parameters should correlate with the slump or spread of a fluid. Yield stress is defined as the minimum stress required to induce an irreversible deformation and flow, and viscosity is described as a fluids resistance to shear stress. Shear stress is the stress that is parallel to the surface of a material. In a mortar or concrete setting where workability is tested by slump or spread, the shear stress produced by the pressure from the height of the sample is what causes the concrete or mortar to flow. The pressure will then gradually diminish as each layer of material continues to spread. The spread will stop once the stress caused by the pressure is equal to or smaller than the yield stress. Thus, the magnitude of the yield stress determines how much the material needs to spread before it stabilizes. The yield stress and viscosity of a cementitious material should therefore correlate with its slump or spread. In this research, the yield stresses and viscosities attained from the viscometer were used to confirm the rheological results attained from the much simpler Hägermann cone spread test. (Roussel and Coussot. 2005.)

5.2 Mortar composition

The mortar produced was that of a simple mixture, including only water, sand, and cement. The cement used was Cementa Bascement, which is of type CEM II/A-V 52.5 N. The cement is produced to comply with the requirements set in EN 197-1, which means that it is a mixture of cement clinker and fly ash. Based on the standard, the cement should consist of 80-94 % cement clinker, 6-20 % fly ash, and a maximum of 5 % other additional constituents. Bascement is recommended to be used for standard concrete work, and it has an ordinary early strength development and higher standard strength characteristics. The technical datasheet for Cementa Bascement is included in appendix 4.

The mixer used for the mortar production could not blend mixtures containing aggregates of a higher D_{max} than 4 mm without a risk of being damaged. Since all of the natural sands included in this study had a D_{max} of 8 mm, they needed to be reduced on a 4 mm sieve before they were tested in mortar. The influence of this reduction was analysed, and the relative amount of aggregate reduced per natural sand was documented. All sands were dried to constant mass in a ventilated oven prior to sieving and testing, so their moisture state was that of oven-dried.

Two different mortar recipes were used to test the variations in rheology induced by the sands. Both recipes had roughly the same w/c, as one had 0.576 and the other 0.574. The difference between the recipes was the volumetric amount of aggregate, which was 40 %

and 45 %, respectively. Not only was the total amount of results increased and thus the research more comprehensive by testing each sand with two different mortar recipes, but the rheological effect produced by an increased volumetric amount of sand could also be determined. Moreover, it could be analysed which recipe worked better for this purpose. All of the materials were of the same temperature during testing, namely 21 ºC.

5.3 Test methods

The mortars were tested for spread, yield stress and viscosity. The equipment used for the spread test is displayed in figures 28 and 29, and it included a 3-speed Hobart mixer with an N50 flat beater, a Hägermann cone, and a smooth aluminium plate. The mixer, bowl and beater all conformed to the requirements for laboratory equipment prescribed in EN 196-1. The yield stress and viscosity were measured with a viscometer of model Viskomat NT. The viscometer operated by the Searle principle, where the sample cup is stationary and the motor rotates the spindle. The geometry used with the viscometer consisted of a sample cup with a jagged inner rubber lining, and a spindle which was a combination of a cylindrical and a vane spindle. The shortest inner diameter at the top of the cup between the jags was 79.4 mm, and the diameter and height of the spindle cylinder were 60 and 70 mm, respectively. The viscometer is displayed in figure 30, and the cup and spindle in figure 31.

Figure 28. Hobart mixer, bowl and beater.

Figure 29. Hägermann cone and aluminium plate.

Figure 30. Viscometer.

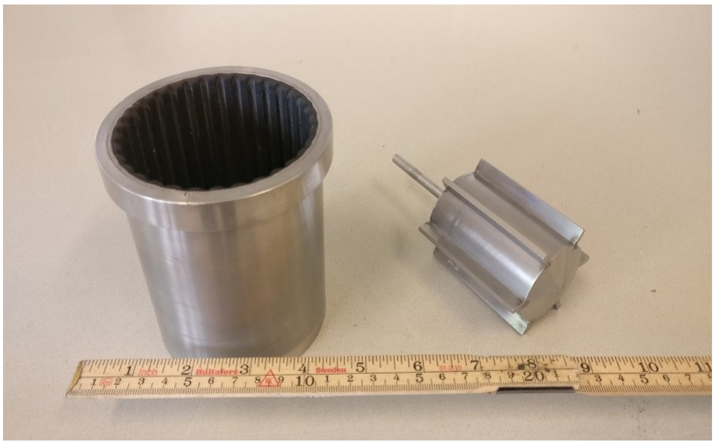

Figure 31. Cup and spindle used with viscometer.

The two mortar recipes used were recipe 1 and 3, hereafter called R1 and R3, and their compositions are displayed in table 1 in section 5.4. One sand was tested at a time with both recipes, and the batch size for each test sequence was 0.5 L. The Hägermann cone spread test method was the following, in chronological order

- The amount of sand, water and cement that was to be included was weighed. The mass of the sand was calculated with its SSD density, and with the volume prescribed in the recipe. A density of 3000 kg/m^3 was used for the cement.
- The dry materials were added to the mixing bowl.
- The mixing was done in the following fashion
  - 0-15 seconds: only dry materials, 1st gear,
  - 15-30 seconds: water was added, 1st gear,
  - 30-60 seconds: mixing, 1st gear,
  - 60 seconds: mixer and timer were stopped; the bowl was scraped free of stuck dry material, which took approximately 30 seconds,
  - 60-75 seconds: timer was turned on again and mixing was continued, 1st gear,
  - 75-105 seconds: mixing, 2nd gear,
  - 105-120 seconds: mixing, 1st gear.
- Once the mixing was completed, the Hägermann cone was filled with mortar. The mortar in the cone was not compacted, however, it was ensured that the cone was completely filled and that the surface was even.
- Once the Hägermann cone had been filled and the surface evened, it was immediately lifted and the mortar was allowed to spread.
- When the spread had stabilized, typically after 10-15 seconds, the diameter was measured along two lines; the widest line and the one perpendicular to that.
- Immediately after the spread test was completed, the mortar was transferred back to the mixing bowl and from there into the viscometer cup. Subsequently, the viscosity tests were commenced.

The test sequence was repeated twice for each sand and recipe, and the average of the two was calculated. However, if the difference in attained spreads for one recipe of a certain sand exceeded 6 mm or 4 %, the test was repeated a third time. In such cases, the invalid spread was excluded from the calculation of the average spread. All relevant equipment, including the plate, Hägermann cone, beater, bowl, and viscometer cup and spindle were washed and dried by hand immediately prior to each test sequence, in order to keep conditions constant. The data gained from the viscometer was exported to an excel template, which automatically computed the yield stress and viscosity of the sample.

The recipes used for the mortar tests were determined by testing. A total of five recipes were analysed, whereas R1 was one that had been used previously at Cementa Research for mortar analysis, and therefore it was used as the baseline recipe. The four other recipes had different variations to the baseline recipe, whereas one had the same w/c but a 5 % decreased total volume of aggregate, one had the same w/c but a 5 % increased total volume of aggregate, one had the same total volume of aggregate but a decreased w/c, and one had the same total volume of aggregate but an increased w/c. The five recipes were tested for spread with two sands, namely NS 8 and MS 7, which were chosen based on their largely different flow coefficients. Table 1 in section 5.4 shows the exact constituents of the recipes alongside the results gained from the analysis.

The influence that the reduction of the natural sands, caused by the limitations of the Hobart mixer, had on their spreads was analysed with NS 4 and NS 8. This was done by hand-mixing mortars including either the reduced or the non-reduced versions of the sands, and examining the results gained. These results were then compared to the relative magnitude of the reduction of each sand. The duration of the hand-mixing was 4 minutes, and once the mortars had been produced their spreads were tested with the Hägermann cone methodology disclosed above. Two repetitions of the test procedure were done for both the reduced and non-reduced versions of each sand, and the average spread was calculated. The recipe used for this test was R1. Since the mortar spreads gained with this test were quite close to the ones gained with the Hobart mixer, it was decided that hand-mixing a manufactured sand in the same fashion should be done as well in order to cover the complete spectrum. Thereby, an analysis regarding the influence of mixing method, whether it be with a Hobart mixer or by hand, could be determined. The manufactured sand chosen for this purpose was MS 7.

Different cements often influence the water requirement in varying ways. Since Cementa Research had information regarding the water requirement for several different cement types on hand, it was tested whether this had a perceivable influence on mortar spread. Four cement types with different water requirements were used in mortar made with R1 and MS 7, and the resulting spreads gained were analysed. The test was repeated twice for each cement type, and the average spread attained was calculated.

5.4 Results

The results of the recipe analysis are shown in table 1. R1 and R3 were chosen for this research of the five, since they produced the biggest difference in spread for the two sands. Furthermore, the mortar produced with NS 8 and recipe 2 displayed signs of segregation, and that recipe could thereby be discredited immediately.

Table 1. The volumetric constituents of the five recipes tested, and the spreads that they produced with NS 8 and MS 7.

Recipe	Aggregate	Water	Cement	w/c	Spread, NS 8 (mm)	Spread, MS 7 (mm)	Δ Spread (mm)
1	40 %	38 %	22 %	0,576	212	169	43
2	35 %	41 %	24 %	0,577	230	195	35
3	45 %	35 %	20 %	0,574	187,5	142	45,5
4	40 %	39 %	21 %	0,619	229	190	39
5	40 %	37 %	23 %	0,536	180	147	33

Table 2 shows the results gained from the test where the influence of excluding the > 4 mm size fractions from the natural sands was analysed. The average spreads and relative reductions have been calculated in the table. Based on these results, it is clear that the elimination of the 4-8 mm size fraction reduces the spread induced by the sand. However, the difference in spread does not seem to correlate with the relative magnitude of the reduction, whereas NS 4 has a larger reduction than NS 8, but a smaller difference in spread. This may of course have been caused by the inconsistent nature of hand-mixing. It could, however, also be evidence of a "top-heavy" grading curve for NS 4, whereas the finer fractions fail to overfill the voids between the larger particles, and thus enhancing internal friction – as suggested by Alexander and Mindess (2005). The phenomenon could also be attributed to a worse particle shape and surface texture of the larger size fractions in NS 4. Nevertheless, it is evident that the difference in spread caused by the exclusion of the > 4 mm particles cannot be estimated based on the relative magnitude of the reduction of a sand.

Table 2. The influence on spread caused by the exclusion of > 4 mm particle sizes for natural sands.

Sand	weight, 0-8 (g)	weight, 0-4 (g)	% reduction	Spread, R1, 0-8 (mm)	Spread, R1, 0-4 (mm)	Δ Spread (mm)
NS 4	1498,8	1214	19,0 %	227,5	221	6,5
NS 8	1237,7	1133,4	8,4 %	225	216	9

Table 3 shows the spreads gained from hand mixing mortars with MS 7, as well as with the reduced versions of NS 4 and NS 8. The table also includes the spreads for the same materials gained when the Hobart mixer was used. The difference in spread caused by the two mixing methods is quite small. Therefore, hand-mixing, although highly dependent on the operator, and quite inconsistent and tedious, may be a somewhat viable alternative for producing mortar of two or more sands with the purpose of comparing spreads if no mechanical mixer is available.

Table 3. Variation in spread when hand-mixing instead of using a Hobart-mixer.

Sand	Spread, hand mixing 4 min (mm)	Spread, hobart mixing (mm)	Δ Spread (mm)
NS 4	221	221	0
NS 8	216	212	4
MS 7	176	169	7

The four cements used to test the impact that different cement water requirements had on mortar spread had individual measured water requirements of 141, 143, 146 and 153 grams. These values are in the form of grams of water needed per 500 g of cement, however in practice they are often converted to % by dividing the amount of water by the amount of cement. Thereby, the percental water requirements for the cements were 28.2 %, 28.6 %, 29.2 %, and 30.6 %. The average spreads attained with these cements by using the Hägermann cone method with MS 7 ranged from 154 to 183.5. As the variation in spread was high, it can be determined that cement water requirement has a significant impact on mortar workability. Figure 32 displays the spreads plotted against the water requirements, and based on the geometry produced it can be concluded that there is a linear correlation between the two variables. This correlation is inverted, whereas an increased cement water requirement results in a decreased spread and workability, which is to be expected.

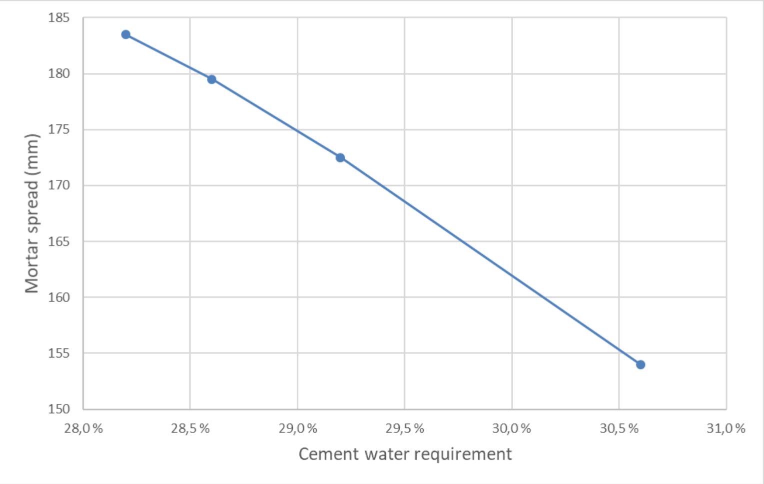

Figure 32. Mortar spread vs cement water requirement.

Figure 33 shows a staple diagram of the spreads attained with the different sands when used in mortar created by R1, in order of magnitude. Figure 34 shows the same data, but with mortar created by R3. Based on both diagrams the natural sands clearly demonstrated a better workability in mortar than the manufactured sands, except for MS 2. This was also evident when the flow coefficients were determined in the aggregate analysis, whereas MS 2 attained a considerably lower flow coefficient than the other manufactured sands. Thus, the conclusion can be drawn that MS 2 had a largely superior particle shape and surface texture than the other manufactured sands. This notion is further strengthened by the fact that MS 2 had a smaller D_{max} than all other sands except for MS 1, as they were the two with size fractions of 0-2 mm, which according to the literature should have had a negative effect on their water requirement.

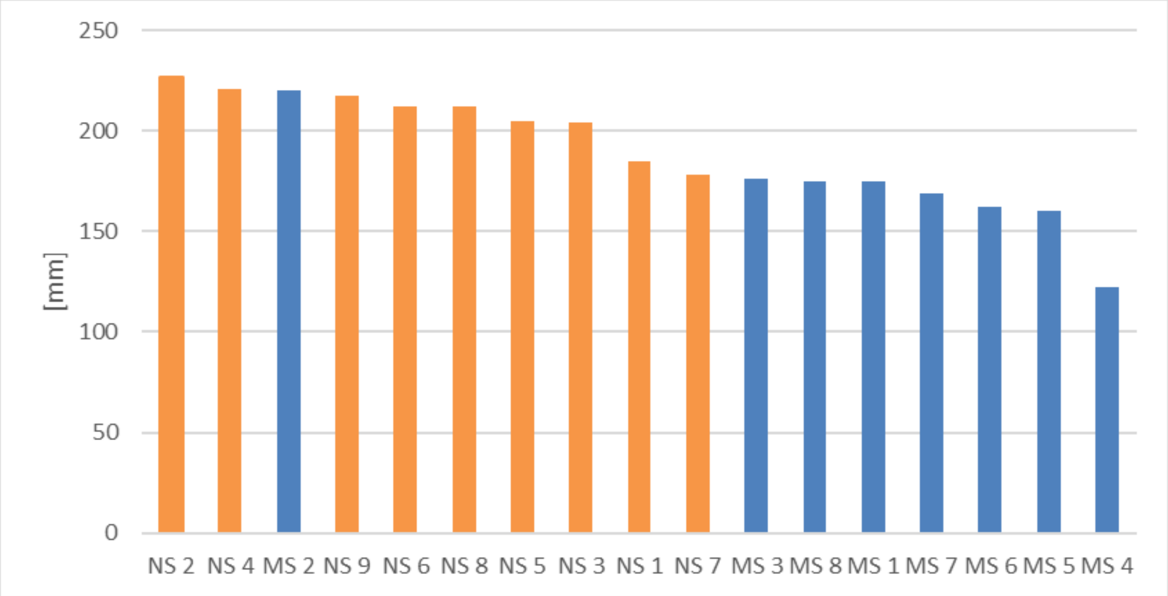

Figure 33. Spreads attained from mortars made by R1 with different sands, by order of magnitude.

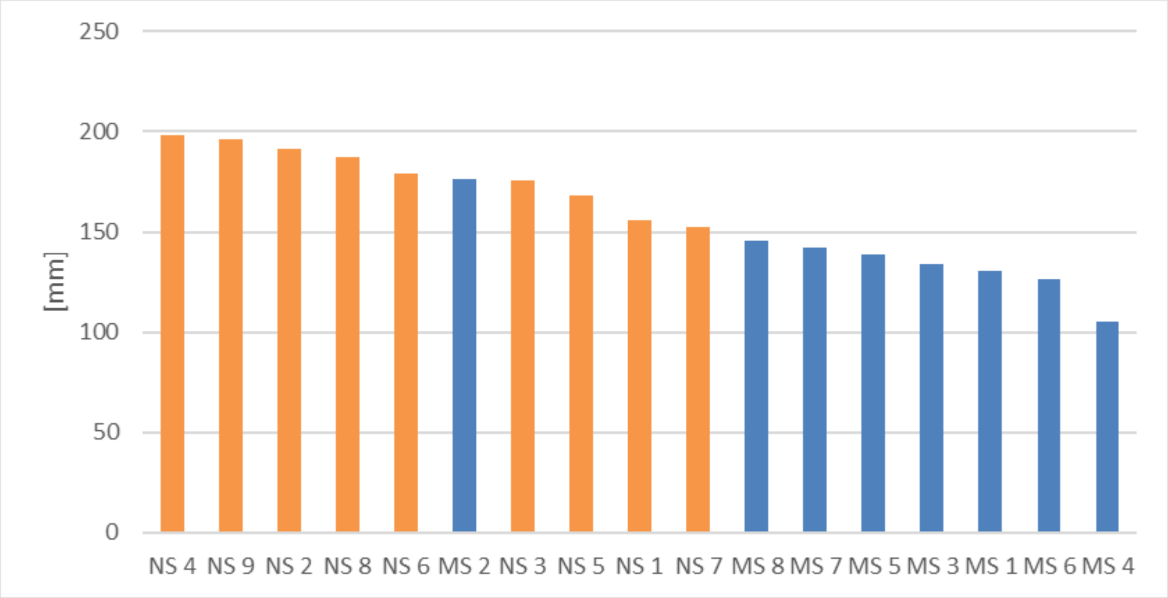

Figure 34. Spreads attained from mortars made by R3 with different sands, by order of magnitude.

MS 4 produced the lowest spread with both R1 and R3, while also having the highest flow coefficient, suggesting that it had the worst particle shape and surface texture of all the sands tested. Furthermore, the R3 spread for MS 4 attained was only 105.5 mm, and the lower diameter of the Hägermann cone is 100 mm. Consequently, that result may not convey an accurate reading of its effect on water requirement, as the mortar almost preserved the shape of the cone. Figure 35 shows the essentially non-existent R3 spread of MS 4.

Figure 35. The R3 spread of MS 4.

Even though the spreads attained by both R1 and R3 clearly differentiate between natural and manufactured sands as per figure 33 and 34, there seems to be some inconsistency regarding the arrangement of the sands between the two sets when their spreads are placed in order of magnitude. Figure 36 displays the spreads gained with the two recipes plotted against each other with a linear regression line, and even though there is an evident linearity it is not as precise as could be expected with identical tests. Specifically, it would seem that the increased volumetric amount of sand in R3 magnified the effect that the properties of the aggregates had on the spread, since all of the green markers clearly below the LRL are those of manufactured sands. This deduction can be further augmented by interpolating the R3 spread of MS 4, which is the red marker in figure 36, to fall on the LRL by utilizing the function of the LRL $y = 0.9282x - 16.952$. By doing so, the R3 MS 4 spread would be 96.3 mm, meaning that the relative difference between the minimum and maximum spread is higher for R3 than for R1, with 106 % and 86 % respectively.

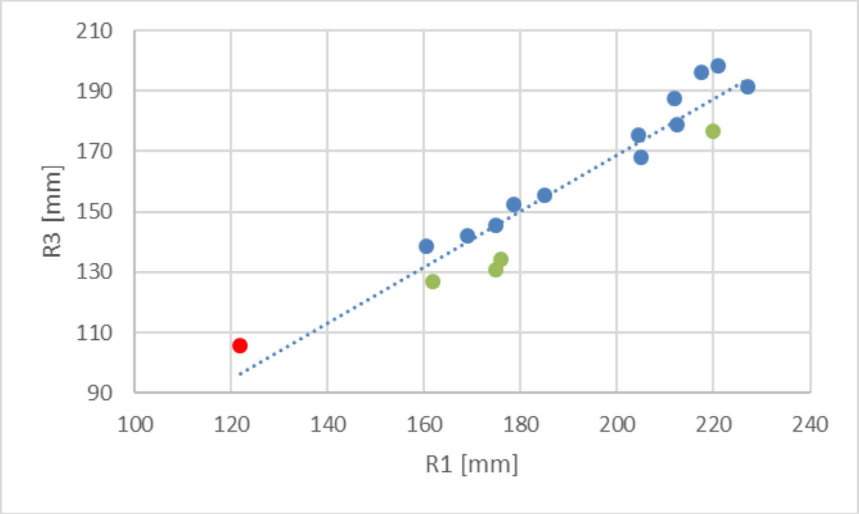

Figure 36. R3 spreads vs R1 spreads.

Figure 37 and 38 display the yield stresses and viscosities gained with R1 as staple diagrams, in order of magnitude. The yield stresses were measured in pascal, while the viscosities were measured in pascal seconds. Both parameters show clear distinctions between natural and manufactured sands, again with MS 2 being an apparent exception. The previously poor performances demonstrated by MS 4 were again evident in the viscometer results. This was particularly apparent in the yield stress results, where the mortar with MS 4 registered almost double the amount of pascal than the second to worst mortar. The yield stress and viscosity results were further utilized to validate the spreads attained with the Hägermann cone, however this is done in chapter 7.

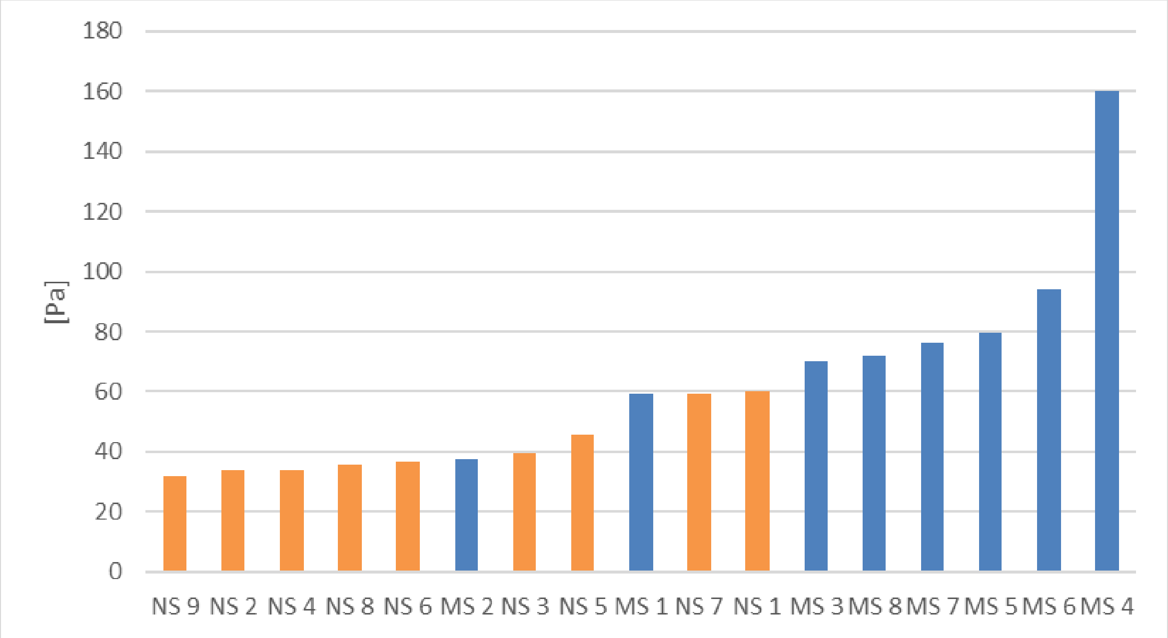

Figure 37. Yield stresses of mortars made by R1 with different sands, by order of magnitude.

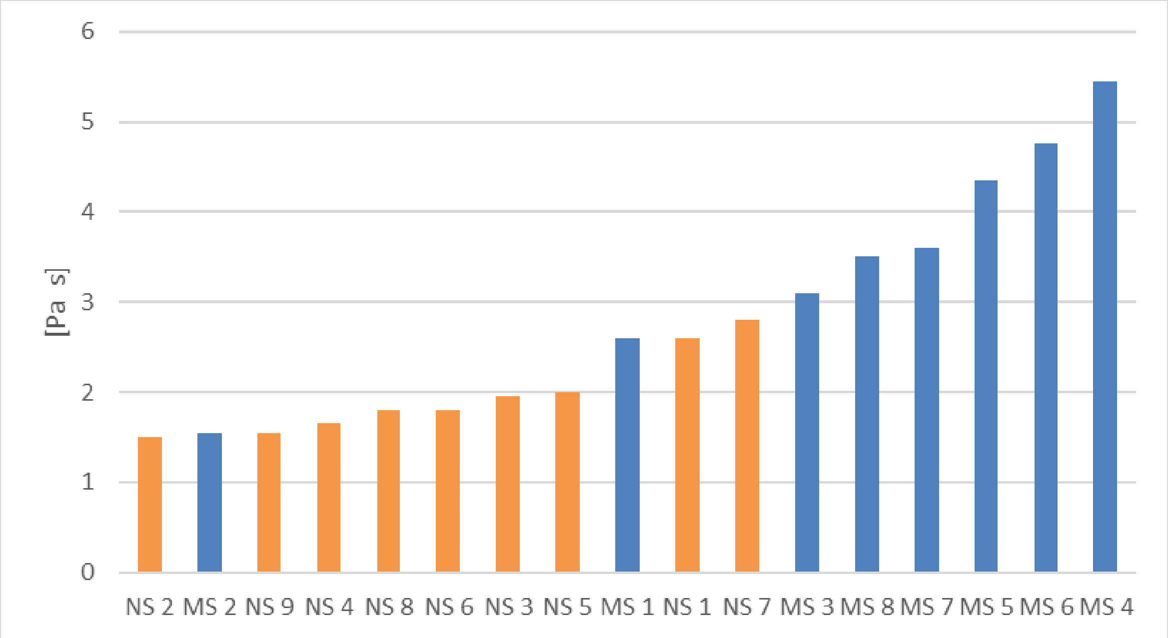

Figure 38. Viscosities of mortars made by R1 with different sands, by order of magnitude.

6 Concrete analysis

6.1 General

The goal of the concrete analysis was to determine the water requirements of the different sands while used as a fine aggregate in a concrete mix. This was done by creating concretes with identical workabilities measured by slump, while the only varying factors in the recipes were the type of sand, and the amount of superplasticizer (SP). The amount of SP required by each sand to reach the target workability was then compared to the results previously gained from the mortar analysis. The linear correlation, or lack thereof, between mortar spread and SP amount was studied, as a clear correlation would verify the Hägermann cone spread test as a valid method for determining the water requirement of sands when used in concrete production. The complete dataset of results gained from the concrete analysis is included in appendix 3.

Aside from determining the amount of SP needed to reach a certain slump, the concretes were also tested for density, air content, yield stress and viscosity in the plastic state, as well as 28-day strength in the hardened state. The sands were tested with two different concrete recipes, whereas one had a w/c of 0.4, and the other a w/c of 0.6.

6.2 Concrete composition

The concretes consisted of water, cement, SP, a coarse aggregate, and the sand that was to be tested. The cement used for the concrete production was the same as the one used for the mortar production, namely Cementa Bascement. The SP used was Sika ViscoCrete RMC-320, which is an SP sold in Sweden that is especially tailored to work with, among others, the cement used in this research. Sika ViscoCrete RMC-320 is suitable for use in all types of concretes, but it works especially well when a lengthened workability retention is desired. A technical data sheet in Swedish of the SP is included in appendix 5.

The coarse aggregate used for the concrete was one that was regularly used at Cementa Research. The moisture state of the coarse aggregate was that of oven dry, and its absorption was 0.3 %. Therefore, the amount of mixing water was adjusted accordingly, and the larger the amount of coarse aggregate, the more mixing water was needed. The size fractions included in the coarse aggregate were 8-16 mm, and its density was 2740 kg/m^3. All of the sands tested had wet moisture states, and their percental moisture contents were determined prior to using them in concrete. Consequently, the amount of mixing water was also adjusted based on the wetness of the sands, whereas a higher moisture percentage led to a reduced amount of mixing water. The densities utilized for the sands where that of the SSD moisture state. Air content was estimated to be 1.5 % for all mixes during the mix proportioning, and the volume occupied by air was reduced from the designed total aggregate volume. The batch size for the concrete mixes was 15 L. Apart from having different w/c ratios, the concrete recipes also differed in the volumetric amount of cement paste and aggregate, and in the coarse to fine aggregate ratio. The mix proportions of the two recipes are shown in table 4.

Table 4. Concrete recipe mix proportions, as percentages of volume.

w/c	Total aggregate	Total cement paste	Coarse aggregate	Sand	Adjusted coarse aggregate	Adjusted sand
0,4	65 %	35 %	45 %	55 %	29 %	36 %
0,6	68 %	32 %	40 %	60 %	27 %	41 %

6.3 Test methods

In order to produce accurate mix proportions, the moisture content of the sands had to be determined. However, such a determination would have been trivial without first ensuring a uniform moisture distribution within the sand that was to be used. Therefore, before each test sequence, the sand was poured into a concrete mixer and water was added during mixing. The wetness of the sand was increased until it reached a perceivable level of 2.5 – 5 %, after which the mixing was continued for a few minutes. Thus, an internal moisture saturation was guaranteed. Subsequently the actual moisture content of the sand was tested by recording its mass in the wet state, drenching it in a flammable fluid, igniting said fluid and letting it burn while stirring. Once all of the flammable fluid had been burned up, the mass of the dry sand was recorded. The difference in mass recorded for the wet and dry sands divided by its wet mass was considered its moisture content.

Once the moisture content of the sand was established, all constituents of the concrete mix were weighed. The superplasticizer dosage was disclosed as percentage of cement mass, and its initial dosage was deduced based on the performance of the sand in the mortar tests. The dry materials, including both aggregate types and the cement, were then added to the mixing bowl and the mixer was started. After 30 seconds of mixing the dry materials, the water was added. Subsequently, once most of the dry material was moist, the SP was added to the mixture. However, the full amount of SP was not added at once, but rather gradually whilst examining the concrete workability visually as to not overdose. After 90 seconds of mixing, the mixer was stopped briefly and the concrete was worked with a scoop in order to determine whether the desired workability had been achieved. The mixer was started again thereafter, and additional SP was added if deemed necessary. The total mixing time was three minutes, excluding the brief stoppage midway through.

The slump test was conducted immediately when the mixing of the concrete had been completed. The target slump was 200 mm, and a deviation of ± 20 mm was accepted. Thereby, the concretes created were of slump class S4 or S5, which require concretes to have slumps of 160-210 mm or ≥ 200 mm respectively, as per EN 206:2014. The deviation is also in accordance with said standard, whereas a target slump of ≥ 100 mm is allowed to deviate a maximum of ± 30 mm. EN 12350-2:2009 defines the slump test for fresh concrete, and the methodology described in the standard was followed in this research.

The air content and the density of the concretes were tested simultaneously. The air content was tested in accordance with the pressure gauge method prescribed in EN 12350-7, and the density in accordance with EN 12350-6. Both methodologies require a full compaction of the concrete, and in order to achieve this a vibrating table was utilized. The volume of the pressure gauge container was known, and the container was weighed prior to adding concrete to it. Thus, the density test could be done prior to the air content test without requiring separate concrete samples.

Yield stress and viscosity was analysed with the same apparatus as was used for the mortar analysis. However, since the gap between the spindle and the inner lining of the viscometer cup was narrow, the D_{max} of the material could not exceed 4 mm. Therefore, the concrete had to be reduced to reach this requirement. This was done by placing a sample of the concrete on a 4 mm sieve with a collection pan underneath. The pan and sieve were then placed on a vibrating table, and by turning the table on and gently working the concrete on top of the sieve by hand, the paste was separated from the larger aggregates. Subsequently, the material retained in the collection pan was moved to the viscometer cup and the viscometer test was commenced.

Once the plastic properties of the concretes had been tested, two specimens of each concrete recipe of every sand were made for 28-day compressive strength tests. The moulds used for the tests were 100x100x100 mm cubes, that conformed to the specifications provided in EN 12390-1. The specimens were prepared and cured in accordance with EN 12390-2, as per which the moulds were filled in two layers, and compacted with a vibrating table. When the specimens had been cured for 28 days, their compressive strengths were tested with the methodology provided in EN 12390-3. The machine used for the compressive strength tests filled the requirements set in EN 12390-4.

6.4 Results

During the concrete testing, notes were transcribed regarding the perceivable characteristics of the concretes. The general consensus was that the concretes made with the manufactured sands were more incohesive and sticky than those made with natural sands. Particularly MS 1 and MS 2 were noted as extremely sticky. This phenomenon is probably a consequence of gap grading, whereas neither the coarse aggregate nor the manufactured sands included particle sizes of 4-8 mm. This gap grading was further enhanced for the concretes made with MS 1 and MS 2, since their missing fractions were expanded to 2-8 mm. Consequently, there was a severe lack of immediately smaller particles to effectively fill the gaps between the coarser aggregates and for the coarse aggregates to “roll” on. This essentially resulted in concretes with two independent sets of aggregates that lacked intermediate interaction, as the coarse aggregates were mostly floating around in the paste made up of sand, water and cement. Hence the perceived stickiness and visible incohesiveness. Figure 39 displays the gap grading for the concrete made with MS 1, evident as a clear discrepancy in the slope of the combined curve.

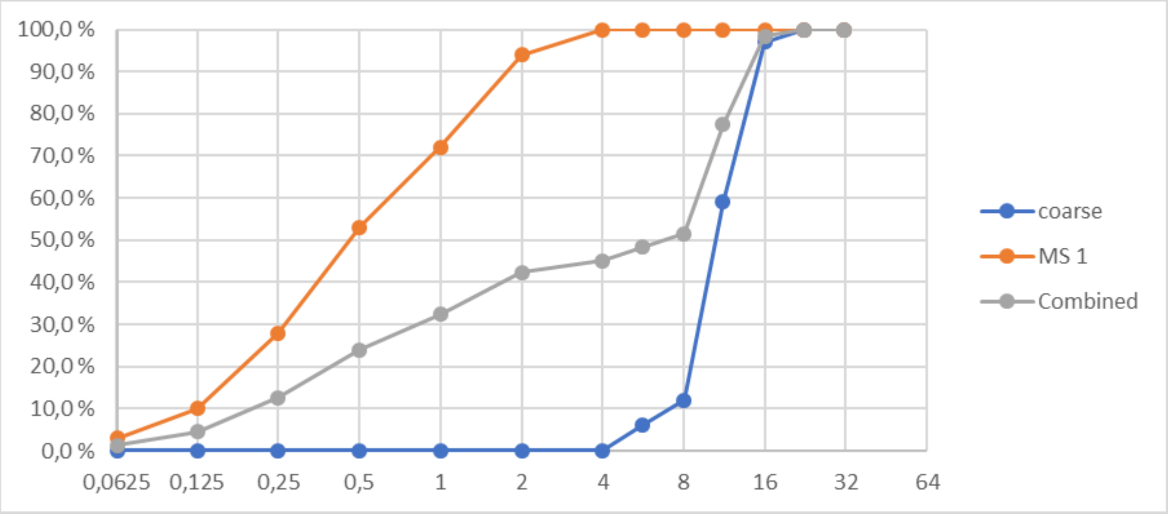

Figure 39. Individual grading curves for MS 1 and the coarse aggregate, as well as the combined curve of the two.

Figure 40 and 41 show the required amounts of superplasticizer in order to reach the target slump with concretes of both w/c ratios. The results are displayed as staple diagrams and by order of magnitude. Based on the figures it is apparent that the concretes made with natural sands in general required less SP than those made with manufactured sands. Additionally, it should be noted that MS 4 again displayed the worst properties of all the sands concerning its effect on water requirement. It was the only sand that, in both concrete recipes, required more SP than the maximum allowed dosage of 2 % set by the SP producer. Not accounting for the MS 4 value, the differences in required SP amount for the 0.4 w/c recipe seem to be considerably smaller than for the 0.6 w/c recipe. Moreover, the order in which the different sands placed concerning the magnitude of their induced SP requirement appears to be different with the two recipes. Figure 42 displays the required SP amounts of the two recipes plotted against each other with a linear regression line. Based on the plotting it would appear that a linear correlation exists, however the two markers that are painted red seem to be anomalies to this linearity.

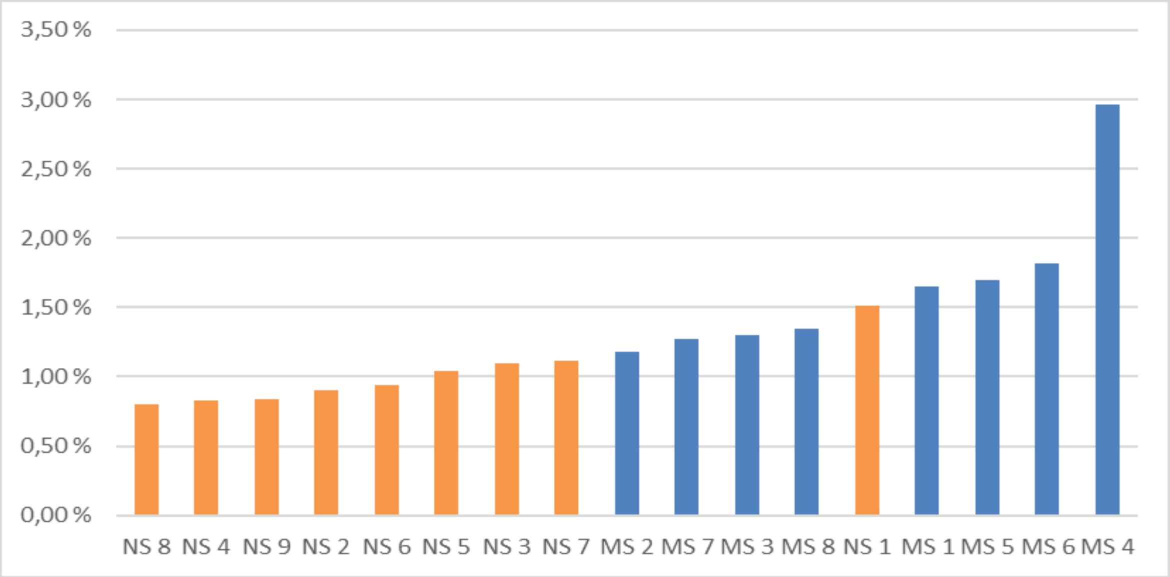

Figure 40. Superplasticizer required to meet the target slump for the concrete recipe with 0.4 w/c, by order of magnitude.

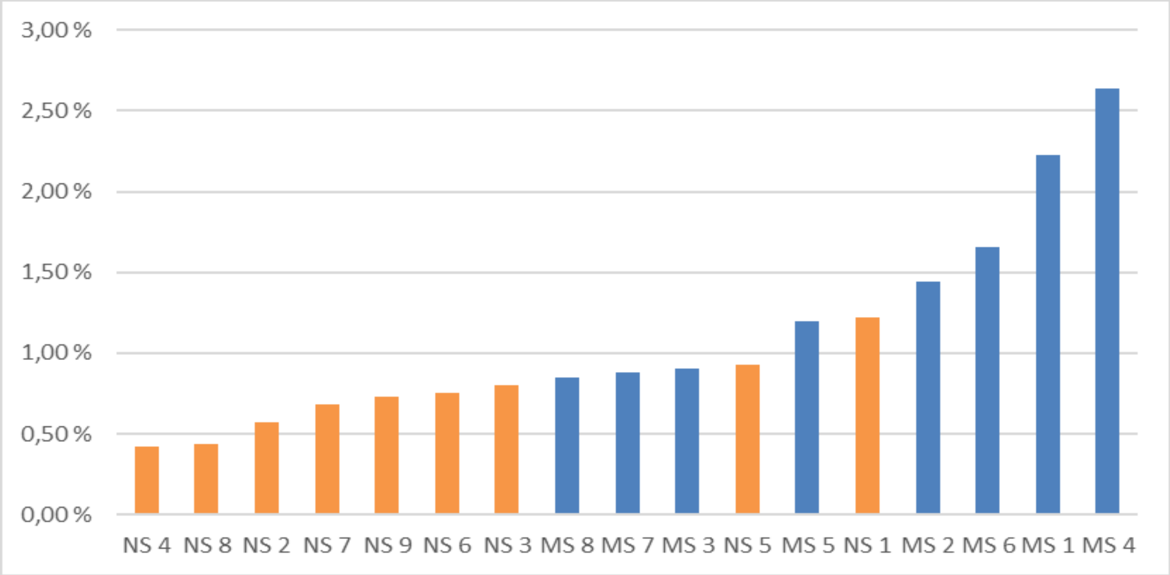

Figure 41. Superplasticizer required to meet the target slump for the concrete recipe with 0.6 w/c, by order of magnitude.

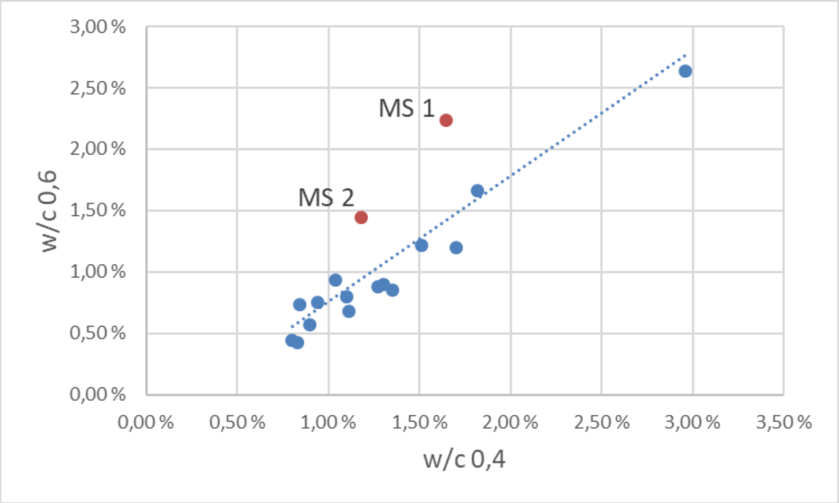

Figure 42. SP requirements of 0.6 w/c concrete vs SP requirements of 0.4 w/c concrete.

The two red markers in figure 42 are those of MS 1 and MS 2, and their abnormalities to the linearity are caused by their concretes requiring more SP for the 0.6 w/c recipe than for the 0.4 w/c recipe. This is in itself counterintuitive, and the reason for it is probably a combination of the gap grading, as well as there being differences between the two recipes other than the w/c. As is shown in table 4, the 0.6 w/c recipe has an increased volumetric amount of sand and a decreased volumetric amount of coarse aggregate. Therefore, the negative effect that the gap grading of the MS aggregates has on workability is enhanced, since there is even less interaction between the coarse aggregates as they are fewer and more dispersed. This enhanced negative effect counteracts the positive effect that the increased w/c has on workability, and apparently completely overrides it for the concretes made with manufactured sands of size fractions 0-2 mm. As for the other manufactured sands, their concretes required on average 35 % more SP with the 0.4 w/c recipe than with the 0.6 w/c recipe, while the same number for the natural sands is 46 %. Therefore, the phenomenon is noticeable for MS 3-8, however not nearly as impactful as for MS 1 and 2.

Figure 43 and 44 show the measured air contents of the different concretes, as diagrams and by order of magnitude. As the D_{max} was identical for all of the concretes, a difference in air content could not be attributed to that property. Actually, there does not seem to be a clear linear correlation between the air content of the concretes and any one particular parameter of the sands measured in this research. The figures suggest that the concretes made with natural sands in general had higher air contents than those made with manufactured sands, the two outliers being MS 1 and MS 2. This can be attributed to the fact that the sands MS 3-8 had higher contents of fines and flow coefficients than the natural sands. Furthermore, the high air contents of the concretes with MS 1 and 2 could also be a demonstration of the incohesiveness caused by the gap grading of their aggregates. Therefore, the air content appears to depend on a combination of several factors, such as content of fines, particle size distribution, and possibly mineralogy.

The densities of the concretes were tested simultaneously as the air contents, and they ranged between 2.38 – 2.56 Mg/m^3 for the 0.4 w/c concrete, and 2.31 – 2.53 Mg/m^3 for the 0.6 w/c concrete. Both the air content of the concretes and the densities of the sands presented in figure 19 had an impact on the densities of the concrete. Figure 45 displays this correlation with a linear regression line, whereas the combined effect the two is attained by multiplying the sand density with (1 – void content).

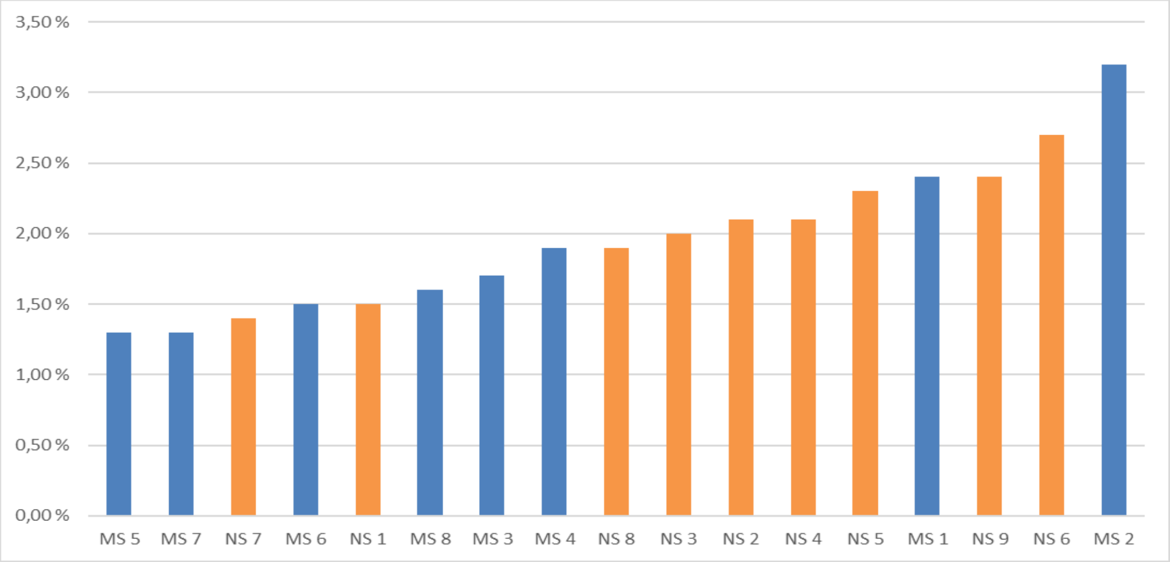

Figure 43. Air contents of the 0.4 w/c concretes, by order of magnitude.

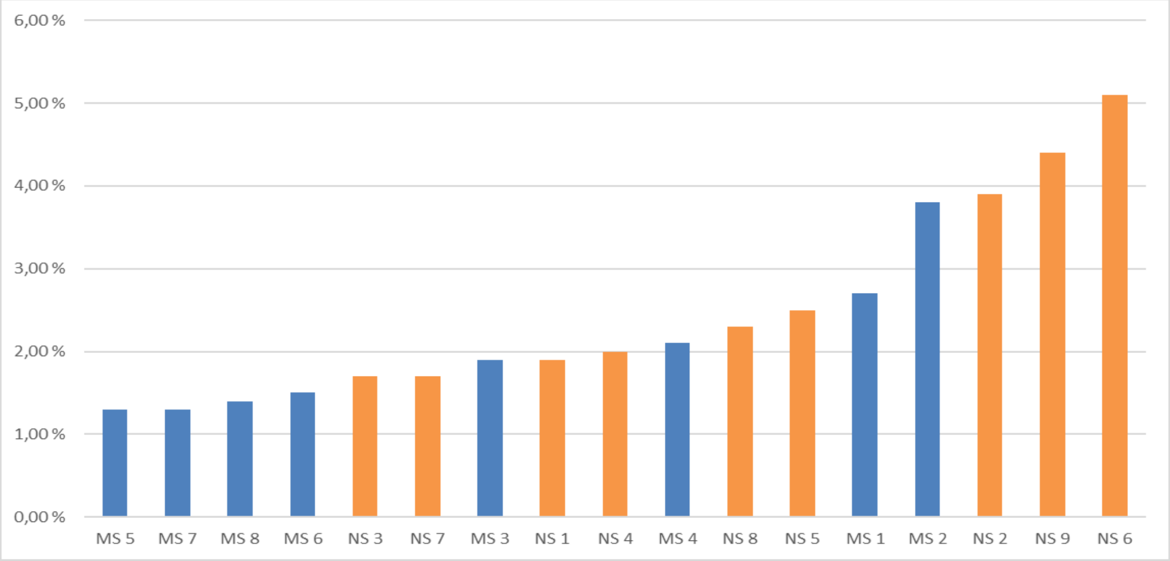

Figure 44. Air contents of the 0.6 w/c concretes, by order of magnitude.

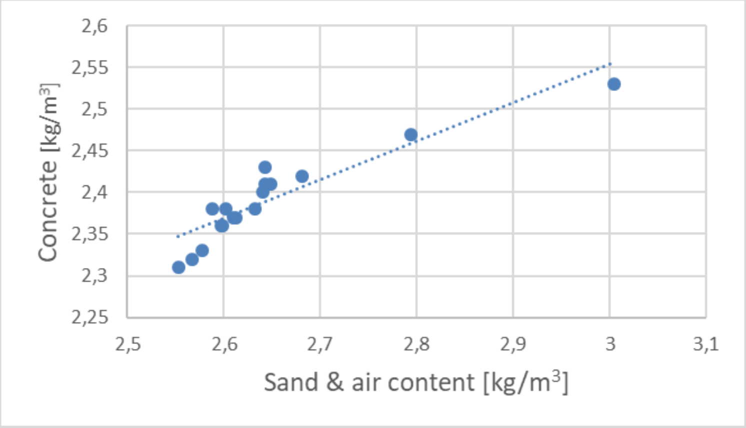

Figure 45. Concrete density vs sand density corrected by concrete air content.

According to Roussel and Coussot (2005) the slump of a cementitious material should correlate with the viscosity and yield stress of that same material. Since the concretes produced for this research all had roughly the same slumps, they should have similar values for viscosities and yield stresses as well. However, this was not the case even for the concretes with similar particle size distributions. The reason for this was surely that the reduction method was imprecise, and thus the reduced concretes ended up with different compositions. Figures 46 and 47 display the fluctuations of the measured viscosities and yield stresses for the 0.4 w/c concretes as staple diagrams. The viscometer could not test the reduced version of the concrete with MS 1, since it was too thick.

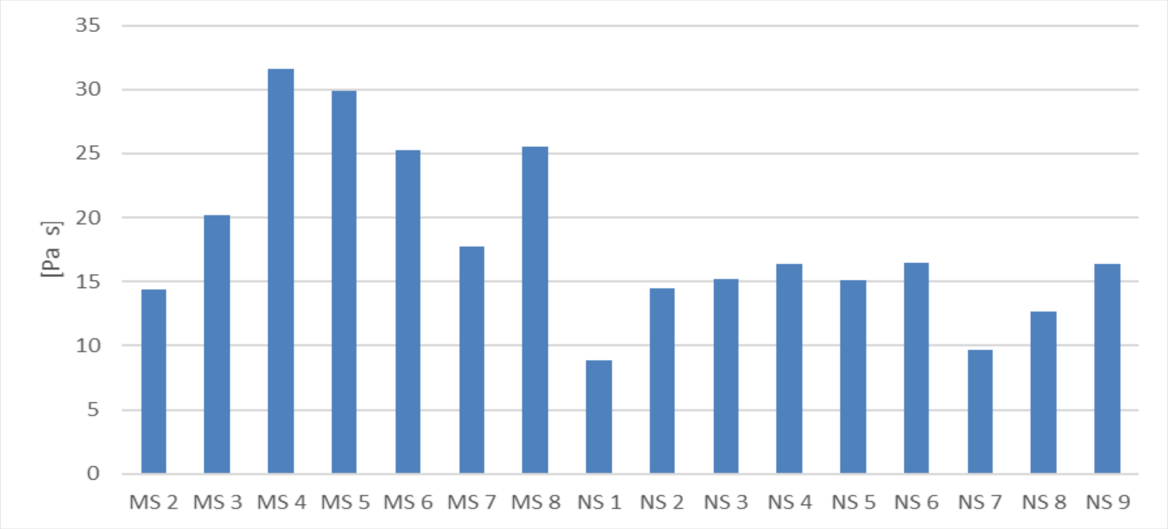

Figure 46. The fluctuation in measured viscosities of the 0.4 w/c reduced concretes.

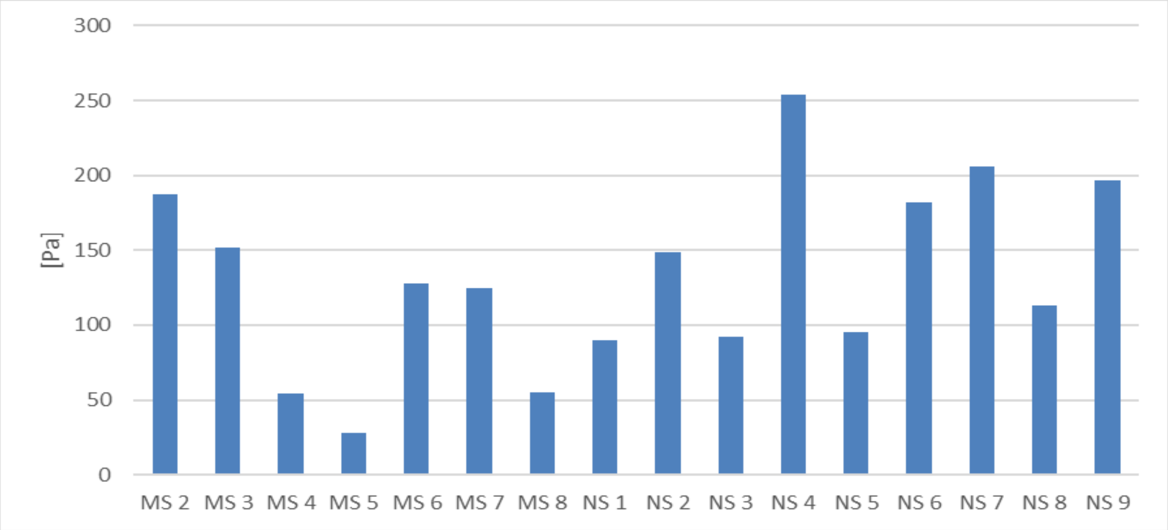

Figure 47. The fluctuation in measured yield stresses of the 0.4 w/c reduced concretes.

The cured concretes were tested for 28-day compressive strength, and the results gained from the 0.4 and 0.6 w/c concretes are displayed in figures 48 and 49. However, the results of the concretes with MS 4 and NS 1 are not included, since they were misplaced in the laboratory during the curing process. The variance in attained strengths was moderate, as the difference between the highest and the lowest for the 0.6 w/c concretes was 8.8 MPa or 21 %, and for the 0.4 w/c concretes 16.5 MPa or 24 %. Moreover, the concretes produced with manufactured sand appear to have attained a slightly higher compressive strength than those produced with natural sands, specifically 3.3 % on average for the 0.4 w/c concretes, and 5.8 % on average for the 0.6 w/c concretes. Furthermore, it should be noted that MS 4, which performed poorly in previous tests, did so again in the compressive strength test.

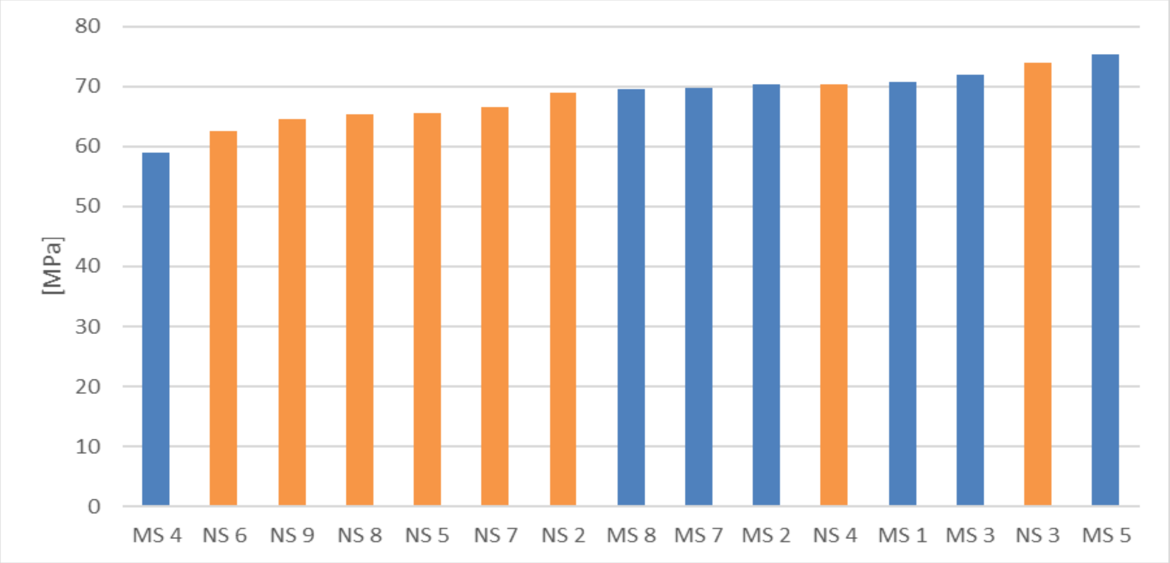

Figure 48. 28-d compressive strength of the 0.4 w/c concretes, by order of magnitude.

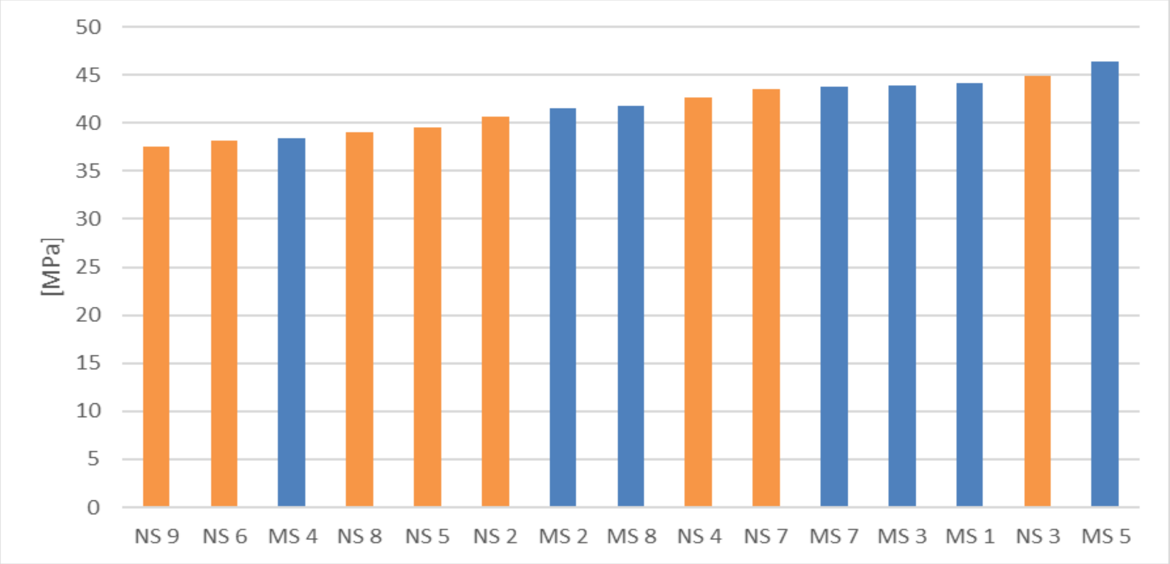

Figure 49. 28-d compressive strength of the 0.6 w/c concretes, by order of magnitude.

7 Validation

7.1 General

In order to conclude whether the proposed Hägermann cone spread test method can be used to determine the effect a sand has on water requirement when used in concrete, the results gained must be analysed. Specifically, the integrity of the mortar spread test must be confirmed, and the results gained from it must be compared to those gained from the concrete tests in order to ensure the existence of a correlation. Furthermore, the accuracy of said correlation should be determined.

For this research, all possible dependencies were assumed to be linear, and linear regression analysis was therefore deemed an appropriate method to study correlations. This is a means to evaluate the relationship between an explanatory variable, denoted x, and a dependant variable, denoted y. A predictive model is then created from the observed values of x and y, which can be used to determine the y-value for a new x-value that is attained. For linear relationships, such a model is a linear regression line. There are several different methods to attain the LRL of a set of observations, but the most common one, and the one used in this research by utilizing Excel, is the least squares approach. The produced LRL is given by $y(x) = ax + b$, whereas a is the slope of the line, and b is the y-intercept of the line.

Alongside the LRL, Excel also produces a coefficient of determination, denoted R^2. R^2 is an effect size statistic that explains how well the observations fit the produced LRL. R^2 varies between 0-1, and the closer to 1 the better the fit. An R^2 of 1 is only achieved if the LRL passes through all of the observations, whereas an R^2 of 0.8 would mean that 80 % of the variation of y is regulated by the linearity of x and y. The R^2 value is calculated by the following formula

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} \tag{9}$$

where R^2 is the coefficient of determination
$SS_{residual}$ is the residual sum of squares
SS_{total} is the total sum of squares.

The residual sum of squares and the total sum of squares are calculated by the following formulas

$$SS_{residual} = \sum_i (y_i - f_i)^2 \tag{10}$$

where y_i are the recorded y-values
f_i are the predicted y-values for the recorded x-values based on the LRL.

$$SS_{total} = \sum_i \left(y_i - y_{avg}\right)^2 \tag{11}$$

where y_i are the recorded y-values
y_{avg} is the average of the recorded y-values.

A normal distribution of observations around the LRL may be assumed for all correlations, in order enable the estimation of their accuracies. This accuracy can either be displayed as a confidence interval or as a prediction interval. A confidence interval portrays an interval in which the true LRL for the population is assumed to lie at a set confidence level. A prediction interval, however, is an interval that depicts how close to the LRL the true y-value for a known x-value will be at a set confidence level, based previous observations. Thereby, the prediction interval was chosen for this research as the slope of the LRL is of little interest for this purpose. Excel cannot produce the prediction interval for a linear regression automatically, so this had to be done manually. The formula used for the prediction interval was the following

$$Y_{int} = Y_{pred} \pm t_{1-\frac{\alpha}{2},n-2} * SE_{Y_{pred}} \tag{12}$$

where Y_{int} is the upper and lower bound of the prediction interval
Y_{pred} is the predicted y-value
α is 1 – the desired prediction level (10 % if the prediction level is 90 %)
$t_{1-\frac{\alpha}{2},n-2}$ is the t-value for α, based on the sample size
$SE_{Y_{pred}}$ is the standard error of prediction.

Regarding the variables in formula 12, Y_{pred} can be determined from the LRL, $t_{1-\frac{\alpha}{2},n-2}$ can be attained from a t-value table, or calculated in Excel by using the command *tinv*, and $SE_{Y_{pred}}$ is calculated by the following formula

$$SE_{Y_{pred}} = s\sqrt{1 + \frac{1}{n} + \frac{(x - x_{avg})^2}{s_x^2(n-1)}} \tag{13}$$

where $SE_{Y_{pred}}$ is the standard error of prediction
s is the standard error
n is the sample size
x is the x-value that the $SE_{Y_{pred}}$ is calculated for
x_{avg} is the average of all recorded x-values
s_x^2 is the standard deviation of all recorded x-values.

The standard error s of a linear regression is one of the outputs gained when using the data analysis tool for regression in Excel. By doing the prediction interval calculation for each recorded x-value, a graph can be plotted where the width of the interval is displayed. The actual magnitude of the interval is defined by the $t_{1-\frac{\alpha}{2},n-2} * SE_{Y_{pred}}$ part of equation 12.

In the produced graphs the blue dotted line is the LRL, the blue markers are the observations from the tests, and the orange lines portray the width of the prediction interval. The widths of the prediction intervals fluctuate depending on where in the graph they are located, since they were calculated individually for each recorded x-value. However, this fluctuation is negligible so the average width is presented in the caption of each graph. Furthermore, the functions of the LRLs are located inside the graphs, as are their respective R^2 values. The decision was made to exclude MS 1 and MS 2 from the validations, because of their induced weird behaviour when used in concrete (as is explained in section 6.4). This exclusion is further justified in section 7.2 when the mortar tests are validated.

7.2 Mortar

As was explained in section 5.1, the spread of a cementitious material should correlate with its yield stress and viscosity. Thereby, the integrity of the Hägermann cone spread tests could be confirmed by establishing such a correlation. Furthermore, by comparing the accuracies of the linearities of sample sets including MS 1 and MS 2 with sample sets excluding MS 1 and MS 2, the exclusion of these sands from further analysis could be validated. Figures 50, 51, 52, and 53 show the mortar spreads attained with R1 and R3 plotted against their viscosities and yield stresses, with linear regression analysis and prediction intervals included. Figure 54 displays the mortar spread of R3 plotted against its viscosity when MS 1 and MS 3 are included, with linear regression analysis and prediction intervals. The prediction levels used for the prediction intervals was 90 %, as strong correlations were assumed.

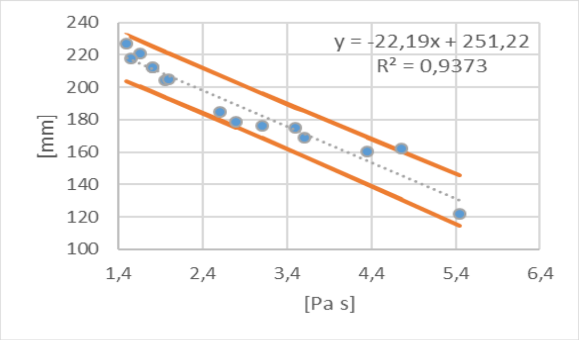

Figure 50. Spread vs viscosity for R1, avg. interval: 28, α = 0.1.

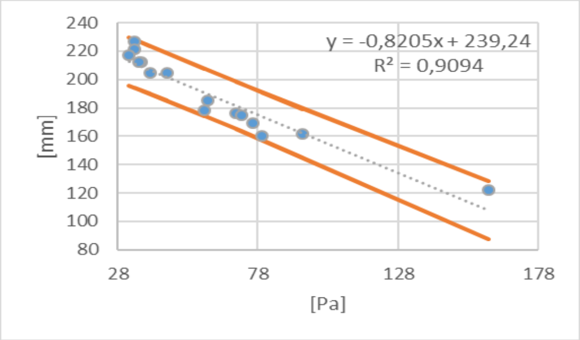

Figure 51. Spread vs yield stress for R1, avg. interval: 34, α = 0.1.

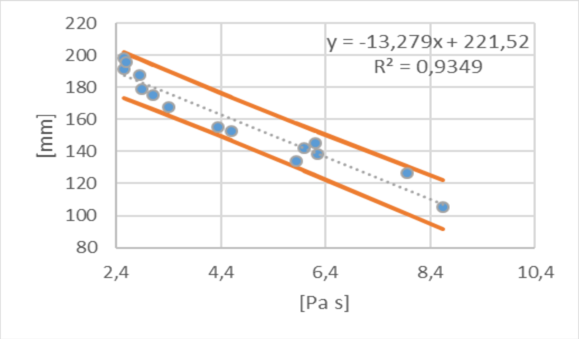

Figure 52. Spread vs viscosity for R3, avg. interval: 28, α = 0.1.

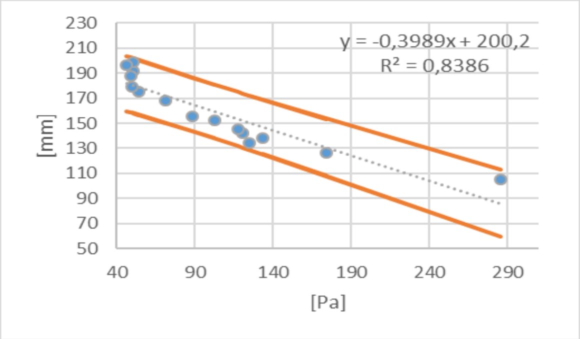

Figure 53. Spread vs yield stress for R3, avg. interval: 44, α = 0.1.

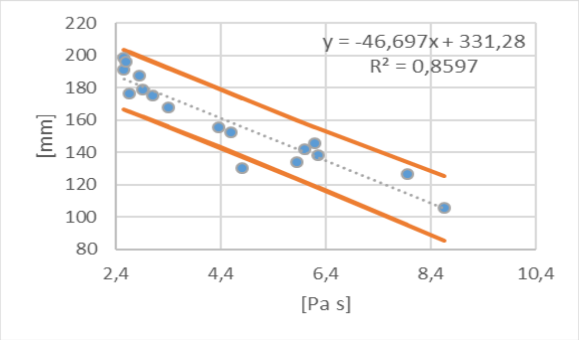

Figure 54. Spread vs viscosity for R3, MS 1 and MS 3 included, avg. interval: 37, α = 0.1.

Based on figures 50-53, there is a clear correlation between the measured viscosities and yield stresses, and the attained spreads of the mortars. This is evident because the R^2 values all exceed 0.83, which indicates a strong correlation, and their respective 90 % prediction intervals are quite narrow. Therefore, it is concluded that the Hägermann cone spread test methodology used in this research is suitable for measuring the effect a sand has on mortar rheology. Moreover, if figure 52 and 54 are compared, it is confirmed that the inclusion of MS 1 and MS 2 in the analysed samples generates inaccurate results. This is because even though the addition of MS 1 and MS 2 increases the sample size, which naturally reduces the t-value in equation 12 and thus should improve accuracy, the R^2 value decreases and the average interval expands. Therefore, it is deduced that the exclusion of MS 1 and MS 2 from further analysis is justified.

7.3 Mortar and concrete

In order to validate the Hägermann cone spread test used in this research as a suitable method for determining the water requirement of a sand when used in concrete, a correlation between the two must be confirmed. Figures 55, 56, 57, and 58 display the superplasticizer requirements of both concrete recipes plotted against the mortar spreads of both mortar recipes. Linear regression analysis and prediction intervals are included in the figures. A prediction level of 80 % was used for the prediction intervals.

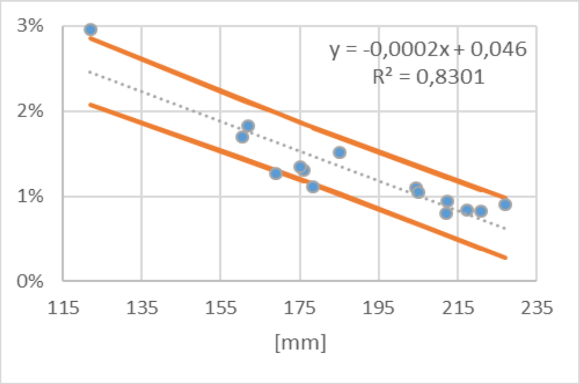

Figure 55. 0.4 w/c concrete vs R1 mortar, avg. interval: 0.68 %, α = 0.2.

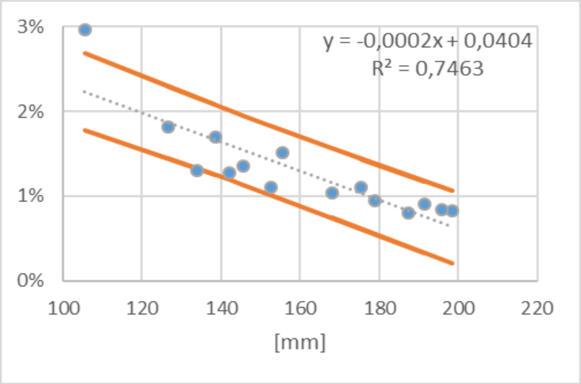

Figure 56. 0.4 w/c concrete vs R3 mortar, avg. interval 0.84 %, α = 0.2.

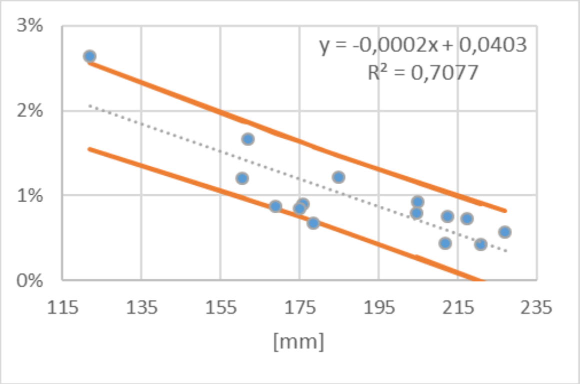

Figure 57. 0.6 w/c concrete vs R1 mortar, avg. interval: 0.90 %, α = 0.2.

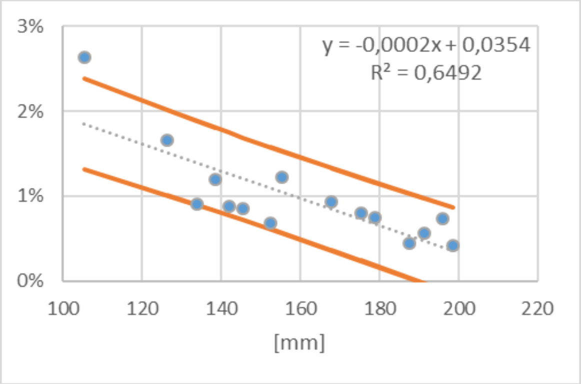

Figure 58. 0.6 w/c concrete vs R3 mortar, avg. interval: 0.99 %, α = 0.2.

There is no general rule as to how large the R^2 value should be in order to confirm a satisfactory dependency between two variables. However, since all of the combinations reached a value of over 0.6, and based on the general orientation of the observations in figures 55-

58, it is determined that a correlation exists between the measured mortar spreads and concrete SP requirements. The combination of 0.4 w/c concrete and R1 mortar achieved the highest correlation accuracy. That combination portrayed an 80 % chance of determining the right amount of SP ± 0.34 % for a desired concrete slump, based on mortar spread for a certain sand.

Another mortar-concrete analysis was also done, in which the correlations for the manufactured sands were examined separately from the natural sands. Thereby the effect that the gap grading had on the manufactured sands was isolated from the continuous grading of the natural sands. By doing so, a total of 8 combinations could be analysed, and the average prediction intervals were reduced across all of them when compared to their respective combined intervals. This is significant since by reducing the sample size to either type of sand, the t-value in equation 12 increases which affects the interval in a negative way. The greatest accuracies were attained with the w/c 0.4 – R1 combination for manufactured sands, and the w/c 0.4 – R3 combination for natural sands. These combinations are displayed in figure 59 and 60, with prediction levels of 80 %. All of the combinations can be found in appendix 6.

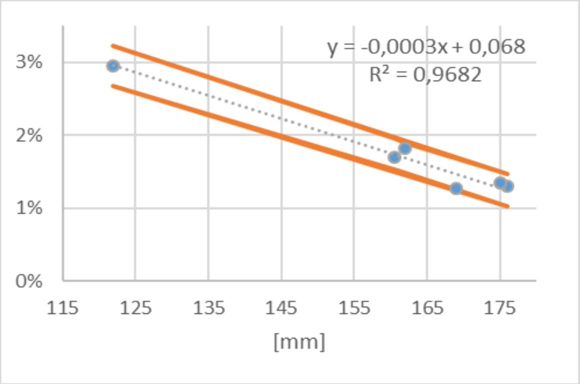

Figure 59. 0.4 w/c concrete vs R1 mortar, manufactured sands, avg. interval: 0.45 %, α = 0.2.

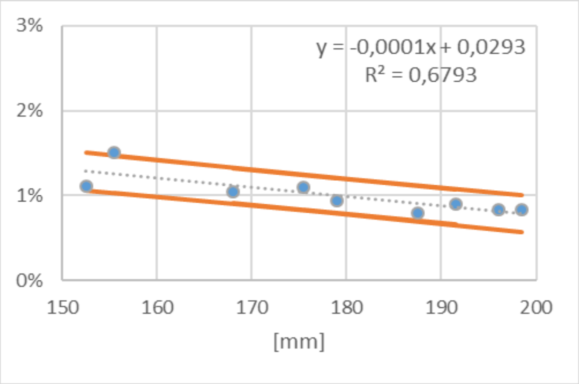

Figure 60. 0.4 w/c concrete vs R3 mortar, natural sands, avg. interval: 0.42 %%, α = 0.2.

Since both size fractions show better results with the 0.4 w/c concrete, it is evident that the correlation accuracies were greater for that concrete than for the 0.6 w/c concrete. This is assumingly due to the fact that the 0.6 w/c concrete had a better basis for workability to begin with, and thus the properties of the sands had less impact its final workability. However, since the manufactured sands proved a better correlation with the R1 mortar, while the natural sands preferred the R3 mortar, it is not possible to determine which mortar recipe is better. Instead, it seems as if the range of spread is of more importance for the correlation accuracy. This conclusion can be drawn since the manufactured sands, that generally had a narrower spread, favoured the mortar recipe that produced a wider spread; while the natural sands, that generally had a wider spread, preferred the recipe that produced a narrower spread. By examining the exact spreads that the two types of sands produced with the respective recipes, it can be deduced that the best results were achieved when the mortar spreads were between 120-200 mm.

Another observation regarding figure 59 and 60 is that the R^2 values are very different, even though the average prediction intervals are similar. This is caused by the difference in slope between the two, whereas the slope of the natural sands is much more horizontal than that of the manufactured sands. The horizontality of the slope is a consequence of the low variation between the measured SP amounts for the natural aggregates, even though they generated largely different spreads in the mortar test. This disparity in effect can be attributed to the reduction of the natural sands in the mortar tests. It has been established that the finer fractions of an aggregate have a larger impact on water requirement, and thus, the differences in the effect that the natural sands had on water requirement were inflated in the mortar spreads. The slope of the LRL in figure 60 could probably be increased by having a different machinery for the mortar mixing that could include the full 0-8 mm spectrum. Thereby, the mortar spreads would better reflect the actual water requirements of the sands.

8 Conclusions

The goal of concrete mix design is to determine the types and amounts needed of different constituents, in order to ensure that the produced concrete meets the requirements set on its plastic and hardened states. Furthermore, this should be done while minimizing costs, which is mainly achieved by reducing the amount of cement and increasing the amount of aggregate. There are several different models and methods available for this purpose. For instance, the w/c is generally accepted to be the crucial factor with regards to concrete strength, while mixing water amount and the D_{max} of the aggregate are considered to be most influential on workability. While these assumptions may be true, solely relying on such variables for mix design is unreliable. Especially for workability, it is widely understood that the properties of the fine aggregate are highly influential. This influence is further enhanced when the amount of aggregate is maximized in order to keep expenses low.

Particle size and surface texture, and the specific surface that depends on these, are regarded as the most significant characteristics of a sand when it comes to the effect it has on the workability of a concrete. Manufactured sands are often deemed worse than natural sands concerning these properties, however this is not always true. Modern crushing techniques can produce particles that are of advantageous shapes and have smooth surfaces. Furthermore, the origin of a natural sand impacts its particle characteristics. For instance, natural sands from pit sources often have significantly worse properties than those from fluvial sources.

Based on the results gained from the aggregate, mortar, and concrete analysis regarding the particle shapes, surface textures, and influence on mortar and concrete water requirements, the manufactured sands generally performed worse than the natural sands. However, there was always some exceptions to this, and the differences between the two types of sand were usually low. Additionally, in some instances the differences between sands of the same type were significant. Therefore, it can be concluded that the conventional notion of adding 10 kg/m^3 of mixing water when using manufactured aggregate, and reducing the same amount when using natural aggregate, is inadequate.

In order to determine the actual water requirement of a sand when used in concrete, the Hägermann cone spread test method for mortar was developed. Tests regarding variance caused by mixing method, cement water requirement, reduction of particle size, and recipe composition were conducted. The difference in attained mortar spreads were similar with hand mixing and usage of a Hobart mixer, however repetitions showed that the Hobart mixing method was more exact. The water requirement of the cement correlated linearly with the mortar spread, however the differences were significant. Therefore, it is imperative that the same cement is used when producing mortars with different sands for the spread test. The particle sizes of the natural sands had to be reduced from 0-8 mm to 0-4 mm, due to the limitations of the Hobart mixer. This reduction caused a narrower spread, however it was not uniform for the different sands, nor did it rely on the magnitude of the reduction. The optimal mortar recipes of the five tested were R1: 40 % sand, 38 % water, 22 % cement; and R3: 45 % sand, 35 % water, 20 % cement, in volumetric ratios. The mortar spreads attained from the Hägermann cone test method were validated by confirming correlations between them and the measured viscosities and yield stresses.

The Hägermann cone spread test method was validated as suitable for determining the water requirement a sand has in concrete. This was concluded since there were clear linear correlations between the mortar spreads induced by the different sands, and their superplasticizer requirements when used in concrete. The method appears to have a higher accuracy for concretes with lower w/c ratios, as the SP is more influential on workability in such mixes. The greatest correlation when manufactured and natural sands were analysed together was found between mortars of R1 and concretes of 0.4 w/c, whereas there was an 80 % chance of interpolating the correct SP amount ± 0.34 %.

By examining natural and manufactured sands separately, the accuracy of the Hägermann cone spread test was increased. By separating the two, the prediction interval shrunk from 0.68 % to 0.45 % for manufactured sands, and to 0.42% for natural sands. This shrinkage is significant, since it occurred even though the sample sizes were reduced, which in itself has an opposite effect on the prediction interval. This phenomenon was presumably a consequence of gap grading in the concrete, whereas the concretes produced with manufactured sands were missing the 4-8 mm size fractions. This presumption was further verified by the two manufactured sands that had size fractions of 0-2 mm, as they displayed very controversial results in the concrete tests. Furthermore, a higher accuracy could probably have been achieved for the natural sands, if a mortar mixing machinery that could include the full spectrum of their particles sizes was used. It was also determined that the method provided the highest accuracy when the mortar spreads were kept in the range of 120-200 mm.

In conclusion, the main result gained from the study is that the proposed methodology is suitable for determining the water requirements of both natural and manufactured sands in concrete. Furthermore, the accuracy of the method can be improved by comparing sands of the same size fractions, by creating mortar with spreads of 120-200 mm, and by using mortar mixing machinery that can include the complete size spectrum of the sands. As for the differences between the types of sands, the manufactured ones generally performed slightly worse than the natural ones with regards to water requirement, however there were exceptions to this.

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Appendix 1. Results from aggregate analysis

					Flow coefficient			Void content		
Sand	Size fraction [mm]	Fineness Modulus	Density$_{SSD}$ [kg/m^3]	Absoprtion	1 – 2 [s]	0.25 - 0.5 [s]	0.125 - 0.25 [s]	1 – 2	0.25 – 0.5	0.125 - 0.25
MS 1	0 - 2	1,97	1972	0,05 %	6,20	3,63	3,81	52,1%	52,5%	55,1%
MS 2	0 - 2	1,71	1715	0,27 %	4,28	3,05	3,10	43,8%	46,0%	47,7%
MS 3	0 - 4	2,33	2331	0,13 %	5,78	3,70	4,33	48,5%	53,5%	56,2%
MS 4	0 - 4	2,48	2483	0,16 %	5,47	4,01	4,63	50,5%	55,7%	59,9%
MS 5	0 - 4	2,45	2454	0,09 %	5,82	3,87	4,15	51,3%	55,5%	56,8%
MS 6	0 - 4	2,67	2671	0,11 %	6,03	3,95	4,12	51,6%	55,6%	57,6%
MS 7	0 - 4	2,63	2627	0,19 %	5,56	3,83	4,39	50,0%	54,4%	56,8%
MS 8	0 - 4	3,02	3019	0,22 %	6,09	4,00	4,26	51,9%	56,3%	58,2%
NS 1	0 - 8	2,95	2955	0,39 %	5,04	3,62	3,78	47,8%	52,1%	54,5%
NS 2	0 - 8	2,56	2559	0,26 %	5,04	3,27	3,10	47,3%	48,6%	47,7%
NS 3	0 - 8	2,50	2504	0,17 %	5,13	3,37	3,22	47,6%	49,8%	49,4%
NS 4	0 - 8	2,58	2580	0,16 %	5,14	3,26	3,12	47,4%	48,5%	48,0%
NS 5	0 - 8	2,78	2779	0,56 %	5,14	3,48	3,39	48,2%	50,7%	51,3%
NS 6	0 - 8	2,42	2421	0,36 %	4,74	3,37	3,15	45,6%	49,5%	49,4%
NS 7	0 - 8	3,23	3227	0,25 %	4,83	3,59	3,86	46,7%	52,4%	55,2%
NS 8	0 - 8	2,51	2514	0,36 %	4,62	3,27	3,25	45,0%	48,4%	49,9%
NS 9	0 - 8	2,05	2051	0,13 %	4,80	3,25	3,06	46,1%	48,3%	47,6%

Grading, passing

11,2 mm	8 mm	5,6 mm	4 mm	2 mm	1 mm	0,5 mm	0,25 mm	0,125 mm	0,063 mm
100 %	100 %	100 %	100 %	94 %	72 %	53 %	28 %	10 %	3 %
100 %	100 %	100 %	100 %	100 %	91 %	65 %	20 %	3 %	1 %
100 %	100 %	100 %	96 %	80 %	61 %	43 %	28 %	18 %	11 %
100 %	100 %	100 %	95 %	75 %	56 %	40 %	27 %	18 %	11 %
100 %	100 %	99 %	95 %	72 %	54 %	42 %	31 %	21 %	13 %
100 %	100 %	100 %	91 %	67 %	49 %	37 %	28 %	21 %	14 %
100 %	100 %	100 %	96 %	70 %	51 %	36 %	25 %	17 %	11 %
100 %	100 %	100 %	93 %	62 %	41 %	28 %	18 %	12 %	8 %
100 %	99 %	92 %	87 %	78 %	53 %	29 %	13 %	5 %	2 %
100 %	98 %	92 %	87 %	77 %	66 %	47 %	23 %	8 %	2 %
100 %	97 %	91 %	86 %	77 %	68 %	52 %	25 %	8 %	3 %
100 %	96 %	91 %	86 %	76 %	64 %	49 %	27 %	9 %	3 %
100 %	98 %	94 %	90 %	78 %	60 %	35 %	15 %	5 %	1 %
100 %	98 %	95 %	91 %	84 %	72 %	49 %	16 %	3 %	1 %
100 %	97 %	88 %	79 %	64 %	48 %	31 %	17 %	9 %	5 %
100 %	100 %	97 %	93 %	83 %	64 %	40 %	19 %	7 %	3 %
100 %	100 %	96 %	91 %	84 %	77 %	62 %	30 %	8 %	1 %

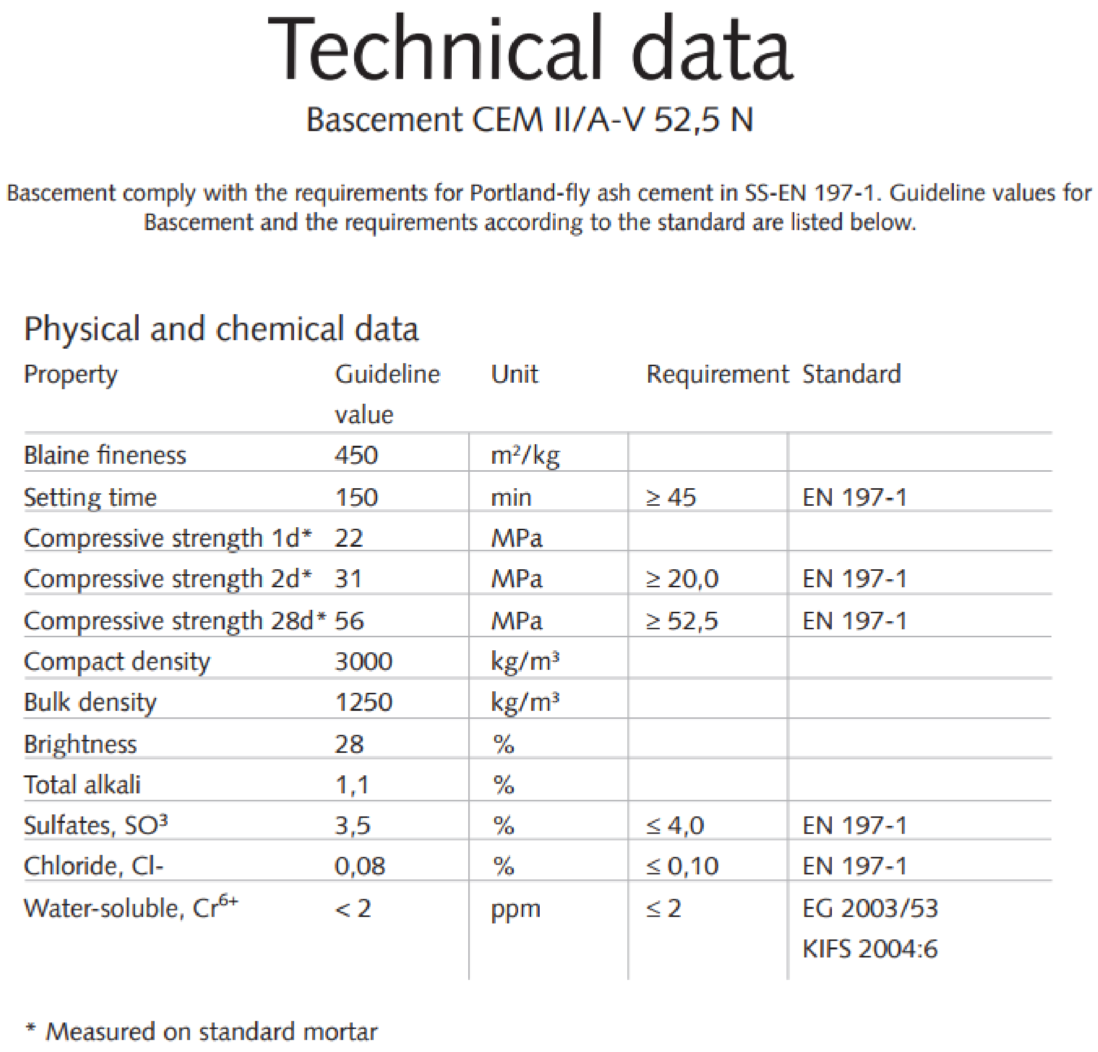
Appendix 2. Results from mortar analysis

	Recipe 1			Recipe 3		
Sand	**Spread [mm]**	**Yield stress [Pa]**	**Viscosity [Pa s]**	**Spread [mm]**	**Yield stress [Pa]**	**Viscosity [Pa s]**
MS 1	175	59	2,6	130,5	95	4,8
MS 2	220	37,5	1,55	176,5	53,5	2,65
MS 3	176	70	3,1	134	125	5,85
MS 4	122	160	5,45	105,5	285,5	8,65
MS 5	160,5	79,5	4,35	138,5	133,5	6,25
MS 6	162	94	4,75	126,5	174,5	7,95
MS 7	169	76	3,6	142	121	6
MS 8	175	72	3,5	145,5	117,5	6,2
NS 1	185	60	2,6	155,5	88,5	4,35
NS 2	227	34	1,5	191,5	51	2,55
NS 3	204,5	39,5	1,95	175,5	54,5	3,1
NS 4	221	34	1,65	198,5	51	2,55
NS 5	205	45,5	2	168	71,5	3,4
NS 6	212,5	36,5	1,8	179	50	2,9
NS 7	178,5	59	2,8	152,5	102,5	4,6
NS 8	212	35,5	1,8	187,5	49,5	2,85
NS 9	217,5	32	1,55	196	46,5	2,6

Appendix 3. Results from concrete analysis

Concrete	0,6 w/c							0,4 w/c						
	Superplasticizer	Density [kg/m3]	Air content	Slump [mm]	Yield stress [Pa]	Viscosity [Pa s]	28-d strength [MPa]	Superplasticizer	Density [kg/m3]	Air content	Slump [mm]	Yield stress [Pa]	Viscosity [Pa s]	28-d strength [MPa]
MS 1	2,23 %	2370	2,70 %	190	-	-	44,1	1,65 %	2420	2,40 %	190	-	-	70,7
MS 2	1,44 %	2310	3,80 %	190	82	7,6	41,5	1,18 %	2380	3,20 %	200	187	14,4	70,3
MS 3	0,90 %	2370	1,90 %	190	154	34,8	43,9	1,30 %	2410	1,70 %	220	152	20,2	71,9
MS 4	2,64 %	2380	2,10 %	200	133	24,3	38,4	2,96 %	2420	1,90 %	220	54	31,6	58,9
MS 5	1,20 %	2470	1,30 %	210	103	30,1	46,4	1,70 %	2490	1,30 %	220	28	29,9	75,4
MS 6	1,66 %	2530	1,50 %	200	104	9,9	-	1,82 %	2560	1,50 %	190	128	25,3	-
MS 7	0,88 %	2420	1,30 %	200	146	34,1	43,8	1,27 %	2440	1,30 %	210	125	17,7	69,7
MS 8	0,85 %	2410	1,40 %	200	88	12,9	41,8	1,35 %	2440	1,60 %	210	55	25,5	69,5
NS 1	1,22 %	2380	1,90 %	190	98	22,2	-	1,51 %	2410	1,50 %	210	90	8,9	-
NS 2	0,57 %	2360	3,90 %	190	156	8,6	40,7	0,90 %	2440	2,10 %	210	149	14,5	68,9
NS 3	0,80 %	2410	1,70 %	200	87	9,6	44,9	1,10 %	2480	2,00 %	220	92	15,2	74
NS 4	0,42 %	2430	2,00 %	180	106	5,9	42,6	0,83 %	2460	2,10 %	200	254	16,4	70,4
NS 5	0,93 %	2360	2,50 %	200	112	6,5	39,5	1,04 %	2410	2,30 %	210	95	15,1	65,6
NS 6	0,75 %	2320	5,10 %	180	120	7,8	38,2	0,94 %	2420	2,70 %	210	182	16,5	62,6
NS 7	0,68 %	2400	1,70 %	200	188	14,2	43,5	1,11 %	2420	1,40 %	200	206	9,7	66,6
NS 8	0,44 %	2380	2,30 %	200	127	8,5	39,1	0,80 %	2430	1,90 %	210	113	12,7	65,4
NS 9	0,73 %	2330	4,40 %	200	99	9,6	37,6	0,84 %	2430	2,40 %	190	197	16,4	64,5

Appendix 4. Technical datasheet for Cementa's Bascement



Technical data

Bascement CEM II/A-V 52,5 N

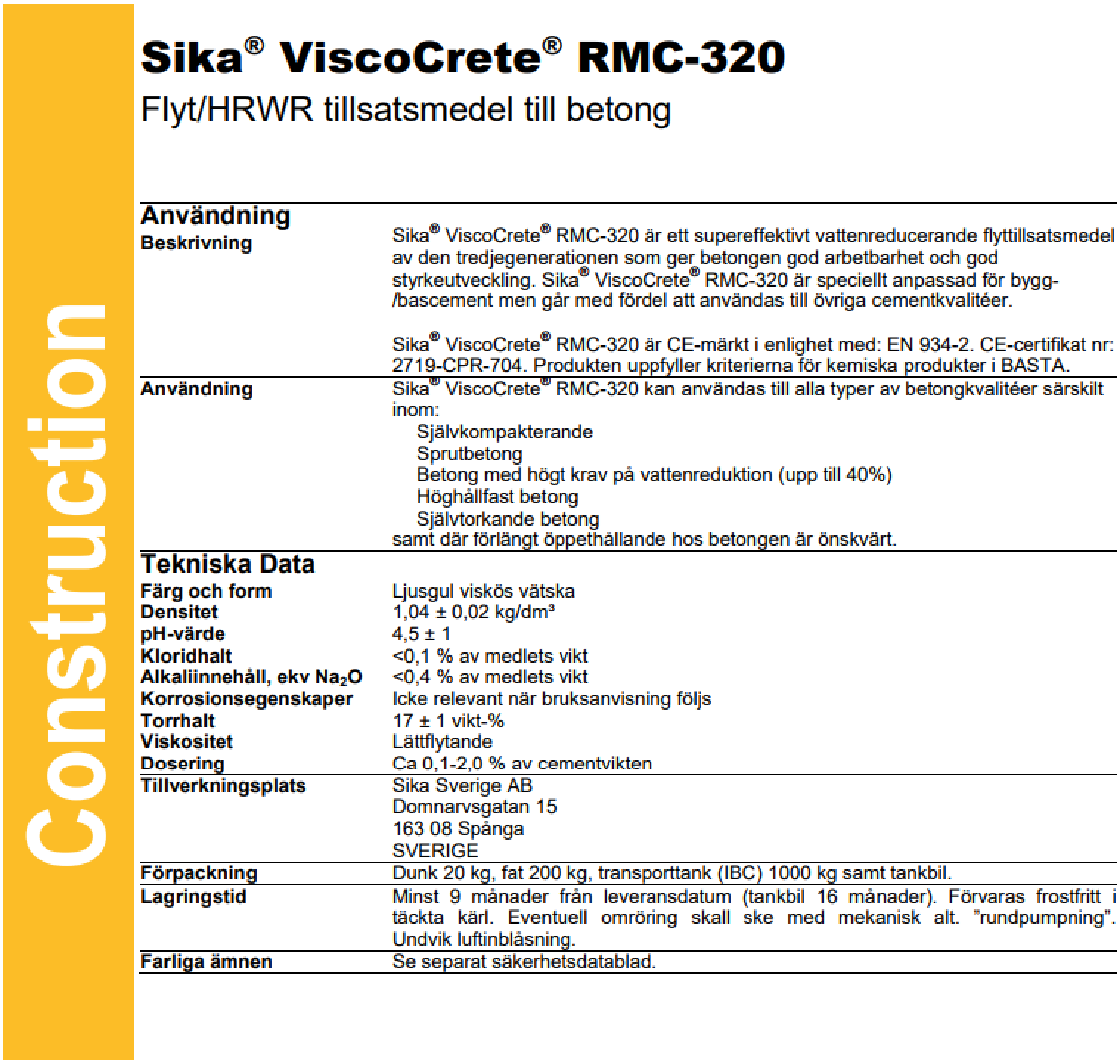
Bascement comply with the requirements for Portland-fly ash cement in SS-EN 197-1. Guideline values for Bascement and the requirements according to the standard are listed below.

Physical and chemical data

Property	Guideline value	Unit	Requirement	Standard
Blaine fineness	450	m^2/kg		
Setting time	150	min	≥ 45	EN 197-1
Compressive strength 1d*	22	MPa		
Compressive strength 2d*	31	MPa	≥ 20,0	EN 197-1
Compressive strength 28d*	56	MPa	≥ 52,5	EN 197-1
Compact density	3000	kg/m^3		
Bulk density	1250	kg/m^3		
Brightness	28	%		
Total alkali	1,1	%		
Sulfates, SO^3	3,5	%	≤ 4,0	EN 197-1
Chloride, Cl-	0,08	%	≤ 0,10	EN 197-1
Water-soluble, Cr^{6+}	< 2	ppm	≤ 2	EG 2003/53 KIFS 2004:6

* Measured on standard mortar

Appendix 5. Technical datasheet for Sika ViscoCrete RMC-320



Construction

Sika® ViscoCrete® RMC-320

Flyt/HRWR tillsatsmedel till betong

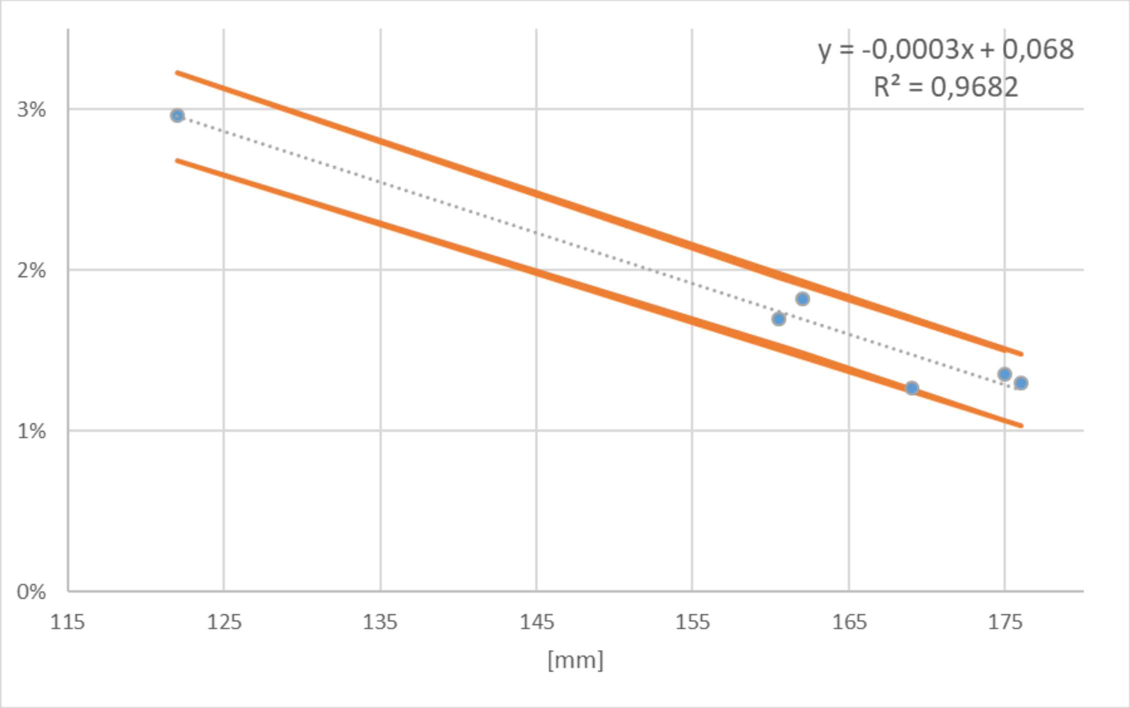
Användning

Beskrivning	Sika® ViscoCrete® RMC-320 är ett supereffektivt vattenreducerande flyttillsatsmedel av den tredjegenerationen som ger betongen god arbetbarhet och god styrkeutveckling. Sika® ViscoCrete® RMC-320 är speciellt anpassad för bygg-/bascement men går med fördel att användas till övriga cementkvalitéer. Sika® ViscoCrete® RMC-320 är CE-märkt i enlighet med: EN 934-2. CE-certifikat nr: 2719-CPR-704. Produkten uppfyller kriterierna för kemiska produkter i BASTA.
Användning	Sika® ViscoCrete® RMC-320 kan användas till alla typer av betongkvalitéer särskilt inom: Självkompakterande Sprutbetong Betong med högt krav på vattenreduktion (upp till 40%) Höghållfast betong Självtorkande betong samt där förlängt öppethållande hos betongen är önskvärt.

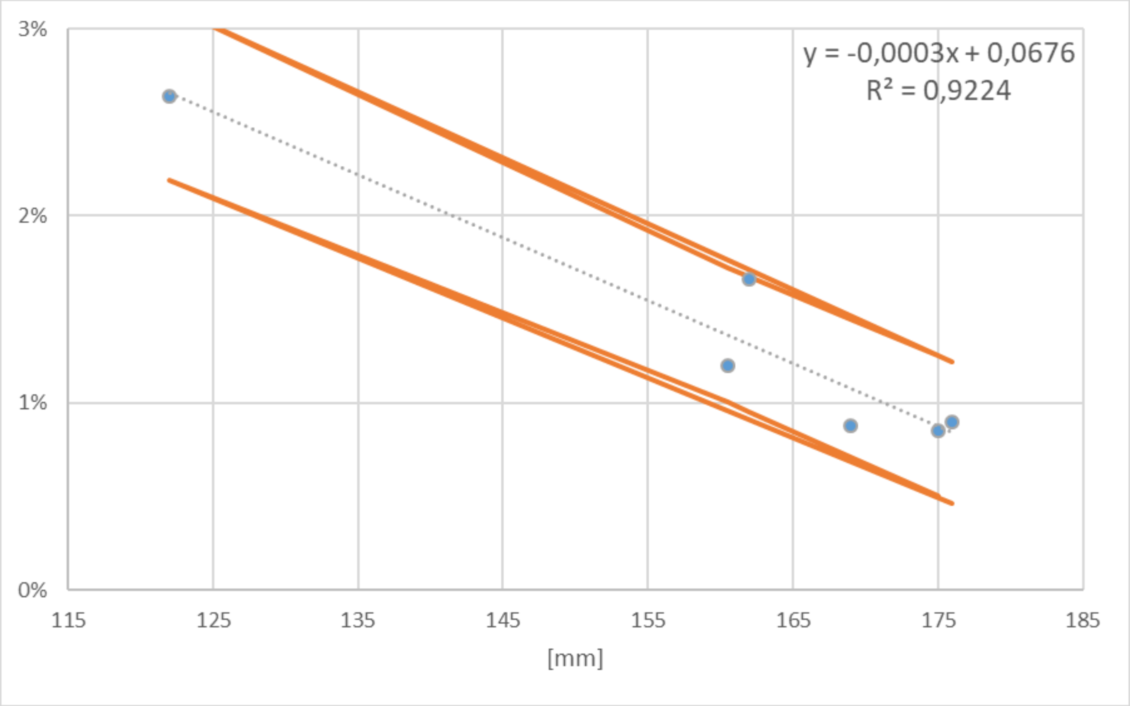
Tekniska Data

Färg och form	Ljusgul viskös vätska
Densitet	1,04 ± 0,02 kg/dm^3
pH-värde	4,5 ± 1
Kloridhalt	<0,1 % av medlets vikt
Alkaliinnehåll, ekv Na_2O	<0,4 % av medlets vikt
Korrosionsegenskaper	Icke relevant när bruksanvisning följs
Torrhalt	17 ± 1 vikt-%
Viskositet	Lättflytande
Dosering	Ca 0,1-2,0 % av cementvikten
Tillverkningsplats	Sika Sverige AB Domnarvsgatan 15 163 08 Spånga SVERIGE
Förpackning	Dunk 20 kg, fat 200 kg, transporttank (IBC) 1000 kg samt tankbil.
Lagringstid	Minst 9 månader från leveransdatum (tankbil 16 månader). Förvaras frostfritt i täckta kärl. Eventuell omröring skall ske med mekanisk alt. ”rundpumpning”. Undvik luftinblåsning.
Farliga ämnen	Se separat säkerhetsdatablad.

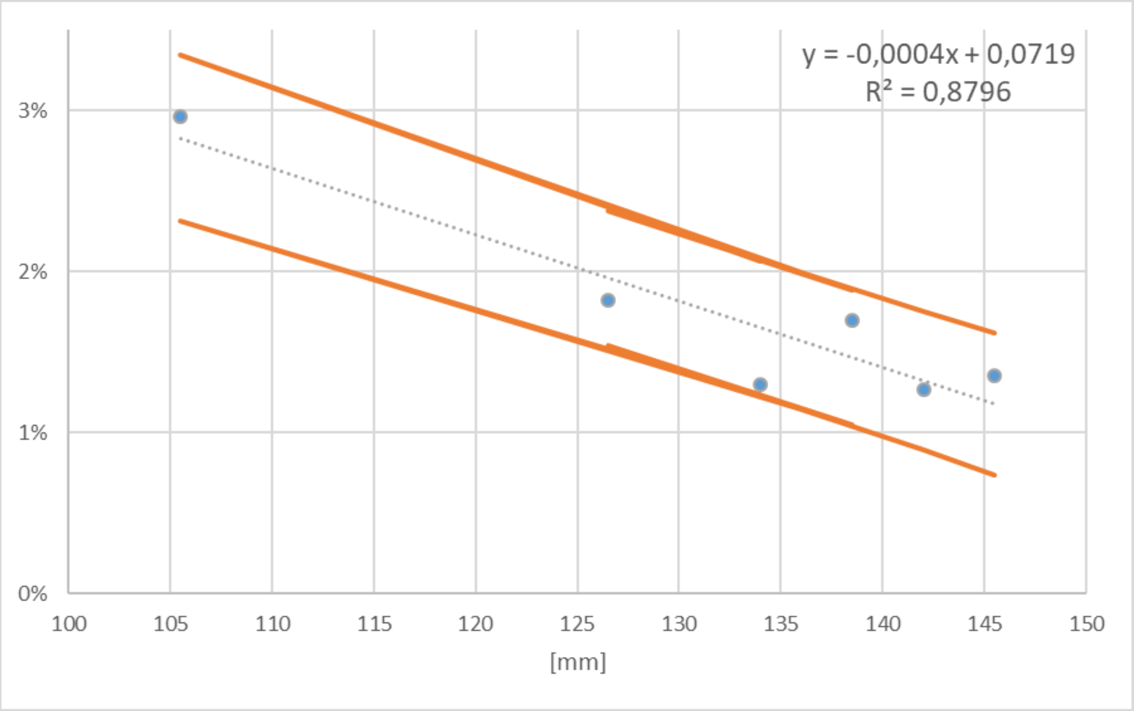
Appendix 6. Correlations between concrete superplasticizer requirement and mortar spread. Manufactured and natural sands separately



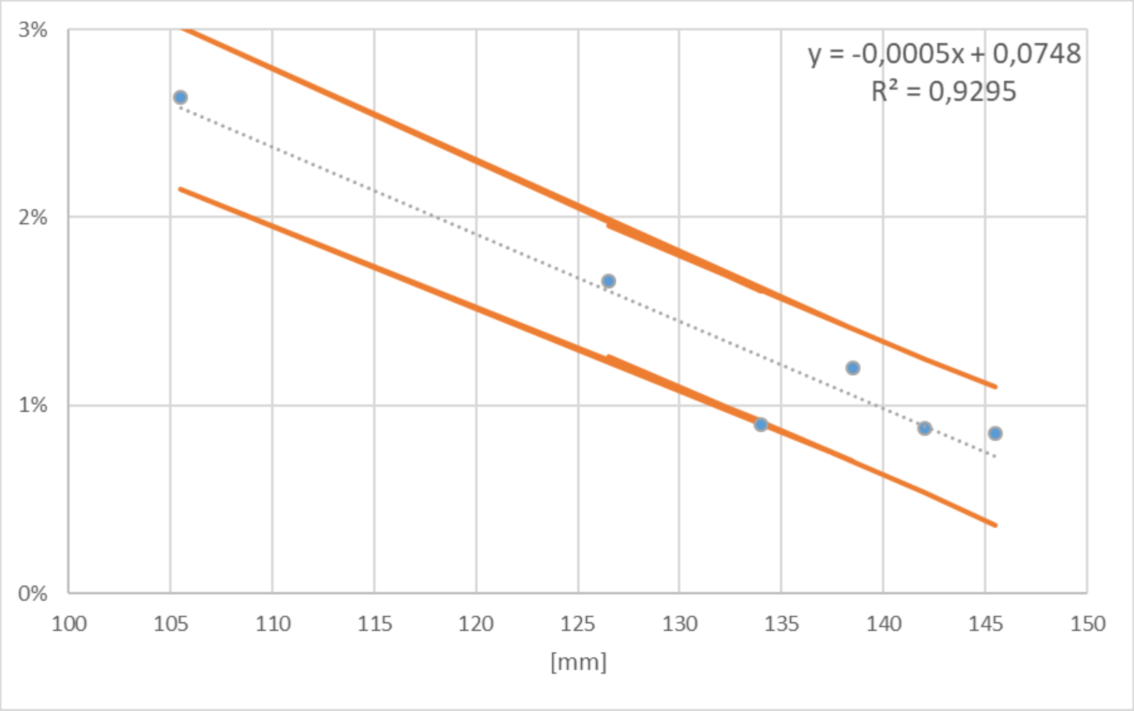
Appendix 3 Figure 2. 0.4 w/c concrete vs R1 mortar, manufactured sand, avg. interval: 0.45, α = 0.2.



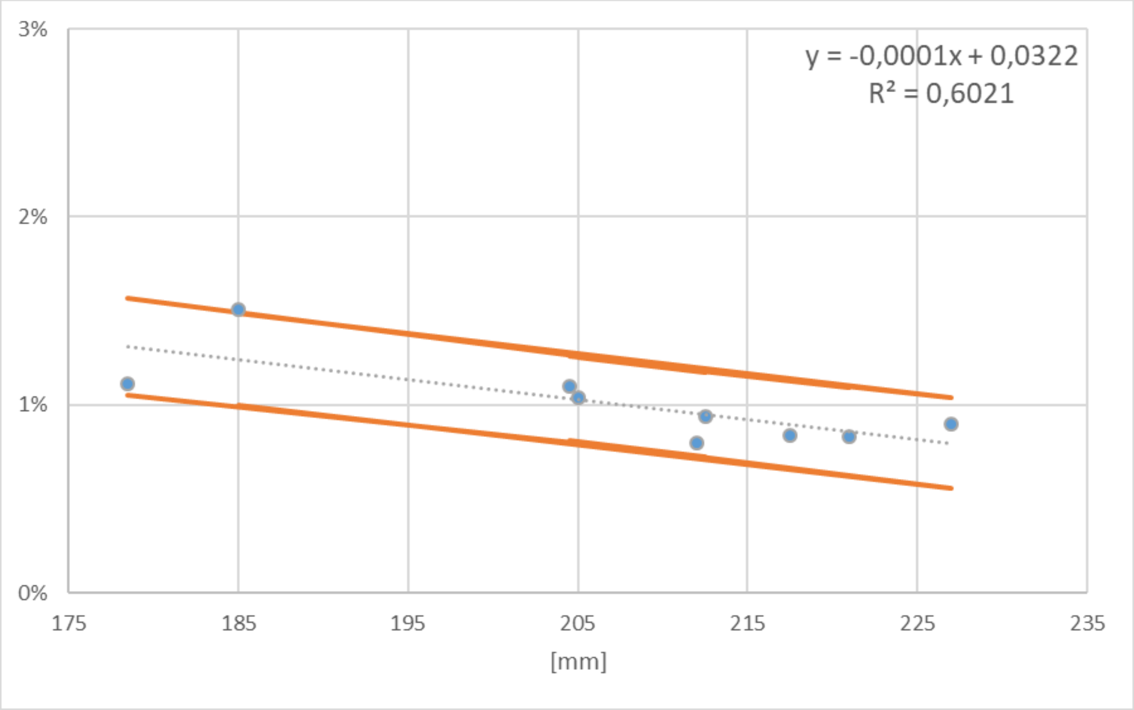
Appendix 3 Figure 2. 0.6 w/c concrete vs R1 mortar, manufactured sand, avg. interval: 0.77, α = 0.2.



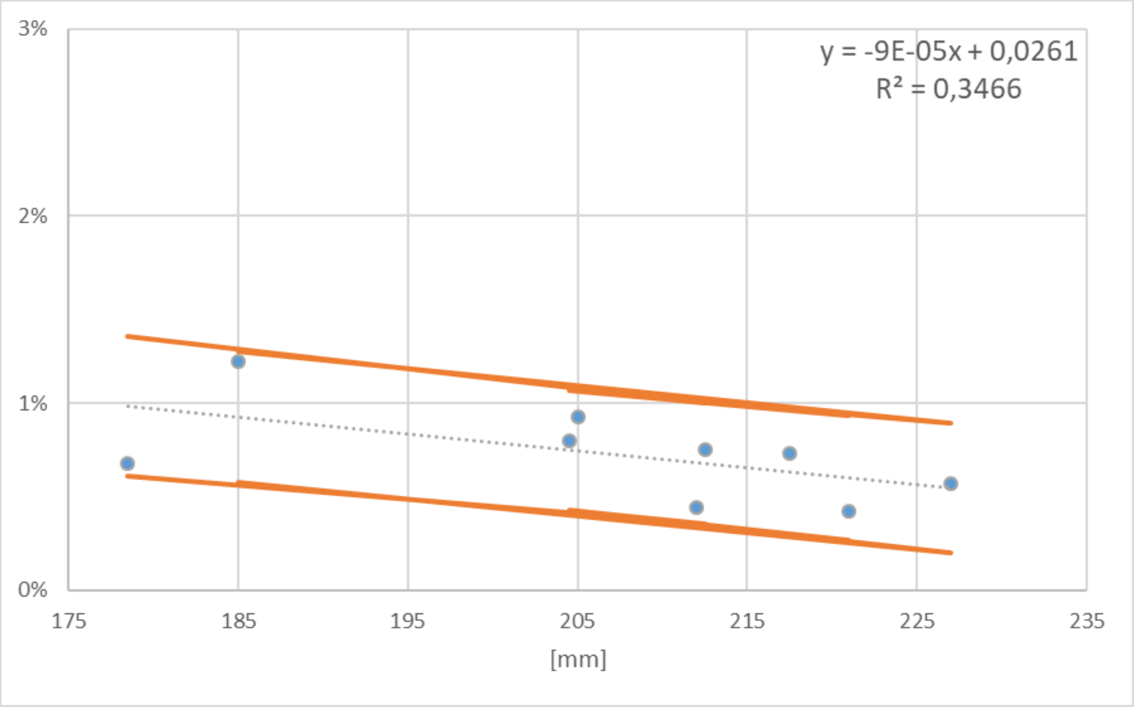
Appendix 3 Figure 3. 0.4 w/c concrete vs R3 mortar, manufactured sand, avg. interval: 0.88 %, α = 0.2.



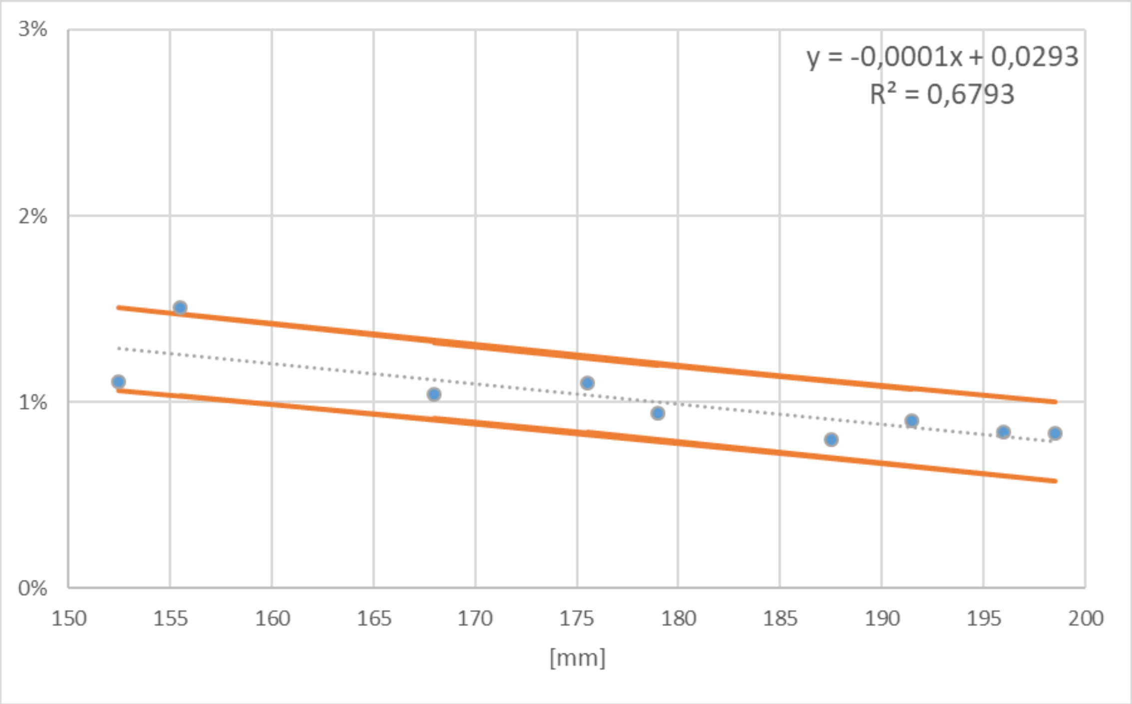
Appendix 3 Figure 4. 0.6 w/c concrete vs R3 mortar, manufactured sand, avg. interval 0.73 %, α = 0.2.



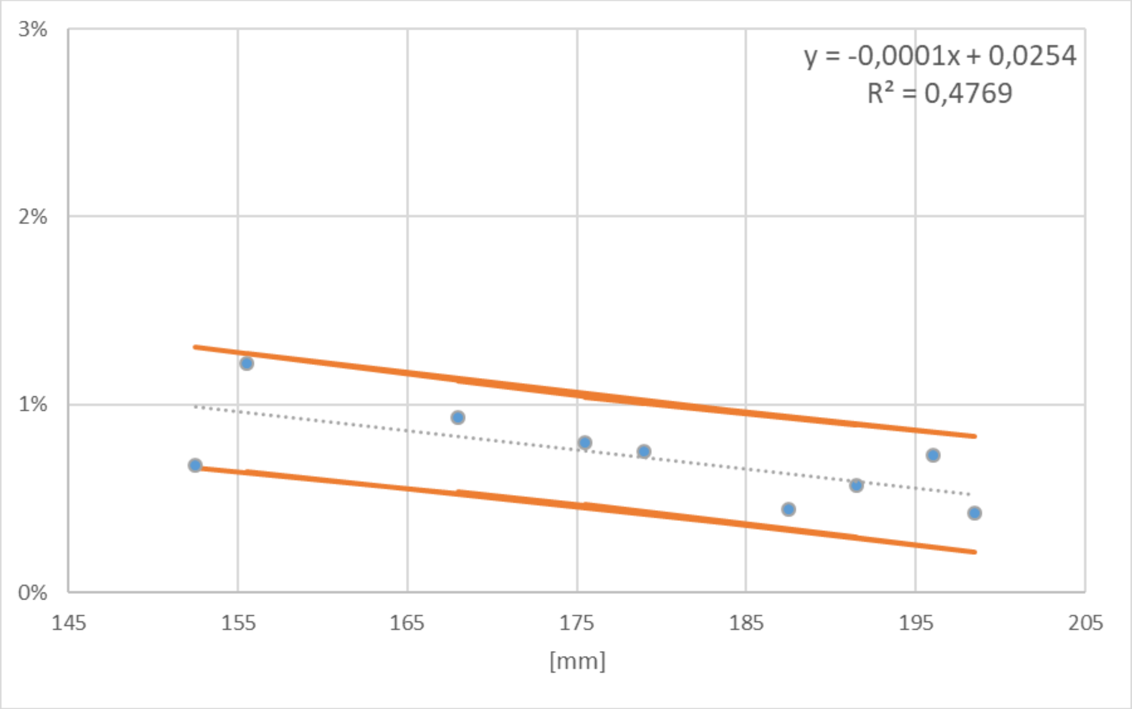
Appendix 3 Figure 4. 0.4 w/c concrete vs R1 mortar, natural sand, avg. interval 0.47 %, α = 0.2.



Appendix 3 Figure 4. 0.6 w/c concrete vs R1 mortar, natural sand, avg. interval 0.67 %, α = 0.2.



Appendix 3 Figure 7. 0.4 w/c concrete vs R3 mortar, natural sand, avg. interval: 0.42 %, α = 0.2.



Appendix 3 Figure 8. 0.6 w/c concrete vs R3 mortar, natural sand, avg. interval: 0.6 %, α = 0.2.