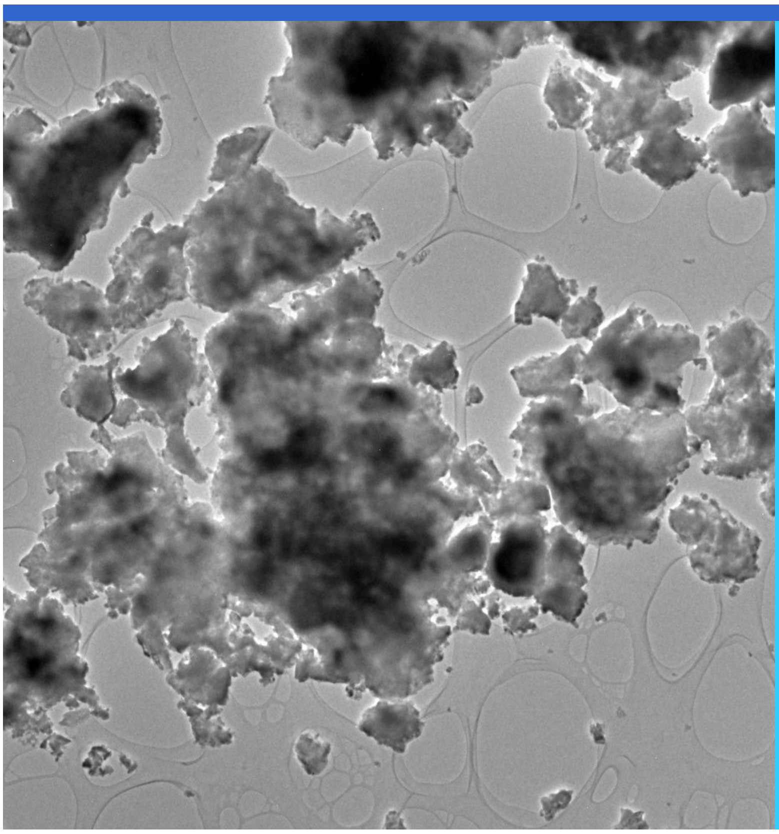
Alternate ash in concrete

Application for sewage sludge ash



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2014

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June 2014

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Preface

This is a bachelor thesis equivalent to 20 ETCS points performed within the field of civil engineering. The thesis is created for the Institute of Structural and Civil Engineering at the Technical University of Denmark.
Guidance and consulting was provided by Lisbeth M. Ottesen who served as supervisor throughout the entire project. Experiments and various activities in the laboratory were performed under supervision and guidance of Ebba C. Schnell. TEM pictures and analysis was provided by Anne-Mette Heie at Haldor Topsoe.

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Summary

It is of great interest both economically and environmentally to investigate whether sewage sludge ash may be used as a partial substitution for cement. Firstly, the building industry is able to reduce the cement production which is the most environmentally harmful part of concrete and secondly, the sewage centre may avoid the cost of transportation to the deposit area with its consequently environmental impact as well as the landfill tax. This report treats sewage sludge ash from Avedøre Sewage center. Sewage sludge ash may presumably vary in composition in the course of a year why it should be mentioned that the sewage sludge ash treated in this report was retrieved mid February and was allegedly retrieved immediately after incineration before storing to ensure a seasonal character. The objective of this report was to identify the properties of mortar with added sewage sludge ash in various quantities in terms of capillarity and compressive strength whereby aspiration quantity and the activity factor were determined as well as the general characteristics and microscopic form. Former studies suggests that sewage sludge ash may have pozzolanic features (Vangsgård and Haubroe, 2013)[2], however, it is difficult continuously to make a extensive assumption that all sewage sludge ash may have pozzolanic properties.

Sewage sludge ash were identified initially by designated experiments in terms of strengthening properties, elementary content, and general characteristics including pH, solubility and loss on ignition among other things.

Compressive strength

The strengthening properties were investigated through compressions tests with initial compositions (A) as reference composition dictated by DS/EN 196-1[4], (B) where 5% by mass cement was substituted with sewage sludge ash and (C) where 10% by mass sand was substituted with sewage sludge ash. The initial experiments were meant to provide an approximation of the properties of this particular sewage sludge ash and essentially form the investigations prospectively.

Initial compressive tests were made for curing time of one, three and five days where both (B) and (C) showed virtually no improvements in compressive strength compared with (A). A new approach was to systematically add sewage sludge ash to composition (A) from 2.5-15% by mass cement which was meant to clarify how sewage sludge ash affect the compressive strength. Compositions (F) and (G) with 7.5% and 10% added sewage sludge ash and a powder-cement ratio of 0.08 and 0.10 both showed a significant increase in compressive strength with 52.0 MPa and 52.1 MPa respectively which by normalization with respect to (A) were found to be 117% and 117% of the reference composition, (A), with its 44.4 MPa. Composition (G) was considered as the optimal powder-cement ratio of 0.10 which was used subsequently

with varying water-cement-powder ratios from $w/(c+P) = 0.42..0.52$. Compositions (J), (K) and (L) with water-cement-powder ratios of 0.42, 0.43 and 0.45 respectively showed significant increase in compressive strength with 54.5 MPa, 55.9 MPa and 52.1 MPa respectively which by normalizing with respect to (A) was found to be 124%, 126% and 117% of the reference composition (A) with its 44.4 MPa.

The activity factor was via Bolomey's adjusted formula and the obtained compressive strengths from initial compositions (B) and (C) and compositions (D)-(G) found to be 0.77 and 0.57 respectively.

Capillarity

The aspiration quantity of initial compositions (B) and (C) was by normalizing with respect to (A) found to be 114% and 140% respectively whereas compositions with added sewage sludge ash, (D), (E), (F) and (G), all showed a decrease in aspiration quantity and was, by normalizing with respect to (A), 82%, 75%, 72% and 84% respectively. Compositions (B) and (C) showed a decrease in aspiration quantity of 87% and 85% for twenty-eight days of curing time compared with seven days of curing time presumably due to its structural development.

TEM

TEM analysis were made for crushed sewage sludge ash in order to clarify its particle form and elementary content. Sewage sludge ash appear to have a course form on the particulate level that variates in particle size from 0.1-$10\mu m$, and was further concluded to have a crystalline atomic structure. Sewage sludge ash in a combination with coal fly ash may collaborate well as a strengthening material in mortar due to their differences in particle form and size.

The most frequent elements of sewage sludge ash were iron, calcium, phosphor, aluminium, magnesium, silicon and zinc. Coal fly ash essentially consist of calcium, iron, aluminium and silicon which may imply that sewage sludge ash have pozzolanic potentiel.

Sammenfatning

Muligheden for, at slamaske delvist kan substituere cement, har både økonomiske og miljømæssige incitamenter. For byggeindustrien kan det medfører en reduktion i produktionen af cement, som er den mest miljøbelastende komponent i beton. Endvidere kan spildevandscentre spare omkostninger både ved transport til og fra deponeringsområdet og deponeringsafgiften, ydermere undgås miljøbelastningen i forbindelse med transporten. Denne rapport behandler slamaske fra Avedøre spildevandscenter. På baggrund af, at slamaskens sammensætning antageligvis er sæsonafhængig, bør det nævnes, at den i rapporten behandlede slamaske blev afhentet i midten af februar. Ifølge Avedøre spildevandscenter blev slamasken udtaget umiddelbart efter forbrænding før opblanding med depotaske, alene for at sikre dens sæsonprægning. Formålet med denne rapport er at identificere effekten af tilsat slamaske vha. kapillarsugning og tryktest. Herved bestemmes opsugningsmængde og trykstyrke samt tilhørende aktivitetsfaktor. Ydermere undersøges slamaskens karakteristik og mikroskopisk struktur. Tidligere undersøgelser indikerer, at slamaske kan besidde puzzolaniske egenskaber (Vangsgård and Haubroe, 2013)[2], men det er til stadighed usikkert, om dette omfatter alle typer slamasker.

Slamaskens egenskaber bestemmes indledningsvis i form af styrkeegenskaber, elementært indhold og karakteristik herunder bl.a. pH værdi, opløselighed og glødetab.

Trykstyrke

Styrkeøgende egenskaber blev undersøgt indledningsvis ved sammenligning med reference mørtel (A) fra DS/EN 196-1[4], (B) hvor 5% cement blev erstattet med knust slamaske og (C) hvor 10% sand blev erstattet med knust slamaske. Disse indledende eksperimenter blev eksekveret med henblik på at approximere egenskaberne af slamasken og forme forløbet fremadrettet.

De indledende styrkeprøver blev lavet for (A), (B) og (C) med hhv. en, tre og fem dages hærdning, hvor blanding (B) og (C) ikke viste udprægede styrkeøgende tendenser. En ny tilgang var, at tilsætte slamaske sytematisk fra 2.5-15% til (A) for på den måde at identificere slamaskens styrkeegenskaber som kompakteringsmiddel i takt med tilsætningensmængden. Blanding (F) og (G) med hhv. 7.5% og 10% tilsat slamaske pr. masse cement og pulver-cement forhold på 0.08 og 0.1 hhv. viste sig at øge styrken significant. Blanding (F) og (G) blev fundet til at være 117% stærkere end (A) med hhv. 52.0 MPa og 52.1 MPa sammenlignet med (A) med 44.4 MPa.

Blanding (G) blev brugt fremadrettet med sit optimale pulver-cement forhold på 0.1, hvorefter vandindholdet blev justeret med hendblik på at forsyne blandingen med den optimale mængde vand. Vand-cement-pulver forhold $v/(c+P) = 0.42..0.52$ blev undersøgt hvor blanding (J), (K) og (L)

viste sig at have de optimale vand-cement-pulver forhold med hhv. 0.42, 0.43 og 0.45. De opnåde trykstyrker på 54.9 MPa, 55.9 MPa og 52.1 MPa viste sig at være signifikante og ved normalisering med hensyn til (A) - 44.4 MPa, blev de fundet til at være 124%, 126% og 117% stærkere.

Aktivitets faktoren blev, med de opnåede styrker for blanding (B) og (C), fundet vha. Bolomeys formel til 0.77. For blandinger (D)-(G) blev aktivitetsfaktoren fundet til 0.57.

Kapillaritet

Blandingerne (B) og (C) viste en reduceret opsugningsmængde for otteogtyve dages hærdetid sammenlignet med syv dages hærdetid på hhv. 87% og 85% hvilket korrelerer med den teoretiske strukturudvikling for mørtel. Ydermere viste det sig, at opsugningsmængden for blanding (B) og (C) var 114% og 140% større end (A), hvorimod (D), (E), (F) og (G) alle viste en reduktion i opsugningsmængden med hhv. 82%, 75%, 72% og 84% sammenlignet med (A).

TEM

TEM analyse blev foretaget for knust slamaske med henblik på en bedre forståelse af slamaskens partikulære form og atomare struktur samt dens elementære indhold. Målingerne viste, at slamasken er grov i sin form med partikelstørrelser omkring 0.1-10μm og krystallinsk i sin atomare struktur. Slamasken blev endvidere, på baggrund af dens partikulære struktur, vurderet til et potentielt kompakteringsmateriale i en kombination med flyveaske.

TEM analysen viste, at de hyppigest fremkomne elementer i slamasken var jern, calcium, fosfor, aluminium, magnesium, silicium og zinc. Flyveaske indeholder calcium, jern, aluminium, silicium som essentielt set også er i slamaske hvilket indikerer, at slamaske på baggrund af sit elementære indhold har puzzolanisk potentiale

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1 Introduction

The objective of this report is to study and therethrough provide understanding of sewage sludge ash in concrete for constructional purposes prospectively as well as ensure workability and hardening retain their stable characteristics. Also, erosion process along with decomposition must meet the environmental requirements. Avedøre sewage center has provided the sewage sludge ash treated in this report. Avedøre sewage center produces around three thousand tons sewage sludge ash per year and they have not yet found suitable receivers for recycling purposes why all produced sewage sludge ash is stored at the sewage center facilities at the moment.

Using sewage sludge ash as a substitute for cement is beneficial for the environment and has a profitable potential. Sewage centers pay a relatively large landfill tax why integrating the sewage sludge ash in concrete would be a profitable solution for them. The building industry also has an economic incentive for investigation if sewage sludge ash may be used as a substitution for cement. Cement is the most expensive part of concrete and sewage sludge ash cost close to nothing i.e. the more cement one substitutes with sewage sludge ash the more money one will save. Sewage sludge ash presumably appears in various compositions corresponding to the variation in sewage sludge in the course of a year. The sewage sludge ash discussed in this report were retrieved in mid February immediately after incineration and before storing to ensure a seasonal character, ASC (I). Comparisons were made concerning certain characteristics with sewage sludge ash which have been stored at the sewage facilities, ASC (II). Sewage sludge ash, ASC (I), were used for all practical purposes such as strength, capillarity, porosity etc. Investigating sewage sludge ash as a substitute for cement is a small part of the ZeroWaste Byg program at DTU whose overall aim is to investigate construction materials leading to a society with zero waste.

Five groups have concurrently addressed the issue of substituting cement and sand with various kinds of ashes and each group made the same tests initially which was meant to provide a general understanding of the properties of each ash and form the basis of prospective investigation. The initial experiments with ASC (I) showed virtually no strengthening properties when substituting cement or sand, however, former studies indicate that sewage sludge ash possess strengthening properties. This report considers the features of added sewage sludge ash in various compositions in terms of compressive strength and capillarity hence to approximate the optimal powder-cement ratio. The approximative optimal powder-cement ratio is used prospectively through which the necessary water-cement-powder ratio is possible to identify.

Transmission Electron Microscopy TEM analysis was meant to clarify the particle form on a microscopic level as well as an atomic level and further to identify the elementary content.

2 Theory

Prior theory for methods and experiments are reviewed in this section.

Theory overview

2.1 Concrete

Concrete is an inorganic malleable and plastic material during manufacture state and a hard stone-like material with great compressive strength in its cured state. Concrete has a low tensile strength similar to stones whereby reinforcing it with steel makes it a supreme material in compression, tension and bending. Concrete consist of water, aggregate, stones and the binder cement. Aggregate and stones usually pose about 75% of concrete. Manufacturing of concrete has relatively low energy consumption as Table 1 show and the prize is low for most of the components (Nepper-Christensen, 1985)[16].

Table 1: Energy consumption for various materials [kJ/kg]

Materials	Energy [kJ/kg]
Concrete	800
Brick	4.200
Cement	6.000
Steel	25.000
Plastic	50.000
Aluminium	120.000

2.1.1 Concrete history

Cement is a hydraulic binder and is called so due to its hardening properties under water. A hydraulic binder mixed with sand and stone is concrete. Hydraulic binders was used by Romans in the year 120-125 A.D., however the binder was not cement but limestone, for which similar reaction products from hydration process is produced. A particular good quality of concrete originated from a town called Puzzouli, where volcanic ashes were mixed with limestone mortar. The name is still used today for various reactive powders called pozzolanes. Unfortunately the Romans knowledge was lost during The Migration Period.

In the 18^{th} and 19^{th} century French and English scientist discovered how to manufacture cement. *Portlandcement* was invented and patented by the Englishman Joseph Aspdin in 1824.

2.1.2 Cement

Cement is complex and this section will only provide a relative brief elaboration of the commonly known chemical reactions and products for *portlandcement.*

Portlandcement manufacturing begins by sintering limestone, sand, clay and ferrous material all together, which creates portlandclinker, which is lumps or nodules as shown in Figure 1. Portlandclinker are ground and mixed with plaster and other inorganic materials. Clinker minerals consists of four main components, *Tricalcium silicate*, *Dicalcium silicate*, *Tricalcium aluminate* and *Tetracalcium aluminoferrite* (Nepper-Christensen, 1985). The cement chemical terminology is listed in Table 2, which show commonly used symbols for clinker minerals, to ease understanding while reading.

Figure 1: Clinker of cement

Table 2: Common symbols for clinker minerals in cement

Clinker minerals	*Symbol*
Tricalcium silicate - $3CaO{\cdot}SiO_2$	C_3S
Dicalcium silicate - $2CaO{\cdot}SiO_2$	C_2S
Tricalcium aluminate - $3CaO{\cdot}Al_2O_3$	C_3A
Tetracalcium aluminoferrite - $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$	C_4AF

Tricalcium silicate (C_3S), also known as *alit*, is the main part of cement, about 55-60%. The addition of water makes C_3S react and creates calcium silicate hydrate and calcium hydroxide. C_3S hydrates quickly and creates a calcium silicate hydrate gel which is the main component for early strength development.

Dicalcium silicate (C_2S), also known as *belit*. *Portlandcement* has around 20% of C_2S and like C_3S it reacts with water and creates calcium silicate hydrate and calcium hydroxide. C_2S reacts significantly slower than C_3S and affect the long term strength development.

Tricalcium aluminate (C_3A). Content is often under 15% in *portlandcement.* C_3A reacts very quickly with water, and would harden after a few minutes, but added plaster delays C_3A's reaction with water. C_3A contributes to the early strength.

Tetracalcium aluminoferrite (C_4AF). Quantities are usually around 5-10% and its contribution to strength development is small compared to the other mentioned clinker minerals.

2.1.3 Aggregate

The aggregate represents sand and stones. It is the least expensive part of concrete and around three quarters of the total volume. Common characteristics from which aggregate is chosen are geometry, physical and chemical features.

2.1.4 Structural development

As earlier mentioned concrete have plastic properties a few hours after mixing after which hydration causes the cement to bind. The binding and developing strength is caused by the chemical reaction between cement and water. Figure 2 show simplified version of the structural development of concrete. Note that porosity decreases over time thus creating a more dense concrete.

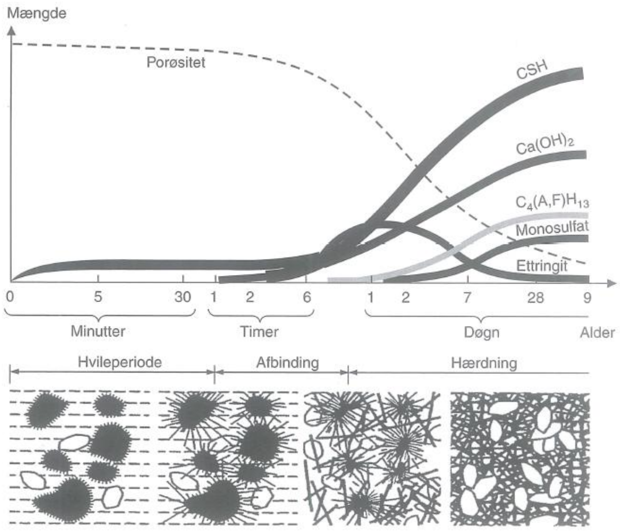


Figure 2: Simplified version of structural development of concrete

2.1.5 Concrete strength

Concrete strength is depended on its composition, compaction, humidity, temperature and curing time. Compressive strength are often considered as the most important property construction-wise do to the fact that many concrete properties have a certain relation to its compressive strength (Nepper-Christensen, 1985)[16]. Concrete is primarily used as a compressive component in buildings since its compressive strength is ten times its tensile strength (Geiker and Kielsgaard, 2008)[8] and may, over decades of hardening, generate compressive strengths of up to twice the design strength.

Standard compressive tests of concrete are usually made with cylindrical shapes with dimensions 150 mm x 300 mm cured for 28 days, however, the objective of this report is to determine compressive strength of the mortar in the early stages why prisms is assumed to provide an adequate approximation. Former studies conclude that seven days of curing time corresponds to approximately 70 percent of the designed compressive strength.

2.1.6 Pozzolans

The most commonly used pozzolanes in Denmark are coal fly ash and silica fume. Pozzolanes do not posses stand alone binding abilities but in a fine form at normal temperatures it will react with calcium hydroxide which is produced during the hydration process in cement. The pozzolanic reaction with calcium hydroxide produces Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H). Both products C-S-H and C-A-H fill up the pores and reduces the permeability of the binder thus hamper the ingress of harmful liquids such as salty water. Pozzolanic materials have shown beneficial features in terms of increased density and compressive strength (Chappex and Scrivener, 2012)[14].

2.1.7 Coal fly ash

According to DS/EN 450-1[7] coal fly ash is a fine powder which mainly consist of spherical glass particles formed during combustion of pulverized coal. Coal fly ash is detained by electrostatic or mechanical precipitation of ash particles in exhaust gas in power plants powered with coal. Coal fly ash consist of SiO_2 and Al_2O_3. The reactive content of SiO_2 determined by EN 197-1 must be at least 25% of the ash for being classified as siliceous. Danish coal fly ash, due to its chemical composition and the choice of combustion, meet the requirements for being classified as siliceous (Bech, Vattenhall and Pade, 2013)[15].

2.1.8 Silica fume

Silica fume SiO_2 is a by-product from manufacture of Silicium or FerroSilicium, which is a mixture of silicon and iron. Particles of silica fume, also called microsilica, are approximately $0.1\mu m$ and spherical. Silica fume does not have binding but pozzolanic properties and its small particle size enables it to enter gaps between cement particles, thus a more dense, impermeable and stronger concrete (Munch-Jensen, 2013)[15], (Nielsen, 2008)[8]. Adding a few percent, 8-10% by cement mass, silica fume may increase compressive strength by 40-50% (Nepper-Christensen, 1985)[16].

2.1.9 Mechanical properties

Concrete strength is primarily dependent on the binder, the cement paste, and its porosity and density. Concrete strength is also influenced by the type of aggregate, however, sand and stone are often stronger than the binder which is why testing only mortar provide a sufficient impression of the concrete strength. Porosity is essential for the strength like many other materials which for mortar is determined by the water-cement ratio. It may be said that a more dense binder is stronger than a less dense binder.

Based on the knowledge about concrete strength Bolomey developed an empirical formula dependent on the water-cement ratio. Bolomey's formula (1) is used for concrete with water-cement ratio $0.45 < w/c < 1.25$ and air content of 1.5-2%.

$$f_c = \mathrm{K}\left(\frac{1}{\mathrm{w/c}} - \alpha\right) \tag{1}$$

where K and α depends on the cement type and curing time as listed in Table 3. Pozzolanes strength contribution is accounted for using an activity factor k, which expresses the relation of the strength contribution given by a pozzolanic material equivalent to the same quantity of cement and depends on the reactivity of the pozzolane. Coal fly ash and silica fume for a curing time of twenty-eight days has an activity factor between 0.3-0.5 and 3-5 respectively. P is the quantity of the pozzolanic material and k·P is the equivalent amount of cement which lead to Bolomey's adjusted formula for compressive strength Equation (2) (Nepper-Christensen, 1985)[16].

$$f_c = \mathrm{K}\left(\frac{1}{\mathrm{w/(c{+}k \cdot P)}} - \alpha\right) \tag{2}$$

2.2 Sewage sludge ash

This report operates with sewage sludge ash provided by Avedøre sewage center which include sewage water from municipalities Brøndby and Vallensbæk. Sewage water is rinsed thoroughly and subsequently discharged into Køge Bay. From Avedøre sewage center's own website (Avedøre sewage center, 2014)[20] the process is briefly elaborated in three stages, *mechanical process*, *biochemical process* and the *incineration process*.

Mechanical process, all visible waste such as paper, rags etc. are collected by grates and deposited in a proper manner, sand is precipitated and separated fat is scraped off.

Biochemical process, micro-organisms initiates depletion of organic material where nitrogen is freed while consuming phosphor. Iron oxide is added to precipitate the remaining phosphor. The rinsed water is discharged 1.1

Table 3: Values of K and α for various type of cement produced in Aalborg (Normann Munch-Petersen, 2013)[15]

Cement type	Curing time [days]	K	α
Basic cement	1	17	0.9
	7	28	0.6
	28	30	0.5
Rapid cement	1	13	0.9
	7	24	0.6
	28	30	0.5
Low alkali sulfate-resistant cement	1	5	0.8
	7	19	0.8
	28	29	0.7
Aalborg white	1	14	1.0
	7	25	0.8
	28	35	0.7
Basic Aalborg cement	1	13	1.0
	7	24	0.7
	28	29	0.6

km out into Køge Bay and the remaining sludge is processed through digestion containers that produce methane which is used to produce heat and electricity.

Incineration process, the remaining sewage sludge ash is dried and incinerated at temperatures around 850°C and the final product sewage sludge ash are then stored at Avedøre sewage facilities.

2.2.1 Why sewage sludge ash

There are several beneficial reasons both economic and environmental for incorporating sewage sludge ash in concrete. The remaining sewage sludge ash stored at the sewage facilities is an environmental burden and by storing it in concrete this may be avoided, also, sewage centers pay landfill tax and transportation to the deposit area which also may be avoided. Cement is by far the most expensive and environmentally harmful component in concrete which makes sewage sludge ash a formidable resource construction-wise if it can partially substitute cement while maintaining the compressive strength and building properties of concrete. Former studies show a tendency that added sewage sludge ash to a standard mortar has strengthening capabilities, however, sewage sludge ash must be investigated for other short and long term developments before incorporating it in concrete. Coal fly ash is added to concrete for strengthening purposes by which DS/EN 450-1 was formulated to ensure the quality of coal fly ash. DS/EN 450-1 describes requirements for coal fly ash in terms of structure, content, water requirements etc. Requirements for adding sewage sludge ash in concrete are non-existing why this report use the restrictions for coal fly ash from DS/EN 450-1[7].

Integrating sewage sludge ash in concrete was an EU funded project in the years 2005-2007 under the name Biocrete. They showed that concrete with sewage sludge ash maintained its durability compared with normal concrete which initiated Biocrete manufacturing, unfortunately the demand was not big enough and it got cancelled. Furthermore, Avedøre sewage center use iron oxide for precipitation of phosphor which colours the concrete in a brown reddish colour depended on the relative added amount, this was also considered an issue.

2.3 Capillarity

Capillarity is a transport-phenomenon. It occurs when the porosity of given materials is small enough thus creating a hydrostatic pressure via surface tension which is essential for capillarity. The speed for which water travels upwards decreases with time due to friction and gravity (Byg.DTU)[12]. Water transport in coarse porous materials is quicker but have a low altitude maximum, whereas water transport in fine porous materials is slow but have a high altitude maximum. Water transport in small pores will travel up with greater force and therefore reach greater altitude (Nielsen, 2008)[9]. Water transport increases proportionally with the amount of cement paste (Nielsen, 1985)[16]. Water transport occurs in the cement paste thus making quantity and quality of the cement paste the dominant factor in water transport.

A concave formed water surface, *meniscus*, occurs in small thin tubes if the attractive force between water and the container material is strong enough (Brandt, 2009)[10]. The following will briefly elaborate on the term meniscus, for which understanding the theory behind capillarity is essential.

2.3.1 Meniscus

The meniscus of a liquid is the curve it makes when it comes into contact with the surface material of a container, for example the inside of a tube, and is caused by surface tension. A meniscus may either be *convex* or *concave.* A *concave* meniscus occurs when the particles in the liquid are more strongly attracted to the container than to each other. Conversely, a *convex* meniscus occurs when the particles are more strongly attracted to each other than to the surface of the container (Moore, 2005)[11]. Arguments for capillary theory in a deeper sense may be found in (Nielsen, 2008)[9] and will not be elaborated further in this report. Simplified theory for *hydrostatic pressure*

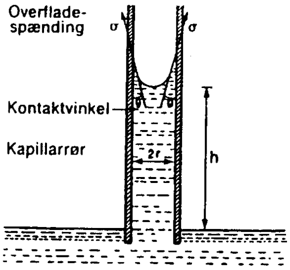


Figure 3: Illustration of capillarity

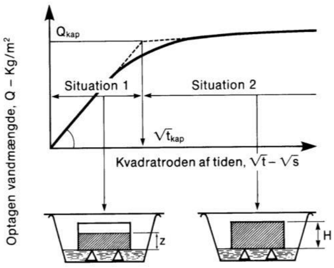


Figure 4: Q_{cap} and t_{cap}

p_{cap}, *aspiration quantity* Q, *capillary rise* h and *capillary resistance* M are explained in the following.

2.3.2 Hydrostatic pressure

The hydrostatic pressure is the pressure of the water below the meniscus and is expressed in Equation (3).

$$p_{cap} = \frac{2\sigma\cos(\theta)}{r} \tag{3}$$

where θ[°] is the contact angle which for common building materials is close to zero (Brandt, 2009)[10], r [m] is the meniscus radius and σ [N/m] is the surface tension (surface tension for pure water is 0.0735 N/m). As shown in Equation (3) hydrostatic pressure increases when meniscus radius decreases (Byg.DTU)[12], (Brandt, 2009)[10].

2.3.3 Aspiration quantity

Water transport will, at a certain point, reach an equilibrium, either because water have reached the top of the material or friction and gravity is greater than the capillarity. At this point most materials will absorb no more water, however, certain materials will continue absorption after the water reaches its maximum due to the fact that the small pores fills up slower. The amount of absorbed water is described as Q in Equation (4).

$$Q = \frac{m_t - m_o}{A} \tag{4}$$

where Q is aspiration quantity [kg/m^2], m_t is mass of the sample at time t [kg], m_0 is mass in dry state [kg] and A is aspiration area [m^2] (Byg.DTU)[12].

2.3.4 Capillary rise

Gravity will at a certain point exceed vertical aspiration. The *capillary rise* is determined by the pressure of the meniscus and how high it is able to carry the weight of its liquid column. By equilibrium the relation is indicated in Equation (5). It is fair to assume meniscus radius is equal to tube radius which lead to $r_K = r \cdot \cos(\theta)$ thus $\cos(\theta) = 1$ (Nielsen, 2008)[9].

$$h = \frac{2\sigma \cos(\theta)}{\rho_v \cdot g} \frac{1}{r} \tag{5}$$

where h is the *capillary rise* [m], $\cos(\theta) = 1$, ρ is the density of water and the gravitational force $g = 9.81\mathrm{m/m^2}$ (Nielsen, 2008)[9], (Brandt, 2009)[10].

2.3.5 Capillary resistance

From experiments of certain materials *capillary resistance* describes the inner resistance which affect the aspiration.

$$M = \frac{t_{cap}}{l^2} \tag{6}$$

where M is the *capillary resistance* [$\mathrm{s/m^2}$] and l [m] is the height of the sample used in the experiment.

2.3.6 Capillarity factor

Figure 4 illustrates how Q_{cap} and t_{cap} are found from experiments followed by calculation of *capillarity factor* using Equation (7) (Byg.DTU)[12].

$$k = \frac{Q_{cap}}{\sqrt{t_{cap}}} \tag{7}$$

2.4 Porosity and density

Porosity and density are proportional and affect the general properties of concrete such as strength, stiffness, permeability and durability (Nielsen, 1985)[16]. Concrete density increase and porosity decrease over time as explained in section 2.1.4.

2.5 Water solubility

Water solubility of sewage sludge ash may have an affect environmental-wise in terms of heavy metals or other chemical substances seeping down and harm the groundwater. The objective is to identify the amount of soluble material in sewage sludge ash.

2.6 Water soluble anions

Quantities of water soluble anions in sewage sludge ash, Chloride $\mathrm{Cl^-}$, Nitrate $\mathrm{NO_3}$ and Sulphate $\mathrm{SO_4}$ must meet the requirements for DS/EN 450-1.

According to DS/EN 450-1 the chloride content must not exceed the limit of 0.1% of cement mass. Also, according to DS/EN 206-1[5] reinforced concrete must meet the requirement for chloride content relative to cement mass listed in Table 4.

Table 4: Allowable content of chloride with reinforced concrete according to DS/EN 206-1

Application	Chloride class	Chloride(%) by mass cement
With out reinforcement	CL 1.0	1.0%
Reinforcement	CL 0.2	0.2%
	CL 0.4	0.4%
Prestressed reinforcement	CL 0.1	0.1%
	CL 0.2	0.2%

2.7 Heavy metal content

Sewage sludge ash has no specific restrictions and is subjected by the same restrictions as coal fly ash. Miljøministeriet (Miljøministeriet, 2010) has submitted restrictions for contaminated materials used in constructions and its allowable applications, applications such as roadwork, noise barriers and more. Oppose to non-contaminated materials, which may be used for all purposes, contaminated materials is divided into two categories indicated in Table 5, both of which specific application are indicated in (Miljøstyrelsen, 2010)[13].

Table 5: Heavy metal content [mg/kg] from (Miljøministeriet, 2010)[13]

Solids	Category 1	Category 2
Arsenic	0-20	>20
Lead	0-40	>40
Cadmium	0-0.5	>0.5
Chrom	0-500	>500
Cobber	0-500	>500
Nickel	0-30	>30
Zinc	0-500	>500

2.8 Conductivity and pH-measurement

2.8.1 Conductivity

Conductivity expresses how well electric current passes through a given sample. Conductivity depends on the amount of present particulates.

2.8.2 pH-measurement

Concrete has an alkaline pH of about 13 which prevents corrosion of reinforcing steel (Grubb, Limaye and Kakade, 2007)[19]. Adding sewage sludge ash may have an effect on the high alkaline environment.

2.9 Loss on ignition

Sewage sludge ash may contain leftover organic material despite the incineration, which is important to identify because organic material rot and create air bubbles which may lead to a weaker mortar. According to DS/EN 450-1 the requirements for loss on ignition are categorized as indicated in Table 6.

Table 6: Limits for loss on ignition acc. to DS/EN 450-1

Category	% by mass
Category A	7.0
Category B	9.0
Category C	11.0

2.10 Water content

By determining the accurate water content of sewage sludge ash one may advance the mixing process with the precise water content when dealing with mixtures on a big scale.

2.11 Laser Diffraction Analysis

Laser diffraction analysis is used to determine the size of the particles by irradiating a dissolved sewage sludge ash sample with laser beam and measure how the laser beam spread. The photons are then detected by photo detectors placed in different angels.

2.12 The curing process

Curing process of concrete may differ for various types of concrete with various w/c ratio. Generally concrete with a high w/c ratio cures slowly but is easy to distribute during casting unlike concrete with low w/c ratio that cures quickly but is more difficult to distribute during casting. DS/EN 450-1 requires the curing process to be no longer than twenty minutes plus twice the curing time for reference (A).

2.13 TEM

The combination of the two techniques transmission electron microscopy (TEM) and analysis (EDS) makes it possible to identify materials by form and structure and contents of elements. This might help the understanding of how sewage sludge ash react with cement and water.

3 Methods and materials

In this section methods and materials for the experiments are reviewed.

Method overview

3.1 Compressive strength

Sewage sludge ash used in this report is from Avedøre Sewage Center and will be expressed as ASC (I). Comparison of certain characteristics with sewage sludge ash from depot, which have been stored outside and considered as a representative storage sewage sludge ash, is expressed as ASC (II). Both ASC (I) and (II) were crushed beforehand since former studies show this to be beneficial.

3.1.1 Compression test

The casting process and compression test were made according to DS/EN 196-1[4] were the reference composition (A) is indicated in Table 7. Compression test were executed with a pressure speed of 2.40 kN/s.. The compression machine output unit is kN which was converted to MPa as indicated in Appendix A.2. Standard deviation for each compression test is indicated on every bar chart and F-test 95% with two tales were made to ensure significance between two results.

Mortar in various compositions with ASC (I) were investigated to identify how sewage sludge ash affect the mortar characteristics.

3.1.2 Initial compositions

Compositions (A), (B) and (C) listed in Table 7 were tested for compressive strength initially. Composition (A) was the reference mortar according to DS/EN 196-1, (B) had 5% cement replaced with ASC (I) and (C) had 10% sand replaced with ASC (I).

Table 7: Initial compositions (A), (B) and (C)

Composition	Water [g]	Cement [g]	Sand [g]	ASC (I) [g]
(A)	225	450	1350	-
(B)	225	427.5	1350	22.5
(C)	275	450	1215	135

3.1.3 Powder-cement ratio

Sewage sludge ash was added systematically to (A) from 2.5% to 15% by cement mass after which compression test were made according to DS/EN 450-1.

3.1.4 Water-cement-powder ratio

Water content was investigated from $w/(c+P) = 0.42...0.52$ to identify the optimal Water-cement-powder ratio. Compression test were made for

Table 8: Compositions with ASC (I) from 2.5%-15%

Composition	Cement [g]	Water [g]	Sand [g]	ASC (I) [g]	P/c ratio
(D)	450	225	1350	11.3	0.03
(E)	450	225	1350	22.5	0.05
(F)	450	225	1350	33.8	0.08
(G)	450	225	1350	45.0	0.10
(H)	450	230	1350	56.3	0.13
(I)	450	235	1350	67.5	0.15

compositions listed in Table 9 according to DS/EN 450-1.

Table 9: Compositions with various water-cement-powder ratios $w/(c+P) =$ 0.42...0.52

Recipe	Cement [g]	Water [g]	Sand [g]	ASC (I) [g]	$w/(c+P)$ ratio
(J)	450	209.5	1350	45.0	0.42
(K)	450	213.8	1350	45.0	0.43
(L)	450	225.0	1350	45.0	0.45
(M)	450	236.3	1350	45.0	0.48
(N)	450	247.5	1350	45.0	0.50
(O)	450	258.8	1350	45.0	0.52

3.1.5 Activity factor k

Bolomey's formula of compressive strength was used to identify the activity factor k based on the general assumptions that ASC (I) had pozzolanic properties and the requirement for water content 1.5-2$ was met. From Bolomey's formula (2) one can isolate the activity factor k and the powder quantity P as so

$$kP = \left(\frac{f_c}{K} + \alpha\right) w - c \tag{8}$$

By using the expression derived from Bolomey's formula (8) one may approximate the activity factor k by plotting the results. The right side of Equation (8) is the y-axis and the left side is activity factor k multiplied by the quantity of sewage sludge ash P where the quantity of sewage sludge ash is expressed along the x-axis.

The Activity factor k describes the factor for which a substance is multiplied to ensure strength equivalence for the substituted amount of cement, it depends on quality, type and time. The activity factor for 28 days curing time for coal fly ash and silica fume are 0.3-0.5 and 3-5 respectively (Geiker and Kielsgaard, 2008)[8].

3.2 Capillarity

Both capillarity and porosity experiments was measured for dried mortar samples which is defined as a change in weight of under 0.1% over four hours. Capillarity is measured for three samples at the time. Normally the samples would have been dried at 105 °C as described in the experimental guide, but former studies show that concrete exposed to high temperatures leads to a coarser pore structure (Hansen, Villadsen and Bager, 1989)[18]. The samples were dried in an incubator at 50 °C to ensure minimum influence on the pore structure and cooled in a desiccator with silica gel to ensure a dry environment. The absorption surface of each sample was measured and used to calculate the aspiration quantity Q and described in section 2.3. The samples were placed in a water vessel with water surface 5 mm above the absorption area and weighed over time $\sqrt{\mathrm{t}}$ [$\sqrt{\mathrm{s}}$].

The experiment was executed in accordance to Appendix C.2.

3.3 Porosity and density

Porosity P and absolute density ρ were calculated using formula (9) and (10) respectively.

$$P = \frac{V_{po}}{V} \tag{9}$$

$$\rho = \frac{m_d}{V - V_{po}} \tag{10}$$

where V is sample volume, V_{po} is volume of open pores and m_d is the mass of the sample in dry state. Density and porosity were made initially for compositions (A), (B) and (C) and later for compositions (D), (E), (F) and (G) from Table 8

For experimental approach see Appendix C.1

3.4 Water solubility

Water solubility experiment was done by dissolving a known quantity of ashes m_1 and pour it onto a filter. The solution is left over night allowing all the water to run through. The filter is dried at 105 °C and reweighed m_2. Solubility in percentages is measured using Equaiton (11)

$$\text{Water solubility\%} = \frac{m_1 - m_2}{m_1} \tag{11}$$

For experimental approach see Appendix C.8.

3.5 Water soluble anions

ASC (I) was mixed with distilled water and placed on a shaking table overnight. The solution was filtered and measured by Atomic Absorption Spectrophotometry (AAS).

For experimental approach see Appendix C.9.

3.6 Heavy metal content

ASC (I) was dissolved in nitric acid (HN_3) after which concentration of acid-soluble metals was determined according to DS 259[6] by Atomic Absorption Spectrophotometer(AAS).

For experimental approach see Appendix C.3.

3.7 Conductivity and pH-measurement

3.7.1 Conductivity

Conductivity is measured according to the experimental guide listed in Appendix C.5 with a conductivity measuring device.

3.7.2 pH-measurement

pH of ASC (I) was measured in a mix relation of 1:2.5 with water containing 1M KCL. For experimental approach see Appendix C.4.

3.8 Loss on ignition

The objective was to identify the quantity of organic material present in ASC (I). A given sample m_1 was subjected to 550 °C for one hour where any present organic material burns off. The sample was cooled off inside a desiccator, in which humidity is zero thus preventing the sewage sludge ash gaining weight from the moisture in the air, and reweighed m_2. Equation (12) was used for determining organic material in percent.

$$\text{Loss on ignition\%} = \frac{m_1 - m_2}{m_1} \tag{12}$$

For experimental approach see Appendix C.6.

3.9 Water content

A random quantity of ASC (I) was weighed m_w and dried in an oven at 105 °C for 24 hours. The sample was reweighed m_d and the water content was identified by using Equation (13).

$$\text{Water content\%} = \frac{m_w - m_d}{m_w} \tag{13}$$

For experimental approach see Appendix C.7.

3.10 Laser Diffraction Analysis

Data output from the Laser Diffraction Analysis was processed using a standard method for data processing for this particular experiment which is to be found in Appendix C.10.

For experimental approach and data processing guide see Appendix C.11.

3.11 The curing process

Vicatronic instrument was used to identify the curing process. The experiment measures how far a needle penetrates a given mortar sample when dropped at a certain height. The needle is dropped every ten seconds thus creating a graph with millimetres of penetration over time.

3.12 TEM

TEM analysis were made for ASC (I) and coal fly ash to compare both the particle form and the elementary content. TEM pictures have been provided from Haldor Topsoe.

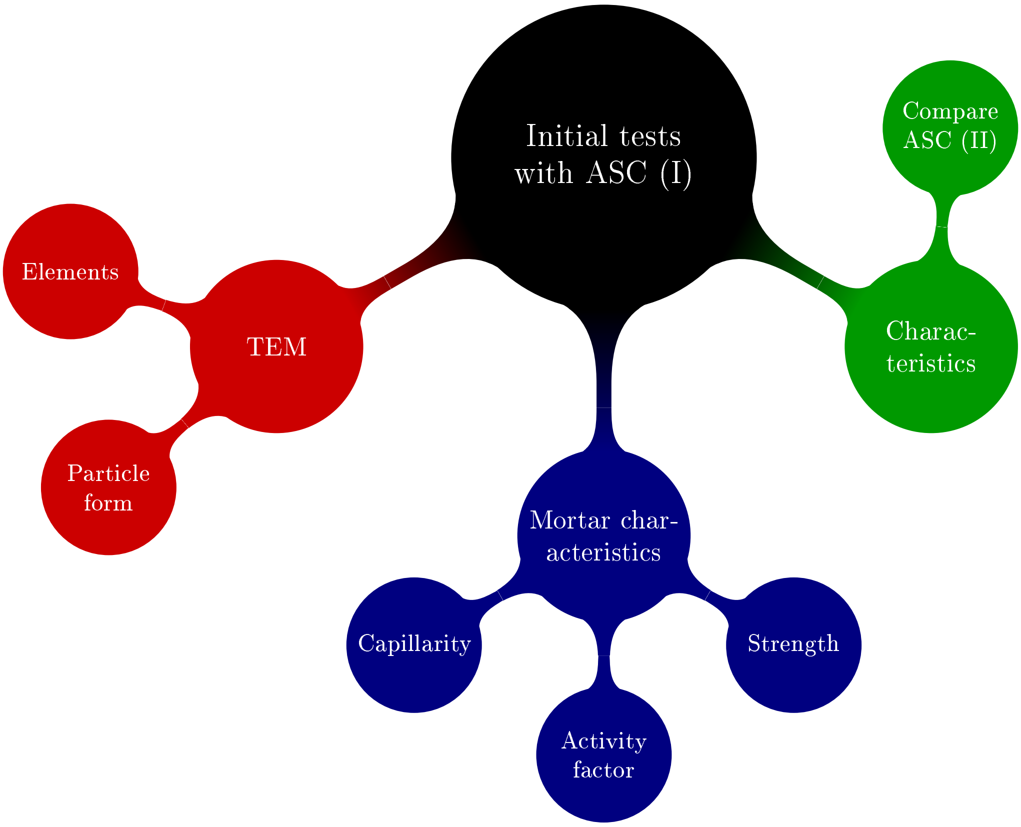
4 Results

This section will review the results from previously mentioned methods.

Results overview

4.1 Screening

Sewage centre process their sewage sludge differently thus initial experiments were required to determine the specific ash characteristics. These experiments was meant to provide a decent approximation of the characteristics and essentially indicate the prospective work. Sewage sludge ash is stored at the sewage facilities outside with no cover, ASC (II), and may have changed in characteristics over time which was identified by comparing ASC (I) and (II). Based on the initial tests with ASC (I) and after determining the particle size it was thought to be the composition and not the characteristics that was wrong. It led to certain mortar compositions with added sewage sludge ash for which characteristics are discussed later in this section. The objective of the various compositions was to approximate the optimal composition in terms of compressive strength and capillarity. The activity factor was estimated additionally based on the compression tests. The microstructure of ASC (I) was investigated by Transmission Electron Microscopy TEM and was meant to provide a better understanding of the strengthening features. Below is illustrated the screening process for the initial and prospective experiments.



4.2 Poster presentation

The screening process was helped along by a midway presentation based on the obtained initial results and a discussion thereof. During the presentation it was assessed that various composition would be interesting prospectively. A poster was made with interim results which is to be found in Appendix B.1.

4.3 Sewage sludge ash characteristics

This section discusses the characteristics of sewage sludge ash obtained by initial experiments. Comparison throughout this section was made for ASC (I) and ASC (II).

4.3.1 Conductivity

Table 10 indicate results of conductivity for ASC (I) and (II). By comparing the two ashes one sees that ASC (II) has a higher conductivity which may be due to a higher content of soluble salts.

Table 10: Conductivity of ASC (I) and (II)

Sample	Conductivity [mS/cm]
(I)	1.51±0.01
(II)	1.71±0.15

4.3.2 pH measurement

Concrete has a high basic pH of about 13 which prevents corrosion of reinforcing steel (Grubb, Limaye and Kakade, 2007)[19]. Substituting cement with ASC (I) may affect the high basic environment. As Table 11 indicate ASC (I) has a pH 8.42 and (II) has pH 7.25. ASC (II) has, as mentioned earlier, been stored outside and washed through by the rain which may dissolve the acidic elements and thus a less alkaline pH. Studies of mortar pH have been made with mortar samples containing 15% ASC (II) by mass sand and show no change in pH (Mathiasen, 2014)[3].

Table 11: pH measurement for ASC (I) and (II)

Sample	pH
(I)	8.42±0.04
(II)	7.25±0.02

4.3.3 Loss on ignition

Table 12 show loss on ignition of ASC (I) and (II). Comparing ASC (I) and (II) one sees that (I) has a slightly higher loss on ignition, however, the difference is assumed too small to have any significance. Comparing the limits for loss on ignition from section 2.9 and the above results one may conclude that (I) and (II) has loss on ignition <7.0% which put ASC (I) and (II) in Category (A). The general low loss on ignition show a sufficient incineration at Avedøre sewage center.

Table 12: Loss on ignition of ASC (I) and (II)

Sample	Loss on ignition [%]
(I)	1.19±0.023
(II)	1.11±0.015

4.3.4 Water solubility

Table 13 indicate water solubility for ASC (I) and (II). The water solubility is highest for (I) which was expected since (II) has been stored outside as mentioned in section 3.1 and may presumably have been washed through by the rain.

Table 13: Water solubility for ASC (I) and (II)

Sample	Solubility [%]
(I)	3.05
(II)	1.47

4.3.5 Water content

Table 14 show water content for ASC (I) and (II). Note that the ash was dried beforehand at 50 °C which may affect the experiment. Also, a slight interference may occur when the ash is taken from the oven to the weight scale thus exposing it to natural humidity in the air where it will seek an equilibrium. Both ASC (I) and (II) have a low and almost similar water

Table 14: Water content for ASC (I) and (II)

Sample	water content[%]
(I)	0.835±0.06
(II)	0.900±0.10

content. This may be due to the same level of dehumidification prior to the experiment.

4.3.6 Water soluble anions

Quantities of soluble anions were done by IC measurement for chloride Cl^-, nitrate NO_3 and sulphate SO_4 and are indicated in Table 15. Three samples were made for both ASC (I) and (II) which are to be found in Appendix A.6. Table 15 show a large difference in chloride content for ASC (I) and (II). Since ASC (II) has been stored outside it may have been washed by the rain and thereby dissolving the chloride. The content of nitrate is largest for ASC (I) and the quantity of sulphate is slightly larger for (I) which is consistent based on the assumption that plants and bacteria are present and therefore consume sulphate. Presumable a high amount of soluble anions lead to a high conductivity, however, this is not consistent with obtained results for conductivity from section 4.3.1.

Table 15: Average quantities of anions present in ASC (I) and (II) in [mg/kg]

Sample	Chloride [mg/kg]	Nitrate [mg/kg]	Sulphate [mg/kg]
(I)	2101±47.54	8.64±1.44	9438±387
(II)	26.12±0.25	33.5±0.51	8374±164

Coal fly ash has restrictions for chloride content due to its enhancing ability of corrosion. The total chloride content is calculated by using data from Table 15 of ASC (I) and considering the amount of ash in compositions (B) and (C). Table 16 show the chloride content for (B) and (C). Requirements for chloride content, for various types of reinforcement described in section 2.6 Table 4 for ASC (I), are meet for (B) and (C) with ash-cement ratio of 0.05 and 0.30 respectively.. Note that compositions from Table 8 also meet the requirements since their ash-cement ratios are all lower than composition (B).

Table 16: Chloride content in initial compositions with ASC (I)

Composition	Cement [g]	Ash [g]	Chloride [mg/kg]	Chloride [%]
(B)	427.5	22.5	2101	0.01
(C)	450.0	135	2101	0.06

4.3.7 Heavy metal content

The quantities of heavy metals of ASC (I), which are listed in Table 17, were identified ICP measurement. The lowest category determines the category and Table 17 shows that ASC (I) is located in category 2 according to (Miljøministeriet, 2010)[13]. The complete ICP measurement output is to be found in Appendix A.7.

Table 17: Heavy metal content in [mg/kg] for ASC (I)

Solids	Content [mg/kg]	Category
Arsen	0.327	1
Lead	123	2
Cadmium	3.38	2
Chrom	57.8	1
Copper	669	2
Nickel	9.70	1
Zinc	2628	2

4.3.8 Laser Diffraction Analysis

Former studies (Reiff and Meldgaard, 2013)[1] reached the conclusion that crushed sewage sludge ash, opposed to non-crushed sewage sludge ash, utilize the strengthening effect optimally. Figure 5 illustrate a rather large decrease in particle size after crushing which was expected.

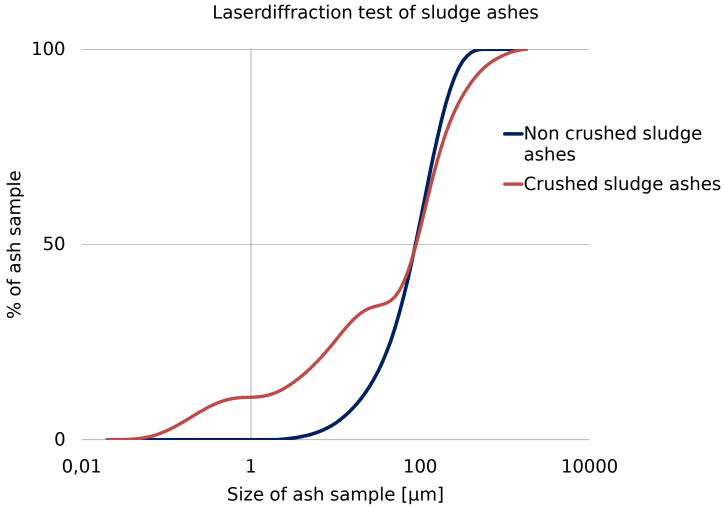


Figure 5: Crushed and non-crushed ASC (I)

4.4 TEM

Figure 6 and 7 show TEM pictures of ASC (I) and coal fly ash (CFA) respectively with specified scale. They show the locations for which TEM analysis were made.

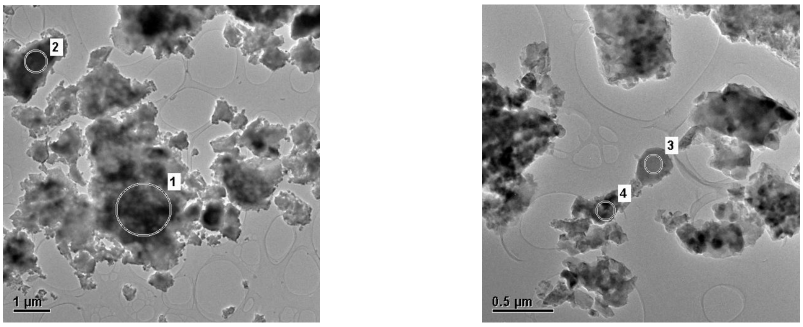


Figure 6: Locations of TEM analysis of ASC (I)

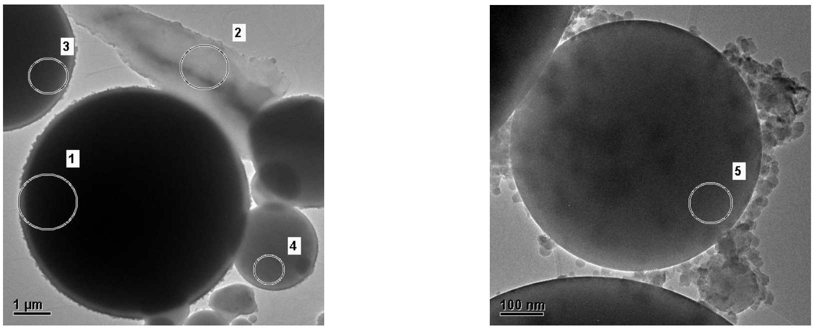


Figure 7: Locations of TEM analysis of CFA

4.4.1 TEM - ASC (I)

The analysis showed that iron, calcium, phospor, aluminum, magnesium, silicon and zinc were the most frequent elements in ASC (I). TEM analysis are located in Appendix A.9, A.10, A.11 and A.12 and visualize the appearance of the each element decently.

4.4.2 TEM - CFA

TEM analyse of CFA showed a more coherent element content where calcium, iron, copper, aluminium and silicon were the most frequent appearing elements. TEM analysis are located in Appendix A.13, A.14, A.15, A.16 and A.17

ASC (I) contains the same elements as CFA which may indicate a pozzolanic potential, however, the quantity of each element in ASC (I) and CFA are yet to be found.

4.4.3 TEM - sewage sludge ash atomic structure

TEM pictures identified the atomic structure of ASC (I) as illustrated in Figure 8 and show that ASC (I) has a crystalline structure.

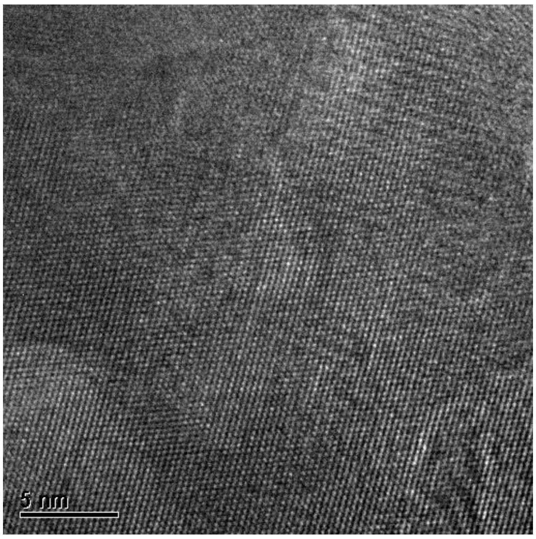


Figure 8: Atomic structure of ASC (I)

4.4.4 TEM - Structure comparison

Comparing CFA and ASC (I) in Figure 9 one sees a significant variation in particle form. Coal fly ash has a spherical uniform form, and it is relative big compared with ASC (I). ASC (I) appears to have particle sizes from 0.1-10μm according to Figure 9 and 6. Considering Figure 9 one may wonder if a combination of the two could lead to an even stronger substitute with known pozzolanic properties of coal fly ash and presumably compacting properties of ASC (I).

4.5 Mortar characteristics

4.5.1 The curing process

The curing process for (A), (B) and (C) were made and is illustrated in Figure 10. Figure 10 show that (A) cures faster than both (B) and (C), and that composition (B) cures quicker than (C) which may due to the high w/c ratio. DS/EN 450-1[7] requires the initial setting time to be maximum

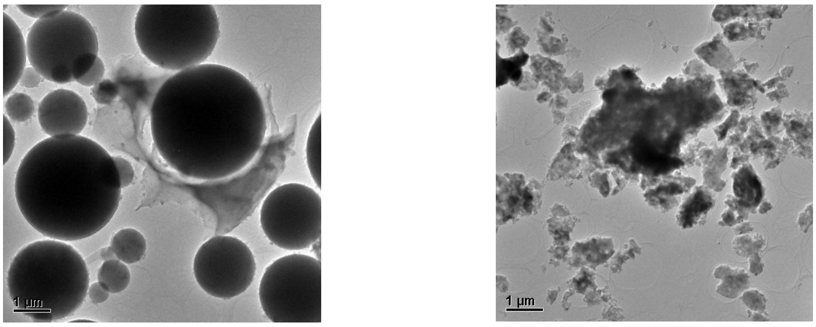


Figure 9: Structure of CFA (left) and ASC (I) (right)

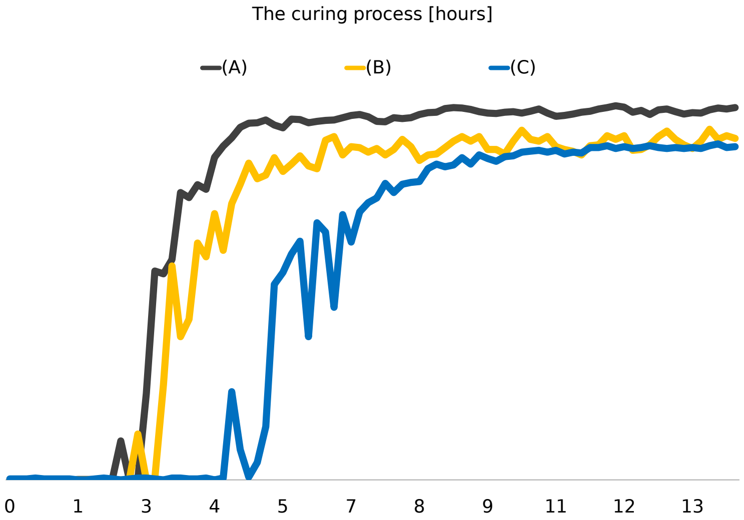


Figure 10: The curing process for (A), (B) and (C)

twenty minutes longer than twice the setting time of that of (A). Figure 10 indicate initial setting time for (A), (B) and (C) are estimated to be around 5, 7 and 11 hours respectively. Initial setting time for (B) meet the requirements according to DS/EN 450-1, however, (C) does not.

4.5.2 Capillarity

Capillarity is crucial for reinforced concrete if exposed to a high chloride concentrated environment. For example if chloride concentrated air is present and reach the rebars through capillarity it will increase the speed of electrochemical oxidation, rust, which ultimately may reduce the strength.

Initial experiments for capillarity for (A), (B) and (C) after seven and twenty-eight days of curing time are illustrated in Figure 11. Aspiration quantity Q expresses the total amount of water absorbed over 240 minutes and is derived in section 2.3.3 in Equation (4). Figure 11 show that for seven

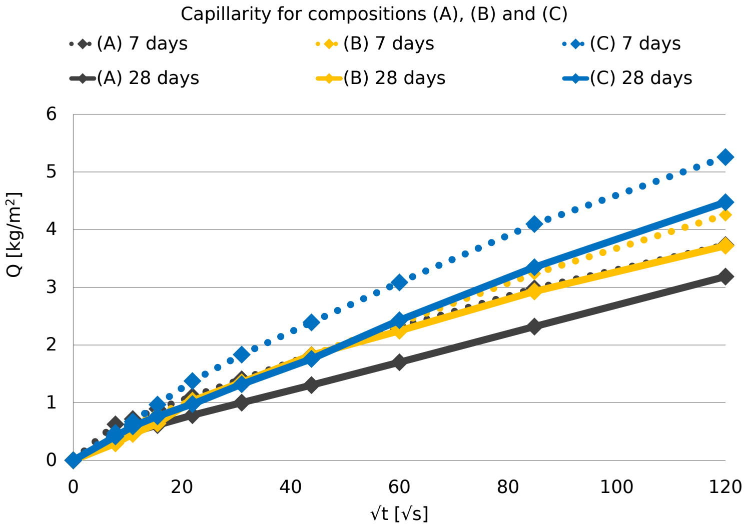


Figure 11: Capillarity for seven and twenty-eight days of curing time for (A), (B) and (C)

days of curing time composition (A) has 3.73 kg/m^2, (B) has 4.26 kg/m^2 and (C) has 5.26 kg/m^2 which for (B) and (C) is found to be 114% and 141% by normalizing with respect to (A). Both (A), (B) and (C) absorbs less for twenty-eight days compared to seven days of curing time, this may be due to a more dense mortar, as explained in section 2.1.4. The capillarity for seven and twenty-eight days of curing time was generally lowest for (A), then (B) and last (C). Composition (C) was the most absorbent which was expected due to its relative large amount of cement paste, composition (B) was the second most absorbent and (A) was the least absorbent.

The difference between seven and twenty-eight days of curing time is for (A) 0.43 kg/m^2, (B) 0.54 kg/m^2 and for (C) 0.78 kg/m^2. All three compositions was expected to increase their density thus decrease their permeability over time according their theoretical structural development described in section 2.1.4 which was the case for all three compositions. Composition (C) has the biggest gap between seven and twenty-eight days of curing time compared to (A) which may indicate pozzolanic properties.

Capillarity for compositions listed in Table 18 are investigated to identify the effect of added sewage sludge ash. Based on the results for capillarity of (A), (B) and (C) illustrated in Figure 11 not much can be expected. Adding sewage sludge ash systematically was meant to provide an approximative general effect on capillarity of added sewage sludge ash. Compositions in Table 18 were cured over seven days and could therefore only be compared with results obtained for (A), (B) and (C) for seven days of curing time.

Table 18: Quantities of added ASC (I) for porosity and density

Sample no.	Percent by mass cement [%]	ASC (I) [g]
(D)	2.50	11.3
(E)	5.00	22.5
(F)	7.50	33.8
(G)	10.0	45.0

Figure 12 show that (D) has 3.06 kg/m^2, (E) has 2.80 kg/m^2, (F) has 2.71 kg/m^2 and (G) has 3.15 kg/m^2 which was found to be 82%, 75%, 72% and 84% by normalization with respect to (A). It indicates that added sewage sludge ash affect the permeability of the mortar in terms of decreased water absorption concurrently with increased added sewage sludge ash, however, Figure 12 indicate that there may be a limit for the beneficial effect correlating with the amount of added sewage sludge ash. It seems that composition (G) may have been added too much sewage sludge ash thus more cement paste which may create a larger pathway for the water. Composition (A) was used as reference and all four compositions from Table 18 have less water absorption than (A) which may indicate compacting properties. One may conclude that added sewage sludge ash affect the capillarity beneficially but to optimally utilize the compacting properties one may consider the ratio between added sewage sludge ash and cement.

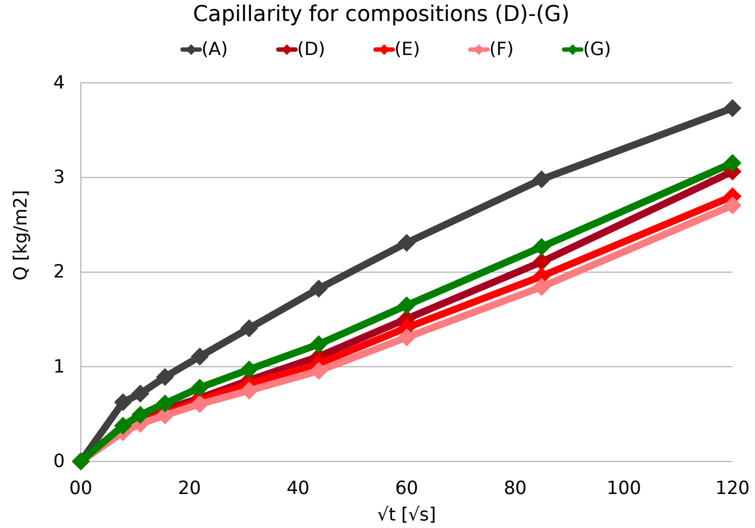


Figure 12: Capillarity for compositions listed in Table 18 in addition to composition (A) as a reference point

The aspiration quantity Q indicates the quantity absorbed over 240 minutes and because the capillarity does not reach an equilibrium, thus determining Q_{cap}, the capillarity factor k can not be determined as explained in section 2.3.6. Note that the experimental approach is designed for bricks, and bricks are more likely to reach the resistance factor within the time limit of the experiment whereas concrete may need more time why the graph does not reach a horizontal gradient as illustrated in Figure 4 i.e. the experiment does not provide a t_{cap}.

The experiment for capillarity should have determined the capillary resistance M described section 2.3.5 but the experiments did not provide a t_{cap} thus the capillary resistance M can not be determined. The hydrostatic pressure is derived in section 2.3, which uses the radius of the pores, however, this requires a method for identifying the size of the pores. One method could be to slice a mortar in half and identify the pores and their size through a microscope. Also, with the size of the pores identified one can calculate the capillary rise by using Equation (5).

4.5.3 Porosity and density

Capillary experiments in section 4.5.2 suggests that the least dense mortar is (C), which was expected to be confirmed in this section. Results for porosity P and density ρ for seven and twenty-eight days of curing time are listed in Table 19 and 20 respectively for (A), (B) and (C). Composition (C) was also expected to be least dense due to the fact that 10% sand was replaced with sewage sludge ash which is assumed to be less dense. Density indicate an increase and porosity a decrease over time as mentioned earlier. Comparing densities for seven and twenty-eight days one may conclude a generally more

Table 19: Porosity and density for (A), (B) and (C) with seven days of curing time

	Porosity [%]	Density [kg/m^3]
(A)	18.6	2102.0
(B)	12.8	2074.0
(C)	17.0	2025.3

Table 20: Porosity and density for (A), (B) and (C) with twenty-eight days of curing time

	Porosity [%]	Density [kg/m^3]
(A)	18.8	2109.2
(B)	12.1	2095.5
(C)	13.8	2035.9

dense mortar for twenty-eight days of curing time which correlates well with the theoretical structural development for density and porosity as explained in section 2.1.4.

Comparing results of capillarity from section 4.5.2 for (A), (B) and (C) one may conclude that a dense mortar compared to a less dense mortar, has less water absorption. Composition (C) decreased its porosity but maintained its density which was not expected, this may indicate that either ASC (I) has unstable compacting properties due to its irregular microstructure or it has pozzolanic properties.

Compositions listed in Table 18 were investigated for their porosity and density and based on results for capillarity in section 4.5.2 composition (D) and (G) were expected to be least dense and most porous. From results in Table 21 one sees that (D) and (G) are most dense which, according to their capillary ability from section 4.5.2, was the opposite of what was expected, however, comparing (D) (G) one may conclude that their porosity corresponds well to their water absorption. Compositions (D)-(G) are less porous compared with (A) from Table 19 and (E) and (F) are virtually just as dense which may indicate filling properties.

Table 21: Porosity and density for compositions listed in Table 18

Sample no.	Porosity [%]	Density [kg/m^3]
(D)	16.3	2119.1
(E)	15.6	2098.2
(F)	16.1	2101.6
(G)	16.5	2119.1

4.6 Compressive strength

Former studies indicate that added sewage sludge ash has strengthening properties, but the properties are not clear at the moment. To identify the effect of added sewage sludge ash this section will review experiments and results from compression tests.

4.6.1 Initial test

The initial tests of compressive strength showed no strengthening effect for (B) and (C) after one, three, and five days of curing time as illustrated in Figure 13.

Mortar obtains seventy percent of its compressive strength after seven days of curing time as mentioned earlier in section 2.1.5 therefore (A), (B) and (C) samples are made with seven days of curing time to get a more

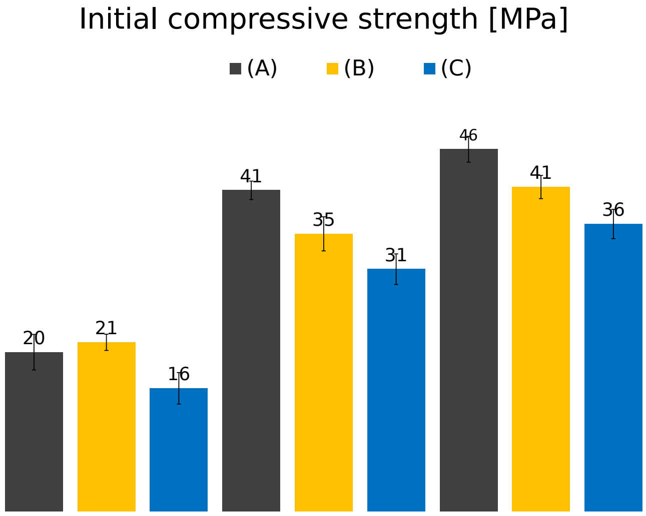


Figure 13: Compressive strengths for initial compositions for one, three and five days of curing time, from left to right respectively

developed mortar thus a more precise approximation. Longer curing time is preferable to obtain decent results.

Figure 13 show that (A) is stronger than (B) and (C) after five days of curing time and that (B) and (C) obtain 90% and 79% respectively of (A)'s compressive strength after five days of curing time. Figure 14 show that (B) and (C) obtain 92% and 94% respectively of (A)'s compressive strength after seven days of curing time. Both (C) and (B) has less compressive strength after five days of curing time, however, comparing (C) after five and seven days one can see that the compressive strength has developed significantly after seven days. Normalizing compressive strength of seven days with re-

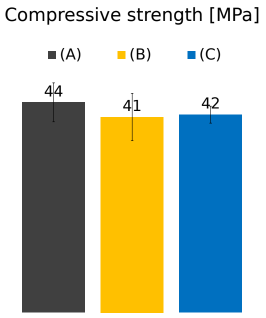


Figure 14: Compressive strength for seven days of curing time for (A), (B) and (C)

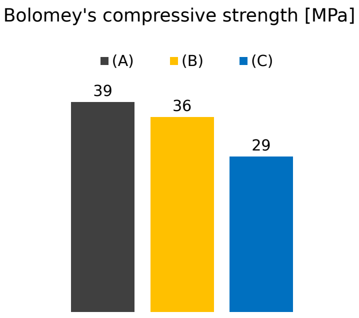


Figure 15: Bolomey's calculated compressive strength for seven days of curing time for (A), (B) and (C)

spect to five days of curing time one sees from Figure 16 that composition (C) obtained 115% of the compressive strength which may indicate pozzolanic properties. Composition (A) reached a greater compressive strength for five days compared to seven days of curing time which was not expected. This might be due to a different vibration device used for samples with seven days of curing. The new vibration device was used for all further experiments with a frequency of 80 Hz.

Figure 17 show the normalized initial compression test with respect to Bolomey's calculated strength from Figure 15. It should be mentioned that composition (A) has 13% greater compressive strength compared with Bolomey's calculated compressive strength and is considered as reference point 1.00 by normalization. Figure 17 show that composition (C) has 31% greater compressive strength than the calculated strength which indicate strengthening properties.

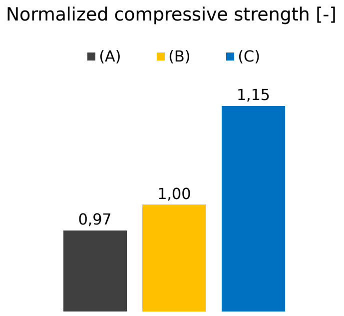


Figure 16: Normalized compressive strength of (A), (B) and (C) with seven days of curing time with respect to five days of curing time

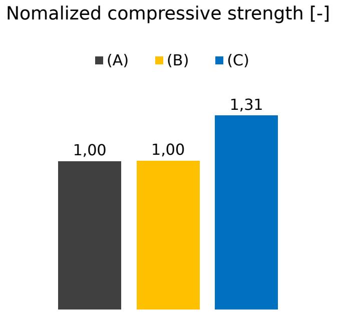


Figure 17: Normalized compressive strength of (A), (B) and (C) with respect Bolomey's calculated compression strengths

4.6.2 Colour of compositions

Sewage sludge ash at Avedøre sewage center is precipitated with iron which colour the ashes and therefore the mortar if the ashes is added in large amounts. Figure 18 show the colour of compositions (A), (B) and (C). Composition (A) has the standard concrete grey colour. Composition (B) show a light reddish colour tends towards pink and composition (C) is brown as expected. It should be mentioned that the container used for curing obtained a clear pink color along the water's edge. Former studies show that concrete with added or substituted sewage sludge ash obtain a pinkish colour which Figure 18 virtually confirms. One may say that the pink appearance has limited applications in its raw concrete state, however, there are several applications such as foundations, colour coated concrete etc. for which the colour have no influence.

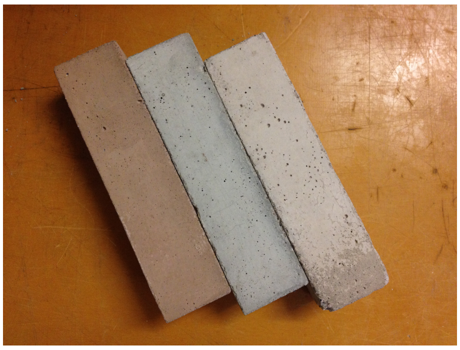


Figure 18: Colour for compositions (A)[mid], (B)[right] and (C)[left] for seven days of curing time

4.6.3 Powder-cement ratio

Based on the general assumption that sewage sludge ash have strengthening properties the following will investigate the powder-cement ratio and if it may, by modifying the ratio, evoke a greater increase in strength. Sewage sludge ash it is added to the reference composition (A) instead of replacing cement or sand which may identify a powder-cement ratio for ASC (I). Table 8 show the new compositions where ASC (I) is added systematically with 2.5% ash by mass cement up to 15% and their corresponding cement-powder (P/c) ratio. Composition (H) and (I) were added water due to a too rigid mortar. Compositions are fairly rough in percentages of added sewage sludge ash, however, they are meant to provide an approximative powder-cement

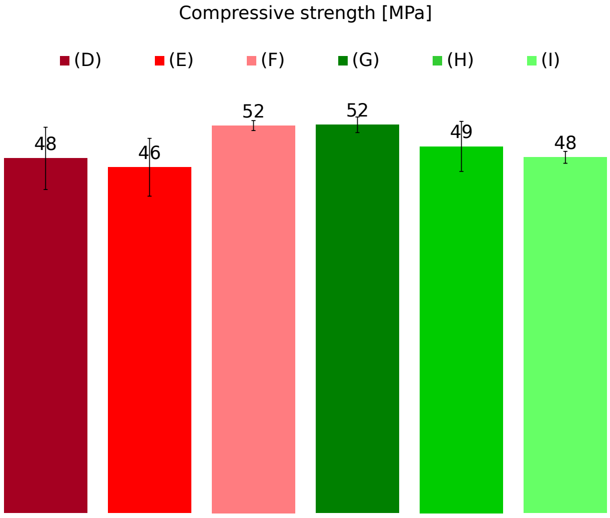


Figure 19: Compressive strength for composition listed in Table 8

ratio. Figure 19 show compressive strength for the compositions listed in Table 8. Composition (G) 52.1 MPa, specified in Appendix A.2, with P/c ratio of 0.10 respectively, have the greatest compressive strength, which correlates well to its density from section 4.5.3. Assuming a 5% significance and using compression results for (A) from Appendix A.2 (G) is significantly greater than (A). Their high compressive strength may be caused by several factors but based on experiments in Figure 19 one may conclude that a P/c ratio of 0.10 is considered optimal.

Adding sewage sludge ash from 1% to 30% by mass cement with a curing time of twenty-eight days would naturally provide more precise effect of sewage sludge ash.

As mentioned (G)'s high strength may be affected by many things, one factor might be the water-cement-powder ratio. Former studies show sewage sludge ash has as coarse structure which may attract water molecules and thus insufficient water supply of the cement. Cement is a hydraulic binder as explained in section 2.1.4 and one may consider if the optimal water-cement-powder ratio is present in (G).

4.6.4 Water-cement-powder ratio

The water quantity was adjusted while treating the powder-cement ratio as a constant thus providing an approximative optimal water-cement-powder ($w/(c+P)$) ratio which led to compositions listed in Table 9. Bolomey's formula (1) implies that the water-cement ratio determines the compressive strength f_c i.e. $w/c = 0.45$ is stronger than $w/c = 0.55$. Compositions (J)

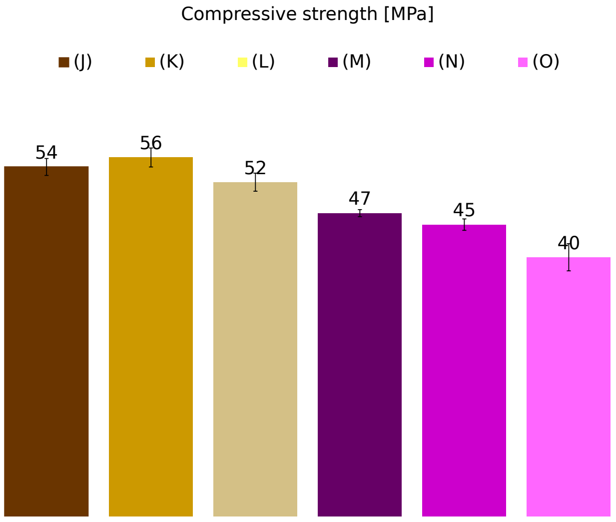


Figure 20: Compressive strengths for compositions listed in Table 9

and (K) are expected to obtain the greatest compressive strengths based

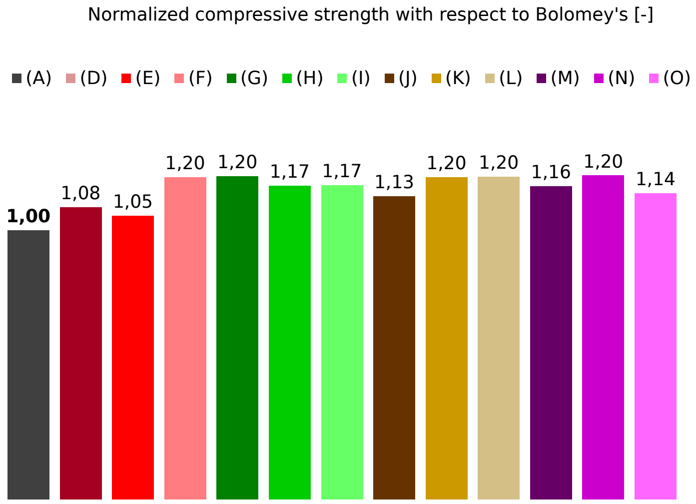


Figure 21: Normalized compressive strengths of compositions listed in Table 8 and 9 with respect to Bolomey's calculated strength

on the general knowledge that a low w/c ratio provide greater strength. Note that (J) was added water due to a too rigid mortar. From Figure 20 one sees that composition (J) and (K) obtain the greatest compressive strengths with 54 MPa and 56 MPa respectively, which was expected. The compressive strength then decreases with increasing water-cement-powder ratio which corresponds to Bolomey's theoretical compressive strength. Precise compressive results are to be found in Appendix A.2.

4.6.5 Normalized compressive strengths

The strengthening level of added sewage sludge ash is identified by normalizing with respect to Bolomey's calculated strengths and are shown in Figure 21. The standard composition from DS/EN 196[4], composition (A), was used as reference and was 13% stronger than Bolomey's calculated compression strength. This deviation is considered intentional as explained earlier and accounted for in the normalization i.e. (A) is expressed as 1.00. Figure 21 show that compositions (D)-(O) all obtain a greater compressive strength compared with Bolomey's calculated compressive strengths which indicate rather clearly that sewage sludge ash have strengthening properties, however, it is uncertain precisely whether they are pozzolanic or compacting. Figure 22 show the obtained normalized compressive strengths for compositions (D)-(O) with respect to (A) to clarify the overall strength properties of added sewage sludge ash. Composition (K) has the greatest compressive strength with 126%, (J) with 123% and (F), (G) and (L) with 117% of (A)'s compressive strength. Both (J) and (K) were rather rigid during mixing

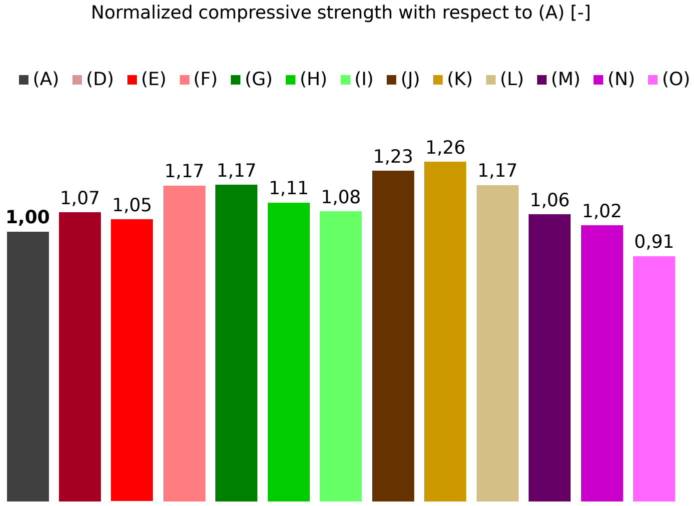


Figure 22: Normalized compressive strengths with respect to composition (A)

and casting which was expected due to their low water-cement-powder ratio, which may hamper the workability. Compositions (F), (G) and (L) have workable textures similar to the reference composition (A).

4.6.6 The activity factor k

The activity factor based on initial compositions (B) and (C) is illustrated in Figure 23 which indicate an activity factor of $k = 0.77$. Compressive strengths for compositions listed in Table 8, specified in Appendix A.2, were used to approximate the activity factor as illustrated in Figure 24 which indicate an activity factor of $k = 0.57$. Both activity factors are plausible although they seem fairly high considering coal fly ash is 0.3-0.5 after twenty-eight days, which may indicate compacting properties oppose to pozzolanic. The amount of added sewage sludge ash was in section 4.5.2 estimated to have a certain limit, which may explain why (F) and (G) in Figure 24 obtained the highest activity factors.

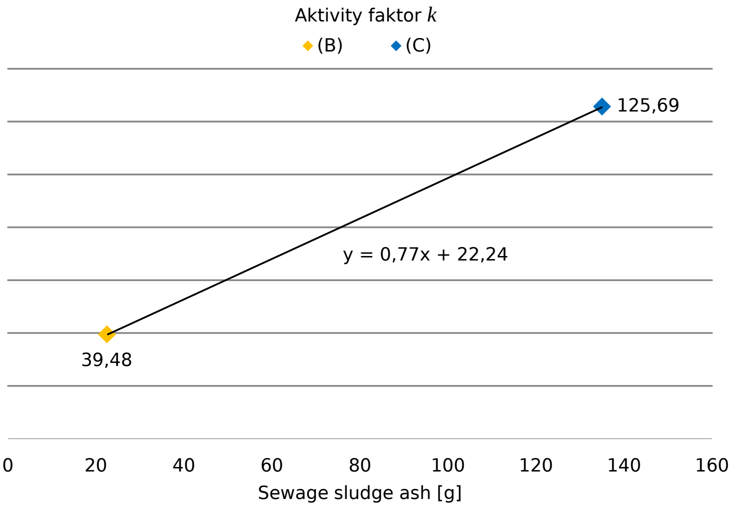


Figure 23: Activity factor k for initial compositions (B) and (C)

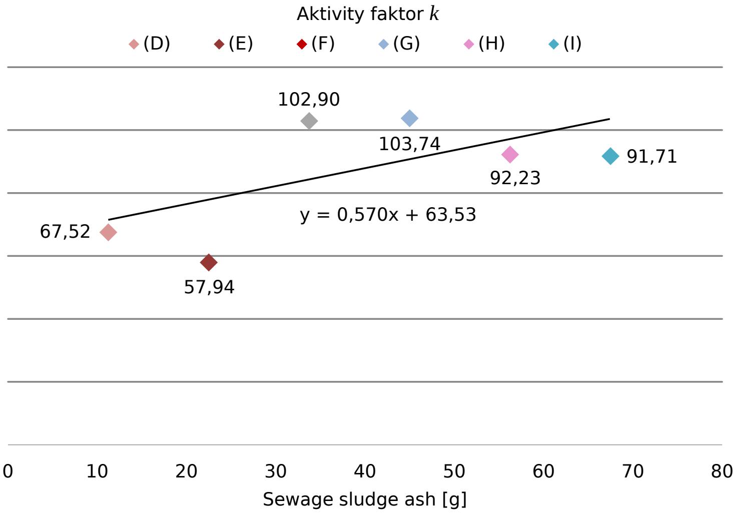


Figure 24: Activity factor k for compositions listed in Table 8

5 Conclusion

Overordnet conklusion

Measurements showed that ASC (I) has a slightly alkaline pH of 8.42 compared to ASC (II) pH 7.25. Substituting up to 15% by mass sand with ASC (II) show no significant impact on the pH of the mortar.

IC measurements confirms that ASC (I) meet the requirements for chloride content in reinforced concrete according to DS/EN 450-1 up to and including ash-cement ratio of 0.30.

ASC (I) was, based on ICP measurements, according to (Miljøministeriet, 2010)[13] located in Category 2 which consequently lead to restricted applications.

TEM analysis showed that ASC (I) appeared to have a relative course form on the microscopic level and a crystalline structure on the atomic level. The analysis showed that the most frequent elements of sewage sludge ash were iron, calcium, phosphor, aluminium, magnesium, silicon and zinc. Coal fly ash essentially consist of calcium, iron, aluminium and silicon which may imply, based on the elementary content, that sewage sludge ash have pozzolanic potentiel.

ASC (I) meet the requirements for initial setting time according to DS/EN 450-1 considering composition (B). Composition (C) does not meet the requirements, however, it is believed to be due to its high water-cement ratio.

The initial experiments showed that compositions (A) was found to have 3.73 kg/m^2 while (B) and (C) was found to have 4.26 kg/m^2 and 5.26 kg/m^2 which by normalizing with respect to (A) is 114% and 141% respectively. Compositions (A), (B) and (C) decreased their permeability over time comparing seven and twenty-eight days of curing time where (C) was found to decrease the most. Added sewage sludge ash was found to decrease the permeability in general which led to compositions (E) and (F) having the least water absorption with 2.71 kg/m^2 and 2.80 kg/m^2 which is 75% and 73% respectively of (A)'s aspiration quantity while (D) and (G) had 3.06 kg/m^2 and 3.15 kg/m^2 which is 82% and 84% respectively of (A)'s aspiration quantity. It may indicate that permeability decreases over time and added ASC (I) decrease the permeability in the short term.

The initial compositions (A), (B) and (C) after seven days of curing time was found to have densities of 2102.0 kg/m^3, 2074.0 kg/m^3 and 2025.3 kg/m^3 respectively, and compositions with added sewage sludge ash (D), (E), (F) and (G) was found to have densities of 2119.1 kg/m^3, 2098.2 kg/m^3, 2101.6 kg/m^3 and 2119.1 kg/m^3 respectively. Porosities for compositions (D), (E), (F) and (G) was 16.3 %, 15.6%, 16.1% and 16.5% respectively which was less than reference composition (A) which was found to be 18.6%. This indicates that added ASC (I) decreases the porosity.

Compression tests showed that compositions (B) and (C) after five days of curing time with 41 MPa and 36 MPa respectively was less than reference composition (A) with 46 MPa which was also the case for seven days of curing time for (A), (B) and (C) with 44 MPa, 41 MPa and 42 MPa respectively. Normalizing (B) and (C) for seven days with respect to five days of curing time showed that (C) increased its compressive strength with 115% while (B) did not increase. Composition (C) was found by normalizing with respect to Bolomey's calculated compressive strength to be 131% while (B) was found to be 100%. Furthermore, the obtained colour from use of ASC (I) is not thought to be a direct issue for hidden away or judiciously marketed applications.

Compositions (F) and (G) was found to have a significant high compressive strength with 52.0 MPa and 52.1 MPa respectively, which by normalizing with respect to reference composition (A) were found to be 117% and 117% which led to the optimal powder-cement ratio of $P/c = 0.1$. Further, compositions (J) and (K) was found to have the highest compressive strength with 54.5 MPa and 55.9 MPa respectively which by normalizing with respect to reference composition (A) was found to be 123% and 126% and its corresponding water-cement-powder ratio was found to be $w/(P + c) = 0.42$. All compositions (D)-(O) by normalizing with respect to Bolomey's calculated strengths was found to be stronger than reference composition (A) which strongly indicate strengthening properties of ASC (I), however, it is difficult to conclude if they are pozzolanic or compacting.

The activity factor was found to be $k = 0.77$ based on initial composition (B) and (C) while based on the compressive obtained strengths for (D), (E), (F), (G), (H) and (I) was found to be $k = 0.57$.

6 Further research

Several subjects seemed appealing to investigate prospectively during this report and they are listed below.

- ICP measurement showed that ASC (I) is rich in phosphor leading to investigating whether its high phosphor content affects the compressive strength.
- Experiments where sewage sludge ash is set to react with calcium hydroxide would provide specific evidence whether or not there is pozzolanic material present based on the knowledge that pozzolanic materials react with calcium hydroxide.
- Capillary experiment for concrete should last at least 17 days according to (Hendrichsen, 1997)[17] and it would be interesting to do so for compositions with added sewage sludge ash.
- Investigating if mortar with sewage sludge ash have any long term disadvantages in terms of corrosion, durability or solubility.
- Identify the amount of elements calcium, iron, aluminium, silicon and compare these with coal fly ash to determine if the necessary elements are present.

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7 Appendices

List of appendices

Appendices A - Results

Appendices B - Poster

Appendices C - Experimental approach

A Results

A.1 Initial compressive tests

Composition (A) - compressive results with 1 days of curing time						
	Compression [kN]		**A [mm^2]**	**Compression [MPa]**		**SD [MPa]**
1	34	31	1663,61	20,44	18,63	1,35
2	35	30	1646,97	21,04	18,03	
3	30	34	1560,00	18,03	20,44	
Composition (A) - compressive results with 3 days of curing time						
1	30	34	1663,61	20,63	21,25	0,65
2	30	34	1646,97	21,25	21,88	
3	31	35	1560,00	21,25	22,50	
Composition (A) - compressive results with 5 days of curing time						
1	73	76	1612,02	45,28	47,15	1,02
2	72	72	1588,00	44,66	44,66	
3	75	73	1592,00	46,53	45,28	
Composition (B) - compressive results with 1 days of curing time						
1	33	36	1604	20,57	22,44	0,64
2	34	35	1592	21,20	21,82	
3	34	34	1600	21,20	21,20	
Composition (B) - compressive results with 3 days of curing time						
1	53	57	1602	33,04	35,54	1,35
2	59	58	1600	36,78	36,16	
3	56	55	1600	34,91	34,29	
Composition (B) - compressive results with 5 days of curing time						
1	66	66	1596	41,15	41,15	0,92
2	63	67	1600	39,28	41,77	
3	66	67	1600	41,15	41,77	
Composition (C) - compressive results with 1 days of curing time						
1	26	25	1604	20,57	22,44	0,64
2	22	24	1592	21,20	21,82	
3	25	28	1600	21,20	21,20	
Composition (C) - compressive results with 3 days of curing time						
1	46	51	1602	33,04	35,54	1,35
2	49	48	1600	36,78	36,16	
3	50	51	1600	34,91	34,29	
Composition (C) - compressive results with 5 days of curing time						
1	60	60	1596	41,15	41,15	0,92
2	56	57	1600	39,28	41,77	
3	57	60	1600	41,15	41,77	

Composition (A) - dimensions - 1 days of curing time

	length [mm	width [mm]	height [mm]	weight [g]
1	160,8	41,3	40,3	575,7
2	160,8	41,0	40,2	572,3
3	160,0	39,0	40,0	564,2
Composition (A) - dimensions - 3 days of curing time				
1	160,8	41,3	40,5	586,3
2	160,1	41,3	40,0	592,6
3	160,3	40,5	40,0	581,2
Composition (A) - dimensions - 5 days of curing time				
1	160,9	40,2	40,1	577,0
2	160,8	39,7	40,0	574,0
3	160,6	39,8	40,0	573,0
Composition (B) - dimensions - 1 days of curing time				
1	160,0	40,0	40,1	563,0
2	160,2	39,8	40,0	570,0
3	160,0	40,0	40,0	567,0
Composition (B) - dimensions - 3 days of curing time				
1	160,0	40,0	40,1	573,0
2	160,5	40,0	40,0	584,0
3	160,5	40,0	40,0	576,0
Composition (B) - dimension - 5 days of curing time				
1	160,0	39,9	40,0	578,0
2	160,0	40,0	40,0	584,0
3	160,0	40,0	40,0	577,0
Composition (C) - dimensions - 1 days of curing time				
1	160,2	39,7	40,1	578,0
2	160,0	40,0	40,1	577,0
3	160,0	40,0	40,0	578,0
Composition (C) - dimensions - with 3 days of curing time				
1	160,1	40,1	40,0	578,0
2	161,0	40,0	40,0	578,0
3	162,5	40,0	42,0	602,0
Composition (C) - dimensions - with 5 days of curing time				
1	160,0	39,9	40,0	578,0
2	160,1	40,0	40.1	572,0
3	162,7	40,0	41,9	600,6

A.2 Compressive tests - 7 days of curing time

Compression results for compositions (A)-(O)

		Compression [kN]		Area [mm^2]	Compression [MPa]		Tensile [MPa]	SD [MPa]
(A)	1	79	74	1640	48,2	45,1	9,0	4,11
	2	70	79	1640	42,7	48,2	7,4	
	3	74	61	1640	45,1	37,2	7,9	
(B)	1	57	57	1620	35,2	35,2	7,8	5,01
	2	67	74	1624	41,3	45,6	7,8	
	3	74	74	1632	45,3	45,3	8,0	
(C)	1	70	70	1608	43,5	43,5	7,6	1,79
	2	70	67	1640	42,7	40,9	6,4	
	3	64	68	1644	38,9	41,4	7,5	
(D)	1	64	80	1620	39,2	49,4	7,2	4,18
	2	80	78	1620	49,4	48,1	7,1	
	3	79	81	1608	49,1	50,4	6,8	
(E)	1	67	69	1636	41,0	42,2	7,1	3,88
	2	81	79	1632	49,6	48,4	7,8	
	3	81	77	1624	49,9	47,4	7,7	
(F)	1	84	84	1620	51,9	51,9	7,0	0,67
	2	83	86	1612	51,5	53,3	6,8	
	3	83	83	1604	51,7	51,7	7,3	
(G)	1	82	85	1624	50,5	52,3	6,7	1,05
	2	82	84	1600	51,3	52,5	6,9	
	3	86	85	1612	53,3	52,7	6,2	
(H)	1	83	80	1620	51,2	49,4	7,1	3,36
	2	82	70	1644	49,9	42,6	7,5	
	3	85	83	1644	51,7	50,5	7,5	
(I)	1	78	79	1632	47,8	48,4	6,6	0,80
	2	77	75	1620	47,5	46,3	7,3	
	3	78	79	1628	47,9	48,5	7,6	
(J)	1	92	89	1620	56,8	54,9	7,8	1,32
	2	87	89	1640	53,0	54,3	7,4	
	3	88	89	1644	53,5	54,1	8,2	
(K)	1	91	92	1636	55,6	56,2	8,1	1,48
	2	91	89	1636	55,6	54,4	11,0	
	3	90	96	1636	55,0	58,7	7,4	
(L)	1	84	83	1600	52,5	51,9	7,6	1,41
	2	84	85	1600	52,5	53,1	8,2	
	3	79	85	1600	49,4	53,1	7,2	
(M)	1	76	77	1636	46,5	47,1	7,4	0,55
	2	79	78	1644	48,1	47,4	7,8	
	3	77	78	1640	47,0	47,6	7,9	
(N)	1	73	75	1628	44,8	46,1	7,7	0,89
	2	74	73	1648	44,9	44,3	7,6	
	3	76	76	1640	46,3	46,3	6,8	
(O)	1	68	68	1604	42,4	42,4	7,5	2,12
	2	66	68	1640	40,2	41,5	7,3	
	3	63	61	1636	38,5	37,3	6,8	

Dimensions for compositions (A)-(O)

		length [mm]	width [mm]	height [mm]	weight [g]
(A)	1	160,5	40,1	41,0	595,0
	2	106,1	40,0	41,0	590,0
	3	160,5	40,0	41,0	591,0
(B)	1	160,3	40,0	40,5	582,2
	2	160,4	40,0	40,6	582,7
	3	160,0	40,0	40,8	580,9
(C)	1	159,9	40,0	40,2	575,0
	2	159,9	40,0	41,0	573,4
	3	159,5	40,0	41,1	576,8
(D)	1	160,0	40,0	40,5	577,0
	2	160,0	40,0	40,5	577,0
	3	160,1	40,0	40,2	576,0
(E)	1	161,5	40,0	40,9	597,3
	2	161,8	40,0	40,8	595,0
	3	161,5	40,0	40,6	596,0
(F)	1	160,0	40,0	40,5	577,0
	2	160,0	40,0	40,3	574,0
	3	160,0	40,0	40,1	578,0
(G)	1	160,0	40,0	40,6	577,0
	2	160,0	40,0	40,0	573,0
	3	160,0	40,0	40,3	573,0
(H)	1	161,8	40,0	40,5	599,6
	2	162,0	40,0	41,1	602,5
	3	161,9	40,0	41,1	601,5
(I)	1	161,1	40,0	40,8	594,0
	2	160,5	40,0	40,5	584,0
	3	161,0	40,0	40,7	588,0
(J)	1	160,0	40,0	40,5	588,6
	2	160,0	40,0	41,0	591,8
	3	160,0	40,0	41,1	589,3
(K)	1	160,0	40,0	40,9	581,7
	2	160,0	40,0	40,9	584,9
	3	160,0	40,0	40,9	584,4
(L)	1	160,0	40,0	40,0	576,2
	2	160,0	40,0	40,0	575,8
	3	160,0	40,0	40,0	575,0
(M)	1	160,0	40,0	40,9	580,3
	2	160,0	40,0	41,1	580,4
	3	160,0	40,0	41,0	579,3
(N)	1	160,0	40,0	40,7	585,3
	2	160,0	40,0	41,2	583,7
	3	160,0	40,0	41,0	583,9
(O)	1	160,0	40,0	40,1	577,6
	2	160,0	40,0	41,0	582,9
	3	160,0	40,0	40,9	582,5

Avg. Compression results and Bolomey's calculated strengths

	Compression avg. [MPa]	Bolomey's compression [MPa]	Normalize w. respect to Bolomey's [Note subtracted 13%)]	Normalize w. respect to (A) [Note subtracted 13%]
(A)	44,4	39,2	1,00	1,00
(B)	41,3	36,4	1,00	0,93
(C)	41,8	29,0	1,31	0,94
(D)	47,6	39,2	1,08	1,07
(E)	46,4	39,2	1,05	1,05
(F)	52,0	39,2	1,20	1,17
(G)	52,1	39,2	1,20	1,17
(H)	49,2	38,0	1,17	1,11
(I)	47,7	36,8	1,17	1,08
(J)	54,5	43,3	1,13	1,23
(K)	55,9	42,1	1,20	1,26
(L)	52,1	39,2	1,20	1,17
(M)	47,3	36,5	1,16	1,06
(N)	45,5	34,1	1,20	1,02
(O)	40,4	31,9	1,14	0,91

A.3 Capillarity

Composition (A) 7 days of curing time

t [min]	√t [√s]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0	517,87	519,85	529,85	0	0	0	0
1	7,7	518,53	521,43	530,56	0,420	1,008	0,448	0,625
2	11,0	518,78	521,48	530,69	0,578	1,040	0,530	0,716
4	15,5	519,06	521,79	530,93	0,756	1,237	0,681	0,892
8	21,9	519,44	522,11	531,25	0,998	1,441	0,883	1,108
16	31,0	519,94	522,54	531,73	1,316	1,716	1,186	1,406
32	43,8	520,67	523,19	532,33	1,780	2,130	1,564	1,825
60	60,0	521,53	523,89	533,06	2,327	2,577	2,025	2,309
120	84,9	522,68	524,90	534,07	3,058	3,221	2,662	2,980
240	120,0	523,69	526,21	535,31	3,698	4,057	3,444	3,733

Composition (A) 28 days of curing time

t [min]	√t [√s]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0	545,39	549,87	556,90	0	0	0	0
1	7,7	546,00	550,46	557,48	0,371	0,359	0,350	0,360
2	11,0	546,21	550,66	557,69	0,499	0,481	0,477	0,485
4	15,5	546,43	550,86	557,89	0,633	0,602	0,598	0,611
8	21,9	546,72	551,13	558,18	0,809	0,766	0,773	0,783
16	31,0	547,07	551,48	558,55	1,022	0,979	0,996	0,999
32	43,8	547,57	551,98	559,06	1,326	1,283	1,304	1,305
60	60,0	548,22	552,64	559,71	1,721	1,685	1,697	1,701
120	84,9	549,25	553,66	560,71	2,348	2,305	2,301	2,318
240	120,0	550,70	555,04	562,17	3,230	3,145	3,183	3,186

Composistion (B) 7 days of curing time

t [min]	√t [√s]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	540,24	561,43	540,81	0	0	0	0
1	7,7	540,91	561,98	541,55	0,416	0,345	0,457	0,406
2	11,0	541,28	562,25	541,96	0,645	0,514	0,710	0,623
4	15,5	541,58	562,51	542,31	0,831	0,677	0,926	0,811
8	21,9	542,02	562,74	542,71	1,104	0,821	1,173	1,033
16	31,0	542,54	563,11	543,35	1,427	1,053	1,568	1,349
32	43,8	543,39	563,65	544,23	1,954	1,391	2,111	1,819
60	60,0	544,37	564,29	545,33	2,562	1,792	2,790	2,381
120	84,9	545,83	565,30	547,00	3,468	2,425	3,821	3,238
240	120,0	547,66	566,58	548,81	4,603	3,227	4,938	4,256

Composistion (B) 28 days of curing time

t [min]	√t [√s]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	mt,1 [kg]	mt,2 [kg]	mt,3 [kg]	0	0	0	0
1	7,7	536,82	531,12	535,05	0,000	0,000	0,000	0,000
2	11,0	537,75	531,71	535,56	0,566	0,363	0,317	0,415
4	15,5	538,09	531,97	535,81	0,772	0,523	0,473	0,589
8	21,9	538,36	532,30	536,06	0,937	0,727	0,628	0,764
16	31,0	538,56	532,77	536,42	1,058	1,016	0,852	0,975
32	43,8	539,15	533,38	536,90	1,417	1,392	1,150	1,320
60	60,0	539,90	534,16	537,51	1,873	1,872	1,530	1,758
120	84,9	541,04	535,35	538,45	2,567	2,605	2,114	2,429
240	120,0	542,59	536,97	539,77	3,510	3,602	2,935	3,349

Composistion (C) 7 days of curing time

t [min]	√t [√s]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	523,14	524,81	521,27	0	0	0	0
1	7,7	523,93	525,57	522,03	0,482	0,469	0,473	0,474
2	11,0	524,25	525,94	522,30	0,677	0,698	0,641	0,672
4	15,5	524,71	526,51	522,70	0,957	1,049	0,889	0,965
8	21,9	525,41	527,18	523,33	1,384	1,463	1,281	1,376
16	31,0	526,07	528,00	524,07	1,787	1,969	1,741	1,832
32	43,8	526,93	528,92	525,01	2,311	2,537	2,326	2,391
60	60,0	528,07	530,05	526,12	3,006	3,235	3,016	3,086
120	84,9	529,61	531,73	527,82	3,945	4,272	4,073	4,097
240	120,0	531,52	533,71	529,58	5,110	5,494	5,168	5,257

Composistion (C) 28 days of curing time

t [min]	√t [√s]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	536,82	531,12	535,05	0	0	0	0
1	7,7	537,75	531,71	535,56	0,566	0,363	0,317	0,415
2	11,0	538,09	531,97	535,81	0,772	0,523	0,473	0,589
4	15,5	538,36	532,30	536,06	0,937	0,727	0,628	0,764
8	21,9	538,56	532,77	536,42	1,058	1,016	0,852	0,975
16	31,0	539,15	533,38	536,90	1,417	1,392	1,150	1,320
32	43,8	539,90	534,16	537,51	1,873	1,872	1,530	1,758
60	60,0	541,04	535,35	538,45	2,567	2,605	2,114	2,429
120	84,9	542,59	536,97	539,77	3,510	3,602	2,935	3,349
240	120,0	544,47	538,99	541,36	4,653	4,846	3,924	4,474

Composistion (D) 7 days of curing time

t [min]	$\sqrt{t}$ [$\sqrt{s}$]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	539,91	539,78	543,46	0	0	0	0
1	7,7	540,45	540,29	543,94	0,333	0,315	0,299	0,315
2	11,0	540,70	540,51	544,13	0,486	0,451	0,417	0,451
4	15,5	540,88	540,66	544,26	0,597	0,543	0,498	0,546
8	21,9	541,10	540,85	544,45	0,732	0,660	0,616	0,669
16	31,0	541,44	541,16	544,71	0,941	0,852	0,777	0,857
32	43,8	541,87	541,57	545,08	1,212	1,105	1,007	1,108
60	60,0	542,56	542,23	545,66	1,638	1,512	1,368	1,506
120	84,9	543,57	543,21	546,59	2,260	2,117	1,947	2,108
240	120,0	545,14	544,75	548,11	3,229	3,068	2,892	3,063

Composistion (E) 7 days of curing time

t [min]	$\sqrt{t}$ [$\sqrt{s}$]	m_t [kg]	m_t [kg]	m_t [kg]	Q [kg/m^2]	Q [kg/m^2]	Q [kg/m^2]	Q [kg/m^2] avg.
0	0,0	541,86	540,66	540,88	0	0	0	0
1	7,7	542,43	541,20	541,37	0,348	0,331	0,302	0,327
2	11,0	542,59	541,33	541,51	0,445	0,411	0,388	0,414
4	15,5	542,77	541,48	541,66	0,554	0,502	0,480	0,512
8	21,9	543,00	541,68	541,88	0,694	0,625	0,616	0,645
16	31,0	543,30	541,95	542,16	0,877	0,790	0,788	0,819
32	43,8	543,65	542,28	542,52	1,097	0,993	1,010	1,033
60	60,0	544,28	542,88	543,15	1,481	1,360	1,398	1,413
120	84,9	545,17	543,74	544,06	2,024	1,887	1,958	1,957
240	120,0	546,53	545,07	545,50	2,855	2,702	2,845	2,801

Composistion (F) 7 days of curing time

t [min]	$\sqrt{t}$ [$\sqrt{s}$]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	545,89	544,23	543,07	0,00	0	0	0
1	7,7	546,40	544,71	543,57	0,31	0,298	0,312	0,308
2	11,0	546,54	544,82	543,75	0,40	0,366	0,424	0,397
4	15,5	546,69	544,94	543,91	0,49	0,440	0,524	0,485
8	21,9	546,88	545,10	544,14	0,61	0,540	0,667	0,605
16	31,0	547,11	545,30	544,40	0,75	0,664	0,829	0,748
32	43,8	547,41	545,58	544,82	0,94	0,837	1,091	0,956
60	60,0	547,95	546,09	545,48	1,27	1,154	1,502	1,310
120	84,9	548,77	546,88	546,45	1,78	1,644	2,107	1,843
240	120,0	550,11	548,19	547,97	2,61	2,457	3,055	2,706

Composistion (G) 7 days of curing time

t [min]	$\sqrt{t}$ [$\sqrt{s}$]	$m_{t,1}$ [kg]	$m_{t,2}$ [kg]	$m_{t,3}$ [kg]	Q_1 [kg/m^2]	Q_2 [kg/m^2]	Q_3 [kg/m^2]	Q [kg/m^2] avg.
0	0,0	543,19	545,84	551,31	0	0	0	0
1	7,7	543,79	546,41	551,96	0,369	0,356	0,403	0,376
2	11,0	544,00	546,59	552,13	0,498	0,469	0,509	0,492
4	15,5	544,22	546,78	552,30	0,632	0,587	0,614	0,611
8	21,9	544,51	547,04	552,56	0,810	0,750	0,775	0,779
16	31,0	544,83	547,33	552,88	1,007	0,931	0,974	0,971
32	43,8	545,28	547,76	553,28	1,289	1,200	1,222	1,237
60	60,0	545,96	548,41	553,94	1,708	1,606	1,632	1,648
120	84,9	546,99	549,41	554,90	2,341	2,231	2,227	2,266
240	120,0	548,42	550,81	556,36	3,221	3,106	3,133	3,153

Composition (A) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	39,15	40,18	161	1573,047	517,87
2	39,02	40,18	161	1567,8236	519,85
3	39,32	40,32	160,5	1585,3824	529,85

Composition (A) 28 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	40,2	40,9	160	1644,18	545,39
2	40,1	41	160	1644,1	549,87
3	39,9	41,5	162	1655,85	556,90

Composition (B) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	40	40,3	160,5	1612	540,24
2	39,9	40	160,3	1596	561,43
3	40,1	40,4	160	1620,04	540,81

Composition (B) 28 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	40	40,5	160,5	1620,00	530,83
2	40	40	151	1600,00	529,61
3	40	40,5	160,5	1620,00	532,44

Composition (C) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	41	40	161	1640,00	523,14
2	40,5	40	162	1620,00	524,81
3	40,1	40,1	160,5	1608,01	521,27

Composition (C) 28 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	41	40,1	161	1644,10	536,82
2	40,6	40	160	1624,00	531,12
3	40,1	40,1	160,5	1608,01	535,05

Composition (D) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	40,1	40,8	160,5	1636,08	517,87
2	40,1	41	161,5	1644,10	519,85
3	40,1	41,1	163	1648,11	529,85

Composition (E) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	41,1	40	160,9	1644,00	517,87
2	40,5	40	161	1620,00	519,85
3	40	41	161	1640,00	529,85

Composition (F) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	40	42	162	1680,00	517,87
2	41	40	161,8	1640,00	519,85
3	41,1	40	161,9	1644,00	529,85

Composition (G) 7 days - dimensions and dry mass

	height [mm]	width [mm]	length [mm]	A [mm^2]	m_d [g]
1	41	40	160	1640,00	517,87
2	41,1	40	160,2	1644,00	519,85
3	40	41,5	161,5	1660,00	529,85

A.4 Porosity and density

Porosity and density for 28 days of curing time

		m_{105} [g]	m_{ssd} [g]	m_{sw} [g]	V [m^3]	V_{po} [m^3]	ρ_{po} [m^3]	ρ_d [m^3]	ρ_f [m^3]	ρ_{ssd} [m^3]	u_{ssd} [m^3]
	1	547,62	596,44	337,10	2,60E-04	4,89E-05	0,188	2107,37	2596,07	2295,24	0,089
(A)	2	552,22	601,85	340,02	2,62E-04	4,97E-05	0,190	2104,86	2597,15	2294,03	0,090
	3	559,12	608,09	344,31	2,64E-04	4,91E-05	0,186	2115,41	2597,65	2300,68	0,088
Avg:		552,99	602,13	340,48	2,62E-04	4,92E-05	0,19	2109,21	2596,96	2296,65	0,089
	1	547,91	578,50	317,95	2,61E-04	3,07E-05	0,117	2098,69	2377,87	2215,86	0,056
(B)	2	548,35	578,61	318,85	2,60E-04	3,03E-05	0,116	2106,77	2384,55	2223,02	0,055
	3	536,83	569,98	312,55	2,58E-04	3,32E-05	0,129	2081,17	2388,78	2209,69	0,062
Avg:		544,36	575,70	316,45	2,60E-04	3,14E-05	0,12	2095,54	2383,73	2216,19	0,058
	1	528,08	563,02	304,27	2,59E-04	3,50E-05	0,135	2036,81	2354,78	2171,57	0,066
(C)	2	527,00	562,62	304,31	2,59E-04	3,57E-05	0,138	2036,10	2361,79	2173,72	0,068
	3	528,51	564,72	305,49	2,60E-04	3,63E-05	0,140	2034,69	2365,05	2174,09	0,069
Avg.		527,86	563,45	304,69	2,59E-04	3,57E-05	0,14	2035,87	2360,54	2173,13	0,067

Porosity and density for 7 days of curing time

		m_{105} [g]	m_{ssd} [g]	m_{sw} [g]	V [m^3]	V_{po} [m^3]	ρ_{po} [m^3]	ρ_d [m^3]	ρ_f [m^3]	ρ_{ssd} [m^3]	u_{ssd} [m^3]
	1	519,02	563,15	318,06	2,46E-04	4,42E-05	0,180	2113,44	2577,54	2293,13	0,085
(A)	2	517,65	564,28	317,30	2,47E-04	4,67E-05	0,189	2091,73	2578,56	2280,15	0,090
	3	526,76	573,86	323,64	2,51E-04	4,72E-05	0,188	2100,98	2588,16	2288,83	0,089
Avg:		521,14	567,10	319,67	2,48E-04	4,60E-05	0,19	2102,05	2581,42	2287,37	0,088
	1	525,89	558,44	304,43	2,55E-04	3,26E-05	0,128	2066,21	2369,90	2194,10	0,062
(B)	2	524,81	556,06	302,06	2,55E-04	3,13E-05	0,123	2062,05	2351,34	2184,83	0,060
	3	527,62	561,00	309,52	2,52E-04	3,34E-05	0,133	2093,86	2414,33	2226,33	0,063
Avg:		526,11	558,50	305,34	2,54E-04	3,25E-05	0,13	2074,04	2378,52	2201,76	0,062
	1	516,54	560,63	305,85	2,55E-04	4,42E-05	0,173	2023,34	2446,76	2196,05	0,085
(C)	2	518,34	561,89	305,89	2,57E-04	4,36E-05	0,170	2020,72	2434,94	2190,49	0,084
	3	514,92	557,30	304,37	2,53E-04	4,25E-05	0,168	2031,75	2440,70	2198,97	0,082
Avg:		516,60	559,94	305,37	2,55E-04	4,34E-05	0,17	2025,27	2440,80	2195,17	0,084
	1	539,91	587,65	332,19	2,56E-04	4,78E-05	0,187	2109,25	2594,02	2295,76	0,088
(D)	2	539,78	578,35	322,85	2,56E-04	3,86E-05	0,151	2108,42	2483,29	2259,07	0,071
	3	543,46	581,54	328,04	2,54E-04	3,82E-05	0,150	2139,54	2517,75	2289,46	0,070
Avg:		541,05	582,51	327,69	2,55E-04	4,15E-05	0,16	2119,07	2531,69	2281,43	0,077
	1	541,86	589,85	331,97	2,58E-04	4,81E-05	0,186	2097,01	2576,47	2282,73	0,089
(E)	2	540,66	576,47	318,02	2,59E-04	3,59E-05	0,139	2087,75	2423,55	2226,03	0,066
	3	540,88	577,35	321,51	2,56E-04	3,65E-05	0,143	2109,91	2460,67	2252,17	0,067
Avg:		541,13	581,22	323,83	2,58E-04	4,02E-05	0,16	2098,22	2486,90	2253,64	0,074
	1	545,89	594,94	334,96	2,61E-04	4,91E-05	0,189	2095,54	2582,84	2283,83	0,090
(F)	2	544,23	581,84	324,83	2,58E-04	3,77E-05	0,146	2113,31	2475,58	2259,35	0,069
	3	543,07	581,67	323,10	2,59E-04	3,87E-05	0,149	2096,08	2463,90	2245,07	0,071
Avg:		544,40	586,15	327,63	2,59E-04	4,18E-05	0,16	2101,64	2507,44	2262,75	0,077
	1	543,19	591,46	332,70	2,59E-04	4,84E-05	0,187	2095,01	2575,44	2281,18	0,089
(G)	2	545,84	585,39	330,15	2,56E-04	3,96E-05	0,155	2134,26	2525,61	2288,90	0,072
	3	551,31	591,25	332,69	2,59E-04	4,00E-05	0,154	2127,97	2516,73	2282,13	0,072
Avg:		546,78	589,37	331,85	2,58E-04	4,27E-05	0,17	2119,08	2539,26	2284,07	0,078

A.5 Characteristics of ASC (I)

Water content

		m_w [g]	m_d [g]	water [g]	Content [%]	Avg.' [%]	SD [%]
ASC (I)	1	12,65	12,54	0,11	0,87%	0,835%	0,059%
	2	11,73	11,64	0,09	0,77%		
	3	17,28	17,13	0,15	0,87%		
ASC (II)	1	11,07	10,97	0,10	0,90%	0,899%	0,117%
	2	11,54	11,45	0,09	0,78%		
	3	9,86	9,76	0,10	1,01%		

Conductivity

		Conductivity [mS/cm]	Avg. [mS/cm]	SD [mS/cm]
ASC (I)	1	1,495	1,51	0,011
	2	1,516		
	3	1,505		
ASC (II)	1	1,566	1,71	0,152
	2	1,693		
	3	1,869		

pH

		pH	Avg [pH]	SD [pH]
ASC (I)	1	8,43	8,42	0,036
	2	8,45		
	3	8,38		
ASC (II)	1	7,27	7,25	0,021
	2	7,26		
	3	7,23		

Loss on ignition for

		m_1 [g]	m_2 [g]	Loss on ignition [%]	Avg [%]	SD [%]
ASC (I)	1	4,944	4,884	1,22%	1,19%	0,023%
	2	4,820	4,763	1,18%		
	3	4,792	4,736	1,18%		
ASC (II)	1	4,231	4,184	1,11%	1,11%	0,015%
	2	4,035	3,990	1,11%		
	3	5,601	5,538	1,13%		

Water solubility

	m_1 [g]	m_2 [g]	Solubility [%]
ASC (I)	109,94	106,59	3,05%
ASC (II)	110,11	108,49	1,47%

A.6 IC measurements

Ionchromotograf

Sewage sludge ash	Ash [g]	Dem. Water [g]	mg/L Cl	mg/kg Cl	mg/l NO3	mg/kg NO3	mg/L SO4	mg/kg SO4
ASC (I)	10,0	50,0	414,2744	2071,3721	2,0575	10,2875	1804,5063	9022,5316
	10,0	50,0	431,1384	2155,6918	1,5373	7,6864	1900,7874	9503,9372
	10,0	50,0	415,0962	2075,4812	1,5873	7,9367	1957,8376	9789,1882
Avg.			420,1697	2100,8484	1,7274	8,6369	1887,7105	9438,5523
ASC (II)	10,0	50,0	5,2801	26,4007	6,6754	33,3768	1678,5664	8392,8318
	10,0	50,0	5,1978	25,9890	6,6192	33,0960	1705,7721	8528,8603
	10,0	50,0	5,1927	25,9634	6,8152	34,0759	1640,4954	8202,4771
Avg.			5,2235	26,1177	6,7032	33,5162	1674,9446	8374,7231

A.7 ICP measurements

ICP measurement via digestion

	ASC (I)			Avg. [mg/kg]
Ash [g]	1	1	1	
Dem. water [mL]	101	100	100	
mg/L Al	287,186	301,347	305,682	
mg/kg Al	29005,786	30134,700	30568,200	29902,8953
mg/L As	0,005	0,005	0,000	
mg/kg As	0,457	0,525	0,000	0,3274
mg/L Cd	0,031	0,035	0,036	
mg/kg Cd	3,096	3,451	3,591	3,3795
mg/L Cr	0,559	0,579	0,590	
mg/kg Cr	56,470	57,872	58,967	57,7698
mg/L Cu	6,442	6,764	6,792	
mg/kg Cu	650,637	676,398	679,231	668,7553
mg/L Ni	0,168	0,062	0,060	
mg/kg Ni	16,960	6,184	5,951	9,6986
mg/L Pb	1,190	1,216	1,269	
mg/kg Pb	120,234	121,587	126,868	122,8965
mg/L Zn	25,168	26,460	26,971	
mg/kg Zn	2541,918	2645,970	2697,060	2628,3158
mg/L Na	34,768	35,642	36,435	
mg/kg Na	3511,598	3564,230	3643,450	3573,0928
mg/L K	56,826	58,800	59,769	
mg/kg K	5739,466	5879,950	5976,890	5865,4355
mg/L P	928,484	992,290	1000,220	
mg/kg P	93776,884	99229,000	100022,000	97675,9613
mg/L Mg	116,416	117,392	124,434	
mg/kg Mg	11758,016	11739,200	12443,400	11980,2053

	ASC (II)			Avg. [mg/kg]
Ash [g]	1,000	1,000	1,000	
Dem. water [mL]	100,000	100,000	100,000	
mg/L Al	297,021	441,838	295,991	
mg/kg Al	29702,100	44183,800	29599,100	34495,0000
mg/L As	0,000	0,000	0,000	
mg/kg As	0,000	0,000	0,000	0,0000
mg/L Cd	0,026	0,039	0,032	
mg/kg Cd	2,608	3,905	3,235	3,2493
mg/L Cr	0,632	0,901	0,648	
mg/kg Cr	63,218	90,088	64,783	72,6962
mg/L Cu	7,743	11,050	7,851	
mg/kg Cu	774,262	1105,040	785,145	888,1490
mg/L Ni	0,019	0,012	0,156	
mg/kg Ni	1,950	1,216	15,626	6,2638
mg/L Pb	1,117	1,608	1,155	
mg/kg Pb	111,669	160,785	115,539	129,3310
mg/L Zn	26,877	40,088	27,044	
mg/kg Zn	2687,710	4008,820	2704,350	3133,6267
mg/L Na	23,958	33,295	24,314	
mg/kg Na	2395,810	3329,510	2431,430	2718,9167
mg/L K	53,388	75,990	53,528	
mg/kg K	5338,840	7598,970	5352,800	6096,8700
mg/L P	996,625	1658,430	979,738	
mg/kg P	99662,500	165843,000	97973,800	121159,7667
mg/L Mg	118,196	199,221	120,975	
mg/kg Mg	11819,600	19922,100	12097,500	14613,0667

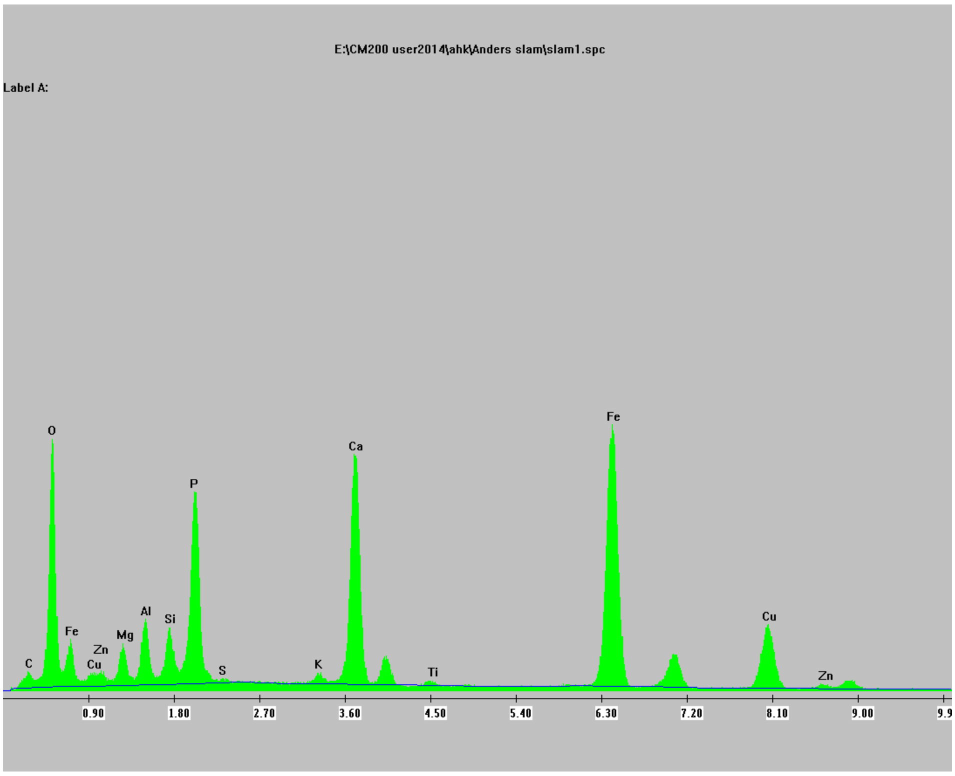
A.8 The curing process - VICA output

Composition (A)				Composition (B)			
Poke no.	**PEN [mm]**	**Prep. [m.s]**	**Initial time of test [m.s]**	**Poke no.**	**PEN [mm]**	**Prep. [m.s]**	**Initial time of test[m.s]**
1	0,1	6,18	0	1	0	10,03	5
2	0,1	16,18	10	2	0	20,03	15
3	0,1	26,18	20	3	0	30,03	25
4	0,1	36,18	30	4	0	40,03	35
5	0,1	46,18	40	5	0	50,03	45
6	0,1	56,18	50	6	0	60,03	55
7	0,1	66,18	60	7	0	70,03	65
8	0	76,18	70	8	0	80,03	75
9	0,1	86,18	80	9	0	90,03	85
10	0,1	96,18	90	10	0	100,03	95
11	0,1	106,18	100	11	0	110,03	105
12	0	116,18	110	12	0	120,03	115
13	0,1	126,18	120	13	0	130,03	125
14	0	136,18	130	14	0	140,03	135
15	0,1	146,18	140	15	0	150,03	145
16	0,1	156,18	150	16	5	160,03	155
17	9,5	166,18	160	17	0	170,03	165
18	26,6	176,18	170	18	0,2	180,03	175
19	23	186,18	180	19	10,4	190,03	185
20	24,3	196,18	190	20	23,3	200,03	195
21	34	206,18	200	21	15,6	210,03	205
22	30,3	216,18	210	22	17,5	220,03	215
23	33,8	226,18	220	23	25,8	230,03	225
24	28,4	236,18	230	24	24,3	240,03	235
25	35,8	246,18	240	25	29	250,03	245
26	37,5	256,18	250	26	25	260,03	255
27	37,4	266,18	260	27	30,1	270,03	265
28	39,2	276,18	270	28	32,2	280,03	275
29	39,9	286,18	280	29	34,5	290,03	285
30	39,9	296,18	290	30	32,8	300,03	295
31	39,7	306,18	300	31	33,2	310,03	305
32	39,2	316,18	310	32	35,1	320,03	315
33	38,8	326,18	320	33	33,6	330,03	325
34	40,1	336,18	330	34	34,4	340,03	335
35	39,2	346,18	340	35	35,3	350,03	345
36	39,2	356,18	350	36	34,2	360,03	355
37	39,9	366,18	360	37	33,9	370,03	365
38	40,2	376,18	370	38	37	380,03	375
39	40,4	386,18	380	39	37,4	390,03	385
40	40,6	396,18	390	40	35,4	400,03	395
41	41,2	406,18	400	41	36,3	410,03	405
42	41,2	416,18	410	42	36,2	420,03	415
43	40,4	426,18	420	43	35,7	430,03	425
44	39,9	436,18	430	44	36,1	440,03	435
45	39,5	446,18	440	45	35,4	450,03	445
46	39,9	456,18	450	46	36	460,03	455
47	39,7	466,18	460	47	37,1	470,03	465
48	40,2	476,18	470	48	36,3	480,03	475
49	40,5	486,18	480	49	34,8	490,03	485
50	40,7	496,18	490	50	35,4	500,03	495
51	40,7	506,18	500	51	35,5	510,03	505
52	41,3	516,18	510	52	36,2	520,03	515
53	41,5	526,18	520	53	36,9	530,03	525
54	41,1	536,18	530	54	37,4	540,03	535
55	40,9	546,18	540	55	36,9	550,03	545
56	40,6	556,18	550	56	37,4	560,03	555
57	40,2	566,18	560	57	36	570,03	565
58	39,9	576,18	570	58	36	580,03	575
59	40,6	586,18	580	59	35,5	590,03	585
60	40,8	596,18	590	60	36,9	600,03	595
61	40,9	606,18	600	61	38,1	610,03	605
62	40,9	616,18	610	62	37,1	620,03	615
63	41,6	626,18	620	63	36,9	630,03	625
64	40,9	636,18	630	64	37,4	640,03	635
65	40,4	646,18	640	65	36,3	650,03	645
66	40	656,18	650	66	36	660,03	655
67	40,5	666,18	660	67	35,8	670,03	665
68	40,8	676,18	670	68	35,4	680,03	675
69	41,1	686,18	680	69	36,4	690,03	685
70	41,2	696,18	690	70	36,5	700,03	695
71	41,3	706,18	700	71	37,5	710,03	705
72	41,4	716,18	710	72	37,1	720,03	715
73	41,1	726,18	720	73	37,5	730,03	725

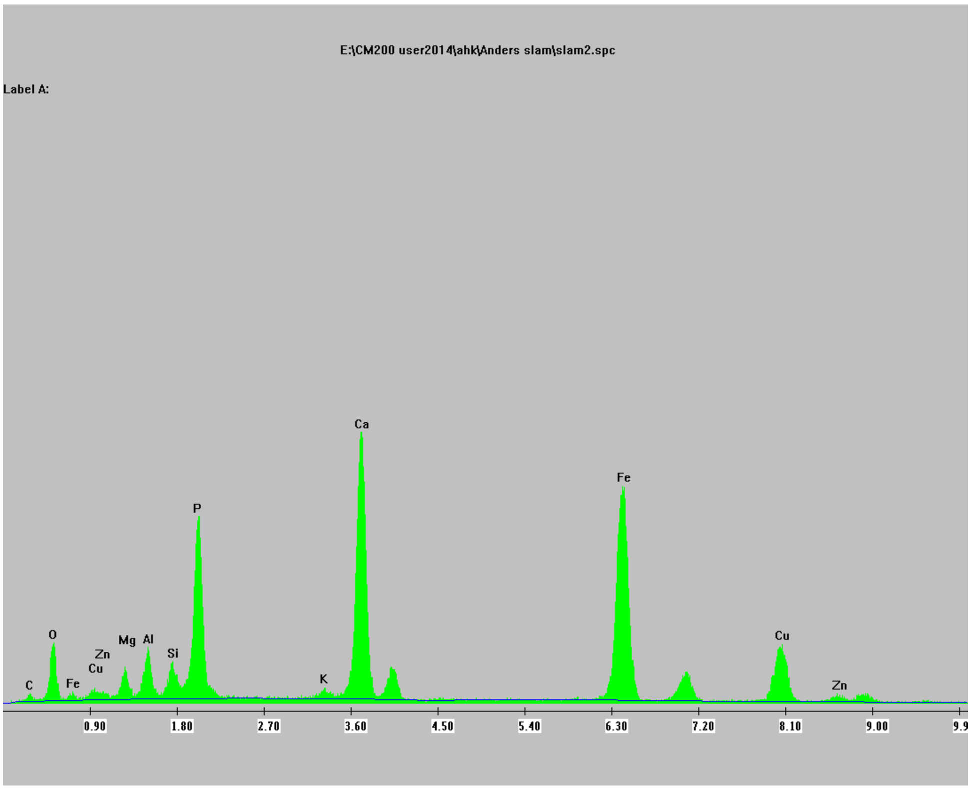
74	40,2	736,18	730	74	35,9	740,03	735
75	40,6	746,18	740	75	36	750,03	745
76	40	756,18	750	76	36,5	760,03	755
77	41,1	766,18	760	77	37,4	770,03	765
78	41,3	776,18	770	78	38	780,03	775
79	40,5	786,18	780	79	37,1	790,03	785
80	40,4	796,18	790	80	36,5	800,03	795
81	40,8	806,18	800	81	36,1	810,03	805
82	40,9	816,18	810	82	36,9	820,03	815
83	41,3	826,18	820	83	38,2	830,03	825
84	41,4	836,18	830	84	37,1	840,03	835
85	40,9	846,18	840	85	37,5	850,03	845
86	40,9	856,18	850	86	37,2	860,03	855

Composition (C)				**Composition (C) continued..**			
Poke no.	**PEN [mm]**	**Prep. [m.s]**	**Initial time of test [m.s]**	**Poke no.**	**PEN [mm]**	**Prep. [m.s]**	**Initial time of test [m.s]**
1	0,1	31,48	5	44	30,7	461,48	435
2	0,1	41,48	15	45	32,3	471,48	445
3	0,1	51,48	25	46	31,3	481,48	455
4	0,2	61,48	35	47	32,2	491,48	465
5	0,1	71,48	45	48	32,4	501,48	475
6	0,1	81,48	55	49	32,5	511,48	485
7	0,1	91,48	65	50	33,9	521,48	495
8	0,1	101,48	75	51	34,4	531,48	505
9	0	111,48	85	52	34,1	541,48	515
10	0	121,48	95	53	34,3	551,48	525
11	0,1	131,48	105	54	35,1	561,48	535
12	0,2	141,48	115	55	34,4	571,48	545
13	0,1	151,48	125	56	35,4	581,48	555
14	0	161,48	135	57	35	591,48	565
15	0,1	171,48	145	58	34,7	601,48	575
16	0,2	181,48	155	59	35,2	611,48	585
17	0,2	191,48	165	60	35,3	621,48	595
18	0,1	201,48	175	61	35,7	631,48	605
19	0	211,48	185	62	35,8	641,48	615
20	0,2	221,48	195	63	35,9	651,48	625
21	0,2	231,48	205	64	35,7	661,48	635
22	0,1	241,48	215	65	35,9	671,48	645
23	0,1	251,48	225	66	35,5	681,48	655
24	0,2	261,48	235	67	35,7	691,48	665
25	0	271,48	245	68	35,6	701,48	675
26	0,2	281,48	255	69	36,2	711,48	685
27	9,6	291,48	265	70	36,2	721,48	695
28	3,3	301,48	275	71	36,4	731,48	705
29	0,3	311,48	285	72	36,1	741,48	715
30	1,9	321,48	295	73	36,3	751,48	725
31	5,8	331,48	305	74	36,1	761,48	735
32	21,3	341,48	315	75	36,2	771,48	745
33	22,6	351,48	325	76	36,4	781,48	755
34	24,6	361,48	335	77	36,2	791,48	765
35	26	371,48	345	78	36,1	801,48	775
36	15,6	381,48	355	79	36,2	811,48	785
37	28	391,48	365	80	36,1	821,48	795
38	27	401,48	375	81	36,2	831,48	805
39	18,8	411,48	385	82	36,1	841,48	815
40	28,9	421,48	395	83	36,4	851,48	825
41	25,9	431,48	405	84	36,6	861,48	835
42	29,2	441,48	415	85	36,2	871,48	845
43	30,2	451,48	425	86	36,3	881,48	855

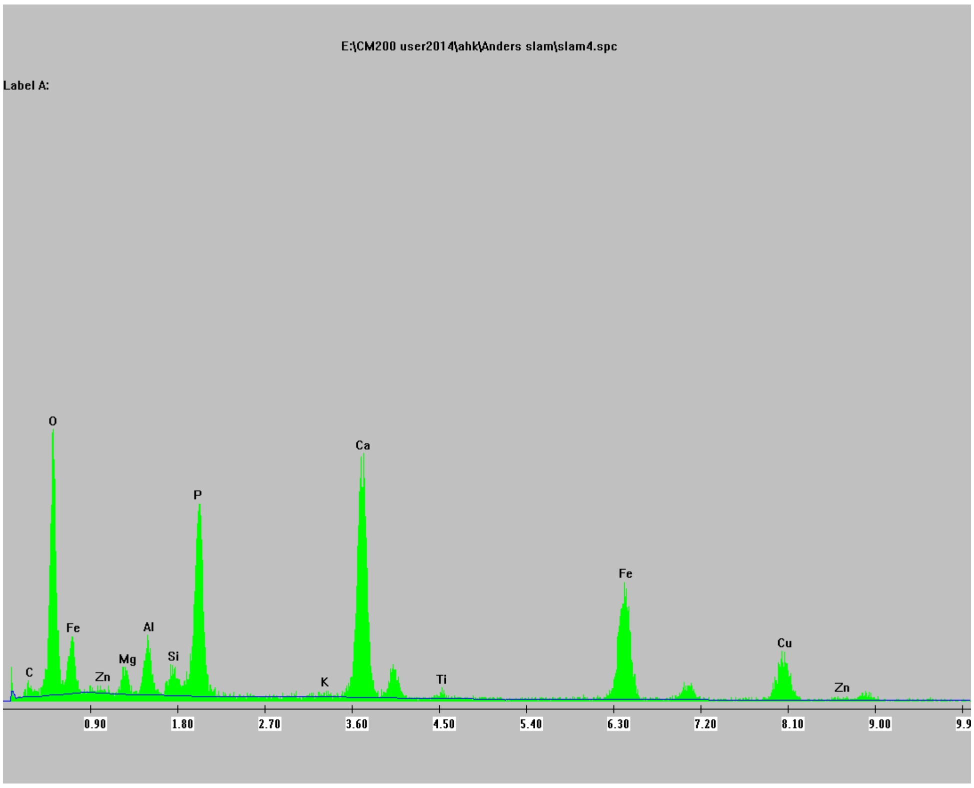
A.9 TEM analysis - ASC (I) location 1



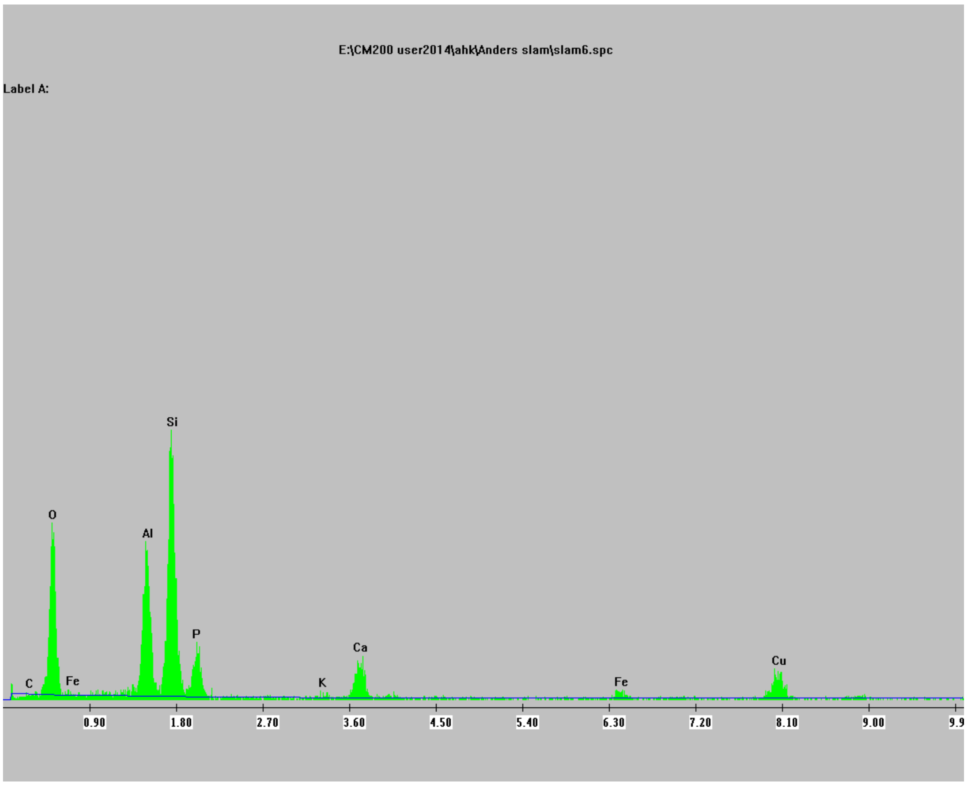
A.10 TEM analysis - ASC (I) location 2



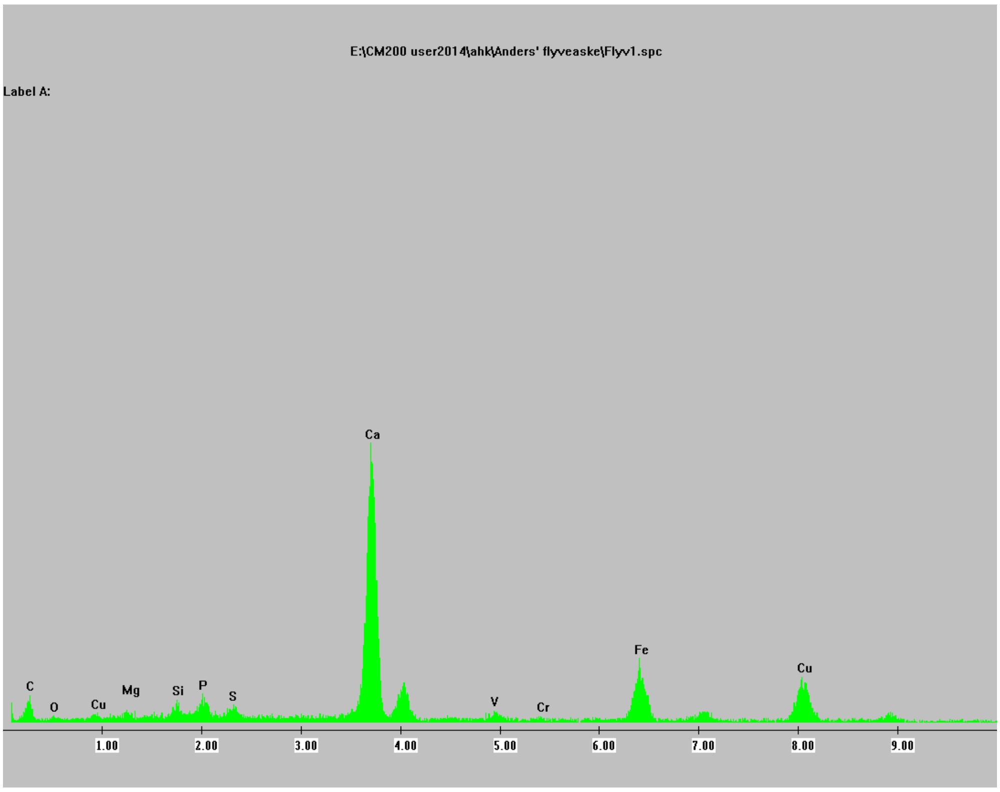
A.11 TEM analysis - ASC (I) location 3



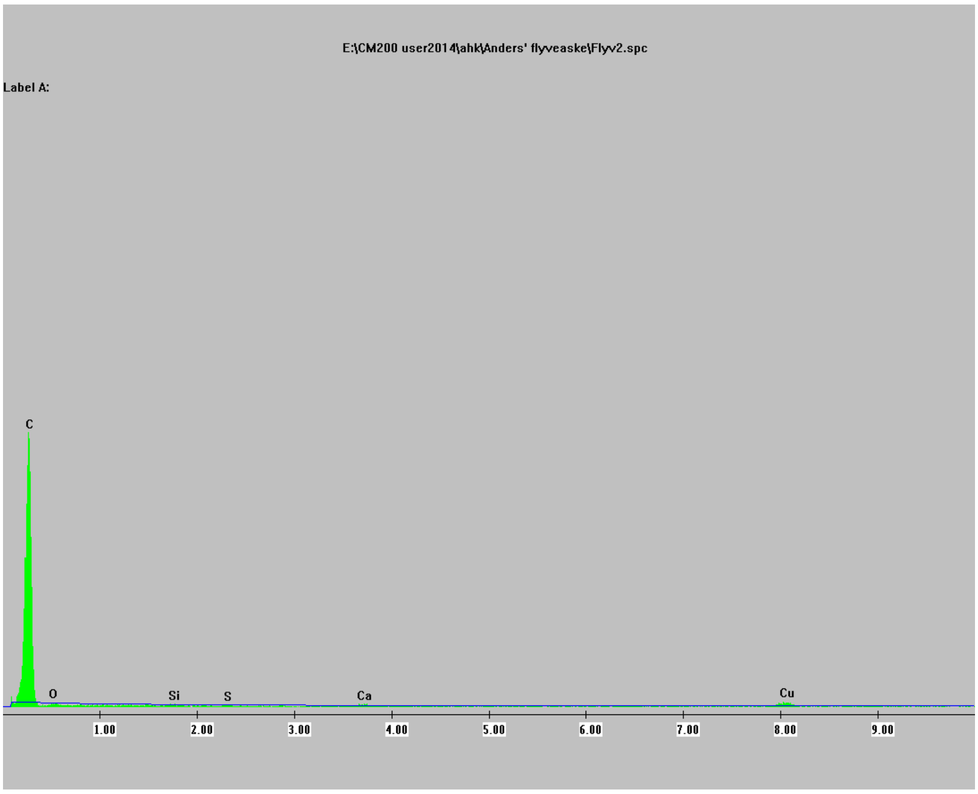
A.12 TEM analysis - ASC (I) location 4



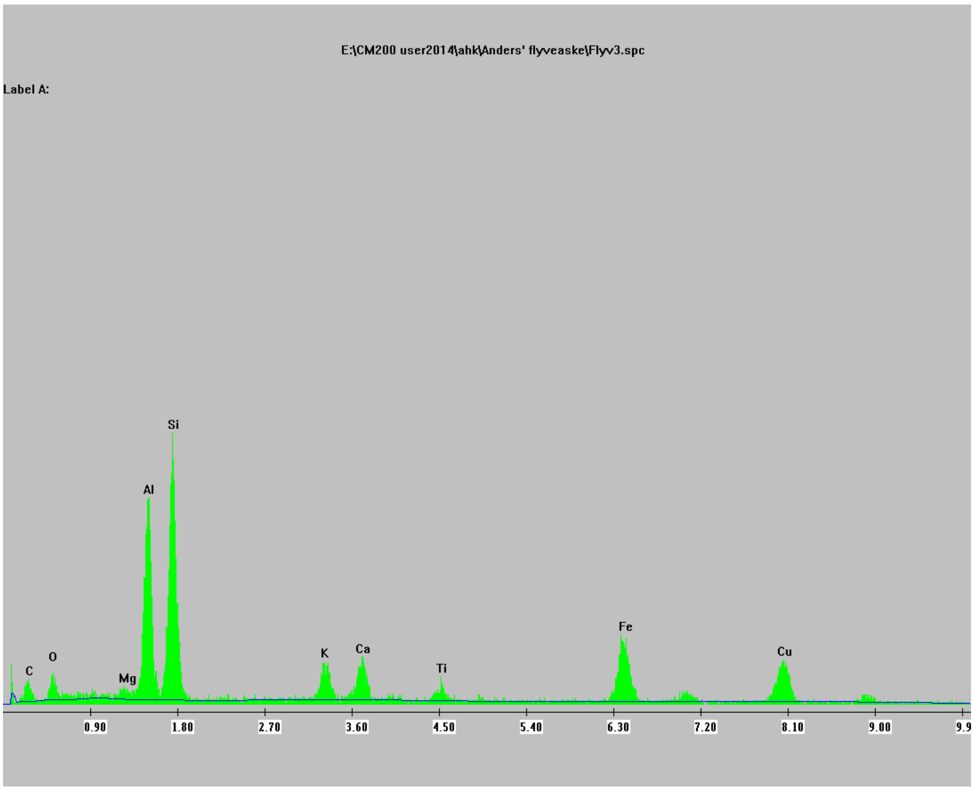
A.13 TEM analysis - CFA location 1



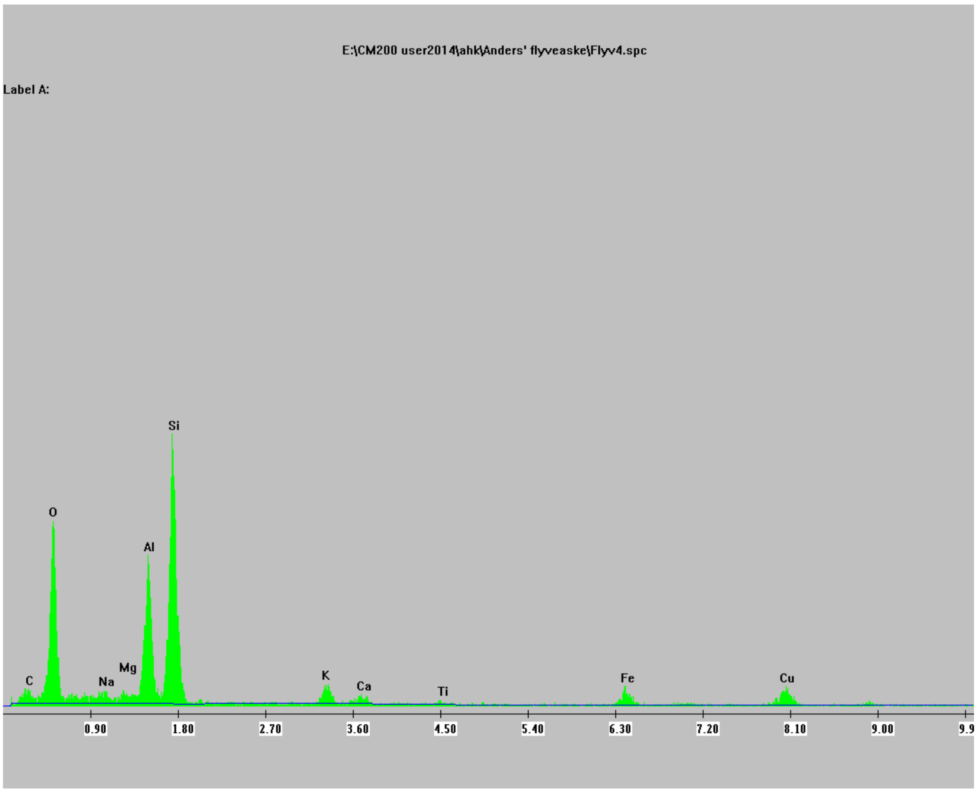
A.14 TEM analysis - CFA location 2



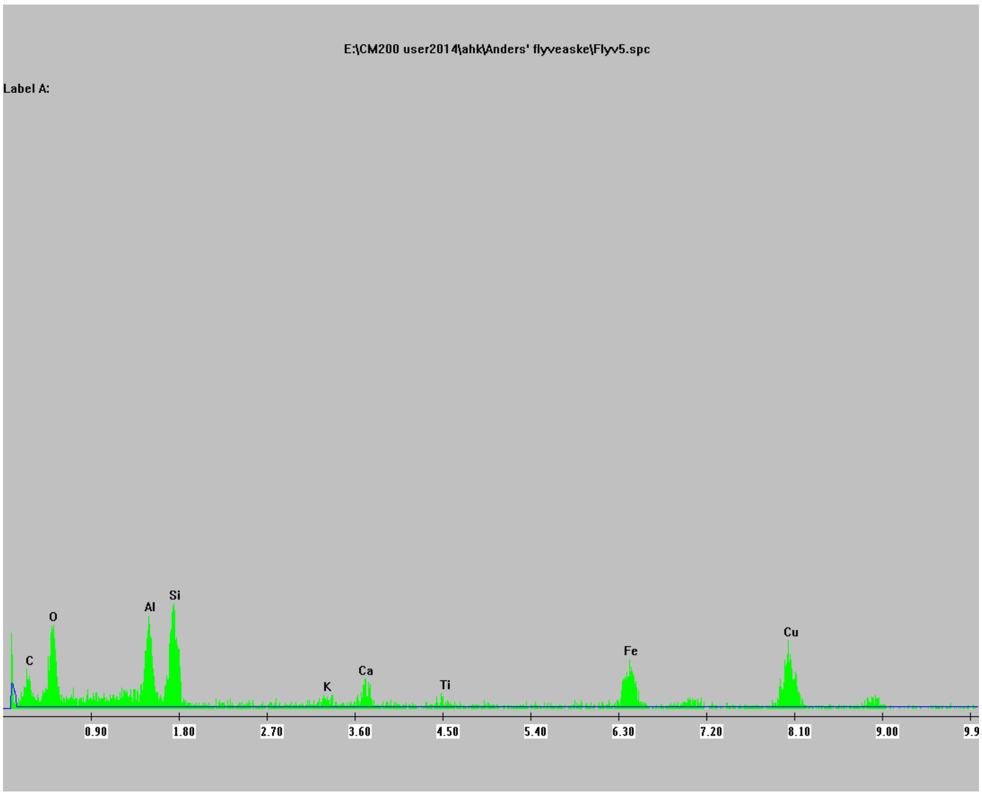
A.15 TEM analysis - CFA location 3



A.16 TEM analysis - CFA location 4



A.17 TEM analysis - CFA location 5



B Calculations

B.1 Poster presentation

Organisk byggeri

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Introduktion

Beton bruges verden over fordi det er et billigt og alsidigt byggemateriale. Beton består hovedsageligt af grus, vand og cement. Desværre medfører cementproduktionen et stort udslip af drivhusgassen CO_2. Cement er desuden dyrt, og her er slamaske interessant som substitution.

Slamaske er afbrændt slam, og er på nuværende tidspunkt et restprodukt med en relativ høj deponeringsafgift. I det henseende er det interessant at undersøge, om slamaske kan erstatte en procentdel af cementen eller sandet uden tab af den puzzolaniske effekt og godkendt til iblanding i beton. I forløbende undersøges fysike egenskaber af møtelprøver med slamaske fra Avedøre spildevandscenter.

Metoder

ICP ICP analyse påviser metaller og bestemmer disses koncentrationen kvantitativt, disse findes i Tabel 1.

STYRKE Betonstyrken findes ved kompressiontest ith. [3] sec. 9.2.

HÆRDNING MATEST Vicatronic detekterer hærdeprocessen for et givent bindemiddel. Test udføres under hele hærdeforløbet automatisk med et tidsinterval på 10 minutter.

Konklusion

Alle undersøgelser er foretaget med kemisk ubehandlet slamaske fra Avedøre spildevandscenter. Slamasken er knust vha. en ringknuser for at opnå en tilpas partikelstørrelse til undersøgelserne.

1. ICP målingerne konkluderer, at ubehandlet slamaske tilhøre kategori 2 iht. [1] §5, hvorved anvendelsen begrænses. Slamasken overholder kravet for kloridindhold i beton iht.[2] sec. 5.2.3.
2. ICP målingerne viser, at slamasken må bruges i beton med spændarmering iht.[4].
3. Kompressionstesten konkluderer, at begge mørtelblandinger har en lavere trykstyrke end referenceprøven efter 5 døgn.
4. 5% cementerstatning overholder kravet for hærdning, hvorimod 10% sanderstatning ikke overholder kravet for hærdning iht.[2] sec. 5.3.5. Vand-cement-forholdet bør for 10% cementerstatning ændres til fra 30% til 25%.

References

[1] Miljøministeriet, *Bekendtgørelse om anvendelse af restprodukter og jord til bygge- og anlægsarbejder og om anvendelse af sorteret, uforurenet bygge- og anlægsaffald*, BEK nr. 1662 2010-12-21

[2] DS/EN 450-1, *Flyveaske til beton - Del 1: Definition, specifikation og overensstemmelsesvurdering*, 2. udgave 2007-11-02

[3] DS/EN 196-1, *Metode til prøvning af cement - Del 1: Styrkebestemmel*, 2. udgave 2005-04-21

[4] DS/EN 206-1, *Beton - Del 1: Specifikation, egenskaber, produktion og overensstemmelse*, 2002

ICP måling

Metalkoncentrationen findes ved ICP måling og afgører hvilken forureningskategori slamasken tilhører iht.[1], desuden om slamasken må blandes i beton iht.[2] sec. 5.2. Katogorisering af restproduktet slamaske sker iht. miljøministeriets bekendtgørelse[1] §4 ,som er anført i Tabel 1. Ifølge bekendtgørelsen må katrgori 1 anvendes uden tilladelse til veje, stier, støjvolde, ramper mm. Kategori 2 underlægges miljøministeriets bekendtgørelse[1]§5, som muliggør anvendelse uden tilladelse, dog jf.§6 :**1)** Afstand til indvindingsanlæg er mindst 30 m. **2)** at restproduktet anbringes over højeste grundvandsspejl. **3)** udlagt restprodukt skal afgrænses med markeringsnet. Kategoriseringen er anført i Tabel 2. Det skal nævnes, at den øverste kategori for et faststofindhold er gældende.

Faststof	Kategori 1	Kategori 2
Arsen	0-20	>20
Bly	0-40	>40
Cadmium	0-0.5	>0.5
Krom	0-500	>500
Kobber	0-500	>500
Nikkel	0-30	>30
Zink	0-500	>500

Table 1: Faststofindhold mg/kg TS iht. [1] Bilag 6

Faststof	Indhold [mg/kg]	Kategori
Arsen	0.327	1
Bly	123	2
Cadmium	3.38	2
Krom	57.8	1
Kobber	669	2
Nikkel	9.70	1
Zink	2628	2

Table 2: Faststofindhold mg/kg TS af Avedøre slamaske

Kloridinholdet udtrykt i Cl^- findes ved ICP. Kloridkoncentrationen har indflydelse på betonens miljøklasse, og i tilfælde af et mærkbart internt kloridbidrag bør dette medtages i den samlede vurdering. Ifølge [2] sec. 5.2.3 må kloridindholdet ikke overskride 0.10% af cementmassen. Kloridindholdet for blandingerne er anført i Tabel 3.

Mørtelprøve	Cementmasse[g]	Aske[g]	Klorid[mg/kg]	Kloridindhold[%]
5% cementerstat.	427.5	22.5	2101	0.01
10% sanderstat.	450	135	2101	0.06

Table 3: Kloridindhold for slamaske

Styrke og hærdeproces

Styrken identificeres ved tryktest af prismeformede støbninger med dimensioner *hxbxl* - 40x40x160mm. Dimensionerne har under testen varieret med ±2mm. Testen udføres af trykmaskinen Toni 300T med et trykareal *h*x40mm, hvor *h* er højden af prismet. I Figur 1 sammenlignes 5% cementerstatning og 10% sanderstatning med referenceprøven. Prismerne støbes og komprimeres iht.[3]. Standardafvigelserne for hver trykprøve er angivet. Bemærk at, 3-døgns referenceprøven bør kasseres eller gentages ifølge T-test$_{2.5\%}$.

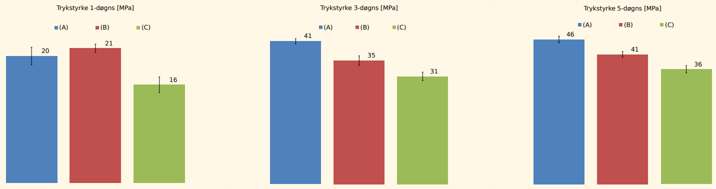


Figure 1: Styrkeprøver for 1-døgn(v);3-døgn(m) og 5-døgn(h)

VICA målingen viser hærdeprocessen over tid. Viden om hærdeprocessen bruges til at afgøre styrkeudviklingen. Hærdnings varighed må, iht. [2] sec. 5.3.5 ikke overskride den dobbelte tid af referenceprøven. Til hærdeforsøget bruges et aske-cement-forhold på 30%, hvor standarden, [2] sec. 5.3.5, bruger et aske-cement-forhold på 25%.

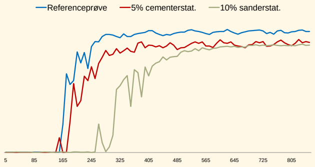
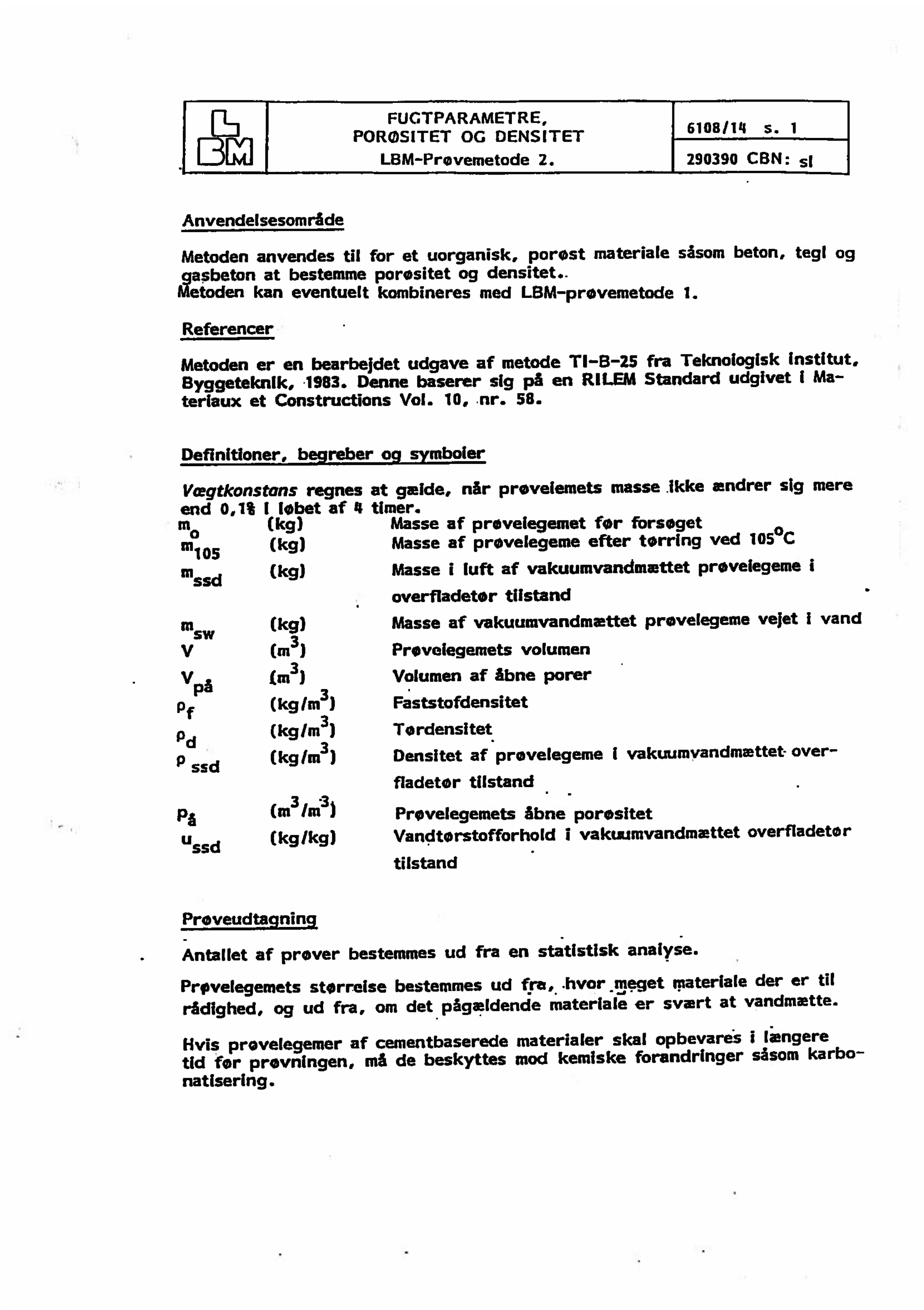


Figure 2: Hærdeproces for mørtelprøver

C Experimental approach

C.1 Porosity and density test



LBM	FUGTPARAMETRE, PORØSITET OG DENSITET LBM-Prøvemetode 2.	6108/14 s. 1 290390 CBN: sl

Anvendelsesområde

Metoden anvendes til for et uorganisk, porøst materiale såsom beton, tegl og gasbeton at bestemme porøsitet og densitet.
Metoden kan eventuelt kombineres med LBM-prøvemetode 1.

Referencer

Metoden er en bearbejdet udgave af metode TI-B-25 fra Teknologisk Institut, Byggeteknik, 1983. Denne baserer sig på en RILEM Standard udgivet i Materiaux et Constructions Vol. 10, nr. 58.

Definitioner, begreber og symboler

Vægtkonstans regnes at gælde, når prøvelemets masse ikke ændrer sig mere end 0,1% i løbet af 4 timer.

m_o	(kg)	Masse af prøvelegemet før forsøget
m_{105}	(kg)	Masse af prøvelegeme efter tørring ved 105°C
m_{ssd}	(kg)	Masse i luft af vakuumvandmættet prøvelegeme i overfladetør tilstand
m_{sw}	(kg)	Masse af vakuumvandmættet prøvelegeme vejet i vand
V	(m^3)	Prøvelegemets volumen
$V_{på}$	(m^3)	Volumen af åbne porer
ρ_f	(kg/m^3)	Faststofdensitet
ρ_d	(kg/m^3)	Tørdensitet
ρ_{ssd}	(kg/m^3)	Densitet af prøvelegeme i vakuumvandmættet overfladetør tilstand
$p_å$	(m^3/m^3)	Prøvelegemets åbne porøsitet
u_{ssd}	(kg/kg)	Vandtørstofforhold i vakuumvandmættet overfladetør tilstand

Prøveudtagning

Antallet af prøver bestemmes ud fra en statistisk analyse.

Prøvelegemets størrelse bestemmes ud fra, hvor meget materiale der er til rådighed, og ud fra, om det pågældende materiale er svært at vandmætte.

Hvis prøvelegemer af cementbaserede materialer skal opbevares i længere tid før prøvningen, må de beskyttes mod kemiske forandringer såsom karbonatisering.

Apparatur

- Varmeskab til udtørring ved 105 ± 5^{o}C
- Ekssikkator med silicagel til opbevaring af prøvelegemerne under afkølingen
- Vægt, hvor prøvelegemernes masse kan bestemmes med en nøjagtighed på 0,1 % - vægtkontrollod
- Udstyr til vejning af prøvelegeme under vand
- Destilleret vand
- Termometer (0,1^{o}C deling)
- Vakuumpumpe til tryk på ca. 100 N/m^2
- Ekssikkator til vakuummætning af prøvelegemer
- Klude

Fremgangsmåde

I tilfælde af, at man skal måle kapillarsugning på de samme prøvelegemer, skal sugningen, jf. LBM-PM-1, være udført først.

Prøvelegemer tørres ved 105 ± 5^{o}C i en ventileret ovn til vægtkonstans. Tørring ved 105^{o}C kan for nogle materialer medføre ændringer i porestrukturen. Disse materialer bør tørres ved en lavere temperatur. Derefter afkøling i ekssikkator til stuetemperatur. Prøvelegemet vejes (vægt m_{105}) (Skema 1).

Det udtørrede prøvelegeme evakueres kontinuerligt tørt i ekssikkator i mindst 3 timer ved tryk på (~torr).

Demineraliseret vand med rumtemperatur ledes ind i ekssikkatoren. Prøvelegemer skal være helt dækket med vand. [redacted] og henstår ved dette tryk i mindst 1 time uden pumpning. Herefter ledes luft ind og prøverne henstår i vandet natten over ved atmosfæretryk.

De vandmættede prøvelegemer vejes i vand (vægt m_{sw}) (Skema 1). Efter aftørring af overfladen med en hårdt opvreden klud vejes prøvelegemer i luft (vægt m_{ssd}) (Skema 1).

Efter tørringen udtørres prøverne ved 105 ± 5^{o}C til vægtkonstans og der foretages en kontrolvejning så det kan konstateres, om der er sket en udvaskning af prøverne ved vandmætningen.

Parametrene bestemmes som vist med formlerne i skema 1.

PORØSITET OG DENSITET, SKEMA 1

Hold:

Sag:

Dato:

Initialer:

Rum: T = °C

Vand: T = °C

Vanddensitet ρ_w = kg/m^3

Vægtkontrollod

Før: Kg,g

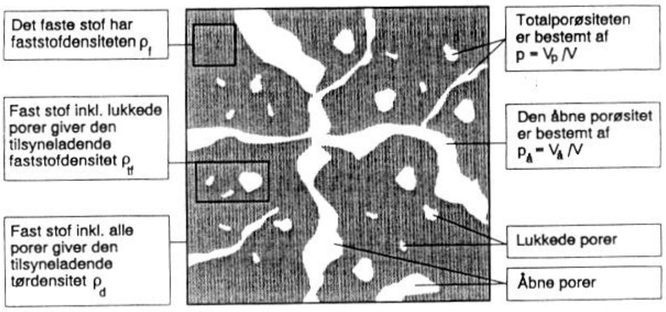
Efter: Kg,g

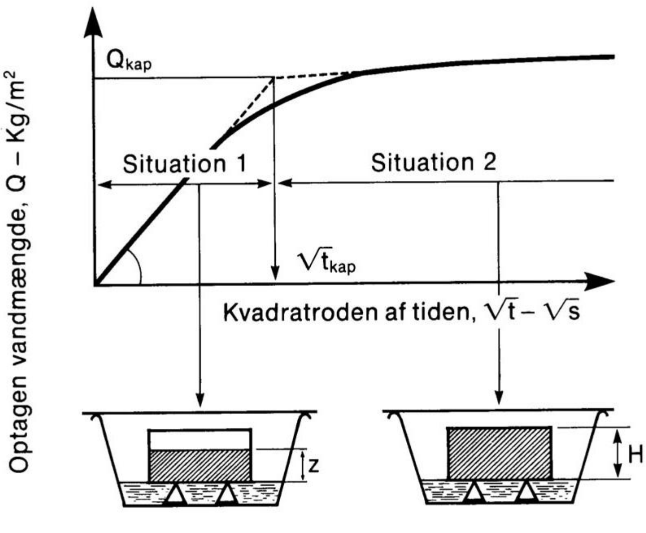
Prøvelegeme nr.					
m_{105}	kg				
m_{ssd}	kg				
m_{sw}	kg				
$V = (m_{ssd}-m_{sw})/\rho_w$	m^3				
$V_{på} = (m_{ssd}-m_{105})/\rho_w$	m^3				
$p_å = V_{på}/V$	m^3/m^3				
$\rho_d = m_{105}/V$	kg/m^3				
$\rho_f = m_{105}/(V-V_{på})$	kg/m^3				
$\rho_{ssd} = m_{ssd}/V$	kg/m^3				
$u_{ssd} = (m_{ssd}-m_{105})/m_{105}$	kg/kg				

Bemærkninger:				

C.2 Capillary effect

PORØSITET, DENSITET OG KAPILLARSUGNING





11735 Materialelære

Indholdsfortegnelse

Forside:
Øverst: *Skitse af et porøst materiale med forskellige materialeparametre defineret.*
Nederst: *Illustration af opsugningsforsøg.*

1. Formål

Øvelsens formål er dels at måle porøsitet og densitet for et eller flere byggematerialer, dels at måle et eller flere byggematerialers kapillarsugningsevne. De anvendte byggematerialer oplyses på forsøgsdagen.

2. Omfang

Indledning: Øvelsen indledes med en fælles orientering om det apparatur, der skal anvendes.

Gruppearbejde: Herefter arbejder grupperne med hver deres prøvelegemer.

Afslutning: Øvelsen sluttes med, at

**alle grupper indtaster måleresultater på Campusnet til brug ved rapporteringen.
Manglende resultater fra en gruppe medfører nedsat karakter i den endelige bedømmelse!**

3. Baggrund

3.1. Generelt

En bygningskonstruktions egenskaber afhænger af hvilket materiale den bygges af. Disse egenskaber kan fx være bæreevnen eller isolansen. Mange af byggematerialernes egenskaber påvirkes af hvor våde de er. Det gælder fx træ som vil angribes af svamp hvis der er et højt fugtindhold i det. Anbringes træet tæt sammen med våd beton vil svamp således angribe træet, ligesom styrken af træet vil mindskes med et øget fugtindhold.

3.2. Porøsitet og densitet

Et materiales densitet er afgørende for mange af dets egenskaber. En generel regel er at jo tungere et materiale er, jo stærkere er det, og jo lettere det er, jo bedre isolerer det. *Densiteten kan bestemmes som massen delt med rumfanget*. Dog kan materialet indeholde en ukendt mængde vand, og den bestemte densitet er derfor en dårligt anvendelig størrelse, hvis masseandelen som vand udgør er ukendt. Derfor arbejdes ofte med følgende fire densitetsbegreber:

faststofdensitet	ρ_f
tilsyneladende faststofdensitet	ρ_{tf}
tørdensitet	ρ_d
densitet i vacuumvandmættet, overfladetør tilstand	ρ_{ssd}

og de dermed sammenhørende parametre til karakterisering af porøsitetsforholdene

total porøsitet	p
åben porøsitet	$p_{å}$
absorption	w_a

Størrelserne ρ_f og ρ_{tf} anvendes dog temmelig sjældent. Fig. 1 illustrerer de tre rumfangsdefinitioner.

I det følgende gives en mere udførlig forklaring på anvendte begreber til karakterisering af porøse eller kornede materialer.

Faststofdensiteten defineres som materialets masse i tør tilstand divideret med faststofrumfanget, der er vist på figur 1. Faststofrumfanget er selve det faste materiale uden nogen form for porer. Faststofdensiteten kan bestemmes ved pulverisering af prøven.

Den tilsyneladende faststofdensitet defineres som materialets masse i tør tilstand divideret med det tilsyneladende faststofrumfang. Det tilsyneladende faststofrumfang betegner rumfanget af det der set udefra fremtræder som faststof, dvs. faststof inklusiv lukkede porer.

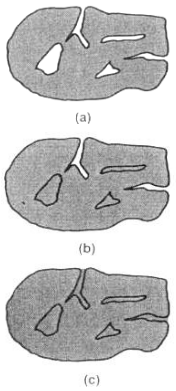


Fig. 1. Rumfangsdefinitioner. (a) absolut faststofrumfang (faststof), (b) tilsyneladende faststofrumfang (faststof + lukkede porer), (c) kornrumfang (faststof + lukkede porer + åbne porer).

Tørdensiteten defineres som materialets masse i tør tilstand delt med prøvelegemets rumfang. Prøvelegemets rumfang betegner det rumfang, faststoffet beslaglægger hvor alle typer porer medtages. Det er altså det ydre rumfang.

Densiteten i vacuumvandmættet, overfladetør tilstand (saturated surface dry, s.s.d.) defineres som prøvelegemets masse i s.s.d.-tilstanden divideret med prøvelegemets ydre rumfang.

Lukkede porer betegner porer der ikke er tilgængelige for vand fra materialets overflade.

Åbne porer betegner porer der er tilgængelige for vand fra materialets overflade.

Totalporøsiteten er forholdet mellem porerumfang (lukkede + åbne porer) og prøvelegemets ydre rumfang. Udtrykt ved de tidligere definerede densiteter haves porøsiteten som

$$p = p_{å} = \frac{\rho_f - \rho_d}{\rho_f} \qquad (1)$$

I de fleste porøse materialer er poresystemet åbent, og derfor vil den åbne porøsitet være lig med totalporøsiteten.

Absorptionen er betegnelsen for massen af det vand der kan optages i de åbne porer via kapillarsugning divideret med massen af det tørre materiale. Den hænger sammen med de to tidligere omtalte densiteter ved følgende ligning.

$$w_a = \frac{\rho_{ssd} - \rho_d}{\rho_d} \qquad (2)$$

Vandindholdet er vand-tørstofforholdet defineres som massetabet af en prøve der tørres ved 105 ºC, udtrykt i % af prøvens masse efter tørringen.

Fugtoptagelsen der foregår i de åbne porer, vil være afhængig af porøsiteten. Hvis der ingen hulrum er, dvs. porøsiteten er nul, vil der ikke kunne optages vand. Hvis der derimod haves en stor porøsitet i et materiale, samtidig med poreradius er mellem 10^{-7}m < r < 10^{-4}m, er der mulighed for at optage meget vand i det givne materiale. Dette er fx tilfældet med teglsten.

3.2.1. Bestemmelse af porøsitet og densitet

Ved den såkaldte veje-dyppe-veje metode kan densiteten og porøsiteten for et materiale findes. Metoden udnytter Archimedes lov der siger at opdriften på et legeme i en væske er lig tyngdekraften på det fortrængte væskevolumen. Dette betyder altså at vægten af prøvelegemet under vand m_u har en opdrift som gør, at prøvelegemet ikke vejer lige så meget under vand, som det gør over vand. Forskellen på vægten under vand og vægten over vand er lig vægten af den væske som prøvelegemet fortrænger.

Volumen af prøvelegemet nedsænket i vand kan bestemmes ud fra nedenstående formel.

$$V = \frac{m_{ov} - m_u}{\rho_w} \qquad (3)$$

hvor

V	er prøvelegemets volumen [m^3]
m_{ov}	er massen i luft af prøvelegemet i vacuumvandmættet, overfladetør tilstand [kg]
m_u	er det målte masse af prøvelegemet neddyppet i vand [kg]
ρ_w	er vands densitet [kg/m^3]

Massen m_{ov} angiver hvor meget prøvelegemet vejer, når det er fyldt med vand i de åbne porer. Massen af prøvelegemet under vand, m_u er mindre end m_{ov} som følge af opdriften beskrevet ved Archimedes Lov.

Voluminet af de åbne porer i prøvelegemet findes efter formlen:

$$V_{\text{å}} = \frac{m_{ov} - m_0}{\rho_w} \qquad (4)$$

hvor

$V_{\text{å}}$	er voluminet af de åbne porer [m^3]
m_0	er tørmassen af prøvelegemet [kg]

Tørmassen er den målte masse efter ovntørring ved 105 °C, hvorved alt vand i det åbne poresystem fordampes. Ud fra det åbne porevolumen kan den åbne porøsitet beregnes ved (5).

$$p_{\text{å}} = \frac{V_{\text{å}}}{V} = \frac{m_{ov} - m_0}{m_{ov} - m_u} \qquad (5)$$

hvor

$p_{\text{å}}$	er den åbne porøsitet [-]

Endvidere kan tørdensiteten af materialet bestemmes ved (6) ud fra den fundne tørmasse og det totale volumen.

$$\rho_d = \frac{m_0}{V} \qquad (6)$$

hvor

ρ_d	er materialets tørdensitet [kg/m^3]

Densiteten af prøvelegemet i vandmættet, overfladetør tilstand bestemmes ved (7).

$$\rho_{ssd} = \frac{m_{ov}}{V} \qquad (7)$$

hvor

ρ_{ssd}	er materialets densitet i vacuumvandmættet, overfladetør tilstand [kg/m^3]

3.3. Kapillarsugning

En vandoverflade i en vandfyldt pore – en menisk – vil altid være krum. I små porer med lille diameter kan denne krumning være betydelig, hvorimod den for meget store diametre – fx i en kop – er uden praktisk relevans. Det hydrostatiske undertryk i vandet umiddelbart under menisken er afgørende for et af de vigtigste transportfænomener i mange porøse materialer – kapillarsugning.

Figur 2 viser stighøjden i et kapillarrør, der ækvivalerer en vandfyldt pore. Som det ses danner meniskens kontakt til kapillarrørets inderside en vinkel med overfladen af kapillarrøret, kaldet kontaktvinklen. Desuden virker en overfladespænding i vandet som vist.

I tilfældet med små diametre, er overfladespændingen afgørende for vandtransporten idet den resulterer i en opadrettet kraft der overstiger tyngdekraften og friktionen med rørvæggen og trækker vandet op i røret.

Hastigheden hvormed vandet bevæger sig op i røret vil aftage med tiden, idet friktionen mellem væg og vand vil stige når vandet dækker et større indre areal i røret. Endvidere øges tyngdekraften med vægten af vandet i røret.

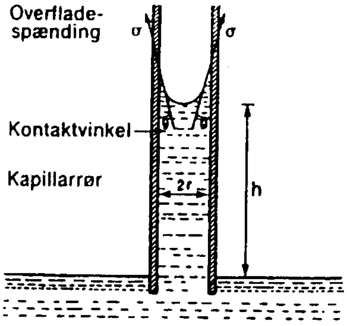


Fig. 2. Stighøjde i et kapillarrør.

Hvis porerne er meget små, vil der være en betydelig modstand mod vandtransporten, der derfor vil foregå meget langsomt. Samtidig vil der være en meget stor kraft idet krumningen på menisken er stor. En væskesøjle kan således i teorien blive flere kilometer høj i meget tynde rør. Dette vil dog tage lang tid at opbygge, samtidig med at det kræver at der ikke er nogen luftbobler i væskesøjlen, idet disse vil bryde kapillarvirkningen. Det er fx ved kapillartransport at et træ får transporteret vand fra rødderne og op til bladene.

Af nedenstående formel ses hvor stort det hydrostatiske undertryk under menisken bliver.

$$p_h = -\frac{2\sigma\cos\theta}{r} \qquad (8)$$

hvor

p_h er det hydrostatiske undertryk [*Pa*]
σ er overfladespændingen [*N/m*]
θ er kontaktvinklen [°]
r er radius i menisken [*m*]

Som det fremgår af (8) bliver undertrykket stort når radius mindskes. I porer over en vis størrelse vil der ikke forekomme kapillartransport, idet det hydrostatiske undertryk ikke vil resultere i en tilstrækkelig stor kraft til at flytte vandet. Derfor er det ikke alle åbne hulrum som kan fyldes ved kapillartransport af vand.

Når et materiale anbringes i kontakt med vand, vil der ved kapillarsugning transporteres vand op igennem materialet. Dette vil foregå ved aftagende hastighed når vandoverfladen har nået toppen af prøvelegemet, eller der er ligevægt mellem kapillarkræfterne på vandet og de modsatrettede kræfter hidrørende fra friktion og tyngdekraft. Ved et kapillarsugningsforsøg anbringes et materiale med kendt overfladeareal i kontakt med en fri vandoverflade, og der foretages en vejning af prøven til forskellige tidspunkter. Resultaterne fra et sådan forsøg ses i figur 3.

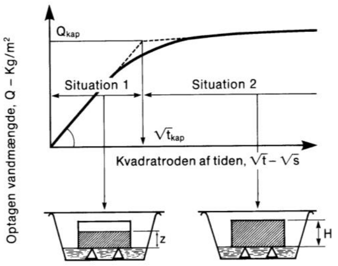


Fig. 3. Illustration af kapillarsugningsforsøg.

Den stiblede linje viser det ideelle forhold, hvor den optagne vandmængde pr. areal, Q som funktion af $t^{1/2}$ afbilder en ret linje, indtil vandmængden svarende til Q_{kap} er opsuget jf. situation 1 i figur 3. Herefter optages ikke mere vand, og hældningen af kurven er derfor nul, jf. situation 2 i figur 3. I virkeligheden vil en kurve se ud som vist ved den fuldt optrukne linje, fordi alle porerne ikke fyldes lige hurtigt. Ligeledes vil der for nogle materialer være en svagt stigende tendens efter vandoverfladen har nået toppen af prøvelegemet; dette skyldes at fyldningen af de mindste porer i materialet tager lang tid.

På figur 3 ses skæringspunktet mellem de to stiblede linjer. Dette skæringspunkt ($t_{kap}{}^{1/2}$, Q_{kap}) findes ud fra tangenter til den krumme kurve. Ud fra koordinaterne til punktet kan kapillaritetstallet, k ($kg/(m^2 \cdot s^{1/2})$) udregnes. Denne parameter angiver hældningen af den første kurve som vist i (9).

$$k = \frac{Q_{kap}}{\sqrt{t_{kap}}} \qquad (9)$$

Et stort kapillaritetstal betyder at opsugningen foregår hurtigt, mens et lavt omvendt angiver at opsugningen foregår langsomt. Dette har fx betydning for hvor meget vand en mursten når at opsuge i regnvejr.

3.3.1. Bestemmelse af opsugningsparametre

Ved et opsugningsforsøg kan en række materialeegenskaber bestemmes. I første omgang skal den opsugede masse pr. areal bestemmes ud fra (10).

$$Q = \frac{m_t - m_0}{A} \qquad (10)$$

hvor

Q	er den opsugede masse pr. opsugningsareal [kg/m^2]
m_t	er massen af prøvelegemet til tiden t [kg]
m_0	er tørmassen af prøvelegemet [kg]
A	er opsugningsarealet [m^2]

Massen af det forkonditionerede prøvelegeme, m_0 henviser til en vedtagen standardtilstand som prøvelegemet skal være i ved forsøgets start. Prøvelegemet har ved denne øvelse været udsat for en temperatur på 105 °C i to døgn inden forsøgets start.

Når t_{kap} er bestemt som tidligere beskrevet kan modstandstallet M beregnes af (11). Dette siger noget om den indre modstand i materialet der påvirker opsugningshastigheden.

$$M = \frac{t_{kap}}{h^2} \qquad (11)$$

hvor

M	er modstandstallet [s/m^2]
h	er højden på prøvelegemet [m]

Som tidligere beskrevet kunne den åbne porøsitet bestemmes ud fra veje-dyppe-veje metoden, der benytter sig af Archimedes lov. Ved opsugningsforsøg kan denne porøsitet ligeledes bestemmes ved (12).

$$p_å = \frac{\left(m_{slut} - m_0\right)}{h \cdot A \cdot \rho_w} \qquad (12)$$

hvor

$p_å$	er den åbne porøsitet [-]
m_{slut}	er massen af prøvelegemet til tiden t_{slut} [kg]

4. Eksperimenter

4.1. Porøsitet og densitet

4.1.1. Apparatur og materialer

- 1 halv mursten
- Ekssikkator til opbevaring af prøvelegeme under vakuumsugning
- Vægt med nøjagtighed på 0,1 %
- Kontrollod
- Udstyr til vejning af prøvelegeme under vand
- Destilleret vand
- Termometer med inddeling på 0,1 °C
- Vakuumpumpe
- Klude til aftørring af prøvelegeme
- Varmeskab til forkonditionering af prøvelegeme

4.1.2. Fremgangsmåde

Først foretages en kontrolvejning vha. et kontrollod, og den målte masse noteres. Prøvelegemerne skal i udgangssituationen være udtørret i en ovn ved 105 °C. Pga. tidsnød er dette gjort i forvejen, og den målte masse udleveres af vejlederen og noteres i skema 1, bilag 1. Det udtørrede prøvelegeme evakueres tørt i ekssikkator i mindst 3 timer. Pga. tidsnød befinder prøverne sig allerede i ekssikkator, hvor de har været evakueret i ovennævnte tidsrum.

Hanen på ekssikatoren lukkes, og pumpen tages af. Herefter sættes en slange på hanen, hvor den anden ende af slangen er neddykket i en spand med destilleret vand. Når hanen åbnes vil undertrykket i ekssikkatoren suge vandet ind i ekssikkatoren. Temperaturen af vandet samt af rumluften måles og noteres. Når vandet når ca. 50 mm op over det øverste prøvelegeme lukkes hanen på ekssikkatoren og vandslangen tages af. Der pumpes ned til vands damptryk.

Prøvelegemerne med vand henstår i 15 min. med undertryk i ekssikkatoren. Hanen på ekssikkatoren åbnes, og der ledes luft ind i ekssikkatoren. Prøverne henstår i vandet ved atmosfæretryk i 15 min. De vakuumvandmættede prøver vejes (m_u) under vandet, og værdien noteres. Hvorledes der vejes under vand vises af vejlederen. Prøvelegemerne aftørres med en hårdt opvredet klud, og vejes (m_{ov}) i luft. Til sidst foretages en kontrolvejning med kontrollod på vægten. Alle omtalte værdier noteres i skema 1, se bilag 1.

4.2. Kapillarsugning i mursten

4.2.1. Apparatur og materialer

- 1 halv mursten
- Ekssikkator med silicagel til opbevaring af prøvelegeme under afkøling.
- Vægt med nøjagtighed på 0,1 %
- Kontrollod
- Fotobakke med afstandsholdere
- Destilleret vand
- Termometer med inddeling på 0,1 °C
- Stopur
- Klude til aftørring af prøvelegeme

4.2.2. Fremgangsmåde

Principielt set skal prøvelegemet være i ligevægt med det klima, hvor det skal bruges. Til sammenligningsgrundlag bør en standardiseret udgangssituation dog benyttes. Den standardiserede udgangssituation opnås i denne øvelse ved at prøvelegemet forkonditioneres i en ovn ved 105 °C i mindst to døgn.

Ekssikkatoren er en lufttæt plast- eller glasbeholder. Silicagelen er et tørremiddel som sørger for, at der ikke er fugt i luften inde i ekssikkatoren. Der benyttes kontrollod til sikring af at vægten vejer korrekt både før og efter forsøget. Prøvelegemet vejes i modtagelsessituationen (m_0), mens dets sugeflade og højdes opmåles.

Fotobakken fyldes med destilleret vand indtil vandet når ca. 5 mm op over afstandsholderne. Herefter anbringes prøvelegemets sugeflade på afstandsholderne, således at vandet går op på siden af materialet. Stopuret startes i det øjeblik der er kontakt med vandet.

Temperaturen i lokalet måles (T_{rum}) og noteres, mens temperaturen af vandet i fotobakken skal være 20 °C ± 2 °C, hvilket måles (T_{vand}). Ved forsøg over længere tid bør fotobakken overdækkes for at udgå fordampning. Med passende tidsintervaller regnet fra starttidspunktet tages prøvelegemet op, aftørres med en hårdt opvredet klud og vejes (m_t). Stopuret stoppes når prøvelegemet ikke er i kontakt med vandet i fotobakken. Der foretages målinger efter 1, 2, 4, 8, 16, 32, 60, 120, evt. 240 minutter fra starttidspunktet. Til sidst kontrolles vægten ved en kontrolvejning og værdien noteres.

Når målearbejdet er færdigt, indtastes måleresultater i et resultatskema der ligger under fildeling på Campusnet. Husk at gemme det indtastede regneark på egen PC og 'uploade' det indtastede regneark på Campusnet.

5. Rapportering

På artikelform (altså ikke en teknisk rapport!) sammenfattes fremgangsmåde, forsøgsresultater, diskussion og konklusion i et omfang af **max. 4 sider**. Dersom sideantallet overskrides, trækker det ned i bedømmelsen!
Da modtageren regnes bekendt med teorien, opstilles kun de vigtigste formler anvendt i beregningen af forsøgsresultater, og der refereres til øvelsesvejledningen. Fremgangsmåden ved forsøgene beskrives særdeles kortfattet (se det udleverede eksempel på artikel), og de vigtigste forsøgsresultater trækkes frem!

Hvad skal artiklen indeholde af resultater?

Porøsitet og densitet
- Søjlediagram over porøsiteter for samtlige gruppers materialeprøver. Angiv materialet ud for hver enkelt søjle.
- Søjlediagram indeholdende tørdensitet og densitet i s.s.d.-tilstand for samtlige gruppers materialeprøver. Inddel diagrammet således at de to densiteter for hver materialeprøve sammenstilles.

Kapillarsugning
- Tabel over Q_{kap} og t_{kap} for alle gruppers resultater. Anfør endvidere porøsiteten for hver enkelt prøvelegeme.
- Tabel over kapillaritetstal og modstandstal for alle gruppers resultater.
- Er der sammenhæng mellem målte porøsiteter og tilhørende kapillaritetstal?

Alle disse resultater diskuteres i videst muligt omfang inden for det anførte maksimale sideantal.

6. Litteratur

[1] Gottfredsen, F.R.; Nielsen, A.: Bygningsmaterialer: Grundlæggende egenskaber. Polyteknisk Forlag, 1997.

Bilag 1: Skema 1 – Porøsitet og densitet

Materiale			
Målinger			
Temperatur	T_{rum} = °C	T_{vand} = °C	ρ_w = 998 kg/m^3
Kontrollod	$m_{før}$ = g	m_{efter} = g	
Prøvelegeme Masse	m_0 = kg	m_u = kg	m_{ov} = kg
Beregninger			
Volumen og densitet	V = m^3 ρ_d = kg/m^3	$V_å$ = m^3 ρ_{ssd} = kg/m^3	$p_å$ =
Bemærkninger			Gruppenr. Dato

Bilag 2: Skema 2 – Kapillarsugning I

Materiale			
Temperatur	T_{rum} = °C	T_{vand} = °C	ρ_w = 998 kg/m^3
Målinger			
Prøvelegeme Dimensioner	h = m	A = m^2	
Masse	m_0 = kg	m_{slut} kg	
Beregninger			
Opsugnings-parametre	Q_{kap} = kg/m^2	t_{kap} = s$^{1/2}$	k = kg/(m^2 ·s$^{1/2}$)
	M = s/m^2	$p_å$ =	
Bemærkninger		Gruppenr. Dato	

Bilag 3: Skema 3 – Kapillarsugning II

Materiale

Temperatur T_{rum} = °C T_{vand} = °C ρ_w = 998 kg/m^3

Kontrollod $m_{før}$ = g m_{efter} = g

Prøvelegeme

t [min]	$t^{1/2}$ [s$^{1/2}$]	m_t [kg]	Q [kg/m^2]	t [min]	$t^{1/2}$ [s$^{1/2}$]	m_t [kg]	Q [kg/m^2]
0				0			
1				1			
2				2			
4				4			
8				8			
16				16			
32				32			
60				60			
120				120			
240				240			

Bemærkninger:
Dette Skema 3 kan anvendes til to prøvelegemer.

Gruppenr.
Dato

C.3 Digestion of ash sample

Oplukning af jordprøve efter DS 259

A Princip

Denne oplukningsmetode er en Dansk Standard (DS 259) til bestemmelse af syreopløselige metaller i jorden. Metalkoncentrationen fundet ved denne metode svarer til en "total-koncentration" af det pågældende metal i jorden. Ved en fuldstændig destruktion af jorden, vil man dog have mulighed for at finde en højere værdi af de forskellige metaller, så DS 259 giver derfor snarere et fastlagt niveau for en metalkoncentration, end en fuldstændig bestemmelse af metalkoncentrationen i jorden.

B Specielt apparatur

Til målingen benyttes et atomabsorptionsspektrofotometer (AAS).

C Kemikalie sikkerhed

Salpetersyre - Brandnærende; Ætsende; Brandfarlig ved kontakt med brandbare stoffer. Alvorlig ætsningsfare. Undgå indånding af dampe. Brug syrehandsker, plastikforklæder, sikkerhedsbriller og stinkskab ved afmåling.

Salpetersyre halv konc. (1:1) - Lokalirriterende; Irriterer øjnene og huden. Brug engangshandsker, sikkerhedsbriller og stinkskab ved afmåling.

Læs kemikaliebrugsanvisningen før arbejdet begynder.

D Reagenser

1) **Salpetersyre halvkonc, (1:1) HNO_3:**
500 mL koncentreret HNO_3 overføres med måleglas til en 1000,00 mL målekolbe som er ½ fyldt med destilleret vand. Der blandes godt og tilsættes vand til mærket. Efter blanding overføres opløsningen til en plastikflaske og mærkes.

E Analysens udførelse

1,00 g tør, knust jord afvejes på teknisk vægt i et pyrex-glas med skruelåg (autoklaveglas) og der tilsættes 20,00 mL halvkoncentreret HNO_3 med fuldpipette (skal foregå i stinkskab).

Autoklavflaskerne lukkes helt til, da HNO_3 ellers vil fordampe. Flaskerne stilles i autoklaven ved 200 kPa (120°C) i 30 minutter. Flaskerne afkøles derefter til stuetemperatur.

Prøverne filtreres med sug gennem et 0,45 µm filter i stinkskab. **Brug engangshandsker**. Autoklaveflasken skylles med 3 gange destilleret vand. Filtreret skal suge tør mellem hvert skyl.

Filtratet hældes i en 100,00 mL målekolbe og der tilsættes destilleret vand til mærket og blandes. Væsken hældes på en 20 mL plast-vials og gemmes til AAS.

F Bestemmelse af metaller

Ekstraktens indhold af metaller måles ved AAS under benyttelse af de standarder som hører til de enkelte metaller.

G Beregning af resultat

På baggrund af standardkurverne beregnes jordens indhold af metaller angivet i mg/kg.

$$\boxed{mg/kg = \frac{A \cdot 0{,}100 L \cdot C}{B \cdot 10^{-3}\ kg/g\ jord}}$$

hvor

A = ekstraktens metal koncentration, mg/L = ppm
B = g jord afvejet
C = fortyndingsfaktor

H Affaldshåndtering

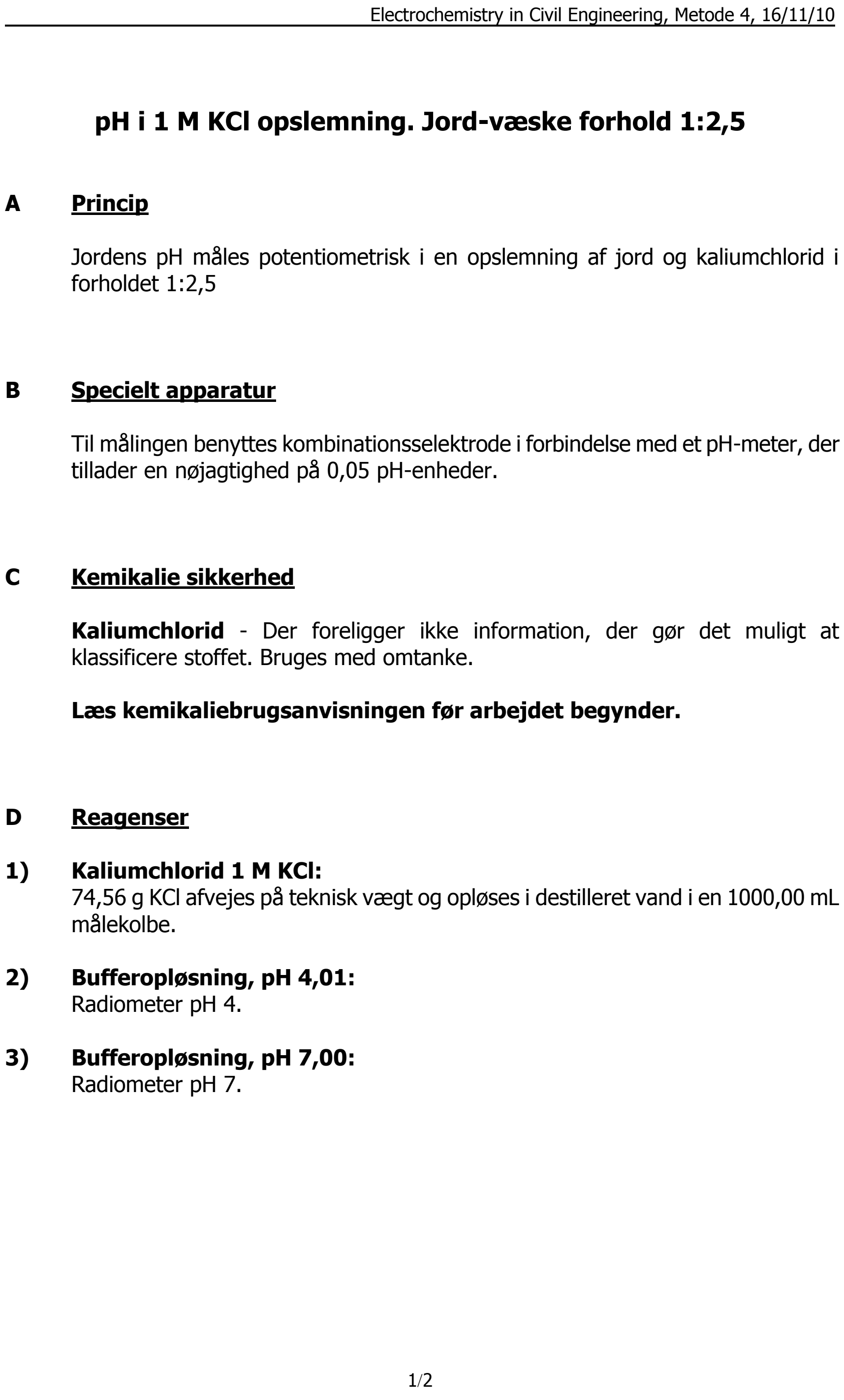
Salpetersyre hældes i affaldsdunke mærket X 4.18.

Ekstrakerne hældes i affaldsdunk mærket X 4.41 (tungmetaller).

Filterpapiret bortkastes i skraldespanden i stinkskabet.

Jorden skal opsamles i beholder til jordaffald.

C.4 pH measurement



pH i 1 M KCl opslemning. Jord-væske forhold 1:2,5

A **Princip**

Jordens pH måles potentiometrisk i en opslemning af jord og kaliumchlorid i forholdet 1:2,5

B **Specielt apparatur**

Til målingen benyttes kombinationsselektrode i forbindelse med et pH-meter, der tillader en nøjagtighed på 0,05 pH-enheder.

C **Kemikalie sikkerhed**

Kaliumchlorid - Der foreligger ikke information, der gør det muligt at klassificere stoffet. Bruges med omtanke.

Læs kemikaliebrugsanvisningen før arbejdet begynder.

D **Reagenser**

1) **Kaliumchlorid 1 M KCl:**
74,56 g KCl afvejes på teknisk vægt og opløses i destilleret vand i en 1000,00 mL målekolbe.

2) **Bufferopløsning, pH 4,01:**
Radiometer pH 4.

3) **Bufferopløsning, pH 7,00:**
Radiometer pH 7.

E Analysens udførelse

1) Fremstilling af jordopslemningen

5,00 g tør, knust jord afvejes på teknisk vægt i en 20 mL plastvials. Der tilsættes 12,5 mL 1 M KCl-opløsning med pipette. Opslemningen stilles på rystebord i 1 time, hvorefter jorden bundfældes i 5-10 minutter, indtil en væskefase har udskilt sig over jorden.

2) Målingens udførelse

Elektroden anbringes i den øvre kolloidfattige del af opslemningen således at diafragmaet er under væskeoverfladen (under måling skal gummiproppen være aftaget). Undgå at elektroden ikke rammer jorden. Forud for hver måling skylles elektroden grundigt med destilleret vand, hvorefter en evt. dråbe aftørres forsigtigt med et stykke papir.

F Beregning af resultat

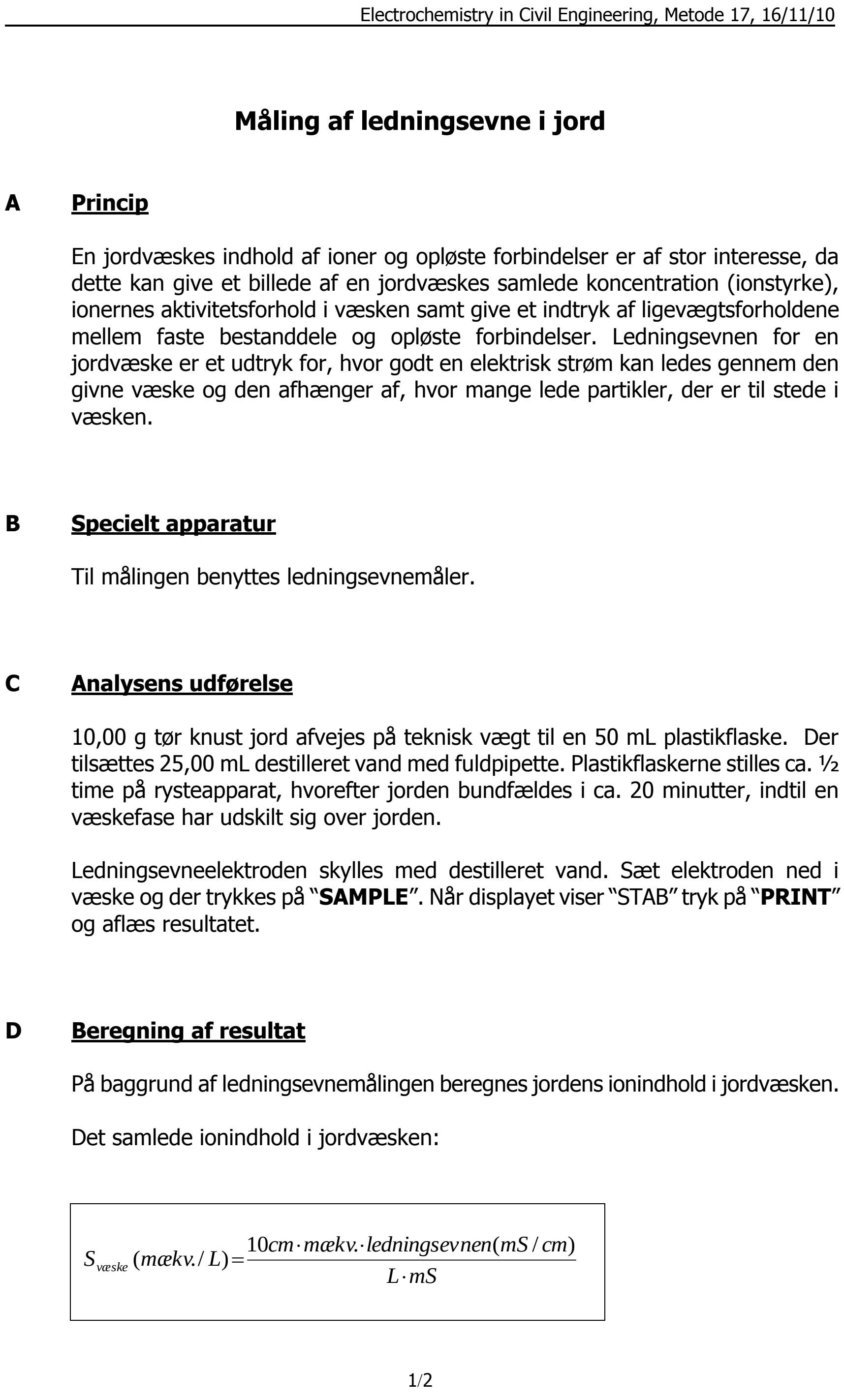
Resultatet aflæses direkte på apparatet og angives som pH (KCl) med en decimal. Aflæsningen anses for stabil når der står *"STAB"* på displayet.

G Affaldshåndtering

Kaliumchlorid og Metrohm pH 4 og pH 7 hældes i vasken.

Plastvial med jorden/KCl skal opsamles i beholder til jordaffald.

C.5 Conductivity



Måling af ledningsevne i jord

A **Princip**

En jordvæskes indhold af ioner og opløste forbindelser er af stor interesse, da dette kan give et billede af en jordvæskes samlede koncentration (ionstyrke), ionernes aktivitetsforhold i væsken samt give et indtryk af ligevægtsforholdene mellem faste bestanddele og opløste forbindelser. Ledningsevnen for en jordvæske er et udtryk for, hvor godt en elektrisk strøm kan ledes gennem den givne væske og den afhænger af, hvor mange lede partikler, der er til stede i væsken.

B **Specielt apparatur**

Til målingen benyttes ledningsevnemåler.

C **Analysens udførelse**

10,00 g tør knust jord afvejes på teknisk vægt til en 50 mL plastikflaske. Der tilsættes 25,00 mL destilleret vand med fuldpipette. Plastikflaskerne stilles ca. ½ time på rysteapparat, hvorefter jorden bundfældes i ca. 20 minutter, indtil en væskefase har udskilt sig over jorden.

Ledningsevneelektroden skylles med destilleret vand. Sæt elektroden ned i væske og der trykkes på "**SAMPLE**". Når displayet viser "STAB" tryk på "**PRINT**" og aflæs resultatet.

D **Beregning af resultat**

På baggrund af ledningsevnemålingen beregnes jordens ionindhold i jordvæsken.

Det samlede ionindhold i jordvæsken:

$$S_{\text{væske}}(\text{mækv.}/L)=\frac{10\,\text{cm}\cdot\text{mækv.}\cdot\text{ledningsevnen}(\text{mS}/\text{cm})}{L\cdot\text{mS}}$$

Det samlede ionindhold i jordvæsken kan omregnes til et samlet ionindhold af ioner pr.

$$\boxed{S_{jord} = \frac{S_{væske} \cdot V_{vandtilsat}}{M_{jord}}}$$

E Affaldshåndtering

Ekstrakerne hældes i affaldsdunk mærket X 4.41 (tungmetaller).

C.6 Ignitionloss

Glødetab i jord

A Princip

Jordens indhold af organisk materiale svarer stort set til det opnåede glødetab ved 550°C. I en tungmetalforurenet jord vil tungmetallerne i høj grad reagere med det organiske materiale i jorden og sidder bundet i denne fraktion.

B Specielt apparatur

Til analysen benyttes et muffelovn.

C Analysens udførelse

3 digler sættes i muffelovn, som er opvarmet til 550°C, hvor de står i 30 minutter (1time hvis ovnen er kold). Diglerne afkøles i ekssikkator og vejes på analyse vægt.

NB: Diglerne transporteres med tang, da fingrene afsætter fugt og derved ændrer vægten.

Derefter afvejes omkring 2,5 g tør, knust jord på analysevægt til hver digel. Diglerne med den tørre jord stilles i en opvarmet muffelovn og glødes ved 550°C i 1 time.

Diglerne med den glødede jord afkøles i ekssikkator og vejes på analyse vægt.

D Beregning af resultat

Glødetabet, som nogenlunde svarer til prøvens indhold af organisk stof, angives i procent af tørstofindholdet.

$$\boxed{\%\,\text{glødetab} = \frac{m(\mathit{muffelovn}) - m(\mathit{efter\ muffelovn})}{m(\mathit{før\ muffelovn})} \cdot 100}$$

E Affaldshåndtering

Jorden skal opsamles i beholder til jordaffald.

C.7 Water content

Vandindhold i jord

A **Princip**

I forbindelse med den elektrodialytisk jordrensning har jordens vandindhold stor betydning, da den elektriske strøm ledes gennem jorden via jordvæsken. Er vandindholdet i jorden mindre end ca. 15 %, er det nødvendigt for forsøgets gennemførelse at tilføre jorden ekstra væske.

B **Specielt apparatur**

Til analysen benyttes et varmeskab.

C **Analysens udførelse**

Ved meget præcis måling:

3 bægerglas stilles i varmeskab ved 105°C natten over.
Bægerglassene stilles til afkøling i eksikator og vejes på analysevægt.

Dette gøres vha. en tang, fingrene afsætter fugt.

Der afvejes 5 g jord i hvert bægerglas og prøverne tørres ved 105°C i varmeskab. Bægerglassene med den tørrede jord vejes på analyse vægt efter afkøling i eksikator.

Ved mindre præcis måling (mest anvendt):

3 bægerglas afvejes på teknisk vægt. Der overføres en vis mængde til hvert bægerglas, som igen vejes på teknisk vægt. Bægerglassene stilles i varmeskab natten over ved 105°C. Bægerglassene med den tørrede jord vejes efter afkøling på teknisk vægt.

D Beregning af resultat

Vandindholdet angives i procent af vægten af den fugtige jord.

$$\boxed{\%\ vandindhold = \frac{m(våd\ prøve) - m(tør\ prøve)}{m(våd\ prøve)} \cdot 100}$$

E Affaldshåndtering

Jorden skal opsamles i beholder til jordaffald og bægerglassene rengøres.

C.8 Water solublility

Vandopløselighed

Analyse:

100,00 g tørret aske afvejes på teknisk vægt til en 1L plastikflaske med låg. Der tilsættes 500 mL destilleret vand. Prøven rystes og henstilles til bundfældning.

Et filterpapir vejes og sættes i en tragt over et måleglas.

Væsken hældes over i filterpapiret. Der tilsættes igen 500 mL destilleret vand til asken og prøven omrystes og henstilles.

Væsken hældes over i det samme filter og der tilsættes igen 500 destilleret vand til asken og prøven omrystes.

Hele prøven hældes over i filteret og stilles til afdrypning.

Når asken er næste tør stilles filteret med asken i varmeskab ved 105°C natten over.

Asken og filteret vejes og vægten noteres.

C.9 Water soluble anions

Vandopløselige anioner

Analyse:

10g tørret aske afvejes på teknisk vægt til 100mL plastikflaske. Der tilsættes 50mL destilleret vand.

Prøven stilles på rystebord natten over.

Prøven filtreres med sprøjtefilter og prøven gemmes til ionchromotograf og AAS

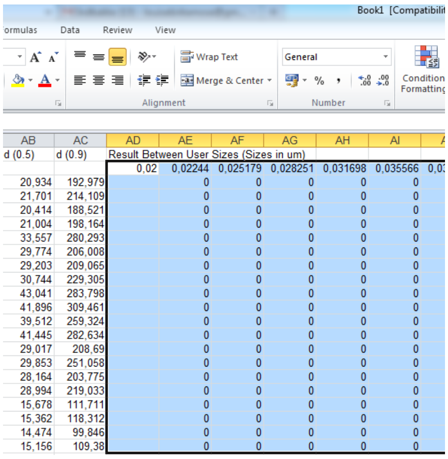
C.10 Laser Diffraction Analysis data processing

Databehandling

På Laserdiffraktormeteret
Når alle tests er kørt vil du se en lang liste over alle prøver samt information.

1. Marker alle prøver du skal bruge
2. Kopier til excel

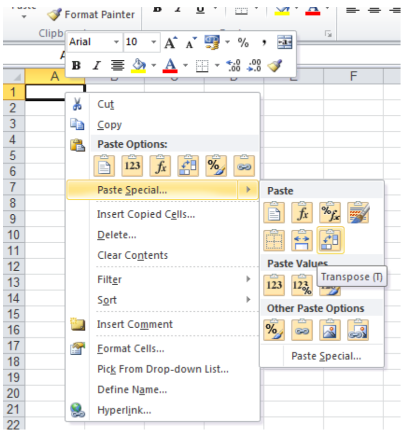
I EXCEL



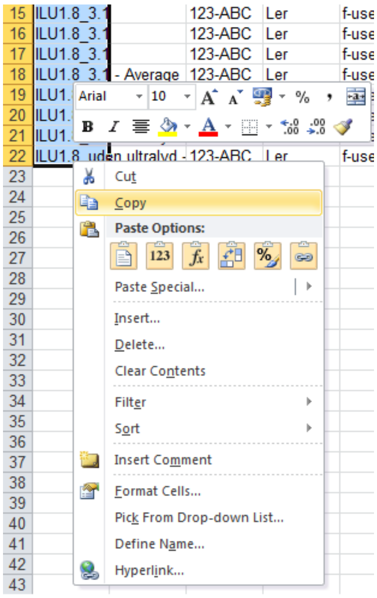
AB	AC	AD	AE	AF	AG	AH	AI
d (0.5)	d (0.9)	Result Between User Sizes (Sizes in um)					
		0,02	0,02244	0,025179	0,028251	0,031698	0,035566
20,934	192,979		0	0	0	0	0
21,701	214,109		0	0	0	0	0
20,414	188,521		0	0	0	0	0
21,004	198,164		0	0	0	0	0
33,557	280,293		0	0	0	0	0
29,774	206,008		0	0	0	0	0
29,203	209,065		0	0	0	0	0
30,744	229,305		0	0	0	0	0
43,041	283,798		0	0	0	0	0
41,896	309,461		0	0	0	0	0
39,512	259,324		0	0	0	0	0
41,445	282,634		0	0	0	0	0
29,017	208,69		0	0	0	0	0
29,853	251,058		0	0	0	0	0
28,164	203,775		0	0	0	0	0
28,994	219,033		0	0	0	0	0
15,678	111,711		0	0	0	0	0
15,362	118,312		0	0	0	0	0
14,474	99,846		0	0	0	0	0
15,156	109,38		0	0	0	0	0

1. Kopier alle linjer du skal bruge fra "ResultBetween User Sizes (Sizes in um)" og hele vejen til højre

TIP: kopier til et nyt ark, da det er mere overskueligt.



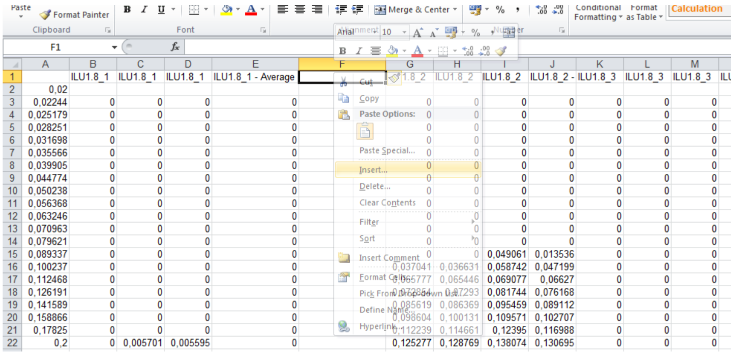
2. *Paste Special* og *Transpose*. Dette vil "vende" dine data 90°C, så toppen står til venstre og nedadgående data ligger til højre.



15	ILU1.8_3.1	123-ABC	Ler	f-use
16	ILU1.8_3.1	123-ABC	Ler	f-use
17	ILU1.8_3.1	123-ABC	Ler	f-use
18	ILU1.8_3.1 - Average	123-ABC	Ler	f-use
19	ILU1.			
20	ILU1.			
21	ILU1.			
22	ILU1.8_uden ultralyd -	123-ABC	Ler	f-use

4. Fra de originale tal kopierer du navnene på dine prøver og indsætter dem på samme måde som pkt. 2 med *Paste Special* og *Transpose*.

Se nedestående billede.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1		ILU1.8_1	ILU1.8_1	ILU1.8_1	ILU1.8_1 - Average		1.8_2	ILU1.8_2	ILU1.8_2	ILU1.8_2 -	ILU1.8_3	ILU1.8_3	ILU1.8_3
2	0,02												
3	0,02244	0	0	0	0		0	0	0	0	0	0	0
4	0,025179	0	0	0	0		0	0	0	0	0	0	0
5	0,028251	0	0	0	0		0	0	0	0	0	0	0
6	0,031698	0	0	0	0		0	0	0	0	0	0	0
7	0,035566	0	0	0	0		0	0	0	0	0	0	0
8	0,039905	0	0	0	0		0	0	0	0	0	0	0
9	0,044774	0	0	0	0		0	0	0	0	0	0	0
10	0,050238	0	0	0	0		0	0	0	0	0	0	0
11	0,056368	0	0	0	0		0	0	0	0	0	0	0
12	0,063246	0	0	0	0		0	0	0	0	0	0	0
13	0,070963	0	0	0	0		0	0	0	0	0	0	0
14	0,079621	0	0	0	0		0	0	0	0	0	0	0
15	0,089337	0	0	0	0		0	0	0,049061	0,013536	0	0	0
16	0,100237	0	0	0	0		0,037041	0,036631	0,058742	0,047199	0	0	0
17	0,112468	0	0	0	0		0,065777	0,065446	0,069077	0,06627	0	0	0
18	0,126191	0	0	0	0		0,072854	0,07293	0,081744	0,076168	0	0	0
19	0,141589	0	0	0	0		0,085619	0,086369	0,095459	0,089112	0	0	0
20	0,158866	0	0	0	0		0,098604	0,100131	0,109571	0,102707	0	0	0
21	0,17825	0	0	0	0		0,112239	0,114661	0,12395	0,116988	0	0	0
22	0,2	0	0,005701	0,005595	0		0,125277	0,128769	0,138074	0,130695	0	0	0

5. Indsæt ny kolonne ved siden af dine Avarage tal (eller de tal du ønsker at arbejde med)

6.

Nr. 1 er formlen = sum af ”Average”

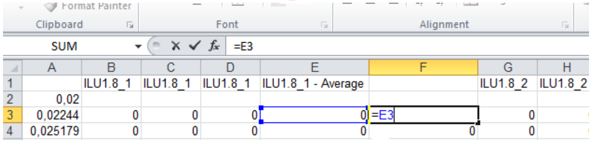
Nr. 2 er formlen = oventående + ny ”Avarage”.

Dette plusser dem alle.

Nr 3 der tager du og hiver nr. 2 hele vejen ned til hvor alle tal stopper.

Du skulle gerne ende med 100 til sidst, da det er 100% af alle partikler der nu er samlet.

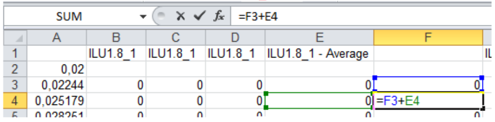
1



SUM =E3

	A	B	C	D	E	F	G	H
1		ILU1.8_1	ILU1.8_1	ILU1.8_1	ILU1.8_1 - Average		ILU1.8_2	ILU1.8_2
2	0,02							
3	0,02244	0	0	0	0	=E3	0	
4	0,025179	0	0	0	0	0	0	

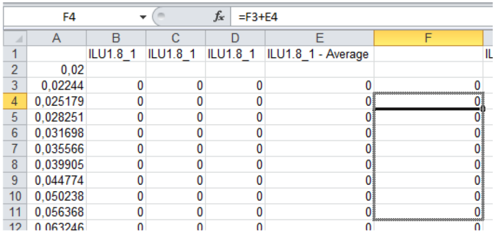
2



SUM =F3+E4

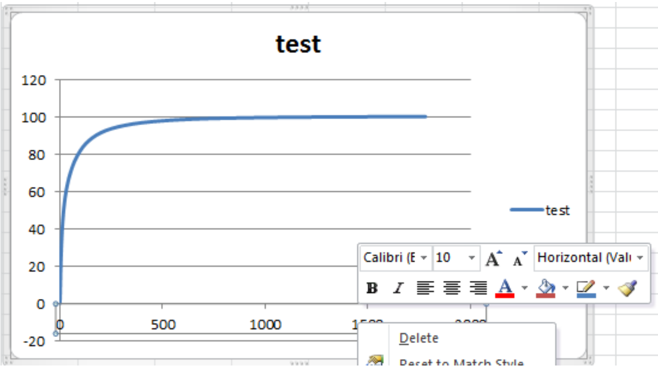
	A	B	C	D	E	F
1		ILU1.8_1	ILU1.8_1	ILU1.8_1	ILU1.8_1 - Average	
2	0,02					
3	0,02244	0	0	0	0	0
4	0,025179	0	0	0	0	=F3+E4

3

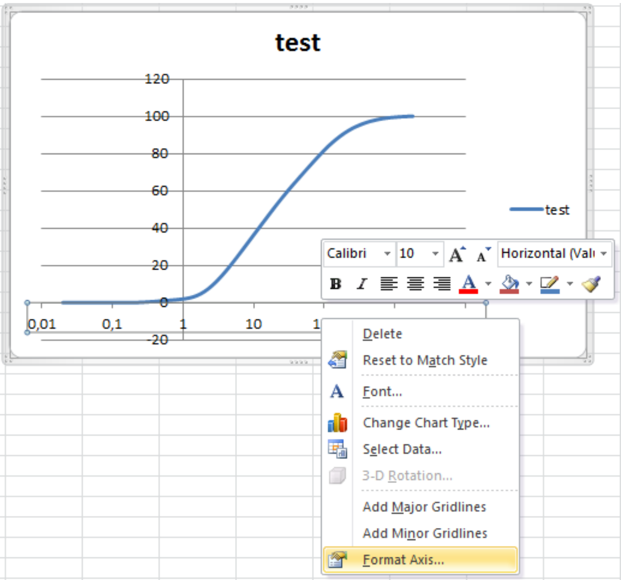


F4 =F3+E4

	A	B	C	D	E	F
1		ILU1.8_1	ILU1.8_1	ILU1.8_1	ILU1.8_1 - Average	
2	0,02					
3	0,02244	0	0	0	0	0
4	0,025179	0	0	0	0	0
5	0,028251	0	0	0	0	0
6	0,031698	0	0	0	0	0
7	0,035566	0	0	0	0	0
8	0,039905	0	0	0	0	0
9	0,044774	0	0	0	0	0
10	0,050238	0	0	0	0	0
11	0,056368	0	0	0	0	0
12	0,063246	0	0	0	0	0



7. Indsæt en graf ”Scatter with smooth lines”.
8. *Select Data* ved højreklik og vælg *Add*
    a. Series name: vælg selv
    b. Series X values: vælg tallene HELT til venstre.
    c. Series Y value: vælg nu tallene fra den indsatte kolonne (pkt.6, nr. 3)



9. For at få en ”S”-form, højreklik ved X-aksen og vælg *Format Axis*.
    a. Derinde sætter du kryds i *LogarithmicScale*

C.11 Laser Diffraction Analysis experimental

Laserdiffraktion, våde prøver

Princip

Laser diffraktion bruges til at måle størrelsen på partikler.
En laserstråle bestråler en prøve og strålen bliver spredt af partiklerne. Det spredte lys detekteres af fotodetektorer, der er placeret i forskellige vinkler. Måden lyset spredes på bliver brugt til at udregne størrelserne på partiklerne via Mie-teorien.

Apparater

Mastersizer 2000
Hydro 2000SM

Reagenser

0,005M Natriumpyrofosfat
Ionbyttet vand

Materiale

Prøver
20ml flasker

Fremgangsmåde

Prøveforberedelse:

1) ½ tsk tilføjes til 20ml flaske
2) Fyld op med natriumpyrofosfat og bland.
    a. Bland godt og grundigt op til det øjeblik hvor prøven skal tilføjes, da bundfældning sker hurtigt.

Software:

Start Mastersizer 2000 (klik OK når den spørger om username)

1) Vælg *File* i hovedmenuen og vælg *New*.
    a. Filnavn er YYDDMM + dit navn og klik OK

2) Hvis du vil konfigurere en SOP vælg *Configure* og *Existing SOP*, ellers gå til pkt. 3
    a. I *Existing SOP*vælges *JordVåd* hvis din prøve er jord eller *AskeVåd* hvis din prøve er aske

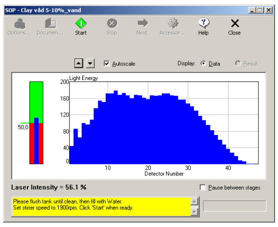
3) Vælg M*easure* og *Start SOP*.
    a. Klik igen på den SOP du skal bruge. Vælg *JordVåd* hvis din prøve er jord eller *AskeVåd* hvis din prøve er aske

    b. Hvis din prøves SOP ikke findes i systemet se vejledningen til *Ny SOP*

HUSK at trykke "Save as" når du har kørt dine prøver! Ellers forsvinder de!

Måling:

1. Når vandet er fyldt i prøvekammeret efter *Flush* sæt RPM til 3000 i et par sekunder og sluk hurtigt.
    a. Dette får boblerne i systemet til at stige til overfladen
    b. Sæt derefter RPM til det den gule meddelelse beder dig op og følg det den siger.


SOP - Clay våd 5-10%_vand

Laser Intensity = 56.1 %

Please flush tank until clean, then fill with Water.
Set stirrer speed to 1900rpm. Click 'Start' when ready.

Læs ALTID hvad der står i den gule boks. Den fortæller hvad du skal gøre.

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