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Feasibility of treated recycled materials for rammed earth structures

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Abstract

Rammed earth is a construction method in which moist soil or similar granular material is compacted into moulds. It offers the potential to reduce the carbon footprint of certain structures that nowadays are constructed using concrete. Such structures include non-load bearing walls such as noise walls, but also blocks that could be stacked to form partition walls or to support and stabilize slopes.

The use of recycled materials in the construction industry is advocated due to increasing regulations on CO2-emissions and preservation of exhaustive natural resources. In this thesis, low emission composites were developed for application in stabilized rammed earth construction. The emissions of the composites in this thesis are lowered by exploring the use of local municipal wastes, namely crushed concrete aggregate, incineration slag and utilizing a low-cement binder. The first section involves a forensic study on an existing rammed earth structure that has been exposed to Nordic conditions for 2,5 years. Based on the forensic analysis on these rammed earth composite samples, strength and moisture-based durability issues are recognized to be pitfalls in visible deterioration of the existing structures. To further improve the performance of these composite (considering strength and durability), new recipes of binder-stabilized rammed earth were explored. Incineration slag was treated with a hydrophobizing agent. This was done to potentially eliminate the degradation caused by the expansion of absorbed water during freezing. The samples were tested to determine their properties after 28 days of curing. These properties included uniaxial compressive strength (including after freeze-thaw cycles), propensity to capillary suction and other analytical inspections. Calorimetric measurements were done on some samples to study the hydration in stabilized rammed earth.

Uniaxial compressive strength values between 2,03 – 20,06 MPa were reached. Freeze-thaw durability of the samples was observed to be good after 15 freeze-thaw cycles, especially in the hydrophobized samples. A significant decrease in the capillary water absorption was observed in the hydrophobized samples, hinting to a possibility of using hydrophobized materials as way of mitigating freeze-thaw damages in rammed earth. Long-term performance of the hydrophobic agent was not studied, but the results indicate that the hydrophobicity is diminished when the samples are subjected to freeze-thaw cycles.

Keywords rammed earth, crushed concrete aggregate, incineration slag, hydrophobization, freeze-thaw

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Tiivistelmä

Sullottu maa on menetelmä, jossa kosteaa maa-ainesta tai vastaavaa rakeista materiaalia tiivistetään muottiin. Menetelmää on käytetty esihistoriallisista ajoista lähtien, ja se tarjoaa mahdollisuuden pienentää rakentamisen ympäristövaikutuksia korvatessaan betonin tietyissä rakenteissa. Tällaisia rakenteita ovat esimerkiksi ei-kantavat seinät, kuten meluesteet ja väliseinät, sekä "legopalikat" jakoseinien rakentamiseen tai luiskastabiliteetin parantamiseen.

Rakennusteollisuudessa kierrätysmateriaalien käyttämistä suositaan kasvavien CO2-päästörajoitusten ja luonnonvarojen ehtymistä rajoittavan sääntelyn vuoksi. Tässä tutkielmassa kehitettiin vähäpäästöisiä komposiittimateriaaleja sullottu maa- menetelmällä. Tutkielmassa kehitettyjen materiaalien päästöjä on pienennetty hyödyntämällä betonimursketta ja jätteenpolton kuonaa sekä vähäpäästöisen sideaineen käytöllä. Työn ensimmäisessä osassa esitetään noin 2,5 vuotta sitten rakennetun koerakenteen suoriutumisen analyysiä. Analyysin perusteella käytettyjen reseptien ongelmiksi havaittiin alhainen puristuslujuus ja eroosioalttius. Reseptien parantamiseksi valmistettiin betonimursketta ja jätteenpolton kuonaa sisältäviä, stabiloituja sullottu maa- näytteitä. Osa näytteistä hydrofobisoitiin, eli käsiteltiin vettä hylkiviksi, tavoitteena vähentää pakkasrapautumista. Näytteistä testattiin yksiaksiaalinen puristuslujuus, vedenimevyys sekä jäätymis-sulamiskestävyys. Kalorimetrillä tutkittiin näytteiden hydraatiota. Röntgenfluoresenssianalyysilla selvitettiin materiaalien kemiallisia koostumuksia.

Saavutetut yksiaksiaalisen puristuslujuuden arvot vaihtelivat välillä 2,03–20,06 MPa. Jäätymis-sulamiskestävyys todettiin hyväksi rajallisten jäätymis-sulatussyklien jälkeen, erityisesti hydrofobisoiduissa näytteissä. Käytetty syklimäärä oli 15. Merkittävä alenema kapillaarisessa vedenimevyydessä havaittiin hydrofobisoiduissa näytteissä, mikä viittaa mahdollisuuteen käyttää hydrofobisoituja materiaaleja pakkasrapautumisvaurioiden estämiseen sullotussa maassa. Vettä hylkivän käsittelyn pitkäaikaiskestävyyttä ei selvitetty, mutta tulokset viittaavat siihen, että jäätymis-sulamissyklit vähentävät hylkimisefektiä.

Avainsanat sullottu maa, betonimurske, jätteenpolton kuona, hydrofobisointi, jäätymis-sulaminen

Table of contents

Preface and acknowledgements

Utilization of circular materials in civil engineering has been the subject of ongoing research in Aalto University during the past few years. This thesis is a part of this line of studies in which novel materials and methods have been tested and developed with end goal of reducing the environmental impact that urbanization will have. This thesis has been made as a part of RAKISEI project, funded by the City of Helsinki.

I want to thank Professor Sanandam Bordoloi for supervising my thesis and for providing invaluable advice during the process. I also want to thank my advisors, Professor Leena Korkiala-Tanttu and Dr. Anoosheh Iravanian. Professor Korkiala-Tanttu provided the original subject and kindly offered me a place in her research group. Dr. Iravanian has offered concrete guidance in practical lab work and in writing of the thesis, which I am very thankful for. I also want to thank the other members of the steering group of this thesis: Juha Forsman, Jouni Punkki and Henry Gustavsson.

I also want to thank the laboratory staff of the Civil Engineering department at Aalto University. I am grateful especially for Jukka Piironen, who guided the usage of numerous laboratory appliances and helped with the procurement of raw materials. I also want to thank other staff and fellow students who aided me during the thesis process, most importantly Soumya Roy for his integral input and Manish Jaiswal for companionship during our mutual thesis projects. I also want to thank all the guys of room R167.

This journey has been long and at times frustrating, but I have also learned a great deal. About circular materials and rammed earth, yes, but maybe most importantly about myself, science and how the world works. It has not been a struggle in vain.

Lastly, I want to thank my family for their support during my studies.

Otaniemi, 17 December 2024
Otso Laurila

Symbols and abbreviations

Symbols

S	Degree of saturation

Abbreviations

OMC	Optimal water content
PSD	Particle size distribution
MDD	Maximum dry density
UCS	Uniaxial compressive strength
PC	Portland cement
SCM	Secondary cementitious material
GGBFS	Ground granulated blast-furnace slag
IS	Municipal waste incineration slag
CC	Crushed concrete
UPV	Ultrasonic pulse velocity
XRF	X-ray fluorescence
ICT	Intensive compaction tester
LCA	Life-cycle assessment
GWP	Global warming potential

1 Introduction

Landfilling has historically been the go-to option for the end-use of side-stream materials deriving from construction, waste management and energy industries. However, as the push for circular economy is growing stronger due to ambitious carbon reduction and preservation efforts, the interest in using previously overlooked mineral materials as recycled aggregate materials is growing. Legislation in the European Union sees landfilling as the least desirable option in the so-called waste hierarchy. (European Parliament, 2008). In Europe, approximately 3 000 million tonnes of aggregate were used by the construction industry in 2021. In Finland, the same figure was 74 million tonnes of which 4 million tonnes are circular. (UEPG, 2024). Increasing demand and depleting natural aggregate resources in high population areas will lead to growing procurement costs and emissions, increasing the attractiveness of circular materials originating from within the growth centres. Natural preservations efforts are also amplified by a decrease in natural aggregate quarrying. (Sormunen, 2017).

The use of waste materials is subject to different legislation due to their potentially hazardous nature. For the recycling of waste to aggregate materials in Finland, directive 843/2017 (Valtioneuvoston asetus eräiden jätteiden hyödyntämisestä maarakentamisessa, MARA) issued by the government of Finland is the one of the most significant legal documents. It pertains to the use of certain waste materials in infrastructure construction and sets the criteria for defining and usage process of said materials. The materials regulated in the directive include concrete, asphalt, different ashes and slags, foundry sands, lime-based waste and rubber tire waste. The directive enables the use of these materials in infrastructure construction without an environmental permit in certain applications and conditions. (Finnish Government, 2017). It is to be noted that the current legislation and guidelines mainly pertain to the usage of recycled materials as a load bearing structural material in road and street structures or in similar filling applications. No guidelines or legislation exists for using recycled aggregates in other applications. Exception to this is that crushed concrete can be used as an aggregate in ready-mix concrete and as a soil improvement substance according to government directive 466/2022.

Crushed concrete is manufactured by crushing demolished concrete rubble into desired fraction sizes. Sources for the waste concrete are demolition sites, ready-mix concrete plants and pre-cast structures industry. Crushed concrete is divided into four different classes based on its purity, grain size and origin. Compared to natural aggregates, the usage of crushed concrete in structures is subject to many limitations and guidelines. Commonly, crushed concrete includes small amounts of other waste materials, such as brick, plastic, wood and metals. The maximum amounts of secondary materials and

other provisions are provided in the application instructions of the MARA-directive. (City of Helsinki, 2019).

Incineration slag refers to processed bottom ash collected from furnaces where municipal waste is burned in an energy production process. The energy is used to generate electricity or to heat up water for district heating networks. Incineration slag has been traditionally used as a fill material in structural layers of landfills and waste processing plants. It has a sand- or gravel-like composition and is used in different grain sizes up to 63 mm. Circa 300 000 tons of incineration slag is formed per year in Finland. As new power plants utilising municipal waste as fuel are being built and landfilling of waste is decreasing, finding new uses for the slag is a timely subject. (Suomen Erityisjäte Oy, 2024).

The purpose of this thesis is to study crushed concrete and incineration slag to gain further information on their characteristics when used as aggregates in hydraulically bound, cement-stabilized structures. This construction method is known as stabilized rammed earth (SRE). Also, the effect of a hydrophobizing agent on the freeze-thaw durability and capillary saturation properties of samples is investigated. The research questions are:

- What is the durability of stabilized rammed earth structures made with crushed concrete and incineration slag in long-term field trials in Nordic conditions and how to assess it?
- What is the suitability of crushed concrete and incineration slag as materials for rammed earth based on long-term field trials and laboratory tests?
- Is hydrophobization of incineration slag a viable remedy for freeze-thaw induced damages in rammed earth structures?
- Is a novel circular binder, EcoIntellect E65, a viable option for stabilizing rammed earth?

This thesis is continuing the work laid out in several theses made in Aalto University about rammed earth and recycling of mineral waste materials. In Kasper Holopainen's thesis from 2022 crushed concrete and incineration slag were investigated through rammed earth test samples and by constructing a test wall structure in Konala, Helsinki. In this thesis, the performance of the test structure is assessed.

2 Rammed earth

The traditional rammed earth construction process has been used throughout history all around the world. In its simplest form, the rammed earth method consists of formwork where moist soil materials are packed using a tamper. This forms a structure that can support its own weight and retain its form after removing the formwork, based on the internal cohesion of the structure. (Minke, 2006).

In this chapter, the basic properties that prescribe the function, strength and durability of rammed earth structures are explored. The soil mixture that forms the body of a rammed structure has the utmost effect on the result. Secondary parameters include the water content of the mixture, compaction energy and external conditions.

Historically, the bulk of the materials used in rammed earth construction have been sourced locally near the construction site. As low carbon emissions are one of the main selling points of modern rammed earth construction, the importance of short transportation distances remains. Also, using recycled material that does not have to be excavated from natural soil formations decreases emissions and offers the possibility to replace the natural materials. To produce and recognize suitable recycled materials, the characteristics of materials suitable for rammed earth construction need to be known. (Reddy, 2022).

2.1 Partially saturated soil and rammed earth

Partially saturated soil refers to soil that is not completely saturated with water nor completely dry. The voids between solid soil grains in fully saturated soils are filled with water, and in dry soil with air. In partially saturated soil, the voids are filled with both. This concept is illustrated in figure 2.1. The degree of saturation, usually denoted with S, expresses the water content of the voids. The degree of saturation can vary between 0 and 100 %. Soil layers situated above the ground water level generally are partially saturated. (Berney, 2004).

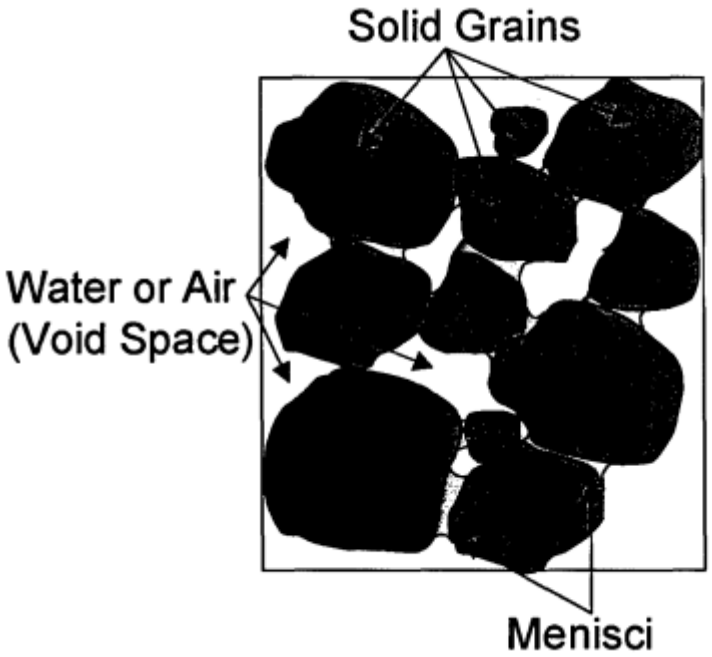


Fig 2.1. A schematic of partially saturated soil. (Berney, 2004).

Water decreases the friction between soil grains, allowing the grains to slide along the surfaces of other grains when subjected to compaction efforts. The smaller the voids between soil particles, the higher will be the density of a finished rammed earth structure. However, if too much water is present in relation to the volume of the voids, the water will push the soil grains apart, preventing compaction. Therefore, to find the greatest compaction state in a given soil, the water content needs to high enough to maximise the lubrication between grains, but low enough to not prevent compaction before this point is reached. This water content is called the optimal water content (OMC). (Berney, 2004).

The internal structure and strength-forming properties of rammed earth are not completely understood. This follows from the historical use of rammed earth as a technique to exploit the local soil, leading to recipes being empirically derived from experience. The use of stabilizing binders in modern rammed earth construction further complicates the strength-forming process. (Jaquin, et al., 2008).

Unstabilized rammed earth can be seen as soil that has been compacted and has a low degree of saturation. As the structure is demoulded, the degree of saturation drops even further as a result of water evaporation. In unstabilized rammed earth, cementation between the soil particles is non-existent. As it stands, the internal force resulting in the soil particles staying in contact is described as suction resulting from the drying of water. This effect is known

as apparent cohesion, as it resembles cohesion, a well-known phenomenon in geotechnical engineering. However, the relationship between the degree of saturation and apparent cohesion is not linear nor uncomplicated. (Jaquin, et al., 2008).

In the study of unsaturated soils, the formation of apparent cohesion is credited to a phenomenon known as liquid bridge. A liquid bridge forms into a soil pore, where both air and water are present. The air pressure acts on the liquid surface, causing tension to form. This tension along with the surface tension of the water causes weak attractive forces between the soil particles. As the water in the structure dries, for example due to evaporation in hot weather conditions, the amount of water lessens, weakening the bond. The structure has a degree of saturation in which the suction force caused by this phenomenon peaks, after which the structure will get weaker if drying persist. (Jaquin, et al., 2008).

As a result of the liquid bridge, many rammed earth structures depend on the relative humidity of their surroundings for their apparent cohesion and strength, although it is unclear how large the effect is in practice. This might be an explaining factor on why some rammed earth structures have survived longer than others.

2.2 Assessment of materials for the rammed earth technique

Grain size distribution

Soil is a granular material. Natural soils contain a range of different grain sizes. The relative proportions of these grain sizes, also known as grading, are presented by with a grain size distribution curve, also known as a particle size distribution curve (PSD). This distribution is the foremost characteristic of a material to be considered when designing rammed earth mixtures. (Reddy, 2022).

Soil particles are classified into subgroups called the particle size fractions based on their grain size. (Finnish Standards Association SFS, 2018) Subgroups used in rammed earth construction are gravel, sand, silt and clay. Very coarse soils are classified into additional subgroups, but they are not considered in rammed earth construction. The classification of soil into soil groups and particle size fractions is presented in table 1.1. (Reddy, 2022).

Table 1.1. Particle size fractions according to the Finnish Standards association.

Soil group	Fraction	Range of particle sizes [mm]
Very coarse soil	Large boulder (lBo)	>630
	Boulder (Bo)	>200 to ≤630
	Cobble (Co)	>63 to ≤200
Coarse soil	Gravel (Gr)	>2,0 to ≤63
	Coarse grave (cGr)	>2,0 to ≤63
	Medium gravel (mGr)	>6,3 to ≤20
	Fine gravel (fGr)	>2,0 to ≤6,3
	Sand (Sa)	>0,063 to ≤2,0
	Coarse sand (cSa)	>0,63 to ≤2,0
	Medium sand (mSa)	>0,20 to ≤0,63
	Fine sand (fSa)	>0,063 to ≤0,2
Fine soil	Silt (Si)	>0,002 to ≤0,063
	Coarse silt (cSi)	>0,02 to ≤0,063
	Medium silt (mSi)	>0,0063 to ≤0,02
	Fine silt (fSi)	>0,002 to ≤0,0063
	Clay (Cl)	≤0,002

Each fraction imposes certain characteristics into the rammed earth mixture and to the finished structure. Coarse gravel and sand particles form “the skeleton” or “the body” of the structure and provide compressive strength. Fine silt and clay particles are needed to create a plastic, cohesive mixture that can be compacted into a mould. In unstabilized rammed earth mixtures, fine particles act as the “binder” by forming a suitable void-grain structure into the mixture. However, too much clay causes shrinking and cracking of the structure. Material considered for rammed earth construction needs to have the fractions in a suitable distribution. Based on several studies into the distribution of the fractions, indicative distributions of the fractions in a rammed earth mixture are 45-80 % sand and gravel, 10-30 % silt and 5-20 % clay. Grain size distribution range suitable for rammed earth soil mixtures produced by Walker et al. is presented in figure 2.1. (Walker, et al., 2005).

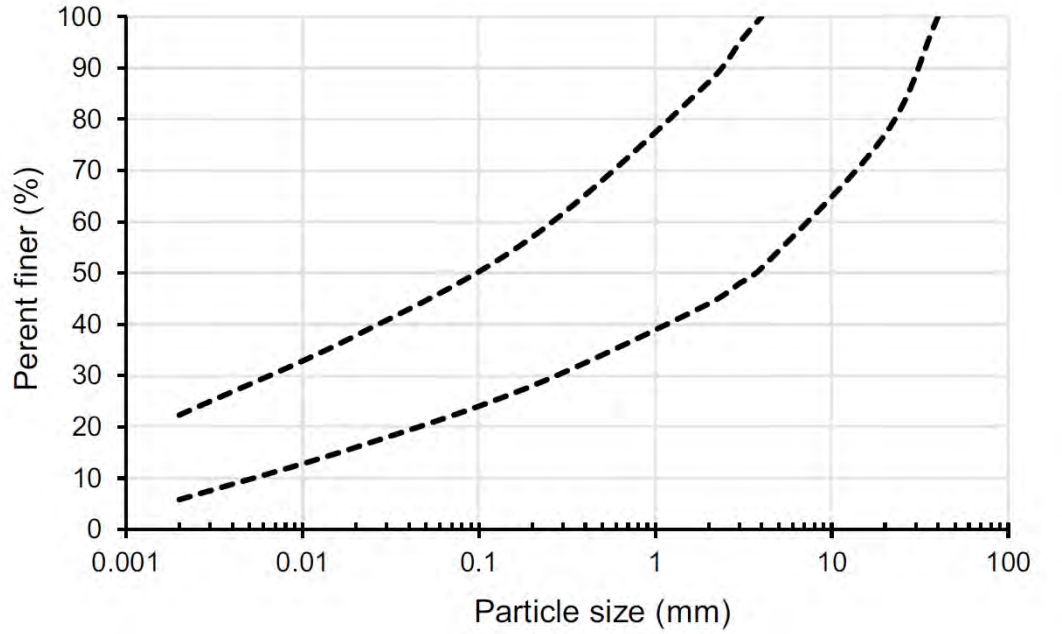


Figure 2.1. The optimal grain size distribution boundaries for rammed earth according to Walker, et al. (2005).

Optimum Moisture Content

The Proctor test is a widely used method to determine the optimum moisture content (OMC) of the granular materials used as a rammed earth construction material. The optimum moisture content is the amount of water needed in the mix to achieve the maximum dry density (MDD) of the mix. However, the distribution of the soil fractions and cement content affect the compaction properties further. Especially high content of clay particles affects the amount of water needed. (Reddy, 2022).

An indicative method for testing whether a rammed earth mixture is close to it's OMC is to grab a handful, compressing the material into a ball. If the soil is cohesionless and cannot be moulded, it is too dry.

According to Holopainen (2022), the moisture content to achieve the highest possible compressive strength when using crushed concrete as the aggregate in stabilized rammed earth mixtures was 2 % under the OMC. Similar results were obtained by (Beckett & Ciancio, 2014) when using natural soil as the aggregate. This differs from unstabilized rammed earth recipes, where a water content close to the OMC is recommended. Therefore, in stabilized rammed earth mixes achieving MDD does not translate into highest possible UCS values. (Jaquin, et al., 2008).

2.3 Stabilized rammed earth and cementitious reactions

Portland cement (PC) is formed by four main chemical compounds: alite (C_3S), belite (C_2S), aluminate (C_3A) and ferrite (C_4AF). Alite forms 50-70 % of cement mass, belite 15-30 % and aluminate and ferrite 5-10 %. Alite and belite are silicates, meaning that silicon oxide (SiO_2) is forms a functional group in their formulas. During the cement manufacturing process silicates form when the raw materials of cement, limestone and clays, are mixed and heated. Silicates are the main reactive compounds present in Portland cement. (Neville & Brooks, 2010).

Secondary cementitious materials (SCM) refer to materials with some hydrating capabilities that are mixed with Portland cement to decrease the CO_2-impact of the resulting binder, or to achieve favourable properties during usage of the cement. Common SCMs are ground granulated blast-furnace slag (GGBFS) and different fly ashes. Currently, they are widely used in concrete industry for increased control over concrete parameters such as heat development and final strength. They are also used and researched for their potential role in decreasing CO_2-emissions of the cement industry, which is responsible for 5-8 % of humankinds annual CO_2-emissions. (Lothenbach, et al., 2011).

The process where dry, powdered cement is turned into a solid, bound structure is known as hydration of cement. As the term suggests, water (H_2O) is an integral part of these reactions. During the hydration process, water and the silicates present in cement form new compounds, known as hydration products. These reactions are exothermic, meaning that they release heat, which is known as heat of hydration. This heat can be easily tracked, and it can be used to infer the different stages of cement hydration that are commonly recognized in the hydration of standard Portland cement. These stages are presented in figure 2.2, after Scrivener, et al. (Neville & Brooks, 2010).

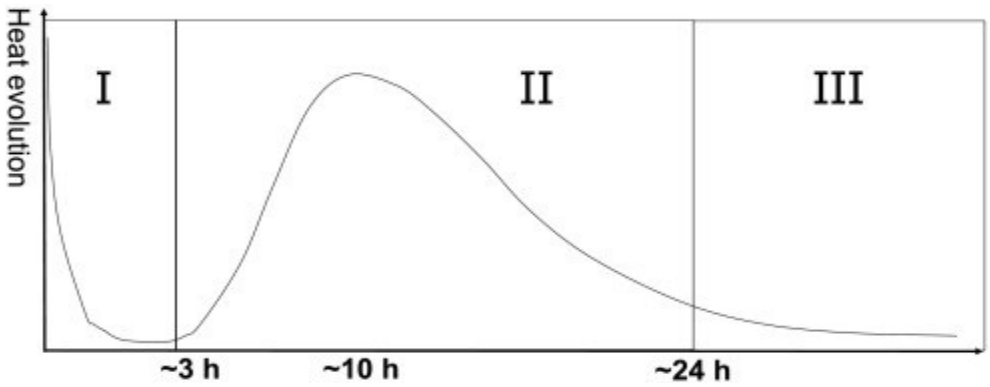


Fig 2.2. Stages of cement hydration. (Scrivener, et al., 2019).

When water is mixed into an aggregate mix containing cement, dissolution of the cement clinker starts immediately. This dissolution releases energy, which is observed as heat. In figure 2.2, this heat is visible in stage I. Stage I includes the initial heat release and the period of slow reaction, also known as dormant or induction period. After some hours, the acceleration period starts in stage II of the hydration, marked by significant heat release. This is the primary hardening phase of cement. After reaching a peak in the heat of hydration, the heat flow starts to lessen. At this point, most of the strength that the cement or concrete mix can achieve has been reached. In 180 days, about 90 % of the heat will be released when using standard Portland cement. The total amount of heat released and the rate of heat release can be controlled with SCMs and by modifying the properties of the binder, for example by grinding it to a finer grain size. The hydration of cement continues in small extent for years, although the heat release from this long-term hydration is so miniscule that it is not observable. However, long-term strength increase in cement-bound structures can be observed when sampling aged structures. (Neville & Brooks, 2010).

The strength gain in concrete, stabilized rammed earth and other structures bounded with cement mainly bases on the formation of calcium silicate hydrates, which are formed after reactions of alite and belite with water. In cement and concrete studies, these hydration products are referred as C-S-H or CSH. They form the cement paste that binds aggregates together. Other constituents of cement also form hydrates, but majority of the void-filling paste is formed from alite. (Hilal, 2016).

Other main hydrates formed are:

- Calcium hydroxide, $Ca(OH)_2$, CH. Also known as portlandite. Formed as a byproduct of calcium silicate (C_3S, C_2S) hydration, calcium hydroxide has some binding properties, while contributing more to the alkalinity of cement, which in turn protects steel rebar from rusting.
- Ettringite, formed from aluminate (C_3A) and gypsum. Ettringite contributes to the early strength development of curing cement.
- Alumino-ferro-monosulfate hydrates, AFm. Group of calcium aluminate hydrates that form when aluminate and ferrite react with water. Ettringite can also form into AFm on the later stages of hydration. (Neville & Brooks, 2010).

The cement hydrates can be identified when a hydrated cementitious sample is observed with a scanning electron microscope (SEM). Example pictures of the hydration products are presented in figures 2.3 and 2.4. C-S-H forms dense needles that protrude from the surface of a cement grain. CH forms hexagonal crystals in the empty spaces between C-S-H needles. Ettringite

forms long hexagonal cylinders, while AFm forms thin flake-like crystals. (Hilal, 2016).

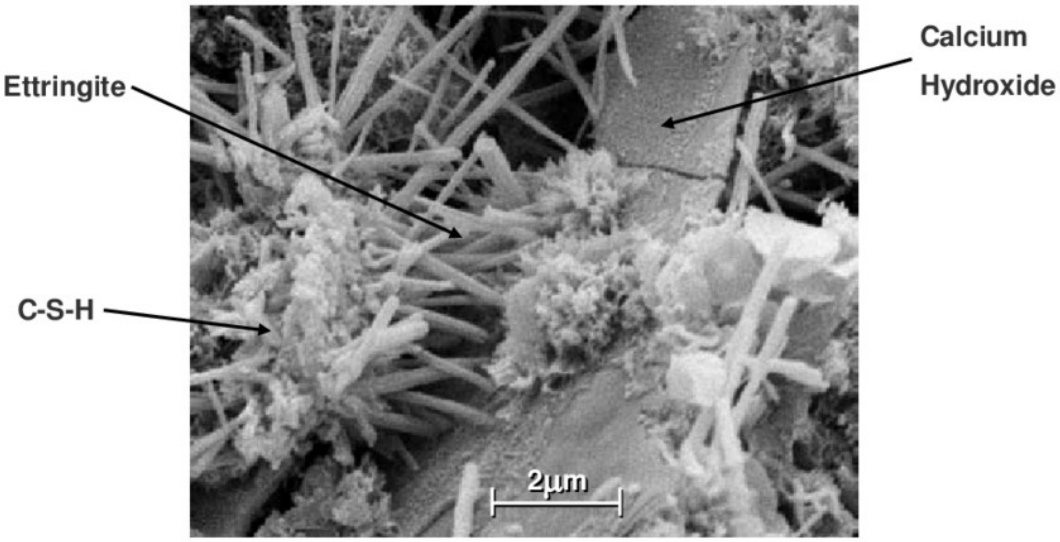
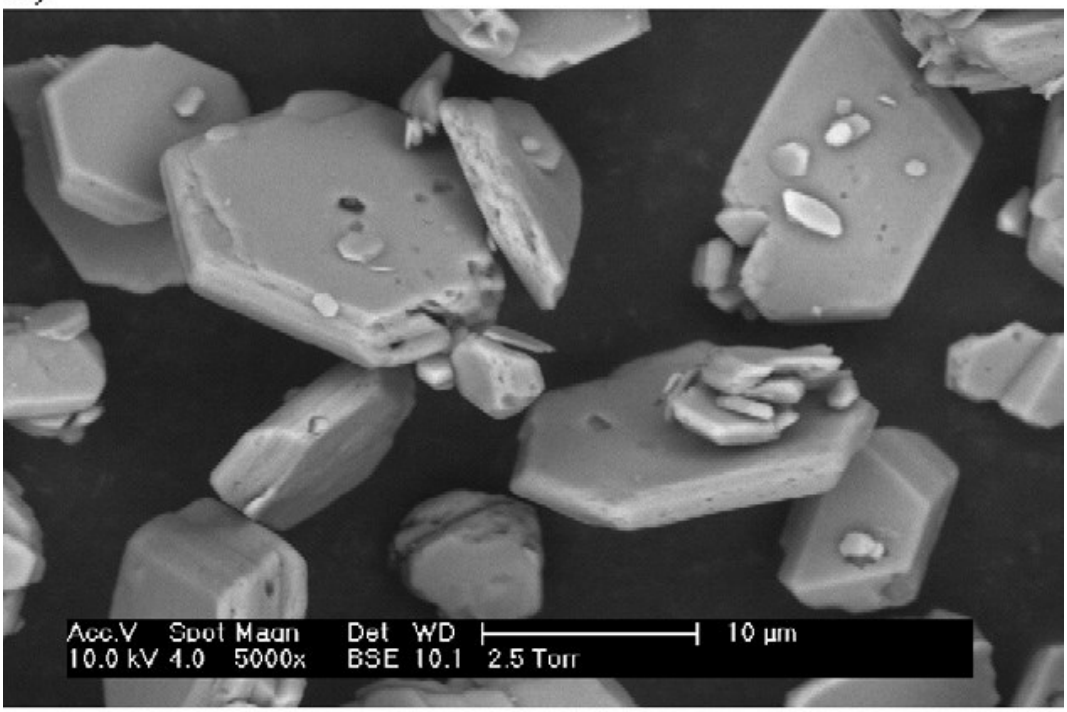


Figure 2.3. C-S-H, CH (calcium hydroxide) and ettringite as seen in SEM-imaging. (Margeson, 2009).

a)



b)

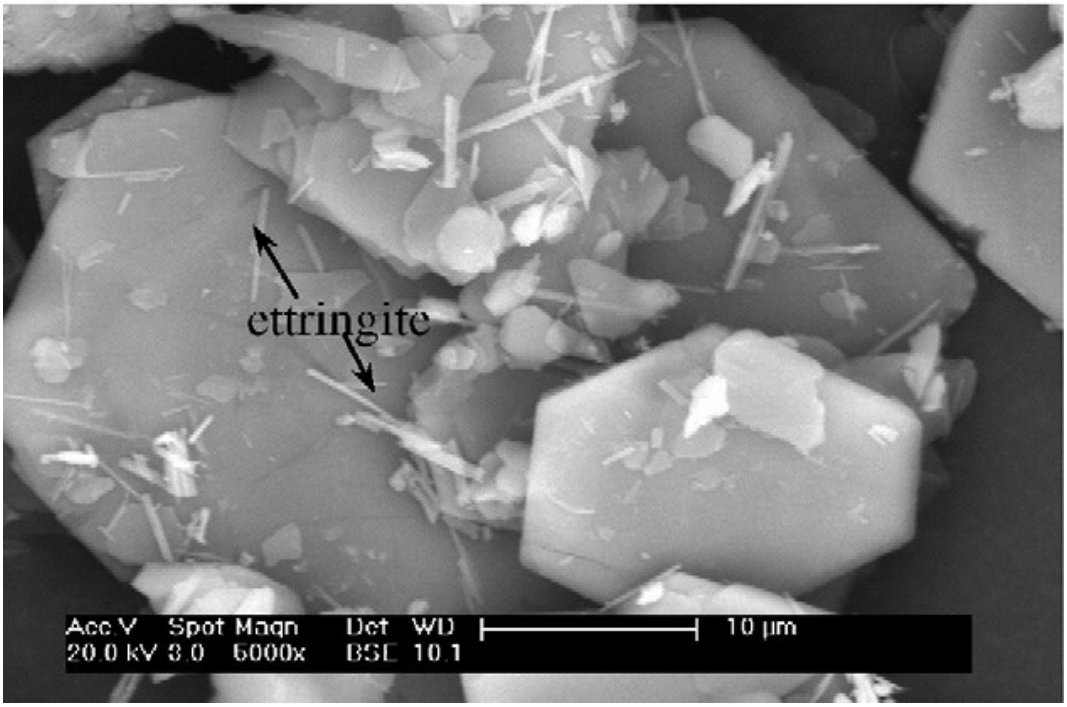


Figure 2.4. AFm flakes in SEM-imaging. (Lothenbach 2007).

3 Forensic study of Konala Test Structure

In October 2021, a test structure consisting of 4 different stabilized rammed earth mixtures was constructed to Konala in Helsinki. The purpose of test wall is to study the suitability of recycled materials as aggregates in stabilized rammed earth structures after they were identified as potential materials in literature review and lab tests. Especially the erosion and degradation of the walls in southern Finnish conditions with numerous freeze-thaw cycles during the winters was of interest. (Holopainen, 2022).

The selection of the materials, lab tests and the construction process of the test structure is documented in Kasper Holopainen's thesis "Rammed Earth noise wall test structure with recycled materials" from 2022. In this thesis, the performance of the different mixtures is assessed, based on a research plan partly derived from Kasper Holopainen's preliminary research plan "Sullotun maan koerakenne, mittaus- ja instrumentointisuunnitelma", done as a special assignment in Aalto University in 2022.

3.1 General description of the test structure

The test structure is a wall with 4 distinct sections separated by plywood boards, each section corresponding to a different rammed earth mixture. The mixtures are presented in table 3.1. The test setup allows for comparison of the different materials in similar conditions. The structure is presented in figures 3.1 and 3.2.

The structure is located on a lot that has been used for storage of soil and construction waste materials. The lot is managed by Stara, city of Helsinki's construction service provider. In 2024, the lot was empty and minimal activity took place there. During the construction of the test structure, soil masses were stored in the lot, which now have been transported elsewhere. The disturbance caused by heavy machinery and trucks operating near the structure is to be considered when assessing the cementation process.

The test structure is situated at the edge of the open lot, the sides facing southeast and northwest. A retaining wall dividing the test area and the neighbouring lot is situated about 4,5 meters from the northwestern face. On the southeast-facing side the wall is facing an empty field.

A roof consisting of wood and a HDPE-film was installed on the top of the test structure. The edges of roof were extended about 150 mm over the test structure and tilted downwards to offer protection from rain.

Table 3.1. Recipes of the wall sections in Konala.

Wall section	1	2	3	4
Recipe	CC + Fly ash (Helen)	CC + Fly ash (UPM)	IS + Fly ash (Helen)	IS + Fly ash (Helen)
Binder to aggregate ratio	1:5	1:5	1:4	1:5
Aggregate (saturated) [kg]	3047	3060	2609	2609
Aggregate w%	9,4	9,4	19,4	19,4
Water in aggregate [kg]	262	263	424	424
Aggregate dry weigth [kg]	2785	2797	2185	2185
Fly ash [kg]	473	476	464	372
Cement [kg]	84	84	82	66
Planned w %	10	10	17	17
Added water [kg]	104	104	90	108
Actual w%	11	11	19	20

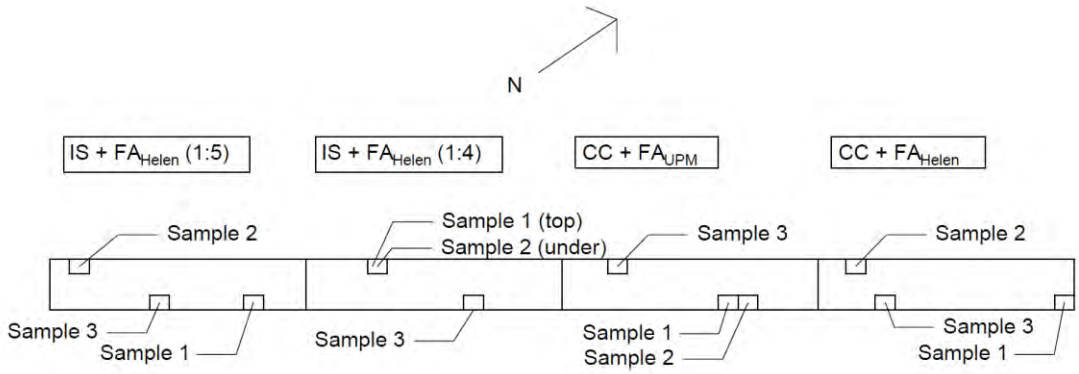


Fig 3.1. Top-view schematic of the test structure with sample locations marked.

Fig. 3.2. The Konala test structure

3.2 Research plan

3.2.1 Erosion assessment

Erosion of the structure was assessed mainly visually and haptically. Each face of each test section was examined, and all damages and alterations were marked into a paper containing a blueprint image of the wall. The results were then studied to recognize common patterns of erosion related damage. The intact parts of the structure were tested using touch and sound. Using their knuckles or an object, the examiner can identify parts of the surface where the smooth surface layer has detached from the aggregate matrix beneath it. These parts gave out a hollow, dull sound when struck, as opposed to intact structure that gave out a noticeably sharper sound.

Additionally, a photogrammetric model of the wall was prepared. This work is described in a special assignment report "Konala wall 3D model regeneration" by Eden Telila. As a reference model was produced when the structure was completed, the amount of erosion could be further assessed using this method.

3.2.2 Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) is a non-destructive testing method commonly used in quality assurance and strength approximation of concrete. The UPV device comprises of a transmitter that sends a signal and a receiver to detect the signal. The time that the signal takes to travel through a structure is measured, and knowing the width of the structure, the velocity of the pulse can be calculated. In concrete, the velocity of the pulse and the density of the material are often correlated, meaning that the pulse velocity is greater when the density is greater. As greater density often correlates with greater uniaxial compressive strength in concrete, the UPV results can be used to approximate or compare the compressive strengths of concrete. Calibration of the system with destructive sampling and testing is needed for accurate results. (Al-Neshawy, et al., 2021).

Ultrasonic pulse velocity has been used in numerous studies relating to rammed earth structures both internationally and in Aalto University. The studies have found positive correlation between UPV and uniaxial compressive strength in rammed earth samples, leading to the conclusion that UPV is a viable option in assessing the compressive strength of rammed earth test samples. (Luoma 2023). However, it's applicability when dealing with structures located in natural conditions and experiencing a varying amount of damage and alteration is still unclear. Experiences from concrete technology indicate that cracking and other discontinuities greatly affect the time that the pulse takes to travel. The presence of these can make the method less applicable for rammed earth than for concrete.

For studying the UPV values in the test structure, a measurement grid with even spacings was designed with four points in the latitudinal direction and three points in the vertical direction on the wall face, totalling to twelve points for every wall section. The measurement points were marked on both sides of the wall for assuring that the transmitter and the receiver are directly opposite. An example of the markings is presented in figure 3.3.


Figure 3.3. Measuring grid for UPV measurements.

3.2.3 Uniaxial compressive strength

Uniaxial compressive strength (UCS) is the single most important material parameter to be considered when designing rammed earth structures. It serves as basis when designing structures, although the UCS itself is derived from testing small, simple test samples. The testing of the compressive strength of hydraulically bound mixtures is standardised in SFS-EN 13286-41. According to the standard, the samples are to be cylindrical or cubical with certain sizes. The samples are subjected to compressive force in a hydraulic or mechanical press. The pressing is carried out with a predetermined speed, for example 3 millimetres per minute. The force required to keep up with this speed is recorded. Knowing the dimensions of the test sample, the induced stress in the sample can be calculated. The highest stress that the sample experiences is the ultimate compressive strength of the sample. If deemed successful, the test results can be used as a basis for structural design of rammed earth structures.

Rammed earth is primarily used in massive structures where compressive stress is the only primary stress. Performing UCS tests to samples produced from tentative granular materials or binders offers a rapid way of gaining insight on the suitability of said materials for use in the rammed earth method.

For the Konala wall structure, a test plan consisting of three samples per each wall section was decided upon. Blocks were extracted from the walls using a gas-powered rotary diamond blade concrete saw. The blocks were cut final sample dimensions using a table saw in the case of sections 1 and 2. Blocks from sections 3 and 4 were cut to sample dimensions using a regular hand saw. A gypsum mortar was used to level the pressing surfaces when required.

3.3 Results

3.3.1 Sampling

The extraction of the samples suffered from practical problems during the sampling process. As a result, the sample sizes especially in samples from sections 1 and 2 where crushed concrete was used as the aggregate is deviating from the planned 100x100 millimetre cube. Firstly, due to the cutting depth of the saw blade (150 mm) and the physical constraints imposed by the tool and the structure samples were able to be extracted only near the surfaces of the walls. As the surfaces experienced various amounts of erosion, the samples were flaky and breaking. The grain size used in sections 1 and 2 was fairly large, which exacerbated the problem. Large grains become loose in the edges of the samples and broke off from the sample body. This indicates that the bond between the crushed concrete grains and the finer paste is very weak. Also, even when there was no significant erosion on the surface, about 20 to 30 mm layer on the surface was clearly weaker than rest of the sample and commonly broke off during processing of the sample. Picture of a sampling location is presented in figure 3.4. The acquired samples along with their dimensions, masses and densities are presented in table 3.2.

Figure 3.4. Crushed concrete- based wall section after sampling. Large grains of crushed concrete can be seen, with the gaps filled with hardened paste.

The aggregate material on sections 3 and 4 was incineration slag graded to 0-2 mm, therefore making it easier to cut samples that were in the correct dimensions. However, the tensile and shear strength of the samples was extremely low, causing samples to fracture during normal handling. A regular hand saw was able to cut through the material, as showcased in figure 3.5. Careful handling was required when processing the samples made from incineration slag.

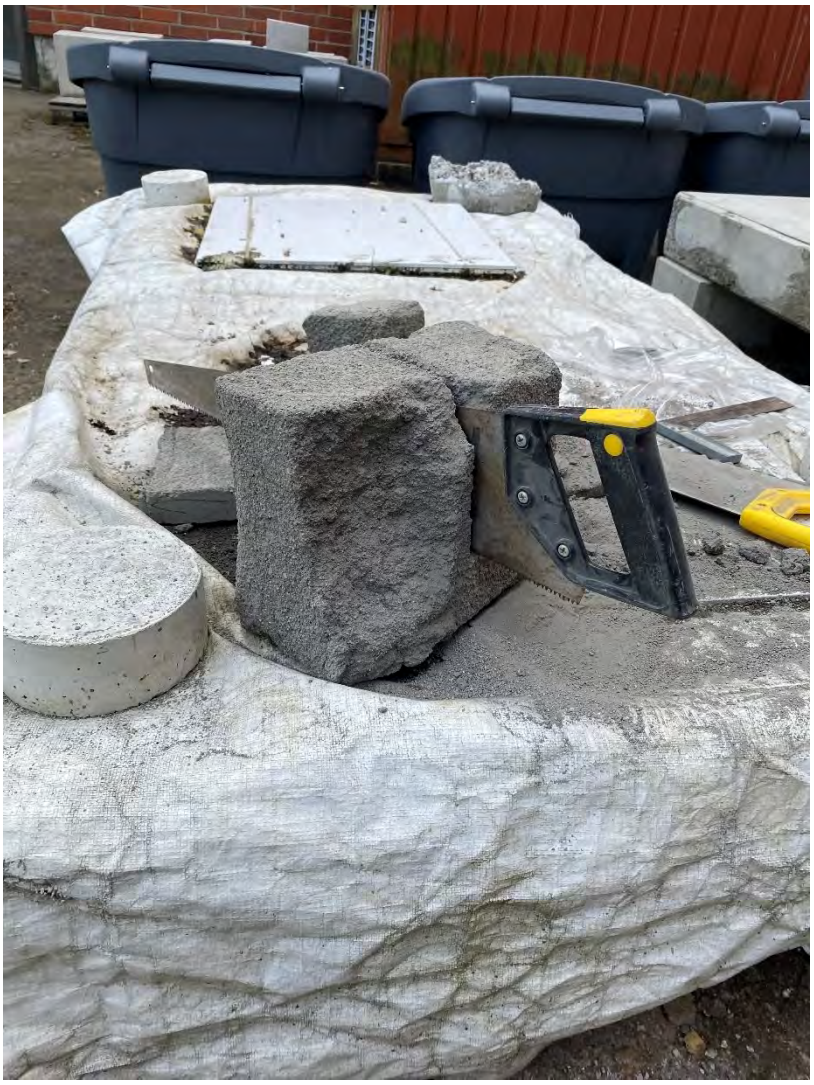


Figure 3.5. The incineration slag- based samples could be cut into correct dimensions using a hand saw.

The finished samples were measured, weighted and photographed. UPV measurements were performed as described in chapter 3.3.2. Before the UCS tests, a gypsum mortar was applied to pressing surfaces of the samples to ensure the evenness of the surfaces. Example picture is provided in figure 3.10.

Table 3.2. Samples taken from each wall section and their final dimensions and masses after processing.

	Dimensions [mm]				
Sample	Height	Width	Depth	Mass [kg]	Density [kg/m3]
1. CC + Fly ash (Helen)					
Sample 1	85	70	72	0,82	1914,1
Sample 2	104	112	94	1,94	1771,8
Sample 3	91	60	61	0,61	1831,5
Sample 4	58	71	61	0,49	1950,7
2. CC + Fly ash (UPM)					
Sample 1	100	53	45	0,42	1761,0
Sample 2	90	105	102	1,72	1784,4
Sample 3	95	94	101	1,56	1729,6
3. IS + Fly ash (Helen) (1:4)					
Sample 1	101	100	102	1,48	1436,6
Sample 2	92	104	108	1,47	1422,6
Sample 3	100	101	103	1,48	1422,7
4. IS + Fly ash (Helen) (1:5)					
Sample 1	102	104	98	1,34	1289,0
Sample 2	95	101	97	1,25	1343,1
Sample 3	102	110	99	1,45	1305,4

3.3.2 Erosion assessment

Cursory visual assessment of the test structure reveals specific failure patterns depending on the aggregate used. In test sections 1 and 2, where crushed concrete was used as the aggregate, surface erosion takes place locally all around the face of the walls. It seems that due to the large grain size used in the mix (max. 60 mm), the fine paste formed by the finer fractions of the mix has not been able to properly fill the voids between the larger grains. This effect is magnified on the wall faces, where the mixture was compacted against a plywood board. This caused cavities to form on the surface of the structure, which later acted as locus points for freeze-thaw induced erosion. The cavities were clearly visible right after the construction process was completed and the formwork stripped, as evidenced by photographs taken by Holopainen (2022).

Upon haptic and auditory examination, it was observed large areas of the visually intact surface on sections 1 and 2 were detached from the grain matrix. In these cases, when struck with a knuckle, a hollow sound was emitted from the surface, indicating a discontinuity beneath the smooth surface layer. Also, these detached areas were situated close to visible patches of erosion, and their edges often crumbled as a result of light touch. These observations

indicate that the erosion and defects are not necessarily visually noticeable. Also, it can be concluded that the condition of the walls is not stable, and accelerating erosion can be expected during the coming winters.

The condition of wall sections 3 and 4 differs markedly from sections 1 and 2. The main difference in the recipes was that on sections 3 and 4 incineration slag (0-2 mm) was used as the aggregate. In sections 3 and 4 the effect of weather protection provided by the roof is evident. The top parts of the walls are mostly intact, but the lower parts are readily disintegrating. Sections 3 and 4 are pictured in figure 3.8. The westernmost end of section 4 is most heavily damaged, as it is open to all directions.

Despite the apparent intactness of the top part, the material is very weak and starts eroding when disturbed with a tool or even a finger. In the bottom parts light touch or even the wind is enough to cause grain erosion. The material erodes in a fine sand-like form, indicating that the bond between the incineration slag particles is very weak. The hastened erosion of the bottom halves of the wall sections is caused by increased exposure to weather conditions, namely rain.

According to the photogrammetric analysis and comparison produced by Telila, the largest recorded surface deformation was located in section 4 of the test structure. This deformation measured to 69,4 mm. In comparison, the largest deformation in crushed concrete-based section 2, was 20,2 mm. Volumetric deformation was measured to be 0,37 %, 0,59 %, 1,39 % and 2,36 % in sections 1-4 respectively. (Telila, 2024). These results are in line with the observations made during the erosion assessment, as the largest deformations are on wall sections where incineration slag was used as the aggregate material. Visual comparisons of the models are shown on figures 3.6 and 3.7.

Figure 3.6. The end of wall section 4 imaged with photogrammetry after and before, showing significant erosion. (Telila, 2024).

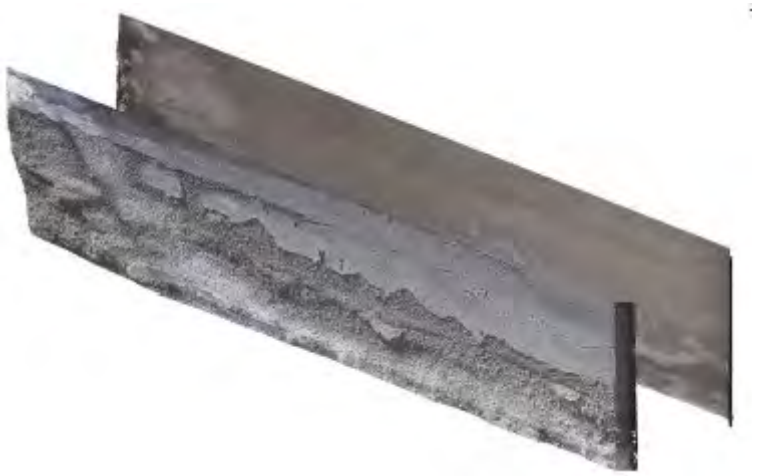


Figure 3.7. Wall section 4. The model only contains the sides of the walls. (Telila, 2024).

White staining is present in all sections. This staining is indicative of a phenomenon known as efflorescence. It occurs due to moisture migration inside the structure. As the structure begins to dry after experiencing a high degree of saturation due to weather conditions, the moisture carries salts to the surface of the wall, where it sticks as a white powder as the water evaporates. Efflorescence is common in concrete structures, and its source is likely the impurities contained in the waste materials. It does not necessarily have a structural effect.

Figure 3.8. Erosion of the test structure.

3.3.3 Ultrasonic pulse velocity

The measurements were made using A1410 Pulsar handheld UPV device. The direct method of measurement was used. This means that the handles of the measurement device were placed directly opposite towards each other on both sides of the wall, and the measurement was taken using the thickness of the wall (500 mm) as the "base" value set in the device. The test setup is presented in figure 3.9.

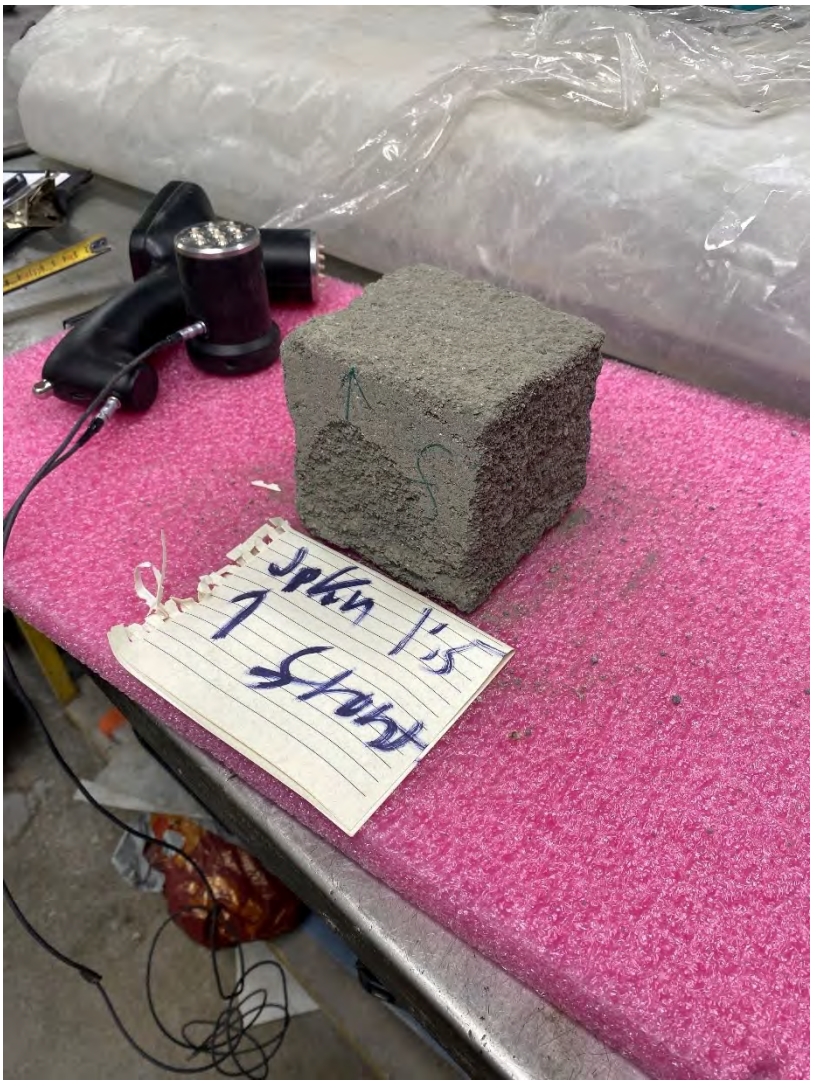


Figure 3.9. UPV testing of sawed cubical samples. The UPV device is seen in the left corner.

The UPV measurements are presented in table 3.3. On sections 1 and 2, results measured from points where surface erosion was minimal are comparable with typical values recorded from concrete structures. However, on many points the UPV values were unrealistically low for concrete structures. On these points, the surface of the wall was eroded and uneven. Excluding the measurements taken from points with clearly damaged surface, the average value for section 1 was 1662 m/s and 1492 m/s for section 2. Comparing to literature values on UPV testing on concrete structures, the results indicate very low strength or damaged concrete.

The UPV measurements were also performed on the samples sawed from the sections for the UCS tests. On section 1 (crushed concrete as aggregate), the average values were 1858 m/s in the direction of compaction, and 2013 m/s

against the direction of compaction. On section 2, corresponding results were 1701 m/s and 2261 m/s. As the field measurements were taken against the direction of compaction, the latter values of each section are regarded as more comparable to the field results. Comparison between the field and sample measurements shows that the velocities from the samples are greater. This can be explained by the fact that the samples are less likely to contain cracks or cavities that slow down the pulses. Also, the edges of the samples are even as they are sawed. Therefore, the values measured from the samples represents an "ideal" value for the UPV. In actual structures lower values can be expected due to errors and random occurrences during the compaction. Also, surface erosion, cracks and other discontinuities appear due to weather conditions and stresses deriving from the usage.

Table 3.3. UPV measurement results.

	UPV, structure average [m/s]	UPV, sample average [m/s]
1. CC + Fly ash (Helen)	1661,9	2013,3
2. CC + Fly ash (UPM)	1491,5	2261,1
3. IS + Fly ash (Helen) (1:4)	735,7*	661,1*
4. IS + Fly ash (Helen) (1:5)	806,6*	731,1*
	*values below threshold for accurate measurements	

In the incineration slag- based sections 3 and 4, most of the measured values fell below 1000 m/s, which is the minimum acceptable value for measurements set by the manufacturer of the device. Thus, the reliability of singular measurements is questionable. Measurements from the heavily eroded lower parts of the wall failed almost completely, yielding no result. This was the case especially in section 3. This result indicates that erosion can significantly reduce the usability of UPV measurement as a method assessing the compressive strength of rammed earth. Also, even the measurements done to the sawed-off samples yielded unacceptably low values. As the samples were visually intact and even, it can be postulated that the low values signal an extremely low compressive strength. This is also evident from other observations made from sections 3 and 4.

3.3.4 Uniaxial compressive strength

The UCS tests were performed using a Zwick & Roell screw press. The test setup is presented in figure 3.10. The results are presented in table 3.4 and figure 3.11. For clarity, results from Holopainen (2022) done on samples made during the construction are also presented.

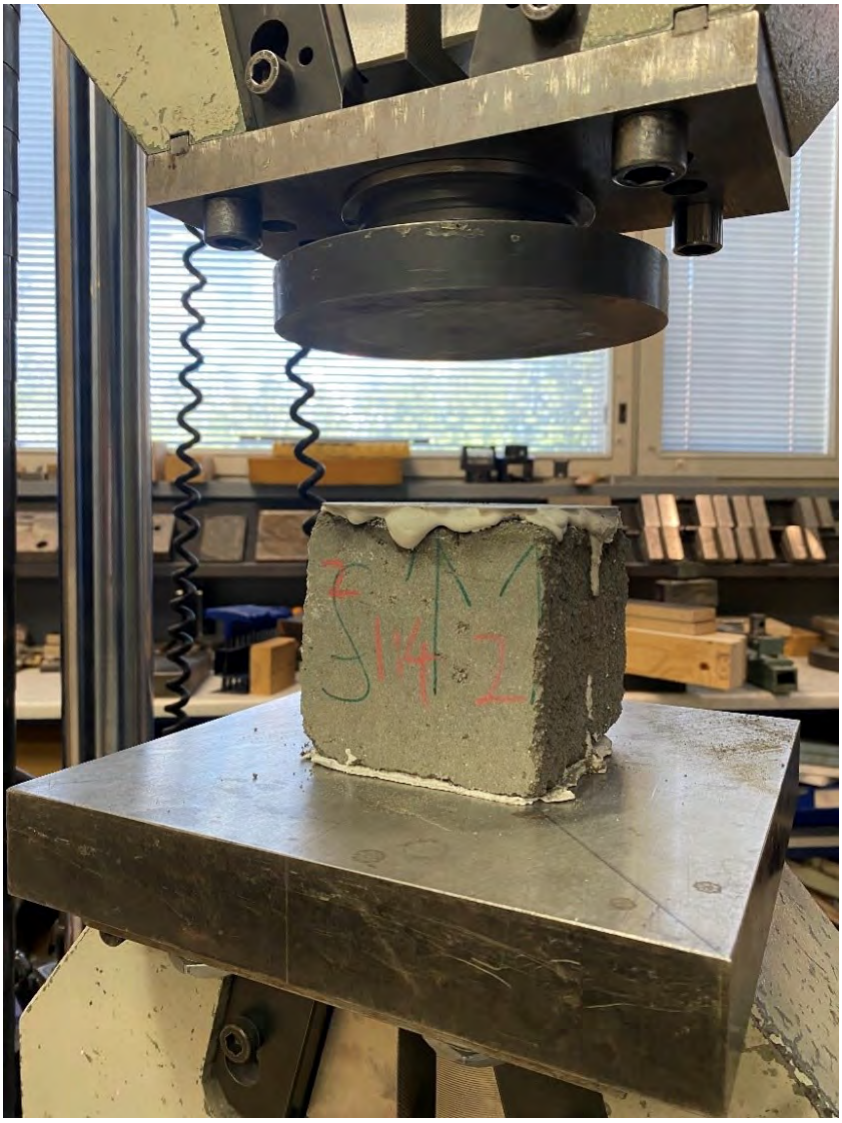


Figure 3.10. Cubical sample ready for pressing. Gypsum was used to level the pressing surfaces.

Table 3.4. The results of the UCS tests. 975-day values were measured in this study. The 28-day values are according to Holopainen.

	UCS (975d) [MPa]	UCS average [MPa]	UCS (28d) [MPa]	UCS average [MPa]
	1. CC + Fly ash (Helen)			
Sample 1	5,51	5,87	3,41	3,68
Sample 2	2,88		4,19	
Sample 3	7,39		3,43	
Sample 4	7,71		-	
	2. CC + Fly ash (UPM)			
Sample 1	2,47	4,48	3,25	3,08
Sample 2	5,17		2,96	
Sample 3	5,79		3,03	
	3. IS + Fly ash (Helen) (1:4)			
Sample 1	0,37	0,44	-	-
Sample 2	0,57		-	
Sample 3	0,39		-	
	4. IS + Fly ash (Helen) (1:5)			
Sample 1	0,48	0,46	1,32	1,25
Sample 2	0,41		1,15	
Sample 3	0,5		1,28	

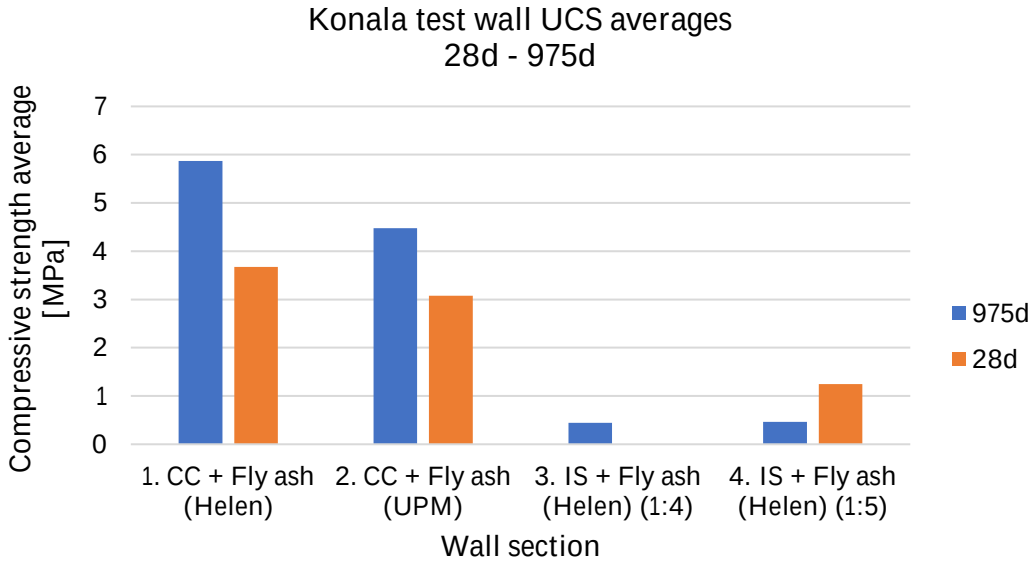


Figure 3.11. The UCS results from test wall sections.

Comparing the results from the samples made during the construction of the test structure and samples extracted from the structure, it can be noted that the UCS value on crushed concrete-based mixes is higher for the samples that were taken from the test structure. One explaining factor is the age of the

samples. The wall samples were 975 days old when tested. The hydration of the cementitious materials used in the mixtures has continued during this time when permitted by the outside conditions. The samples made from the same mix during the construction were 28 days old upon testing. However, according to Holopainen (2022), the samples made during the construction are not completely representative of the test structure, because they were made using a 100x100x100 millimetre cube mould. The mixes used in the construction of the test structure contained grain sizes up to 60 millimetres, which is too large considering the moulds. This means that the degree of compaction these samples reached was likely less than in the test structure. Compared to samples made in laboratory with maximum grain size of 16 millimetres, the UCS of section 1 reached only 31,7 % of the compressive strength. Density was 92,8 % of the laboratory reference. In section 2, the corresponding values were 39,7 % and 93,9 %. The average strength of samples made in the laboratory with the same recipe as in section 1 was 11,61 MPa and 7,76 MPa in section 2. These values are clearly higher than the values acquired from testing the 975-day samples, even when these samples should not suffer from the suboptimal compaction that is likely causing the low values of the 28-day samples. The low strength values of the 975-day samples can be explained with the low quality of the samples. The sample size was too small considering the grain size and low bond strength of the mix. The samples suffered from dimensional defects. Many samples contained structural defects, such as cracks and voids due to detached aggregate grains.

The UCS values for samples taken from sections 3 (IS + Fly ash (Helen) (1:4)) and 4 (IS + Fly ash (Helen) (1:5)) are similarly low. In these sections, incineration slag was used as the aggregate. During the construction, samples for section 3 were discarded due to the mass sticking to the mould walls. In section 4, the UCS value of the 975-day sample is only 37 % of the UCS value of the 28-day sample. Both values are smaller than what achieved in laboratory with similar recipe, where UCS was 3,35 MPa. Results indicate that despite ongoing hydration, the UCS of the incineration slag-based mixtures has decreased. This might have been caused by outside disturbance to the test structures. Earth-moving activities using excavators and heavy trucks have taken place near the test structures during the hardening period. The vibrations caused might have broken the weak bonds forming between the binder paste and the incineration slag grains. Also, considering the offset between the laboratory values and the onsite 28-day values, it can be inferred that the mixture made onsite is not equal to the laboratory mixture. According to Holopainen (2022), the mixture used in section 3 was visibly drier and dustier compared to the lab mixture, which suggests that the water content was lower than planned. This was the case despite that water content measured from the mix during the construction process was higher than the planned 17 %, up to 21 %.

4 Laboratory Test Program

A laboratory test program was planned to further investigate the use of crushed concrete and incineration slag as aggregate materials to be used in the rammed earth method. The objective of the test program was to study the effect of mixing a minor portion of incineration slag to crushed concrete to form the aggregate. Another group of tests was planned to study the effect of hydrophobizing the mixture by applying a hydrophobizing agent to the incineration slag and mixing it with crushed concrete. Also, samples were made to study and compare the function of a novel circular binder, the EcoIntellect E65 with established binders containing waste materials, CEMIII/A and CEMIII/B. Methods for assessing the performance of different recipes include uniaxial compression test, capillary rise test, water absorption test and freeze-thaw test. The test matrix and sample sets are presented in table 4.1.

Table 4.1. The laboratory test matrix.

	Objective	Aggregate	Binder type	B-A ratio	Water %	Hydrophobization	UCS	Cap. sat.	Freeze-thaw
Set 1	Control	100 % CC	E65	1:6	10/12/14		x		
Set 2	Recipe properties (strength)	80 % CC, 20 % IS	E65	1:6	14		x		
Set 3	Recipe properties (strength, freeze-thaw)	80 % CC, 20 % IS	E65	1:6	14		x		x
Set 4	Recipe properties (water absorption)	80 % CC, 20 % IS	E65	1:6	14			x	
Set 5	Effect of hydrophobization on freeze-thaw UCS	80 % CC, 20 % IS	E65	1:6	14	x	x	x	x
Set 6	Effect of hydropbization on water absorption	80 % CC, 20 % IS	E65	1:6	14	x	x	x	
Set 7	Study the effect of crushed slag on hydrophobization	80 % CC, 10 % IS, 10 % powdered IS	E65	1:6	14	x	x	x	
Set 8	Comparison of E65 and CEMIII/B	100 % CC	CEMIII/B	1:6	14		x		
Set 9	Comparison of E65 and CEMIII/B	80 % CC, 20 % IS	CEMIII/B	1:6	14		x		
Set 10	Comparison of E65 and CEMIII/B	100 % CC	CEMIII/A	1:6	14		x		
Set 11	Comparison of E65 and CEMIII/B	80 % CC, 20 % IS	CEMIII/A	1:6	14		x		

4.1 Materials

4.1.1 Crushed concrete

Crushed concrete is made by crushing demolished concrete structures to appropriate grain sizes. Usually, the maximum grain size is 90 mm, and the most commonly used variety of crushed concrete contains grain sizes from 0 to 63 mm. Crushed concrete has been used in Finland as material for structural layers of roads and streets since the beginning of the nineties. As a waste material, its carbon footprint is significantly smaller than that of virgin aggregate materials. It also offers excellent strength capabilities, surpassing even virgin materials in this regard. Crushed concrete also experiences some degree of cementation after it has been deposited in a structural layer as unreacted cement is exposed to water, further increasing the strength. (City of Helsinki, 2019).

In Finland, crushed concrete is considered as waste even after processing. Therefore, an environmental permit is needed to use it, except in cases outlined in the government directive 843/2017, the so-called MARA-directive. This directive and its application directive provide an alternative procedure for using crushed concrete in street and road layers. However, the MARA-procedure can be only used in restricted conditions. For example, the construction site must not be located in an area where the ground water reservoirs are exploited for drinking water. Also, any body of water must not be closer than 30 meters. (City of Helsinki, 2019) The applications studied in this thesis do not fall within the scope of the MARA-directive.

Concrete is alkaline. This imposes restrictions on using crushed concrete as fill material, as water passing through a layer of crushed concrete can contaminate natural water reservoirs. (Finnish Government, 2017).

According to Arrigoni et al. (2018) using crushed concrete aggregate as an aggregate in stabilized rammed earth mixtures decreases the compressive strength of rammed earth. However, this effect seemed to be caused by the varying grain size distribution and low quality of the crushed concrete aggregates. (Arrigoni, et al., 2018)

The crushed concrete used in this thesis is originating from Rudus Oy's crushing and recycling plant in Vantaa. Figure 4.1 presents the overall texture of the material. The grain size distribution is presented in figure 4.2.

Figure 4.1. Crushed concrete aggregate containing grains from 0 to 16 millimetres.

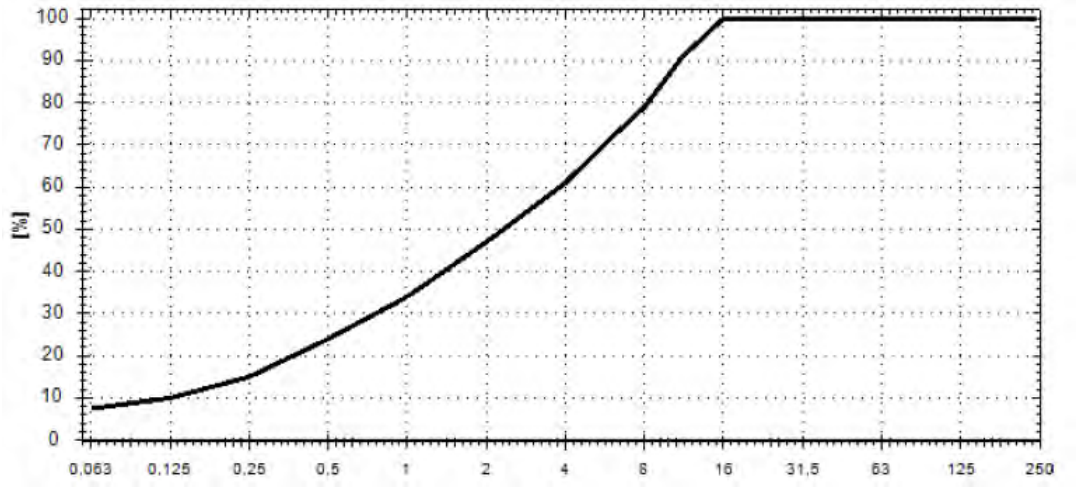


Figure 4.2. Grain size distribution of the crushed concrete used in this study. (Rudus Oy, 2024).

4.1.2 Incineration slag

Incineration slag refers to processed slag that is left behind after municipal waste is burned at a waste-to-energy power plant. Processing entails separation of ferrous and other metallic items and particles from the raw slag. This is done through magnetic separation. However, due to technical limitations of this method the end-product contains small ferrous particles. Similarly as crushed concrete, incineration slag can be used as a construction material in Finland with a permit from the environmental authority or in limited applications according to the procedure described in the MARA-directive. (Finnish Government, 2017).

In Uusimaa region, all municipal mixed waste is transported to a waste-power plant operated by Vantaan Energia in Vantaa. In the Helsinki metropolitan area, Helsinki Region Environmental Services (HSY) is responsible for collecting and transporting the waste. After incineration, the unprocessed slag is transported to a HSY storage site in Ämmässuo, Espoo. There the slag is processed to remove large ferrous objects and stockpiled. The processing also involves crushing the slag and sieving it to different grain size distributions. In 2024, the available grain sizes are 0-2 mm, 2-5 mm, 5-16 mm, 16-50 mm and 2-50 mm mixed from the other fractions. In Ämmässuo, the slag has been used as a structural fill material in the stockpiling yards. As the usage of the recycled slag is much less than the amounts that are being stockpiled yearly, available space is diminishing. From a legal point of view the stockpiled slag is in intermediate storage, which means that it is awaiting transport to an end-of-life destination. Landfilling is one option, but considering the waste directive of the European Union recycling is seen as the more favourable option. However, the use of incineration slag in road and streets structures needs to increase in the coming years to offset the increasing

amounts of slag formed. New uses for the slag should also be investigated. (Rautiainen, 2024).

Incineration slag used in laboratory studies of this thesis is originating from the HSY 0-2 mm stockpile in Ämmässuo. The grain size distribution curve for similar material is presented in figure 4.4. The material can be observed in figure 4.3. Production batch number was 15. According to leaching tests, the leaching values are too high for chromium (Cr), mercury (Hg), molybdenum (Mo), antimony (Sb), F^- (fluoride ion), SO4 (sulfate) and TDS (total dissolved solids) for the incineration slag to be considered as inert waste. However, none of the values are high enough to cause the slag to be considered as dangerous waste. The complete result sheet is presented in the appendices.

The high aluminium content of incineration slag prevents it from being used as a sole aggregate material in rammed earth structures. Aluminium forms hydrogen gas, that can cause the structure to crack. Also, the silicates present in the slag, originating from glass waste, can lead into alkali-silicate reactions. (Telén, 2023).

Figure 4.3. Incineration slag in grain size 0 to 2 millimetres.

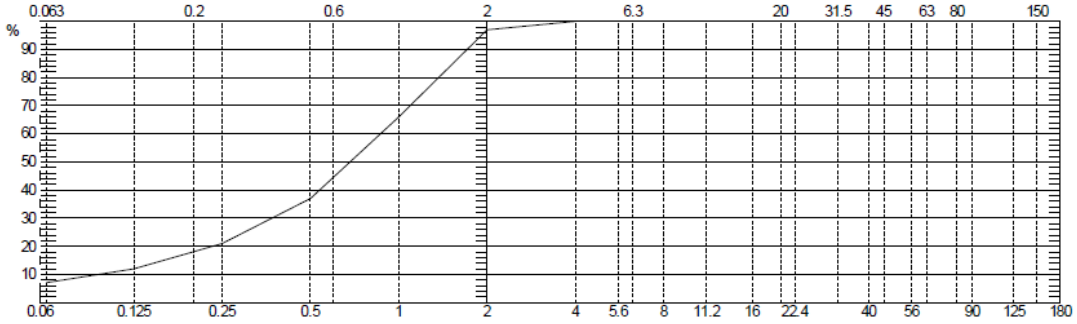


Figure 4.4. The grain size distribution of 0-2 mm incineration slag. (Helsinki Region Environmental Services HSY, 2024)

4.1.3 Binders

Three different were used in this study: EcoIntellect E65, CEMIII/A and CEM/IIIB. After consideration on the scope and resources of the thesis, decision to use only productized binders was made. Fly ash and other circular additives were excluded to decrease the amount variables, as controlling the quality and properties of these substances would have been unreasonably difficult and out of the scope of this thesis. However, all the binders used had high proportion of circular materials.

EcoIntellect E65 is a novel binder developed by EcoIntellect Oy. The batch used in this study was produced in a pilot plant in Turku by Renotech Oy. Full-scale production of the binder is commencing in EcoIntellect Oy's facility in Hämeenlinna. The E65 binder contains 65 % of fly ash, 20 % of gypsum and 15 % of cement. The carbon footprint of manufacturing the E65 binder is 107 kg CO_2e/t. It is designed to be used in soil stabilisation: column stabilisation, mass stabilisation and stabilisation of structural layers of roads. (EcoIntellect Oy, 2024).

CEMIII/A is a cement with a high content of foundry slag. It is manufactured by Finnsementti Oy in Parainen. It contains 36 % to 65 % of foundry slag, rest of the composition is cement clinker. 2-day compressive strength is 10 MPa and 28-day compressive strength is 52,5 MPa. Its total global warming potential indicator (GWP-tot) is 446 kg CO_2e/t. (Finnsementti Oy, 2022).

CEMIII/B is also a foundry slag-based cement produced by Finnsementti Oy. It contains a larger proportion of foundry slag, 66 % to 80 %, than CEMIII/A. 7-day compressive strength is 16 MPa and 28-day compressive strength is over 42,5 MPa. One of its notable properties is its low heat of hydration. (Finnsementti Oy, 2023).

4.1.4 Stearic acid

Stearic acid (also known as octadecanoic acid) is a saturated fatty acid. It is a component in many animal and vegetable fats. It is produced by separating it from different fats and oils through a chemical process. Stearic acid is commonly used in a range of industries for different purposes, and it is non-toxic. It is used for example in coatings of medicine capsules, as an additive in skin-care products and soaps and in food manufacturing. It can be purchased as solid, waxy pellets with white colouring and a grain size of about 2-4 mm. Stearic acid is known to be somewhat prone to degradation through environmental stresses like ultraviolet light exposure and mechanical stresses. (National Center for Biotechnology Information, 2024).

According to Roy et al. (2024), stearic acid can be used as a hydrophobizing agent in low-strength cementitious blocks. In their study, stearic acid was used to coat fly ash and iron ore tailing slag used as components of mortar with cement and fly ash as binders. One of their findings was that when 30 % of the base aggregate was replaced with the similar aggregate that had been hydrophobized, the water absorption of cemented mortars reduced as much as 87 % in conditions of 100 % relative humidity. (Roy, et al., 2024).

In this thesis, the hydrophobization procedure described by Roy et al. (2024) was applied to the rammed earth method. Samples with parts of hydrophobized incineration slag went through tests to determine their capillary water absorption properties and resistance to freeze-thaw induced damages. The results were compared against values from tests made with control samples. As the ethanol that is used as dispersing agent for mixing in the stearic acid is evaporated, the stearic acid is left behind and it impregnates the surface of the incineration slag grains. This forms a waterproof, hydrophobic lining to the pore surfaces of the granular material or aggregate. This lining prevents excess moisture originating from air humidity or capillary action for absorbing into the aggregates.

4.2 Sample preparation

In this study, cylindrical samples with a diameter of 100 mm and height of approximately 150 mm were made to be used in the laboratory tests. This specimen type was selected based on the reported experiences by Holopainen (2022) and Aromaa (2021). Cubical samples were used in these studies, but they suffered from break-offs in the sharp corners of the samples, and sticking of the rammed earth mixture to the walls of the moulds. Cylindrical samples were also used by Luoma (2023) and Wayu (2024) in their studies on the rammed earth method. Cylindrical in presented in figure 4.5.

Figure 4.5. A cylindrical stabilized rammed earth sample.

Manufacturing of the samples adhered to following process. First, materials were prepared as needed. Aggregate materials were placed into a 105-degree oven for 24 hours to reach oven-dry conditions. Hydrophobized materials were prepared as described in chapter 4.4. The dry materials were measured by weight into a steel mixing pan. The inner walls of the mixing pan were wetted beforehand to prevent the dried material left behind from previous mixes absorbing the water used in the recipe. The pan was inserted into a Hobart plane mixer, and the dry materials were mixed briefly. A “flat beater” type of mixing blade was used. After the dry materials were visibly mixed, water was measured and added into the pan. Mixing was commenced for 60 seconds, using the slow speed setting on the mixer. After 60 seconds, the mixing was stopped, and the walls of the pan were cleaned from stuck material with a spatula. Then, the mixing was continued for 30 seconds, this time with the second highest speed setting. The mould used for making the

samples was prepared. The mould used was originally meant for making intensive compaction testing (ICT) samples and deemed to work sufficiently for making rammed earth samples. The mould consisted of a cylindrical main body, a base plate and a thin top plate. The plates were inserted into the bottom of the mould. Using a jacking device, the finished samples could be extruded out of the mould by applying force to the base plate. A round plastic sheet was also inserted to the bottom of the mould before commencing the sample-making. This is done to help the sample slide off the base plate after extrusion. The walls of the mould were also lubricated with oil. The samples were made by pouring the mixture into the prepared mould using a scoop. Each sample consisted of five layers of approximately 440 grams of rammed earth, totalling into an approximately 150 mm high sample. Each layer was compacted with 20 blows of the VTT hammer. The VTT hammer is comprised of drop weight fixed to a steel bar and a bottom plate with a diameter of 100 mm. As the 4 kg weight is dropped from an elevation of 0,45 m, it delivers 17,7 joules of compaction energy. Compaction is showcased in figure 4.6. Tops of each layer, except of the top layer, was scored using a knife or a steel rod to facilitate interlocking between the aggregate grains of the upper and lower layers. The finished samples were slid of the jacked base plate onto a rigid plastic sheet to avoid any deformation due to uneven stresses. Then they were covered with a plastic bag and placed into a curing room with constant moisture and temperature. The relative humidity of the room was >95 % and the temperature 21 °C. The samples were kept in the curing room for 28 days according to the test program before subjected to the tests described in earlier chapters.

Figure 4.6. Compaction of a stabilized rammed earth into a mould using the VTT hammer.

4.3 Hydrophobization

To study the effect of hydrophobization on the capillary rise and water absorption experienced by the sample, samples were made using hydrophobized incineration slag as a material. The procedure for hydrophobizing the materials was outlined by Roy et al. (2024) and applied for this study.

First, the incineration slag was dried overnight in an oven at 100 °C. Then, ethanol was measured into a glass beaker. The mass of incineration slag used in one batch should correspond to two thirds of the mass of the ethanol measured into the beaker. After the ethanol, stearic acid was placed into the beaker. The amount of stearic acid was 3 % of the weight of the ethanol. The ethanol and the stearic acid were mixed using a magnetic stirrer until the stearic acid was completely dissolved into the ethanol, leaving behind a clear

liquid. Heat was applied into bottom of the beaker through the stirrer apparatus to facilitate dissolution of the stearic acid. After dissolution, the stirring rod was removed, and the ethanol-stearic acid mixture was placed with the incineration slag into a separate container. The mixture was stirred with a wooden stick for 5 minutes. After 5 minutes, the container was placed under a ventilation hood and kept there until most of the ethanol had evaporated. During this process, the mixture was stirred a few times to facilitate rapid evaporation. End effect of hydrophobization is presented in figure 4.7. Hydrophobized material floats in water while plain incineration slag sinks. Before using the hydrophobized slag it was mixed with a Hobart bench mixer to break up any clumps formed during the evaporation.

Fig 4.7. Plain (left vial) and hydrophobized (right vial) incineration slag in water.

To test the effect of the grain size on hydrophobic properties, part of the incineration slag was powdered using a pulverizing mill. This powdered mass was hydrophobized using the same procedure as described above. The stearic acid used in this study was generic stearic acid manufactured by VWR International, CAS-number 51-11-4. The ethanol used was Industol PE2, manufactured by Anora Group Oyj.

4.4 Freeze-thaw resistance

Water is present in soil-like materials as free water, capillary water, bounded water or vapor. Sources for water include rain, melting snow and ice, capillary rise, changing ground water conditions and humidity. When water freezes, it experiences a growth in volume. Upon thawing, the volume of the water is again reduced, causing further movement in the structure. (Ehrola, 1996).

With a notable content of fines and weak interparticle bonding, rammed earth structures situated in outdoor conditions are very susceptible to damages caused by freeze-thaw cycles. Primary way of assessing the extent of these damages in certain rammed earth mixtures is to perform uniaxial compression tests on samples that have gone through a certain number of freeze-thaw cycles. For practical reasons, the amount of cycles is usually several tens, but in more specific studies the amount can be over 100.

In this study, a control sample was kept in a curing room for 28 days and tested for its compressive strength. Then other samples were made using plain and hydrophobized recipes, but after 28 days they were moved to climate-controlled cabinet where they underwent 15 freeze-thaw cycles. Each cycle lasted for 24 hours. After the cycles, the samples were allowed to return to room temperature and were tested for their compressive strength.

The freeze-thaw tests were done in accordance of CEN/TS 13286-54:en. A control sample was prepared by placing clean 8-16 mm crushed rock aggregate into a metal container and filling it with water up to a few centimetres above the top level of the aggregates. The control sample was placed centrally to the freeze-thaw apparatus. A thermocouple temperature measurement conduit was placed into the aggregates, and the container was covered with a lid. A freeze-thaw schedule described in the standard was programmed into the apparatus. Before starting the freeze-thaw cycles with the samples, a test run of 24 hours was completed to ensure that the control sample stays within limits given in the standard. During the test run, old concrete test cubes were inserted into the chamber of the apparatus to simulate the thermal mass of the specimens. The test setup is showcased in figure 4.8.

Figure 4.8. Freeze-thaw cabinet with samples. The white bucket is the control sample.

4.5 Uniaxial compression test

The procedure and equipment of the UCS test is explained in chapter 3.2.3. The only difference in the laboratory test program is that cylindrical samples

were used, as explained in the previous chapter. Also, gypsum plaster was not applied to the pressing surfaces as they were adequately smooth and level.

4.6 Capillary saturation

As a general rule, the more a soil material consists of fractions finer than 0,02 mm, the more susceptible to frost it is. One of the reasons for this is the increased capillarity of the soil. Capillary rise is caused by the intermolecular forces between water and soil causing the water to rise. The surface tension of the water must be high enough to prevent the thin film of water from dissipating. This is why fine-grained soils experience heightened capillarity. (Ehrola, 1996).

The capillary rise that a sample experiences when in contact with moisture source was determined with a test procedure outlined in European Standard EN 13057:2002. The procedure was done using a cylindrical sample that is 100 mm in diameter. First, the sample was heated in an oven at 40 °C until its mass did not change more than 0,2 % during 2 hours. This mass was recorded. Then, the sample was placed in a vessel containing a thin layer of water, separated from the bottom with thin metallic support bars. The bottom part of the sample was kept submerged for a length of about 1 mm. The capillary rise was visible as a dark patch on the side of the sample. On timepoints specified in the standard EN 13057 (12 min, 30 min, 1 h, 2 h, 4 h and 24 h) or whenever the capillary rise had advanced adequately, the height of the rise and the timepoint was recorded. The sample was divided into even sections to specify different rates of capillary rise in the sample. The sections were marked with insoluble marker. The weight of the sample was recorded after wiping excess water off from the surface of the sample. Then, the sample was returned to the test vessel until the next reading. The test setup is presented in figure 4.9. (SFS Finnish Standards Association, 2002).

A sorption coefficient was calculated for each sample. The sorption coefficient is the slope of a graph where water uptake per unit area is plotted against the 0,5-th power of time. Water uptake per unit area was calculated for each timepoint by diving the weight of absorbed water with the surface area of the sample.

The capillary rise is assessed to set a baseline for the capillary water intake of the mixtures. Comparing the results from hydrophobized and control samples will give insight on the effectiveness of the hydrophobization. From this, the applicability of hydrophobization in reducing freeze-thaw related damages in rammed earth structures can be assessed.

Figure 4.9. Capillary saturation test setup.

4.7 X-ray fluorescence analysis

X-ray fluorescence analysis (XRF) is a method for determining the chemical composition of a sample. In principle, the method entails an apparatus for generating x-rays (also known as Röntgen rays) that are emitted to the sample surface. The x-rays cause the surface atoms of the sample to be excited, which then in turn will emit secondary x-rays that are detected using a detector and represented on a spectrum based on their energy level. Certain sets of x-rays with different energy levels are associated with different elements, acting as a "fingerprint" for the element. Using this data, a complete elemental spectrum of the sample can be produced, offering information on the relative amounts of different oxides present in the sample. (Klockenkämper & von Bohle, 2015).

In this study, XRF analysis was used to determine the elemental spectra of incineration slag, crushed concrete and EcoIntellect E65 binder. This data was further utilized when reviewing the hydration reactions and cementitious compounds present in the samples achieved with different mixes. The samples for XRF analysis were prepared by drying them for 24 hours and then pulverizing them. The analyses were performed in the Department of Chemical Engineering in Aalto University.

4.8 Calorimetry

A calorimeter is a measurement device for accurately tracking the heat of hydration of a cementitious sample. This information can used to assess and compare the hydration of different binders and cementitious mixes. A calorimeter comprises of an insulated chamber wherein the samples are placed shortly after water has been added into the mix. As the hydration reactions start, temperature sensors are used to measure the increase in thermal energy in the chamber that is otherwise kept in a constant temperature. (Linderoth, et al., 2021).

Specific samples were prepared and tested in a calorimeter to gain insight on the strength-forming properties of different binders and the effect of certain parameters to the hydration of stabilized rammed earth mixtures. Samples were prepared similarly as described in chapter 4.2, expect the loose mixture was placed into a small plastic testing vessel and compacted using a plastic rod. The samples were compacted in 4 layers, with the total weight of the sample being at least 250 g. The sample-making process is illustrated in figure 4.10.

Figure 4.10. Calorimeter sample and compaction rod.

4.9 Scanning electron microscopy

Scanning electron microscopy (SEM) is an imaging technology that uses a focused beam of electrons to create magnified, grey-scale images of sample surfaces. The magnification that can be achieved using SEM far surpasses that of traditional, optical microscopy. SEM reaches magnification levels of even 300,000 times the original size. In contrast, the maximum magnification of optical microscopy is commonly circa 1000 times the original size. (Azad & Avin, 2018).

In material science, SEM is a common method for analysing the microstructure of a material. Different compounds that form the material can be observed with this technology, as well as other properties, like porosity. In cement and concrete studies SEM is used particularly to observe and identify the hydration products that are present in cured specimens. These

observations can be used to assess the hydration reactions. Examples pictures cement hydrates pictured with SEM are presented in chapter 2.3.

In this study, SEM imaging was performed of selected samples that were extracted from the main set of samples. The sample size was circa 1 cm in diameter. Samples were irregularly shaped, as they were simply broken off from inside of the cylindrical samples. The samples were then prepared by placing them into a sealed bag where they were submerged in alcohol. This was done remove water from the samples. The samples were placed into small trays, where they were fastened with sticky rubber. The trays were inserted into the SEM apparatus, and the surface was viewed through a PC monitor. On representative locations and magnifications, the images were recorded onto a hard drive. The images are presented in the results chapter. The imaging was done in Aalto University's Department of Civil Engineering. The SEM apparatus used was a Quanta FEG 450.

5 Results and analysis

In this chapter, results from the laboratory tests described in chapter 4 are presented and analysed.

5.1 Uniaxial compressive strength

Results from the UCS tests are presented in figures 5.1, 5.2 and 5.3. Full numerical data is presented in the appendices. The results indicate that samples made with just crushed concrete as the aggregate are significantly stronger than mixes containing 20 % incineration slag, as observed in figure 5.2. This is because the final water content in the composite mixes was low due to water absorption in the incineration slag. The slag contains fines and impurities which cause the water absorption capacity of the slag to be significantly higher than that of natural aggregates.

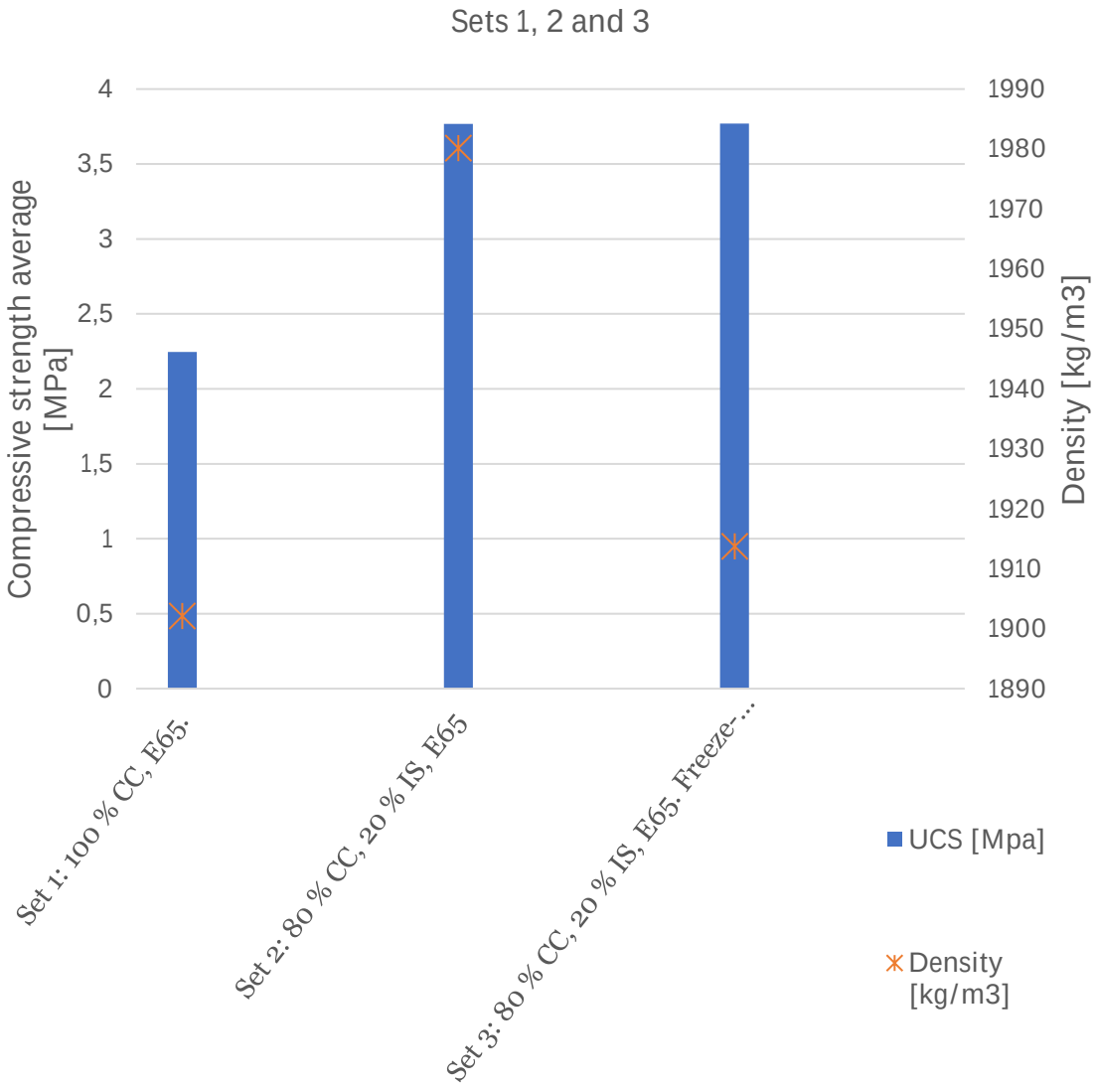


Figure 5.1. UCS and density results for sample sets 1, 2 and 3.

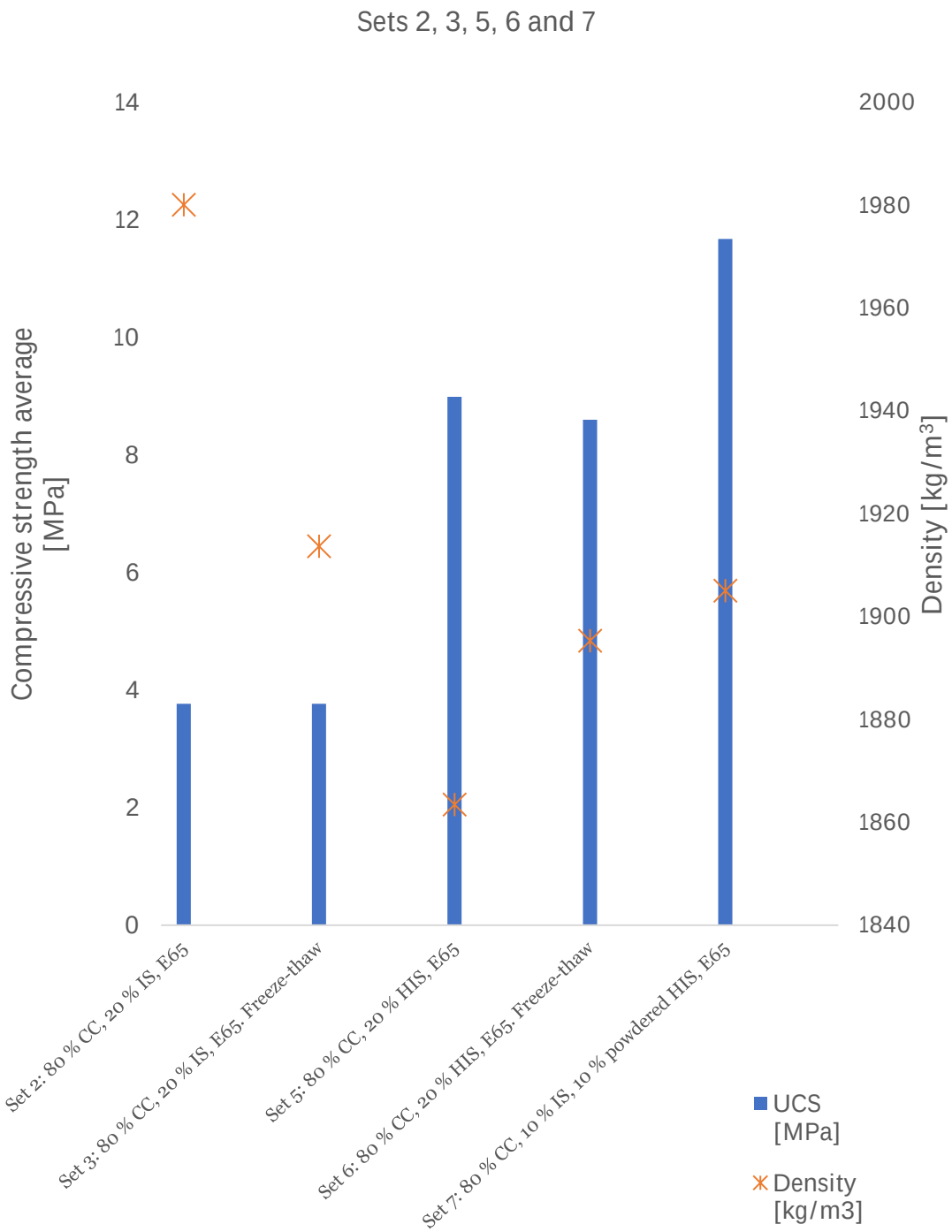


Figure 5.2. UCS and density results for sample sets 2, 3, 5, 6 and 7. Results from sample sets 2 and 3 shown to ease visual comparison. Sample sets 5, 6 and 7 are hydrophobized.

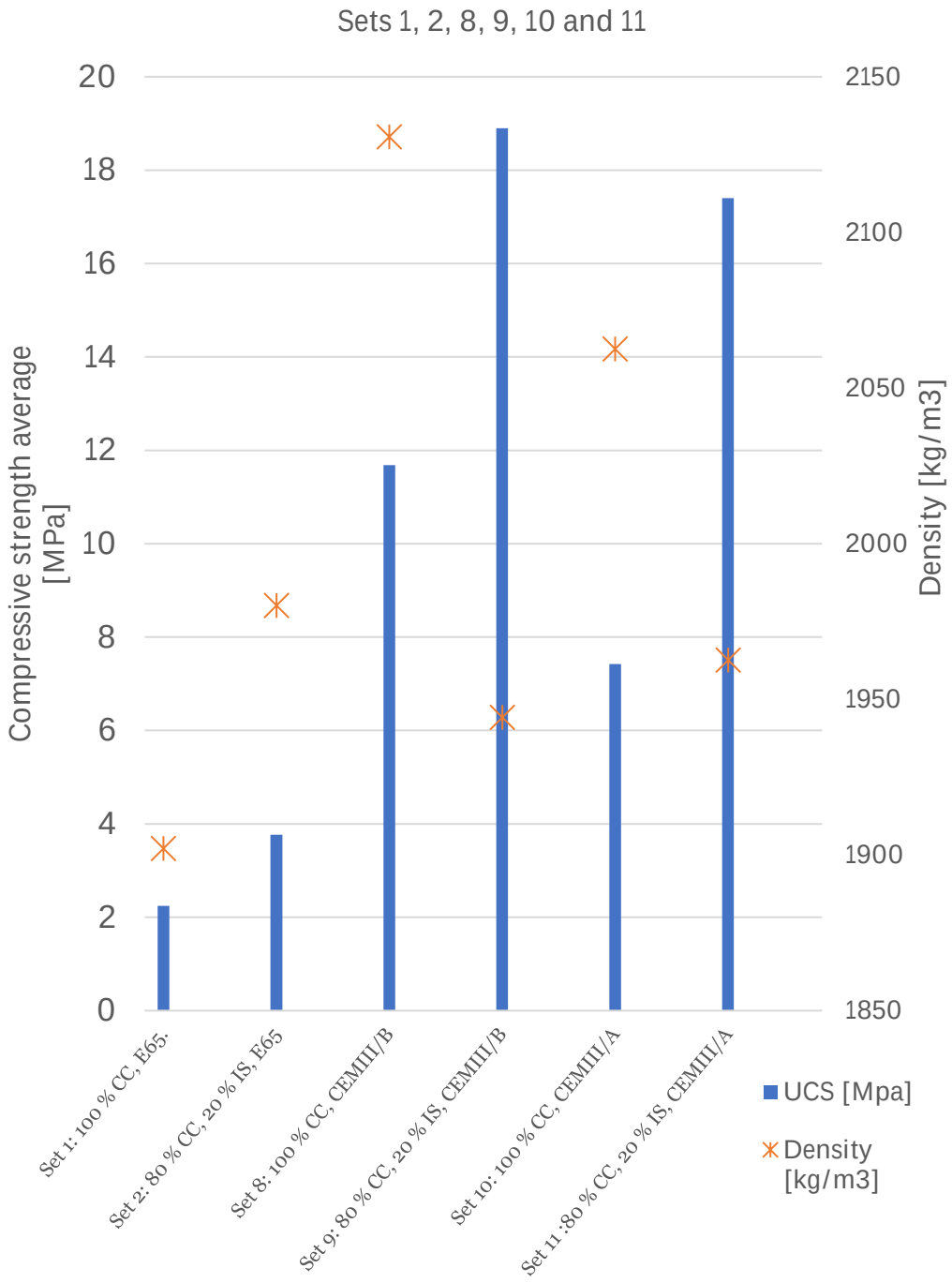


Figure 5.3. UCS and density results for sample sets 8, 9, 10 and 11. Sets 1 and 2 are displayed for comparison.

As was observed from figure 5.2, hydrophobization did not affect the UCS detrimentally. On the contrary, UCS results from test sets 6 and 7 are higher

than comparative sets made without hydrophobized materials. This is likely because the hydrophobization improved the water-to-aggregate ratio of the final mix. Water absorption of the slag was greatly reduced as grains of incineration slag were coated with the hydrophobic stearic acid. This led improved hydration of the samples. The density of the samples was not differing between hydrophobized and plain samples, indicating further that a larger degree of hydration was reached with the hydrophobized samples.

Apart from the hydrophobized samples, density of the samples correlated with the UCS. Highest density, 2130 kg/m^3 on average, is achieved with a recipe incorporating 100 % crushed concrete as the aggregate and CEMIII/B as the binder. This was also the strongest sample set in terms of the UCS, reaching average value of 18,9 MPa. The second most dense and the second most strong sample set was also made with 100 % of crushed concrete, using CEMIII/A as the binder. Sample set made with 100 % crushed concrete and E65 as the binder differs from this trend, as it only reached average UCS value of 2,25 MPa, and an average density of 1902 kg/m^3. This is because the mass of the water used in the recipe was only 10 % of the dry mass. The water content was corrected to 14 % in the other sample sets.

In recipes containing 80%-20 % crushed concrete-incineration slag as the aggregate, correlation between density and the UCS is not as strong. The strongest sample sets are sets 11 and 13, using CEMIII/B and CEMIII/A as the binders. The sample sets reached average UCS values of 7,43 MPa and 8,40 MPa. In sample set 2, where E65 was used as the stabilizing binder, average strength of 3,77 was reached. This is likely due to the lower reactivity of the ash-based E65 binder, as opposed to the other binders which incorporate foundry slag and cement.

The E_{50} moduli values of the sample sets are presented in table 5.2. The values correlate well with the UCS results. Highest E_{50} modulus was achieved with set 10. The modulus was determined to be 20,8 GPa, meaning that it required the most force for half of total strain to happen, meaning that it is the stiffest sample set. Regular concrete generally has a E_{50} value of circa 30 GPa.

Table 5.2. Secant modulus E_{50} averaged for each sample set.

Sample set	E_{50} - average [GPa]
Set 1	0,7
Set 2	1,3
Set 3	2,1
Set 5	9,8
Set 6	10,4
Set 7	15,2
Set 8	20,8
Set 9	6,2
Set 10	18,6
Set 11	12,2

Comparison to previous studies

In this chapter, the UCS results of the laboratory studies are compared to values obtained by Aromaa (2021) and Holopainen (2022) in similar test programs. It is to be noted that in these studies, cubical samples were prepared, as opposed to cylindrical. The aggregate and binder materials used in these studies are presented in the tables 5.3 and 5.4 below.

Table 5.3. UCS results from Aromaa's master's thesis. UCS values are average values. (Aromaa, 2021).

Aggregate	Water content	Binder content*			
		6 %		10 %	
		A*	B*	A	B
Rock dust 0/4	7 %	5,06	6,06	7,95	6,36
Rock dust 0/4	9 %	5,00	5,15	9,70	9,78
Foundry sand 0,125/1 + rock dust 0/4	10 %	2,38	2,02	6,61	6,68
Foundry sand 0,125/1 + rock dust 0/4	12 %	1,99	1,67	4,75	4,34
		* binder used was Ecolan Infra 80			
		*A = after 10 f-t cycles *B = control			

As can be observed from these results, the strength results reached by Aromaa are lower than the values reached in this study. Reasons for this are the smaller binder content used by Aromaa, 6 and 10 % of solid dry mass. In this study, the corresponding value was 16,67 %. Also, it can be noted that the aggregates used were finer, which also decreased the compressive strength. Like in this study, the freeze-thaw cycles did not affect the UCS greatly. This raises the question, whether the number of freeze-thaw cycles is large enough to cause greater damages.

Table 5.4. UCS results after Holopainen. (Holopainen, 2022).

Aggregate	Binder	Water content	Uniaxial compressive strength				Average
			Sample number				
			[MPa]				[MPa]
		w%	1	2	3	NaOH	
IS	Fly ash-$_{HELEN}$15	13	0,88	0,93	1,09	0,59	0,97
	Fly ash$_{UPM}$15	14	0,43	0,47	0,48	1,01	0,46
	Fly ash-$_{HELEN}$15	15	2,12	1,86	1,56	-	1,85
	Fly ash-$_{HELEN}$15	17	3,43	3,74	2,89	-	3,35
CC	Fly ash-$_{HELEN}$10	10	4,84	5,15	5,13	6,08	5,04
	Fly ash-$_{HELEN}$15	10	11,27	11,71	11,85	6,51	11,61
	Fly ash$_{UPM}$10	10	6,65	7,11	6,69	5,68	6,82
	Fly ash$_{UPM}$15	10	7,75	7,89	7,64	5,54	7,76
Fly ash/desulfurization end product	Fly ash-$_{HELEN}$15	11	1,43	1,44	1,7	1,49	1,52
	Fly ash$_{UPM}$15	12	1,64	1,61	1,59	1,62	1,61

The maximum UCS values reached by Holopainen were also lower than the ones reached in this study. Especially interesting are the results observed from samples containing crushed concrete as the aggregate, as they are somewhat comparable to the tests made with samples containing only crushed concrete in this study. The largest difference is the binder used, as Holopainen was using different fly ashes activated with small amounts of Portland cement. It can be observed that EcoIntellect E65 produced lower UCS values than the fly ashes. One reason for this might be that the gypsum used in E65 is not reacting in the conditions present in the rammed earth mixture. However, when using the foundry slag- based cements CEMIII/A and CEMIII/B, even three times higher UCS values are recorded. This is due to the higher portion of cement in these binders.

5.2 Capillary Saturation

Figure 5.4 depicts the water uptake experienced by the samples during the saturation tests. Samples in set 4 were control samples, samples in sets 5, 6 and 7 were hydrophobized. Set 5 went through the saturation test after being subjected to 15 cycles of freeze-thaw and UCS testing. Additional sample from set 2 was tested after UCS testing to see whether UCS testing affects the saturation properties.

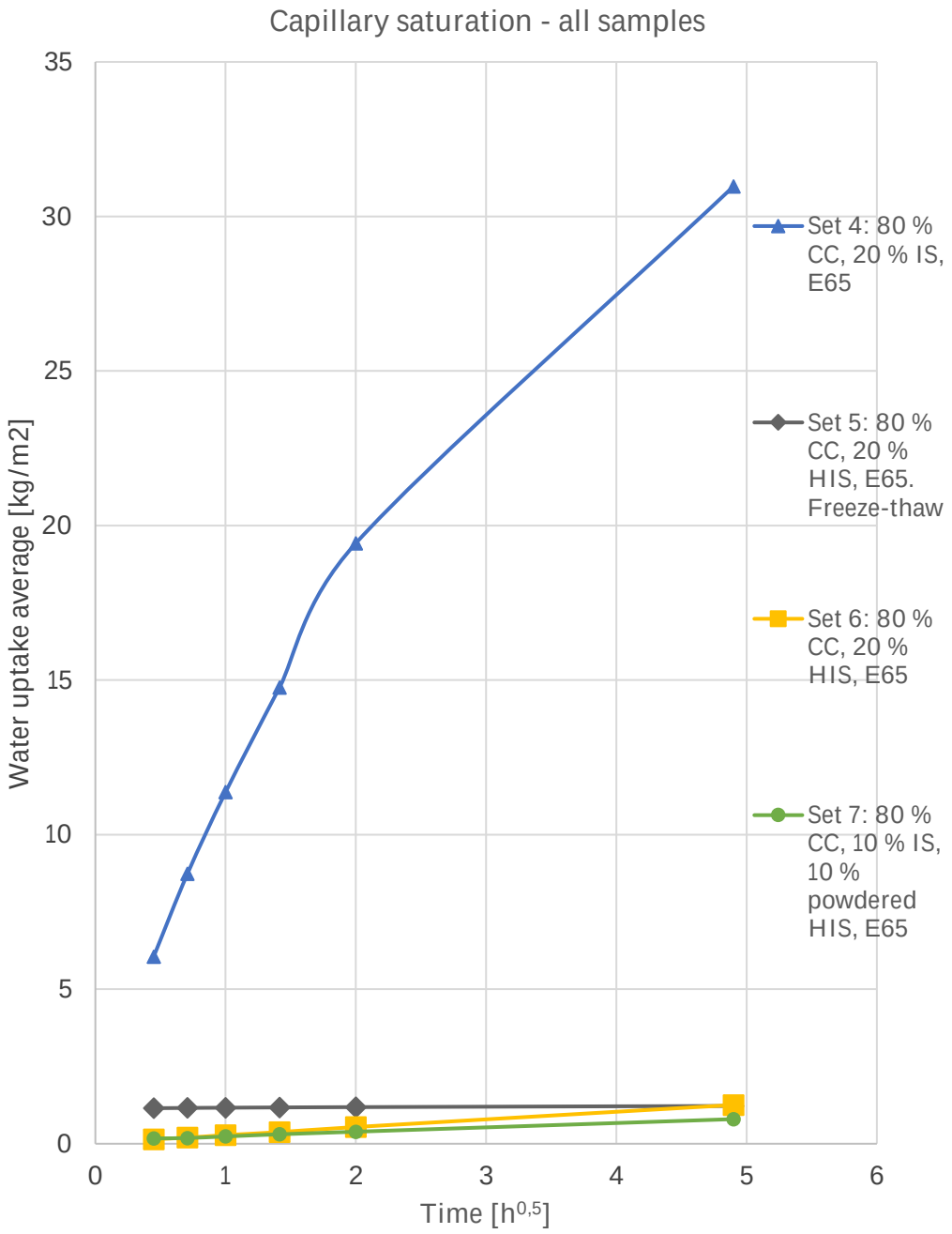


Fig 5.4. Water uptake versus time under test. Water uptake values are averages obtained from testing 2 samples.

Hydrophobization greatly reduced the water uptake of the samples. Figure 5.5 showcases the effect that hydrophobization has on a standard sample. Water uptake of the non-hydrophobized sample set 4 at 24 hours of testing was 31 kg/m^2, whereas in the hydrophobized samples it was around 1 kg/m^2. This result indicates that the hydrophobization process presented in this thesis is successful in producing lab-scale hydrophobized materials, and that it can have a great effect on the capillary saturation experienced by rammed earth structures. The capillary saturation of set 5, tested after 15 cycles of freeze-thaw and UCS tests, was observed to be slightly larger than of the other hydrophobized test sets. This is likely due to the degradation caused by freezing pressure on the hydrophobic coating. Water uptake increased by about 1,5 kg/m^2 on sample 2 of set 6, which is miniscule compared to the non-hydrophobized samples, which boasted water uptake of over 30 kg/m^2. Powdering half of the incineration slag and thus increasing the amount of fines in sample set 7 did not have significant effect on the scale of the water absorption. However, it is noteworthy that almost the same reduction in water uptake was achieved when the hydrophobization was applied into this smaller amount of fine aggregate. Further studies are needed to determine the optimal grain size and portion of hydrophobized material.

Figure 5.5. Hydrophobized sample.

From the results made with hydrophobized samples, it can be concluded that the hydrophobic coating is somewhat prone to degradation due to freeze-thaw. Further studies are needed to find out the magnitude of this degradation. Field tests in outdoor conditions should be conducted to include the effect of other elements also.

5.3 X-ray fluorescence

The elemental and oxide constitutions of the materials are presented in table 5.5. From the results can be seen that large portions of the raw materials consists of oxides like silica (SiO_2), aluminium oxide (Al_2O_3) and calcium oxide (CaO). Upon contact with water, these oxides dissolve. It can be expected that when using hydrophobized incineration slag as one of the aggregates, the concentration of the hydrating oxides is smaller in the water contained by the mix, leading to smaller strength gains than with non-hydrophobized materials.

Table 5.5. Oxide content of selected materials.

Oxides	CCA	IS	E65
SiO_2	51,63	30,07	12,94
CaO	18,47	26,42	62,8
Al_2O_3	11,78	14,15	7,15
Fe_2O_3	6,05	13,15	2,12
K_2O	5,14	1,86	0,92
MgO	2,13	2,2	1,44
SO_3	1,49	3,18	10,21
Na_2O	1,38	1,77	0,3
P_2O_5	0,67	2,16	0,67
TiO_2	0,6	1,67	0,62
MnO	0,2	0,26	0,13
ZrO_2	0,07	0,05	0,08
SrO	0,07	0	0,29
BaO	0,06	0,21	0,04
ZnO	0,06	1,44	0,06
Cl	0,05	0,37	0,12
WO_3	0,03	0	0
Rb_2O	0,03	0,01	0,01
V_2O_5	0,02	0	0,02
Cr_2O_3	0,02	0,15	0,01
CuO	0,01	0,54	0,03
Co_3O_4	0,01	0,04	0

NiO	0,01	0,04	0,01
Ga_2O_3	0,01	0	0
Ac	0	0	0
PbO	0	0,18	0
Au	0	0	0
OsO_4	0	0	0
Dy_2O_3	0	0	0
CeO_2	0	0	0,04
Y_2O_3	0	0	0
Kr	0	0	0
As_2O_3	0	0	0

5.4 Calorimetry

The composition of different samples used in the calorimetry experiments is shown in table 5.6.

Table 5.6. The mixes used in the calorimetry measurements.

Mixes	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Crushed concrete [g]	116	114,4	116	136	178	0
Incineration slag [g]	29	28,6	29	34	0	0
Natural aggregate [g]	0	0	0	0	0	190
Binder type	E65	CE-MIII/A	CE-MIII/B	CE-MIII/B	CE-MIII/B	CE-MIII/B
Binder amount [g]	29	28,5	29	34	36	38
Water % [g]	14	17	17	22	18	10

The results for the calorimeter measurements for samples corresponding to the recipes used in the full-sized samples are presented in figures 5.6 and 5.7. The cumulative heat release is presented as joules per gram of binder and the thermal power at given moment is presented as watts per gram of binder. This is to normalize the results to allow comparison with recipes that have varying amounts of binder. Results from the first 45 minutes of the tests are omitted due to disturbance in the measurements caused by loading of the samples into the calorimeter.

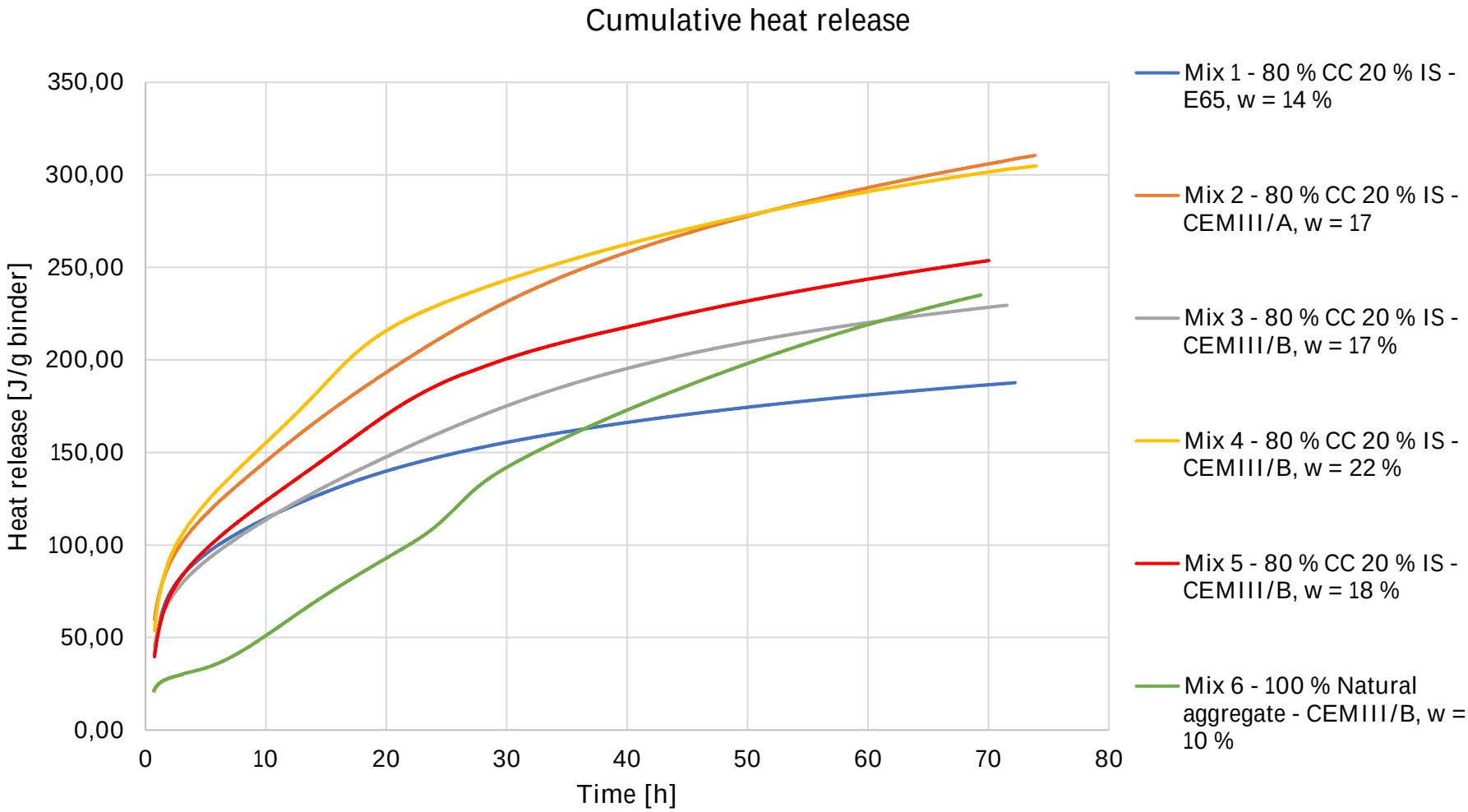


Figure 5.6. The cumulative heat release versus time.

The highest cumulative heat release is achieved with mix 2, which contains CEMIII/A as the binder. The heat release is about 310 joules per gram of binder. CEMIII/A has the highest portion of cement among the binders used in this study, therefore it is expected to have the highest total heat of hydration. Clear difference is seen between mixes 3 and 4, which have the same constitution, expect mix 4 has a water content of 22 %, as opposed to the 17 % water content of mix 3. Mix 4 has a total heat of hydration of 305 joules per gram of binder, whereas the equivalent figure for mix 3 is 230 joules per gram of binder. The difference is 25 %. This result shows that rammed earth recipes might contain too little water to facilitate early strength gain, making excessive use of binder redundant. Mix 4, containing 22 % of water, cannot be used as rammed earth recipe, as it contains too much water to be compacted and would be too plastic upon demoulding.

Mix 6 was made with natural aggregate to determine whether the chemical composition of the recycled aggregates influences the heat of hydration. Comparing mix 6 to other samples made with the same binder, it was observed that except for mix 3, mix 6 had lower heat of hydration. This hints that the oxides present in crushed concrete and incineration slag, namely silicon oxide and calcium oxide, assist in the early strength forming process. Crushed concrete might also contain trace amounts of non-hydrated cement, increasing the binder content of the recipe.

Lowest heat of hydration was observed in mix 1, which uses EcoIntellect E65 as the binder. This is in line with the UCS test results, where the lowest results were achieved with E65. The E65 binder contains the lowest amount of cement among the binders used in the tests, which means that early strength gains are limited.

When plotting the thermal power against time, results differing from typical values for concrete can be observed. The high peaks at the beginning of the tests result from handling of the test specimen. It was observed that on mixes 1-3 there are no peaks in the heat of hydration that commonly are seen on standard cementitious samples. In sample mixes 4-6 hydration peaks can be clearly seen. The heat flow values are circa 0,001 to 0,002 watts per gram of binder. Results for concrete are typically higher than this, ranging from 0,003 to 0,007 watts per gram of binder. Considering the low cement content of the binders and the low proportion of binder in the mixes, this result was expected.

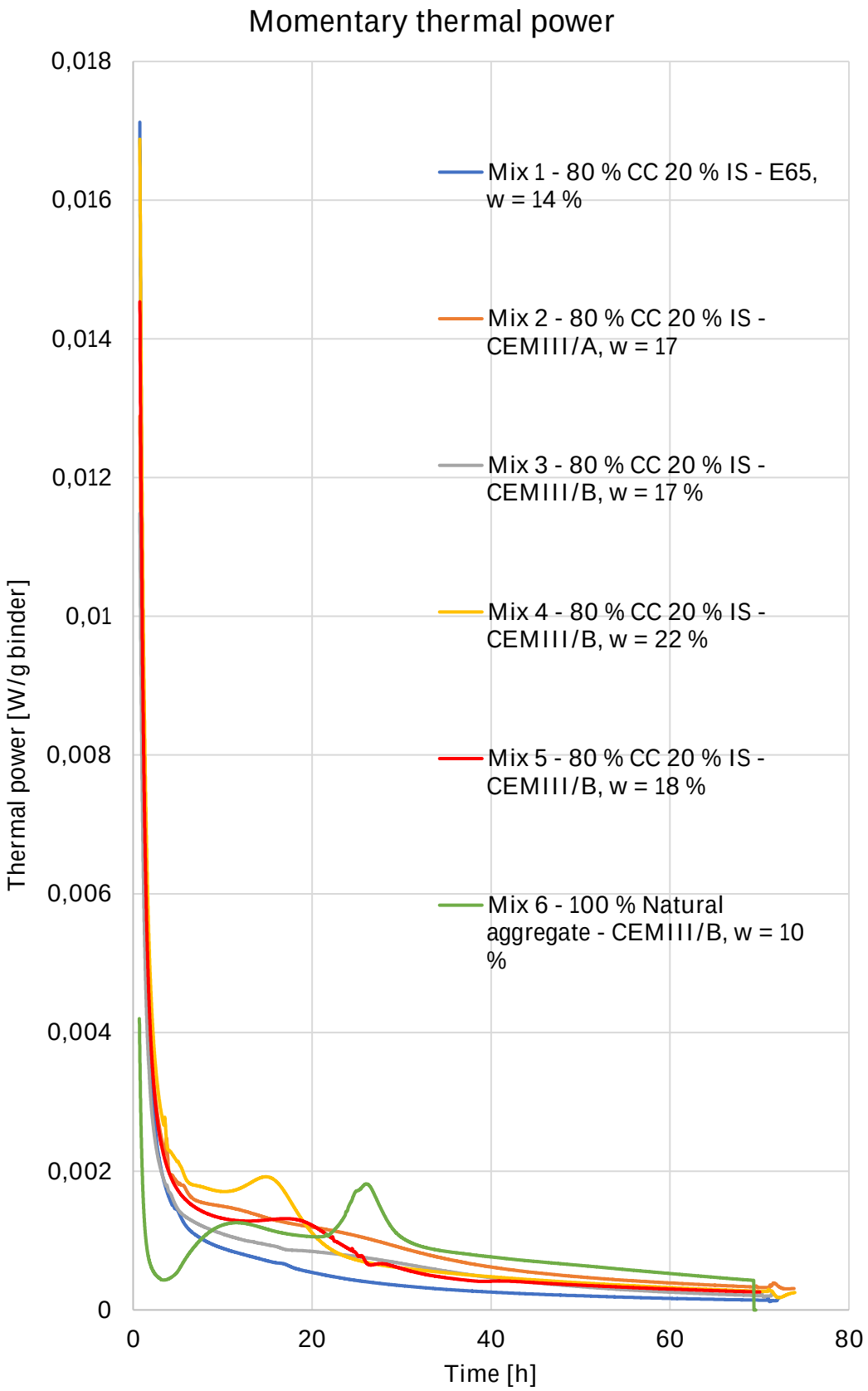


Figure 5.7. Thermal power versus time.

5.5 Scanning electron microscopy

SEM imaging results are presented in figures 5.8, 5.9, 5.10, 5.11 and 5.12. Hydration products can be identified from all the samples. The most significant difference can be seen between hydrophobized and non-hydrophobized samples. Most extensive crystal formation can be seen when using CEMIII/A as the binder. In non-hydrophobized samples where E65 was used as the binder, vast formation of ettringite can be seen. In hydrophobized samples this is not so prominent, which hints that the hydrophobization prevents the slag from partaking into the hydration process, leading to increased strength.

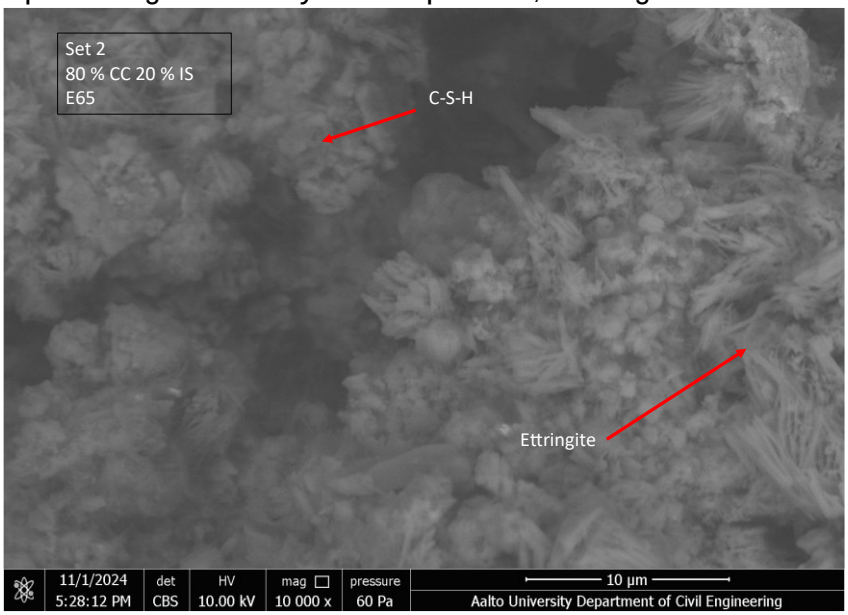


Figure 5.8. Set 2 SEM image.

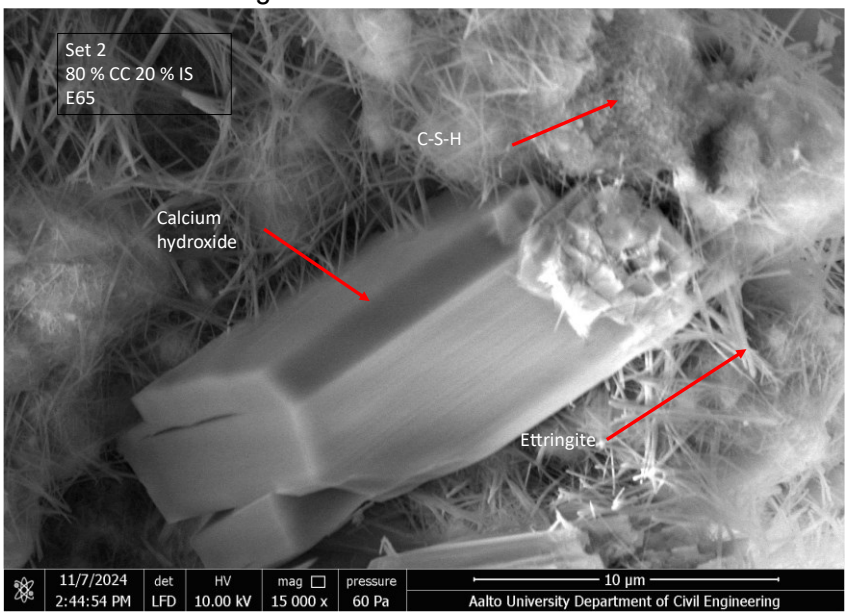


Figure 5.9. Set 2 SEM image.

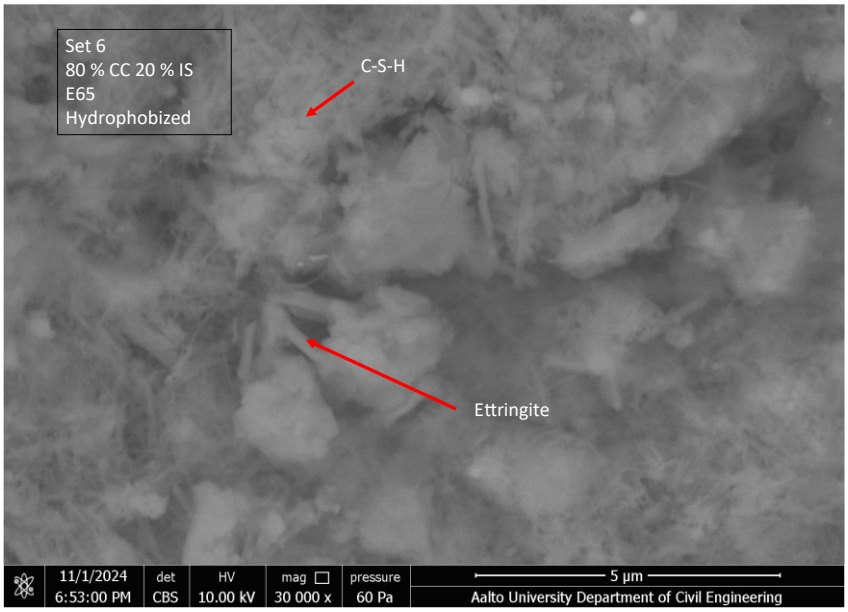


Figure 5.10. Set 6 SEM image.

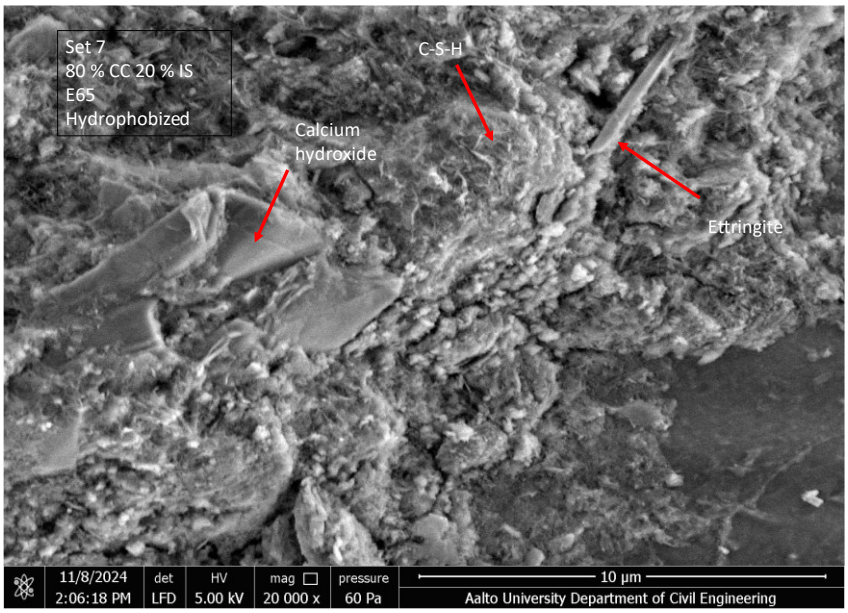


Figure 5.11. Set 7 SEM image.

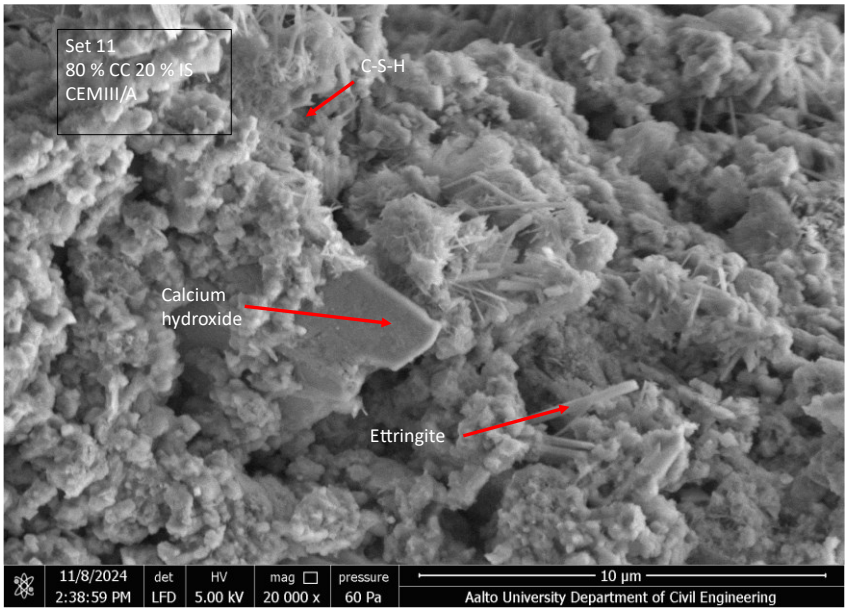


Figure 5.12. Set 11 SEM image.

5.6 CO_2-emissions

A rudimentary life-cycle assessment (LCA) was done to compare the total emissions of the recipes developed in this thesis to common concrete. The calculations are based on total CO_2 equivalent emissions of each material. Transport emissions and emissions caused by work inputs are not included in the assessment. The consumption of aggregate materials was calculated using densities achieved in the laboratory samples.

Table 5.8. CO_2 equivalent values used for the life-cycle assessment. Source included in brackets.

GWP	
A1-A3	CO_2e kg/kg
Crushed concrete (co2data.fi)	0,0046
Incineration slag (co2data.fi)	0,00025
CEMIII/A (co2data.fi)	0,435
CEMIII/B (Finnsementti/Ramboll)	0,315
E65 (EcoIntellect Oy)	0,107

The GWP of concrete is taken as 210 kg CO_2e/m^3 for concrete with strength class of C20/25. (co2data.fi)

The results of the LCA calculation are presented in table 5.9. Lowest total GWP is achieved when using E65 as the binder; compared to concrete, same volume causes almost seven times less emissions. However, the work inputs required to compact rammed earth structures are significant, which should be considered when calculating final emissions for rammed earth structures.

CEMIII/B causes less emissions than CEMIII/A, as it has a larger proportion of Portland cement replaced with foundry slag.

Table 5.9. Results of LCA calculation.

Component	CC (CO2e kg)	IS (CO2e kg)	Binder (CO2e kg)	Total (CO2e kg/m3)
Binder				
E65	4,6	0,1	26,8	31,4
CEMIII/A	4,6	0,1	108,8	113,4
CEMIII/B	4,6	0,1	78,8	83,4
Reference - Concrete				210

6 Conclusions

6.1 Conclusions from the test structure

The results indicate that the study of rammed earth test structures is a demanding task that requires forethought during the planning phase of the test. Methods commonly used in assessment of concrete structures are not as applicable due to the hastened erosion rate and low compressive strength of rammed earth structures. When planning a test program containing full sized test structures, this should be considered and the objectives of the test structure along with the practical methods for assessing whether these objectives are met should be specified.

Incineration slag failed as an aggregate material. The main reason for this is most likely the incorrect grain size distribution of said material. While the largest fraction size was 2 millimetres, many times finer than in crushed concrete-based test structures, it is likely that the mix did not contain enough fine, clay-size particles to facilitate the interparticle bonding of the larger slag grains. This caused the bonds to be weak and brittle, leading to particle erosion and loss of compressive strength as the structure was subjected to freeze-thaw and other outside disturbance such as moisture load and vibration. According to particle size distribution curves provided by Holopainen (2022), only about 6 % of the incineration slag passed a 0,1-millimetre sieve. It is suggested that a rammed earth mixture should contain clay-sized particles (≤0,002 mm) up to 20 % of its total mass (Walker et al. 2005). However, during the construction phase incineration slag worked well, and should not be written out from future consideration. To use incineration slag as a material in rammed earth research, the grain size distribution curve should be produced using wet sieving or the areometer test. Based on the curve, a portion of the incineration slag could be pulverised and remixed to increase the proportion of the clay-size particle fraction. This should lead to formation of fine paste that increases the effectiveness of binders used in stabilized rammed earth. It can also assist in the formation of optimally sized voids in the mixture, leading to increased apparent cohesion of relatively less stabilized mixes. One aspect of incineration slag also needs additional research is the effect of its high aluminium content on hydration properties. According to a literature review by Bo Telén (Telén, 2023), using incineration slag as the sole aggregate hinders the strength gain of the mix, and therefore the portion of incineration slag in a given mix should be limited.

Crushed concrete exhibited favourable properties that give reason to continue study of its use as an aggregate material in rammed earth construction. Especially promising are the relatively high UCS values that were recorded when testing samples extracted from the test structure. Values of over 7 MPa

were recorded despite the low quality and multiple defects of the samples, pointing that the mix could be suitable for a range of different applications as outlined in Eurocode 6. Results indicate that crushed concrete-based rammed earth experiences long-term strength gain also in natural conditions when subjected to numerous cycles of freeze-thaw. For future research one of the main points can be studying the surface erosion that was also observed in the Konala test structure. Mitigation of the erosion can be achieved with optimizing the grain size distribution to gain a smooth finish for the structure as it is demoulded, using various coatings and hydrophobic additives to decrease the pressure caused by freeze-thaw to the surface from within the structure and by designing other protective structures around the rammed earth structure, such as roofs or cladding.

6.2 Conclusions from the laboratory tests

Designing stabilized rammed earth mixtures is complicated task that requires consideration of multiple parameters, all of which could not be studied in the scope of this thesis. Especially the water content of the mixture is in key part when it comes to performance, as the water contained in the mix is facilitating both the compaction and the hydration of a stabilized rammed earth structure. These are the most important subprocesses in the rammed earth construction process when it comes strength-gain.

In order to fully understand the parameters affecting the performance of stabilized rammed earth, more in-depth studies are needed. The circular aggregate materials used in this study, crushed concrete and incineration slag, have great potential in use in stabilized structures, as their chemical compositions contain oxides that are part of the hydration process. However, they also have drawbacks in this regard, as evident from Bo Telén's findings. The high aluminium content in incineration slag sets boundaries for its use as an aggregate material in stabilized rammed earth.

Hydrophobization is a potential method for improving the freeze-thaw durability of rammed earth structures. In this study, reduction of 96 % in capillary saturation of water into samples was observed. By decreasing the water absorption and therefore freezing pressure in the aggregate matrix, longer-lasting structures could be built. However, more research is needed on the durability of hydrophobic materials in natural conditions. Results of this study indicate that freeze-thaw cycles potentially cause degradation of the hydrophobic coating. Also, other environmental factors such as exposure to ultraviolet light is known to cause degradation of stearic acid. Also, methods for applying the hydrophobization on granular materials should be studied. The procedure presented in this thesis is suitable for lab scale sampling, but even when producing enough hydrophobized material for a test structure the consumption of ethanol would be quite high. It was also observed in this study,

that a recipe where half of the incineration was powdered and hydrophobized instead of all the incineration slag, produced higher UCS results. This might be explained by the fact that the powdering improved the grain size distribution of the aggregate mix. Another way to explain this is that hydrophobization usually decreases the compressive strength by weakening the bonds between aggregate particles, and when applied into a smaller amount of finer aggregate, this effect is weakened. Also, hydrophobization improved the UCS of samples by 58 %, which can be explained by more favourable water-to-aggregate and water-to-binder ratios when excess water is not absorbed by the incineration slag.

Incineration slag is a suitable aggregate material for stabilized rammed earth structures. However, when designing a rammed earth mix incorporating incineration slag, some of its qualities should be well understood. First, the water absorption capacity of incineration slag is significantly higher than that of natural aggregates. Second, the grain size distribution of even a fine slag can be surprisingly coarse. Therefore, thorough testing of the index values should be conducted before mix design, keeping in mind that slags sourced from different incineration facilities and different batches can have differences. Also, in order to assess the freeze-thaw durability of these structures more realistically, test programs with a larger number of freeze-thaw cycles should be conducted. Also, as mentioned the high aluminium content and its effect on hydration should be considered when designing mixes with incineration slag. In practice, this means that the portion of slag in a stabilized mixture should not exceed 50 %.

EcoIntellect E65 yielded lower UCS results than other binders. However, values over 5 MPa were achieved with certain recipes, which qualifies the materials for different uses as masonry blocks, as per Eurocode 6. Foundry slag cements, CEMIII/A and CEMIII/B, were more effective in stabilizing the samples, as can be expected as their cement content is higher.

6.3 Limitations and suggestions for future research

This thesis pertained to general properties of selected materials in terms of performance in stabilized rammed earth construction. Main limitations are the small sample size and the varying nature of recycled waste materials. In freeze-thaw tests, the number of cycles was limited to 15, which is low considering the use-cases of the studied structures.

Chemical properties of the aggregate materials were not considered when deciding on the laboratory research program. In future studies, the strength-forming properties of different recycled materials should be studied from the perspective of their chemical components. This means studying whether some side-stream material hold properties that promote or limit hardening

when mixed with binders. From an environmental point of view, the stability of potentially hazardous substances contained in side-stream materials should be also studied. Hydrophobization of slag could offer a way to prevent leaching of contaminants, also while improving the freeze-thaw resistance of the final structure.

In future studies, the application of hydrophobization should be developed. Alternative methods should be studied, with the goal of reducing the ethanol consumption of the process described in this thesis. Also, the grain size and portion of the hydrophobized material should be studied to form a theory of how to produce hydrophobized composites with the least amount of work and materials. Also, the long-term durability of hydrophobic coating should be studied in rammed earth applications and in Nordic conditions.

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Attachments

Attachment 1: Compilation of UCS results from laboratory program
Attachment 2: UCS graphs for samples taken from the Konala test wall
Attachment 3: UCS graphs for samples made during the laboratory program
Attachment 4: Leaching results, incineration slag

		Sample UCS (MPa)			
Set	Set description	1	2	3	Avg
1	Set 1: 100 % CC, E65.	2,03	2,3	2,41	2,247
2	Set 2: 80 % CC, 20 % IS, E65	3,91	4,18	3,21	3,767
3	Set 3: 80 % CC, 20 % IS, E65. Freeze-thaw	3,96	3,24	4,11	3,77
5	Set 5: 80 % CC, 20 % HIS, E65	8,64	9,34		8,99
6	Set 6: 80 % CC, 20 % HIS, E65. Freeze-thaw	7,72	9,48		8,6
7	Set 7: 80 % CC, 10 % IS, 10 % powdered HIS, E65	10,41	12,95		11,68
8	Set 8: 100 % CC, CE-MIII/B	17,64	20,16		18,9
9	Set 9: 80 % CC, 20 % IS, CEMIII/B	6,11		8,74	7,425
10	Set 10: 100 % CC, CEMIII/A	15,98	18,82		17,4
11	Set 11 :80 % CC, 20 % IS, CEMIII/A	7,25	10,29	7,67	8,403

19.06.24

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Test report

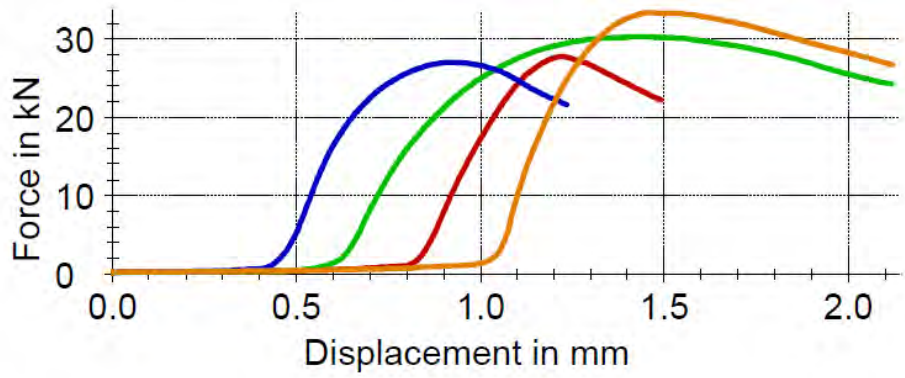
Customer	: Aalto/CE/Soil Lab.	Specimen type	: Sawed cube
Group	:	Tester	: Otso Laurila
Material	: BeM+LTHelen	Notes...	: Max grain size 60 mm

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	h_0	ρ_0	Mass	F_{max}	σ_M	dL at F_{max}
			mm	kg/m³	g	**kN**	N/mm²	mm
	1	**1**	83,5	1939	816	**27,77**	5,51	1,2
	2	**2**	99,0	1863	1942	**30,31**	2,88	1,4
	3	**3t**	84,0	1988	611	**27,03**	7,39	0,9
	4	**3s**	53,3	2109	487	**33,38**	7,71	1,5

Series graph:



Statistics:

Series	ρ_0	σ_M
n = 4	kg/m³	N/mm²
$\bar{x}$	1975	5,87
s	103,2	2,22
v	5,23	37,77

19.06.24

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Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

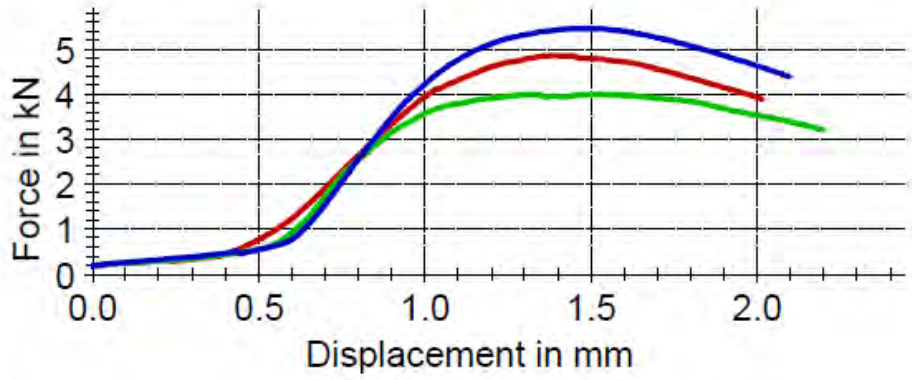
Customer	: Aalto/CE/Soil Lab.		Pre-treatment	:	
Group	:		Tester	:	Otso Laurila
Material	: JpKu + LThelen (1:5)		Notes...	:	
Specimen type	: Sawed cube				

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	h_0	ρ_0	Mass	F_{max}	σ_M	dL at F_{max}
			mm	kg/m³	g	kN	N/mm²	mm
	1	1	97,3	1350	1339	4,85	0,48	1,4
	2	2	94,7	1346	1249	3,99	0,41	1,5
	3	3	103,6	1287	1452	5,46	0,50	1,5

Series graph:



Statistics:

Series	ρ_0	σ_M
n = 3	kg/m³	N/mm²
$\bar{x}$	1328	0,46
s	34,86	0,05
v	2,63	10,58

19.06.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

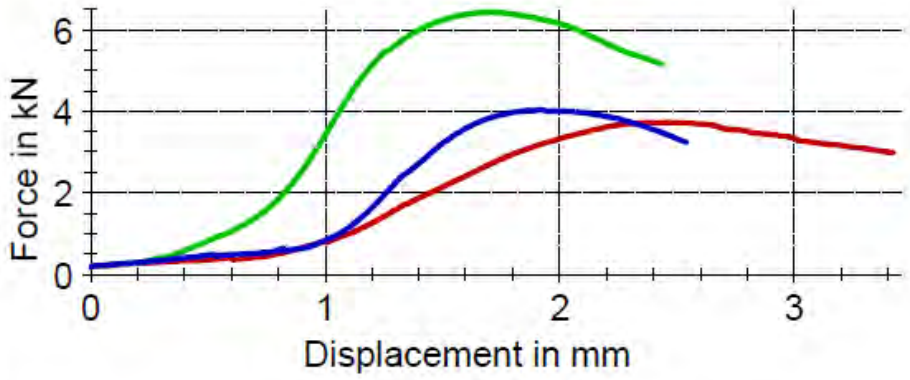
Customer	: Aalto/CE/Soil Lab.	Pre-treatment	:		
Group	:	Tester	:	Otso Laurila	
Material	: JpKu + LThelen (1:4)	Notes...	:		
Specimen type	: Sawed cube				

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	h_0	ρ_0	Mass	F_{max}	σ_M	dL at F_{max}
			mm	kg/m³	g	kN	N/mm²	mm
	1	1	107,0	1355	1479	3,74	0,37	2,5
	2	2	94,5	1380	1465	6,44	0,57	1,7
	3	3	104,2	1369	1483	4,04	0,39	1,9

Series graph:



Statistics:

Series	ρ_0	σ_M
n = 3	kg/m³	N/mm²
$\bar{x}$	1368	0,44
s	12,3	0,11
v	0,90	25,68

19.06.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

Customer : Aalto/CE/Soil Lab.
Group :
Material : BeM+LTUPM

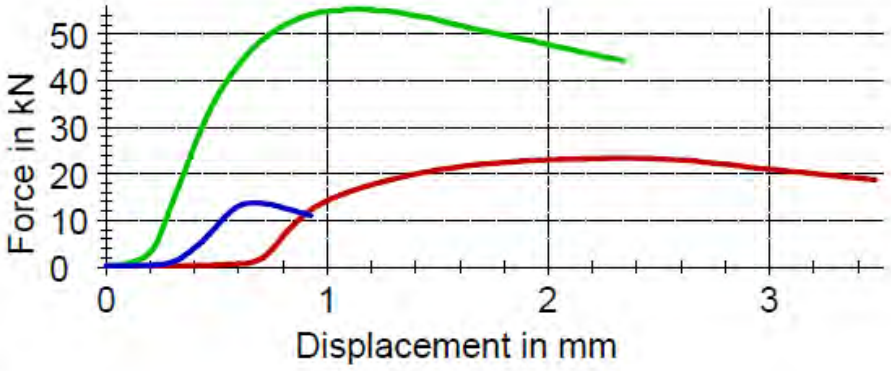
Specimen type : Sawed cube
Tester : Otso Laurila

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	87,9	1864	1556	23,42	2,47	2,3
	2	2	84,4	1907	1724	55,37	5,17	1,1
	3	3	95,6	1834	418	13,81	5,79	0,7

Series graph:



Statistics:

Series n = 3	ρ_0 kg/m³	σ_M N/mm²
$\bar{x}$	1868	4,48
s	36,61	1,77
v	1,96	39,49

05.08.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

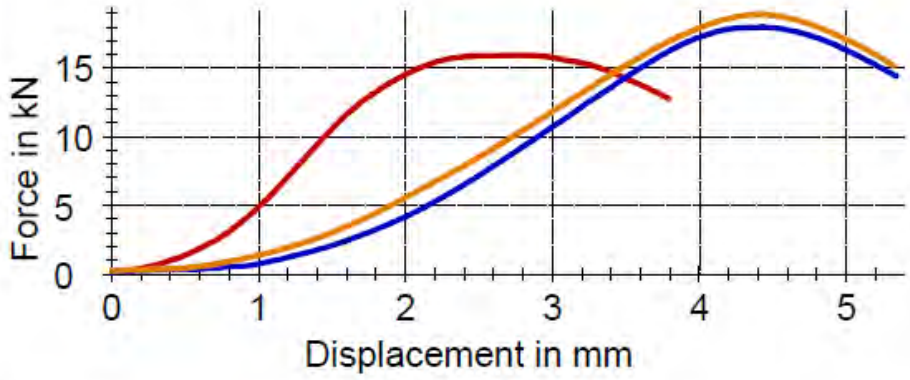
Customer	: Aalto/CE/Soil Lab.	Specimen type	: Cylindrical
Group	: Set 1	Tester	: Otso Laurila
Material	: Crushed concrete 100 %	Notes...	:

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	2	1	100,00	146,7	1329	2124	15,97	2,03	2,7
	4	2	100,00	153,4	1370	2289	18,03	2,30	4,4
	5	3	100,00	162,1	1379	2433	18,95	2,41	4,4

Series graph:



Statistics:

Series n = 3	ρ_0 kg/m³	σ_M N/mm²
$\bar{x}$	1359	2,25
s	26,21	0,19
v	1,93	8,66

07.08.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

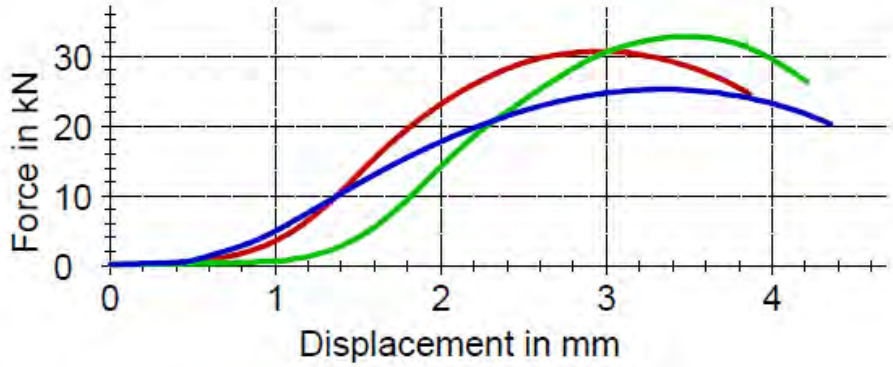
Customer : Aalto/CE/Soil Lab.
Group : Set 2
Material : Crushed concrete 80 % + Incineration slag 20 %
Specimen type : Cylindrical rammed earth
Pre-treatment :
Tester : Otso Laurila
Notes... :

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	100,00	154,7	1398	2355	30,67	3,91	2,9
	2	2	100,00	165,6	1390	2506	32,82	4,18	3,5
	3	3	100,00	164,3	1386	2480	25,25	3,21	3,4

Series graph:



Statistics:

Series n = 3	ρ_0 kg/m³	σ_M N/mm²
$\bar{x}$	1391	3,77
s	6,097	0,50
V	0,44	13,19

02.09.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

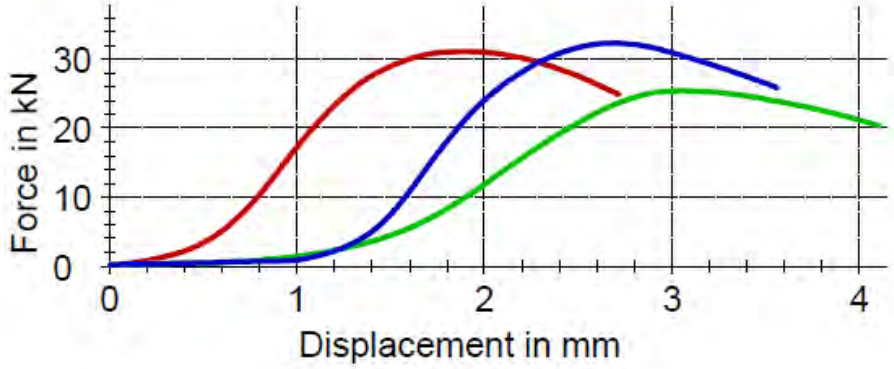
Customer : Aalto/CE/Soil Lab.
Group : RAKISEI
Material : Crushed concrete + incineration slag + E65
Specimen type : Cylindrical rammed earth
Pre-treatment : Freeze thaw 15 cycles
Tester : Otso Laurila
Notes... : Sample 3 damaged

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	100,00	168,0	1361	2491	**31,12**	3,96	1,9
	2	2	100,00	165,8	1386	2503	**25,44**	3,24	3,0
	3	3	100,00	132,6	1359	1962	**32,31**	4,11	2,7

Series graph:



Statistics:

Series n = 3	ρ_0 kg/m³	σ_M N/mm²
x	1369	3,77
s	15,09	0,47
v	1,10	12,40

27.09.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

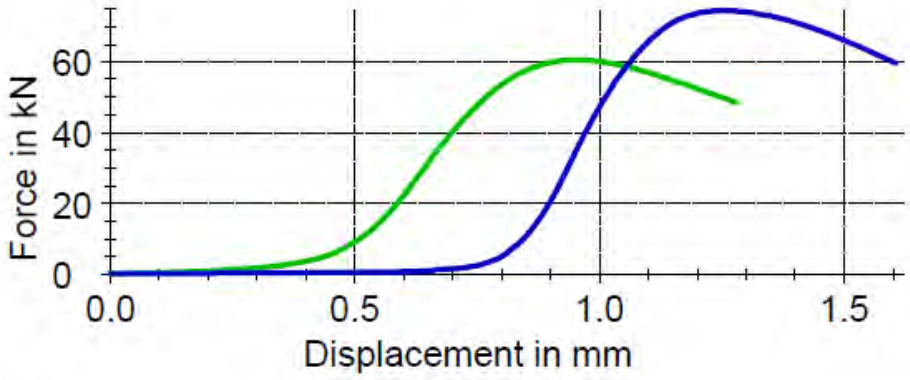
Customer	:	Aalto/CE/Soil Lab.	Pre-treatment	:	Freeze-thaw 15 cycles
Group	:	Set 6	Tester	:	Otso Laurila
Material	:	80 % CC + 20 % HIS, E65	Notes...	:	
Specimen type	:	Cylindrical rammed earth			

Pre-load : 200 N
Test speed : 3 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0	h_0	ρ_0	Mass	F_{max}	σ_M	dL at F_{max}
			mm	mm	kg/m³	g	kN	N/mm²	mm
	∔1	1	100,00	-	0,000	2246	-	-	-
	2	1	100,00	154,0	1339	2246	60,60	7,72	1,0
	3	2	100,00	147,6	1380	2218	74,48	9,48	1,3

Series graph:



Statistics:

Series	ρ_0	σ_M
n = 2	kg/m³	N/mm²
x	1360	8,60
s	29,35	1,25
v	2,16	14,53

20.09.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

Customer : Aalto/CE/Soil Lab.
Group : Set 7
Material : 80 % CC 20 % Hydrophobized IS
Specimen type : Rammed earth cylinder

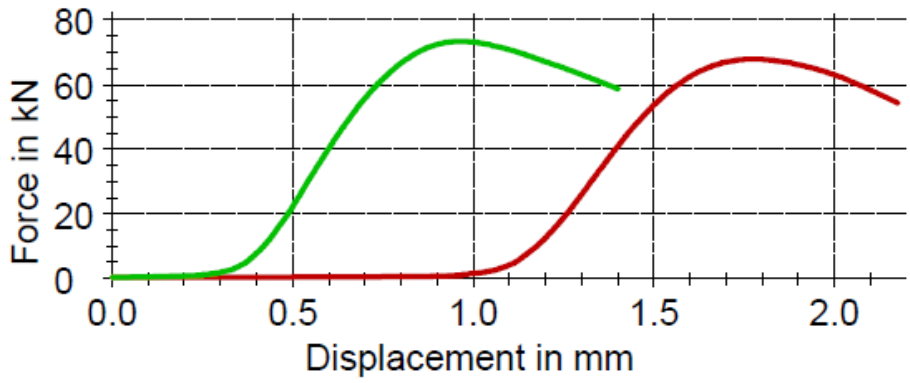
Pre-treatment : Drying at 40 C, saturation test
Tester : Otso Laurila
Notes... :

Pre-load : 200 N
Test speed : 3 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	100,00	151,1	1291	2123	67,88	8,64	1,8
	2	2	100,00	150,2	1302	2131	73,35	9,34	1,0

Series graph:



Statistics:

Series n = 2	ρ_0 kg/m³	σ_M N/mm²
x̄	1296	8,99
s	8,354	0,49
V	0,64	5,48

20.09.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

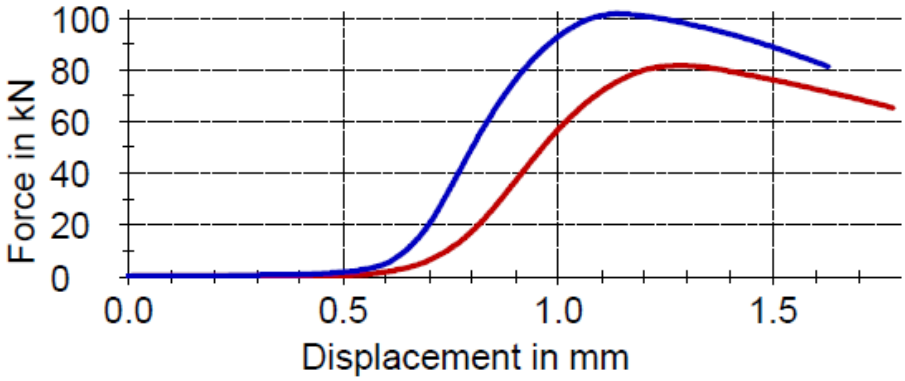
Customer : Aalto/CE/Soil Lab.
Group : Set 8
Material : 80 % CC + 10 % 0-2 mm IS + 10 % powdered hydrophobized IS
Specimen type : Rammed earth cylinder
Pre-treatment : Drying at 40 C, saturation test.
Tester : Otso Laurila
Notes... :

Pre-load : 200 N
Test speed : 3 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0	h_0	ρ_0	Mass	F_{max}	σ_M	dL at F_{max}
			mm	mm	kg/m³	g	kN	N/mm²	mm
	1	1	100,00	148,4	1358	2194	81,73	10,41	1,3
	☩2	2	100,00	-	0,000	2189	-	-	-
	3	2	100,00	143,7	1399	2189	101,67	12,95	1,1

Series graph:



Statistics:

Series	ρ_0	σ_M
n = 2	kg/m³	N/mm²
x̄	1378	11,68
s	29,03	1,80
v	2,11	15,38

15.08.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

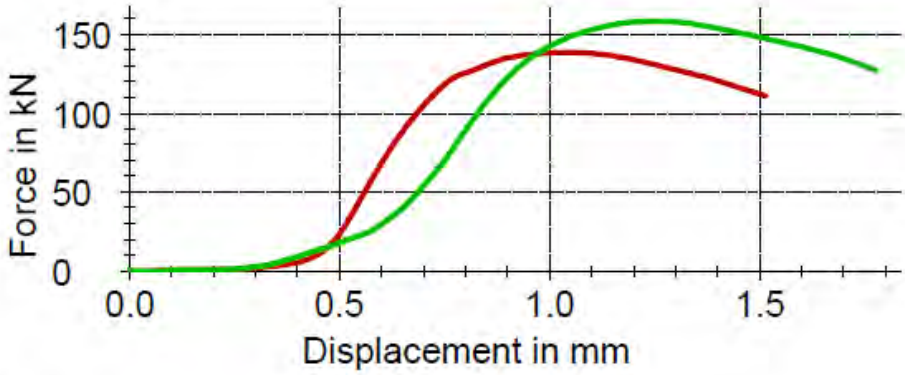
Customer	:	Aalto/CE/Soil Lab.	Pre-treatment	:	
Group	:	Set 10	Tester	:	Otso Laurila
Material	:		Notes...	:	Set 10
Specimen type	:				

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	3	100,00	141,5	1519	2341	138,55	17,64	1,0
	2	1	100,00	108,0	1551	1824	158,34	20,16	1,2

Series graph:



Statistics:

Series n = 2	ρ_0 kg/m³	σ_M N/mm²
x̄	1535	18,90
s	22,68	1,78
V	1,48	9,43

15.08.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

Customer : Aalto/CE/Soil Lab.
Group : Set 11
Material : CC + IS
Specimen type : Cylindrical rammed earth

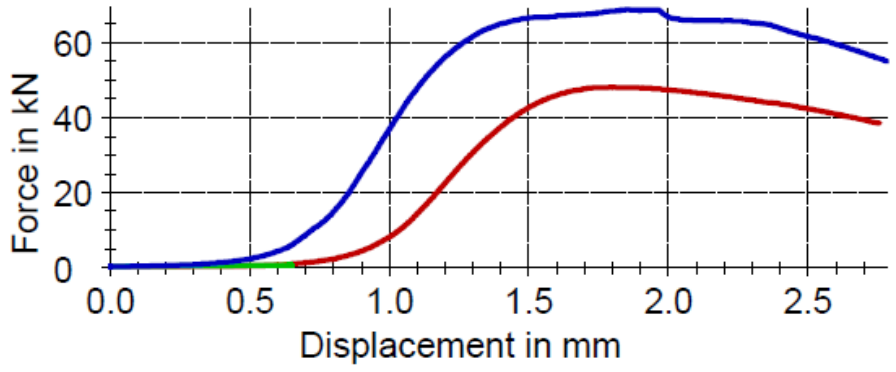
Pre-treatment :
Tester : Otso Laurila
Notes... : Set 11

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	100,00	151,3	1366	2251	47,99	6,11	1,8
	2	2	100,00	94,2	1347	1382	0,70	0,09	0,6
	3	3	100,00	146,7	1411	2254	68,63	8,74	1,9

Series graph:



Statistics:

Series n = 3	ρ_0 kg/m³	σ_M N/mm²
$\bar{x}$	1375	4,98
s	33,03	4,43
V	2,40	89,04

26.08.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

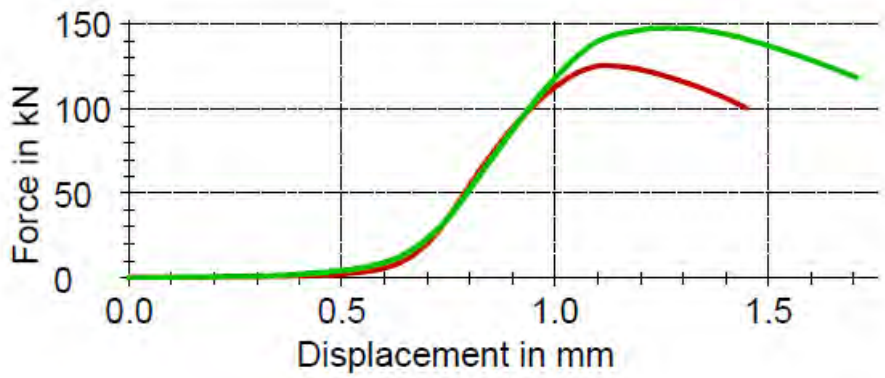
Customer	:	Aalto/CE/Soil Lab.	Pre-treatment	:	
Group	:	Set 12	Tester	:	Otso Laurila
Material	:	Crushed concrete + CEMIII/A	Notes...	:	
Specimen type	:	Cylindrical rammed earth			

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	100,00	143,1	1474	2297	**125,50**	15,98	1,1
	2	2	100,00	137,9	1511	2270	**147,84**	18,82	1,3

Series graph:



Statistics:

Series n = 2	ρ_0 kg/m³	σ_M N/mm²
x	1493	17,40
s	26,42	2,01
V	1,77	11,56

15.08.24

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Rakennustekniikan laitos

Test report

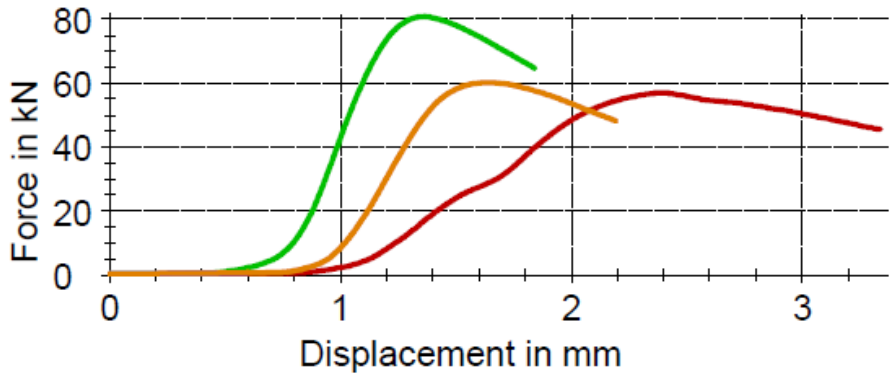
Customer	:	Aalto/CE/Soil Lab.	Pre-treatment	:	
Group	:	Set 13	Tester	:	Otso Laurila
Material	:		Notes...	:	Set 13
Specimen type	:	Cylindrical rammed earth			

Pre-load : 200 N
Test speed : 1,5 mm/min

Test results:

Legends	Nr	Specimen identifier	d_0 mm	h_0 mm	ρ_0 kg/m³	Mass g	F_{max} kN	σ_M N/mm²	dL at F_{max} mm
	1	1	100,00	155,4	1390	2351	56,93	7,25	2,4
	2	2	100,00	150,2	1414	2313	80,82	10,29	1,4
	3	3_failed	100,00	154,2	1388	2331	0,63	0,08	0,6
	4	3_extra press	100,00	154,1	1389	2331	60,23	7,67	1,6

Series graph:



Statistics:

Series n = 4	ρ_0 kg/m³	σ_M N/mm²
$\bar{x}$	1395	6,32
s	12,7	4,37
v	0,91	69,18

MetropoliLab

TESTAUSSELOSTE 2023-41270 1(1)
Korvaa testausselosteen samalla numerolla päiväyksellä 10.1.2024 18.07.2024

Tilaaja
2274241-9
317 HSY Jätehuolto, jätteen jalostus (kuona)

PL 210
00066 HSY

Maksaja
317 HSY Helsingin seudun ympäristöpalvelut -kuntayht Ostolaskut

PL 303
00066 HSY

Näytetiedot	**Näyte**	Jäte, 2-vaiheinen liukoisuustesti		
	Näyte otettu	27.12.2023	**Kellonaika**	11.00
	Vastaanotettu	29.12.2023	**Kellonaika**	12.35
	Tutkimus alkoi	29.12.2023	**Näytteenoton syy**	Omavalvonta
	Näytteenottaja	Tilaajan toimesta		
	Viite	Hannu Juntunen		
	Korvaavuuden syy:	Näytteen nimi korjattu		

Analyysi		Menetelmä	41270-1 Jäte, 2-vaiheinen liukoisuustesti 0-2 KM15	Yksikkö	MU %
2-vaiheinen ravistelutesti L/S=10L/kg	*	SFS-EN 12457-3:2002	Liite 1		

MU % = mittausepävarmuus, joka pätee MetropoliLabin tuottamilla tuloksilla näytteille tyypillisellä pitoisuusalueella. Tarkemmat tiedot mittausepävarmuudesta on saatavilla laboratoriosta. * = Akkreditoitu menetelmä

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Alv. Nro
FI23400568

MetropoliLab

LIITE 1 testausselosteeseen 41270-1
Sivu 1 / (2)

KAKSIVAIHEINEN RAVISTELUTESTI UUTTOLIUOKSEN JA KIINTEÄN JÄTTEEN SUHTEISSA 2 l / kg ja 8 l / kg *

Jäte, 2-vaiheinen ravistelutesti
SFS-EN 12457-3:2002
LIMS-numero: 2023--41270-1+2

Näyte: 0-2 KM15

Ensimmäisen vaiheen liukoisuus
A2 = C2 * [(L2 / MD) + (MC / 100)]
(Merkinnät viitestandardin laskukaavoista)

L/S = 10 l/kg, Kumulatiivinen liukoisuus, mg / kg kuiva-ainetta
A2-10 = C2 * (VE1 / MD) + C8 * [(L2 + L8 - VE1) / MD + (MC / 100)]

Analyytti	Liukoisuudet	Yksikkö	Analyytti	Liukoisuudet	Yksikkö	Mittausepä-varmuus	VnA 331/2013 & 1030/2021 kaatopaikka-kelpoisuuden enimmäispitoisuudet: Pysyvä jäte	Vaaraton jäte	Vaarallinen jäte
pH	10,8		**pH** *	11,2		0,5 pH-yks.			
Sähkönjoht.	970	mS/m	**Sähkönjoht.** *	180	mS/m	30 %			
As	< 0,01	mg/kg	**As** *	< 0,05	mg/kg	40 %	0,5	2	25
Ba	0,09	mg/kg	**Ba** *	0,25	mg/kg	40 %	20	100	300
Cd	< 0,002	mg/kg	**Cd** *	< 0,010	mg/kg	40 %	0,04	1	5
Cr	3,25	mg/kg	**Cr** *	3,97	mg/kg	40 %	0,5	10	70
Cu	0,39	mg/kg	**Cu** *	0,62	mg/kg	40 %	2	50	100
Hg	0,005	mg/kg	**Hg** *	0,010	mg/kg	40 %	0,01	0,2	2
Mo	0,87	mg/kg	**Mo** *	1,05	mg/kg	50 %	0,5	10	30
Ni	< 0,01	mg/kg	**Ni** *	< 0,05	mg/kg	40 %	0,4	10	40
Pb	< 0,01	mg/kg	**Pb** *	< 0,05	mg/kg	40 %	0,5	10	50
Sb	0,03	mg/kg	**Sb** *	0,22	mg/kg	40 %	0,06	0,7	5
Se	0,02	mg/kg	**Se** *	< 0,06	mg/kg	40 %	0,1	0,5	7
Zn	< 0,03	mg/kg	**Zn** *	0,37	mg/kg	40 %	4	50	200
V	0,03	mg/kg	**V** *	0,11	mg/kg	40 %	-	-	-
Cl^-	4 876	mg/kg	**Cl^-** *	4 752	mg/kg	40 %	800	15 000	25 000
F^-	5	mg/kg	**F^-** *	< 12	mg/kg	40 %	10	150	500
SO_4	3 657	mg/kg	**SO_4** *	5 368	mg/kg	40 %	1 000	20 000	50 000
DOC	120	mg/kg	**DOC** *	< 169	mg/kg	40 %	500	800	1 000
TDS	13 002	mg/kg	**TDS** *	16 996	mg/kg	40 %	4 000	60 000	100 000

*** = Akkreditoitu menetelmä**

Lisätietoja näytteen esikäsittelystä ja ravistelutestistä: Were Nyandoto, Ympäristöasiantuntija, puh. 010 3913 427

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MetropoliLab

Menetelmätiedot

pH	SFS 3021:1979
Sähkönjohtavuus	SFS-EN 27888:1994
Alkuaineet	SFS-EN ISO 17294-2:2016, ICP-MS
Ionit (Cl, F, SO_4)	SFS-EN ISO 10304-1:2009
DOC	SFS-EN 1484:1997
TDS	SFS 3008:1990
Fenoli-indeksi	ISO 14402:1999 (CFA)