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Flow Properties of Green Cementitious Binders: Influence of Superplasticizer on Flowability of Clay Containing Cementitious Binders

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Gothenburg, Sweden 2022

www.chalmers.se

EXAMENSARBETE ACEX20

**Flow Properties of Green Cementitious Binders:
Influence of Superplasticizer on Flowability of Clay Containing
Cementitious Binders**

Examensarbete inom högskoleingenjörprogrammet Samhällsbyggnadsteknik



CHALMERS

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May, 2022

Institutionen för arkitektur och samhällsbyggnadsteknik

Avdelningen för byggnadsteknologi

Byggnadsmaterial (Building Materials Research Group)

CHALMERS TEKNISKA HÖGSKOLA

Göteborg, 2022

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ABSTRACT

With increasing populations worldwide, building new constructions and infrastructures grows to fulfill societal demands. But at the same time, discussions around the topic of sustainable development, and the concerns with greenhouse gas emissions assigned to building material production has been a major focus. Construction industry in Sweden is responsible of the CO₂ emissions, the major CO₂ is assigned to the employed construction materials, mainly due to the production process (Boverket, 2021).

The most popular structural construction materials are concrete, timber and steel. Concrete has been used in the construction industry for a long time because of so many good advantages assigned to it. The modern developed societies require a built environment that is unimaginable without the widespread use of concrete which enables construction anywhere, at low cost, of complex and massive shapes from water, gravel, sand, and cementitious powder. Although other common building materials such as timber or steel, when available can replace fraction of construction needs, however many structures such impressively engineered bridges and dams, architecturally innovative skyscrapers, roads and railways, high-rise apartments cannot be constructed without concrete. But cement as one of the main constituents of concrete is the third largest source of anthropogenic emissions of carbon dioxide, accounting for approximately 8% of global emissions in the world (Andrew, 2018).

Although, use of industrial wastes like coal combustion fly ash or ground granulated blast furnace slag as cement replacement materials for manufacturing concrete with lower cement clinker content has been an answer to tackle this challenge but expected lower availability of these materials in the near future has been another recent obstacle. This has brought a lot of attention to natural resources like clays to be considered as future alternative cement replacements. However, industrial application of these new alternative binders is still dependent on further research mainly in terms of performance, and durability of these new engineered binders. Therefore, aiming to demonstrate the potentials of activated clays as a clinker replacement (future green binders) to reduce greenhouse gas emissions and environmental impact when constructing infrastructure buildings made from concrete. This project is performed to study the fresh properties of calcined clay containing concrete. In this context the water demand and consequently, the effect of using superplasticizers (SP) on the workability of clay blended cements is investigated. Two kinds of clays obtained from separate geographical locations in Sweden were studied in this project for their rheological behaviour as a potential future of supplementary cementitious material (SCM).

The results showed that the flow properties of the clay were affected by the particle size distribution of the clays and the state of the clay (uncalcined or calcined). Further, it was also found that the SP requirement varied with the water demand of clays. Out of the two kinds of PCE superplasticizers studied, one type was found to disperse the clay particles for longer durations while one was observed to retard the workability beyond a certain duration. Finally, it was observed that calcinated clays did not require superplasticizer for particle separation or for achieving a target flow spread in the mixes with high water to solid ratios.

Key words: Calcined clay, superplasticizer (SP), Ordinary Portland cement, clinker, flowability, rheology, SCM, LC³, concrete, water demand, particle size distribution.

SAMMANFATTNING

Med den ökande befolkningen i hela världen, ökar byggande av nya konstruktioner och ny infrastruktur för att möta samhällets behov. Samtidigt har diskussioner kring ämnet hållbar utveckling och oron kring utsläpp av växthusgaser som tilldelas byggmaterialproduktion varit ett stort fokus. Byggindustrin i Sverige står för stor del av CO₂-utsläppen, den största koldioxiden tilldelas de använda byggmaterialen, främst på grund av deras produktionsprocess (Boverket, 2021).

De viktigaste konstruktionsmaterialen för byggbranschen är betong, timmer och stål. Betong har använts i byggbranschen under lång tid på grund av dess många goda egenskaper. Det moderna samhället kräver byggnationer som till stor del är otänkbara utan utbredd användning av betong. Betongen möjliggör komplicerade konstruktioner på annars svårtillgängliga platser samt till en låg kostnad. Även om det till viss del är möjligt att använda andra vanliga byggnadsmaterial, såsom timmer eller stål, kvarstår behovet av betong då imponerande konstruerade broar och dammar, arkitektoniskt innovativa skyskrapor, vägar och järnvägar, samt väldiga höghus, ofta inte kan byggas utan betong. Cement som en av huvudbeståndsdelarna i betong är den tredje största källan till utsläpp av koldioxid i Sverige och står för cirka 8% av de globala utsläppen i världen (Andrew, 2018).

Användning av industriavfall som flygaska från kolförbränning eller mald granulerad masugnsslagg som cementersättningsmaterial för tillverkning av betong med lägre cementklinkerinnehåll har varit en lösning för att minska klimatpåverkan, men förväntad lägre tillgänglighet av dessa material inom en snar framtid är särskilt ett hinder. Detta har väckt stor uppmärksamhet åt naturresurser som leror för att övervägas som framtida alternativa cementersättningar. Industriell tillämpning av dessa nya alternativa bindemedel är dock fortfarande beroende av ytterligare forskning, främst när det gäller prestanda och hållbarhet hos dessa nya konstruerade bindemedel. Syftet är därför att demonstrera potentialen hos aktiverade leror som en klinkersättning (framtida gröna bindemedel) för att minska utsläppen av växthusgaser och miljöpåverkan vid uppförande av infrastrukturbyggnader av betong. Detta projekt utförts för att studera färskas egenskaper hos aktiverad lera innehållande betong. I detta sammanhang undersöks vattenbehovet och följaktligen effekten av att använda tillsatsmedel på bearbetbarheten av lerblandade cement. Två sorters leror från olika geografiska platser i Sverige har studerats i detta projekt för deras reologiska beteende som en potentiell framtida SCM.

Resultaten visade att lerans flygegenskaper påverkades av lerornas partikelstorleksfördelning och lerans tillstånd (inaktiverad eller aktiverad). Det upptäckte också att SP-kravet varierade med lerornas vattenbehov. Två typer av PCE-supermjukgörare studerades och det visade sig att en typ av tillsatsmedel spred lerpartiklarna under längre tid medan den andra observerades fördröja bearbetbarheten utöver en viss varaktighet. Slutligen observerades att kalcinerade leror inte krävde supermjukgörare för partikelseparering eller för att uppnå en målflödesspridning.

Nyckelord: Aktiverad lera, flyttillsatsmedel, Portlandcement, klinker, flytbarhet, reologi, SCM, LC³, betong, vattenbehov, partikelstorleksfördelning.

PREFACE

This thesis presents my work on the topic Flow properties of green cementitious binders: influence of superplasticizer on flowability of clay containing cementitious binders. The degree project was carried out at Chalmers University of Technology, in the department of architecture and civil engineering.

I chose this subject because I was eager to understand how we can make concrete a more sustainable building material. At a time when Sweden faces an acute cement crisis that has been ongoing for a while, I wanted to contribute to finding sustainable alternatives that could help the construction sector. From my education and through the course of this thesis work, I learned that using locally available building materials presents a valuable opportunity for a more sustainable building environment. This project is an experimental work, conducted with help and guidance from my supervision team as well with help of the previous literature work regarding this subject.

For his support through this journey, I want to thank my examiner Professor Luping Tang. I extend special thanks to both of my supervisors Arezou Babaahmadi and Amrita Hazarika. They were a supportive team from the beginning of my project until it was done. Their motivation and passion in their work, motivated me at every step and inspired me to come up with my own ideas to conduct my work in the best way.

At the end I want to thank my husband Shaho and my daughter Yaran, who were so patient and helpful during the whole time of my education.

Hanar Ali

Gothenburg, Maj 2022

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ABBREVIATIONS

DLS	Dynamic Light Scattering
ICP	Inductively Coupled Plasma
LC ³	Limestone calcined clay cement
NK	Norrköping clay
NKOPC	Norrköping substituted with Portland cement
NKSP	Norrköping clay with Superplasticizer
NKOPCSP	Norrköping substituted with ordinary Portland cement and Superplasticizer
NKC	Norrköping calcined clay
OPC	Ordinary Portland cement
PSD	Particle size distribution
PCE	Polycarboxylate ether
SCM	Supplementary cementitious material
SP	Superplasticizer
SK	Skåne clay
SKC	Skåne calcined clay
SKSP	Skåne clay with superplasticizer
SKOPC	Skåne clay substitute with ordinary Portland cement

1

INTRODUCTION

1.1. BACKGROUND

Concrete is the most widely used construction material in the world. It is used to build bridges, tunnels, roads, railways, houses, and buildings. Concrete is strong, cheap, easy to use and handle, it can be used as a prefabricated or as cast on-site. In general constructions that are built with concrete lasts long and do not need much maintenance, which has a benefit gain minimizing the cost for reparation and maintenance. Compared to the other types of building materials, concrete is a better and safer choice as it is moisture resistant and does not rot. Concrete is fire resistant and sound absorbing, which helps to create suitable living environments. It is also possible to recycle and reuse concrete to reduce environmental impact and achieve an economic benefit (Al-Emrani et al., 2019).

Timber is the other well-known building material. Timber is considered a very desirable construction material and has been used for many years in building industry. It is easy to use and transport, a natural resource, renewable, with a low environment footprint and energy consumption assigned to its production compared to concrete. Nevertheless, timber has also a disadvantage side, which is susceptible to fire, water damage and very sensitive for mold growth when in contact with moistures. These issues compromise the quality of the construction (Al-Emrani et al., 2019). In the constructions sector however, timber has a reputation and is considered a key construction material thanks to its low environmental impact. This should however be noted that if timber would be used in the volumes that concrete is used today, the result will also exhibit a high total global environmental footprint (Hart and Pomponi, 2020). Moreover, the life cycle assessment analysis of timber production, if taking into consideration the release of its adsorbed CO₂ to the environment, which is currently neglected, would have estimated different environmental performance for timber (Hart and Pomponi, 2020). Furthermore, the availability of timber and production volume potentials is not only a concern in construction sector, but wood is also considered a raw material for production of biomass power generation, biofuels for transport and bioplastics in an attempt towards replacing petroleum from the products with biogenic equivalent. The increase demands for timber require planting more trees and this would require land. Moreover, overexaggerated mining of trees can lead to loss of biodiversity and a negative impact on the soil (Hart & Pomponi, 2020).

This is therefore important to remember that all the construction materials have pros and cons even with respect to the environmental effects. In accordance with Hållbarbyggnade (2018)

the focus should change from an absolute replacement of concrete with timber towards finding solutions to improve sustainability of concrete instead as well as, combining different types of building materials together in every project to benefit from all the positive effects while minimizing the needed volumes of each material to create a better functionality with respect to performance, service life and environmental footprint.

To be able to improve sustainability of concrete, it is important to get familiar with the reason behind its environmental effects. Concrete contains cement, water, and aggregates (gravel, sand and stone) with some additives to affect concrete properties (Burström and Nilver, 2018). Cement is a key component in concrete, because when cement mixed with water it gets hardened and glues the aggregates together. But cement as one of the main constituents of concrete is also the third largest source of anthropogenic emissions of carbon dioxide, accounting for approximately 8% of global emissions in the world (Yu et al., 2021).

The production of cement is a complex process that starts with quarrying of limestone and then mixed carefully with clay or shale in the roller mill to get particles smaller than 90 μ m. Then heating the raw ground material is the next step, with the mixture heated to 1450 °C in a rotary kiln. The chemical reaction occurs between raw materials, which turns them into a new compound called clinker. The clinker is cooled about 60 °C, then its ground with small quantity (3-5%) of gypsum to prevent quick hardening of cement (Soutsos and Domone, 2017). Emissions of carbon dioxide is mainly due to the CO₂ released during the calcination of limestone. The emitted CO₂ amounts in this stage is responsible for almost 60% of the total CO₂ attributed to manufacturing cement (Schmid and Plank, 2020).

Cement production and its impact on the environment is an ongoing debate in Sweden since a long time ago. This is as a result of the fact that limestone is not only responsible for CO₂ emissions when calcined, but even quarrying limestone influences the ground water in Silte, Gotland. when limestone is extracted, the ancient waterways in the bedrock are damaged and it results to lowering the ground water in the area (Aftonbladet, 2020). Cementa which is the only cement production company in the region and responsible for approximately 60% of cement production in Sweden, has permission to extract limestone accessible until the end of December 2022 (Byggnadsarbetaren, 2021). This has caused even new concerns recently in construction sector for seeking alternative cementitious materials not only due to CO₂ emissions but also scarcity of limestone for production of cement. A well-known strategy towards improving concretes sustainability, is substitution of cement clinker in concrete with Supplementary Cementitious Materials (SCM's). It is well established that lower CO₂ footprints can be achieved if part of the Portland cement in concrete is replaced with suitable SCM's in right proportions (Nair et al., 2020).

The most known SCMs are coal combustion fly ash and grand granulated blast furnace slag.

Slag is obtained during the production of steel in a blast furnace and can be used as a replacement material in concrete instead of clinker. Slag can replace clinker up to 60% with has a good impact on concrete properties as a fresh and harden states (Yuksel, 2018). The availability of the material worldwide is an issue, because it is available for only about 5-10% of the amount of cement produced. However, the amounts of slag may decrease even more with recycling of steel in building industry (Scrivener et al., 2018).

Fly ash is produced in coal combustion powerplants and it is suitable to use in concrete as a replacement of clinker, but the amount of cement that can be substituted with fly ash is limited, due to the effects on concrete's properties and quality. Cement can be substituted up to 30-40% with fly ash while an acceptable workability and early compressive strength in concrete is obtained (Nair et al., 2020). Even though fly ash can be used as a replacement in concrete to reduce impact on climate change, but there is only 30% of fly ash available compared to cement needs and the available volumes are decreasing dramatically with time, since the source of producing fly ash is a threat on environment itself (Scrivener et al., 2018).

Consequently, scarcity of the most common SCMs soon has created new concerns. Therefore, seeking to find alternative SCMs, calcined clays are introduced to the construction sector in the last decade as the new generation of SCMs (Justnes & Ostnor, 2015).

1.2. CALCINED CLAYS

Clay is a natural resource available as an abundant material in most of the countries. Clay has an ability to get activated and act as a pozzolanic material when treated with heat or in another word calcined (Samet et al., 2007). This is due to the changes encountered in its structure after heat treatment. The right temperature to activate calcined clay is between 600 to 800 °C (Samet et al., 2007). The processes of calcining the clays are rather simple and required lower energy compared to the processes of the heating clinker in cement that need to heat up to 1450 °C. The reactivity of calcined clay depends on the type of clay and the total content of kaolinite in clay, this is because kaolinite is found to be the most reactive clay mineral (Scrivener et al., 2018). Ordinary Portland cement (OPC) can be reduced by using calcined clay with limestone. The binder in which the calcined clay is mixed with limestone in proportions of 30% clay and 15% limestone aiming to replace 50% of clinker known as Limestone Calcined Clay Cement (LC³). This binder is found to be one of the most efficient binder mixes (Yu et al., 2021). This should also be noted that limestone is already a raw material in cement production but needs to be calcined, however in the context of LC³ binders, no heat treatment is required, and therefore no further environmental impact is associated with this material (Dhandapani et al., 2018).

Consequently, LC³ has a lower environmental impact and material cost per unit strength, which is why it is referred to as the solution towards climate crisis in the construction industry (Yu et al., 2021). According to Scrivener (2018) despite the same mechanical properties of LC³ as ordinary Portland cement (OPC), LC³ also helps to lower the carbon dioxide emission with 30% in building industry. This is even though production of calcined clay costs eventually more than materials such as fly ash and slags because it needs to be calcined to gain the potential of being used as supplementary cementitious material (Diaz et al., 2017).

A point of importance in all research categories in this topic is that the clays mineralogy plays a huge role in dividing the clays into several classification in terms of their pozzolanic potential, temperatures required for their activation and eventually their hydration and durability related properties. Consequently, the weight of available research for clays of kaolinitic origin, which are proven to exhibit highest pozzolanic potential is considerably higher than illite or Smectite clays (Fernandez et al., 2011). This matter gets even more complicated when mixed layer clays are in focus. Although this topic is investigated by few researchers, there is still a gap of knowledge when natural mixed-layer clays are in focus.

Most clays found in Sweden or around the world are mixed layer clays containing minerals such as illite, smectite, and sometimes chlorite, in addition to kaolinite. So, to apply these naturally available clays in the construction sector, it is important to study the behaviour of mixed layer clays (Plusquellec et al., 2020).

1.3. HYDRATION OF CEMENTITIOUS MATERIALS

Water is one of the raw materials in concrete which when in contact with cement reacts and gets hardened binding aggregates in concrete together. The chemical reaction that happens when cement and water mixed is called hydration. The service functions of concrete like the strength and durability, are governed by the progress and efficiency of the hydration reaction. The products formed after cement and water reacts are called hydration products. These products impart different properties to the hardened concrete. The most important ingredient for an efficient hydration process is water (Burström and Nilver, 2018). However, the water cannot add too much as then the strength is lowered. Too little water will also negatively affect the hydration as all cement particles will not be hydrated and the required strength cannot obtain later. So, the amount of water that is added, must be correct and is a crucial factor to remember (Burström and Nilver, 2018).

Cement and water are used as per their ratio called cement- water ratio (w/c), that has important impact on concretes properties. The regular w/c ratio is (0.4-0.5) for ordinary Portland cement concrete (OPC), but this ratio can change depending on the requirement of the binder. For instance, for high strength buildings, we can use high strength concrete that is made with very low w/c. The quality of water should be tested very carefully because it effects concretes durability and strength (Burström and Nilver, 2018). According to the Nikhil et al. (2014) potable water is suitable to use to the process, because of the balance value of ph. Increasing pH value of water decreases the strength of concrete, because high pH value deteriorates calcium silicate hydrate (C-S-H) which is responsible of strength of concrete. Water demand changes in the process of replacing clinker with calcined clay. The internal porosity of calcined clay requires more water than the regular Portland cement, which in turn affects workability and performance of the concrete (Yu et al., 2021). That is why it is important to consider the water demand of clays and evaluate the water-binder ratio when we have clays as binder.

1.4. FRESH PROPERTIES OF CEMENTITIOUS MATERIALS

Concrete properties are categorized in fresh and hardened state. The quality of the concrete in its hardened state can to a large extent depend on the fresh properties such as viscosity and yield stress. This is mainly because availability of water in the system not only affects hydration and consequently hardened properties, but it also affects fresh properties or in another word workability of cementitious materials (Muzenda et al., 2020).

The mixture proportions and the materials' characteristics in terms of particle size distribution, specific surface area as well as water demand have the main impact on the result of rheological properties (Feys et al., 2017).

Rheological properties are a necessary process to understand and control the fresh properties of cementitious materials, which in turn helps to obtain the successful behavior of concrete. In

general, balancing the rheological properties of concrete can help to resolve the segregation, minimizing pumping pressure and producing a good surface finish in concrete (Muzenda et al., 2020).

When it comes to calcined clay as a SCMs in concrete, this modification should fulfil the rheological performance of cement, so the performance of concrete is intact. As noted by Muzenda et al. (2020) clay that contain metakaolin increases the yield stress and viscosity of the cement paste, hence this material affects the paste and create a powerful interconnected network.

Using chemical admixtures such as superplasticizers have shown to enhance the workability challenges in calcined clay containing binders (Schmid and Plank, 2020). The main aim of using superplasticizers is to increase the plastic properties of the concrete mixture and its spread ability without changing the w/c ratio (Lei et al., 2022). The efficiency of the blended cement can be increased as well by using the superplasticizer as the dispersion will be enhanced (Schmid and Plank, 2020).

Several types of superplasticizers are available, and every kind has some purpose when it's used in concrete. Superplasticizer used sometimes to increase service life by making durable concrete, because less water is needed in concrete and in result concrete is going to have low porosity and low permeability (Flatt, 2012). However, in the context of calcined clay containing cementitious materials, superplasticizers are almost always needed as clays have high absorption of water. PCE based superplasticizers are suggested in literature as being most compatible with clay-based binders (Schmid and Plank, 2020). According to Sposito et al. (2022) with increasing calcined clay as a replacement of the Portland cement the amount of the PCE probably increase as well, while the PCE dosages requirement in only pure Portland cement is less in general compared to calcined clay. The demand for superplasticizers is therefore an important area of study while checking the rheological behavior of clay blended binders.

1.5. AIM AND OBJECTIVES

This project aims to study the fresh state properties of two types of clays obtained from two different regions of Sweden. Rheological behavior through flow tests and particle size effect of these clays have been aimed to be evaluated. Additionally, it is aimed to screen available admixtures (superplasticizers) in terms of type and required quantity to tackle the challenges encountered with workability of calcined clay containing binders.

The primary objectives in this project are:

1. To account for water demand of calcined and uncalcined mixed layer clays naturally available in Sweden.
2. To account for the correlation of grinding-particle size distribution and water demand of clays as well as the effectivity of superplasticizers in this context.
3. To investigate and screen the effect of different available types of superplasticizers on workability of calcined clay containing binders.

1.6. LAYOUT OF THE THESIS

The composition of the report is as follows. Chapter 1 introduces the topic and presents the objective of the project. Chapter 2 presents the materials and experimental methodology followed in the project. Chapter 3 presents the results, followed by the discussion on Chapter 4. Chapter 5 summarizes the main findings in the topic and concludes the project. Below is an illustration of the thesis layout.

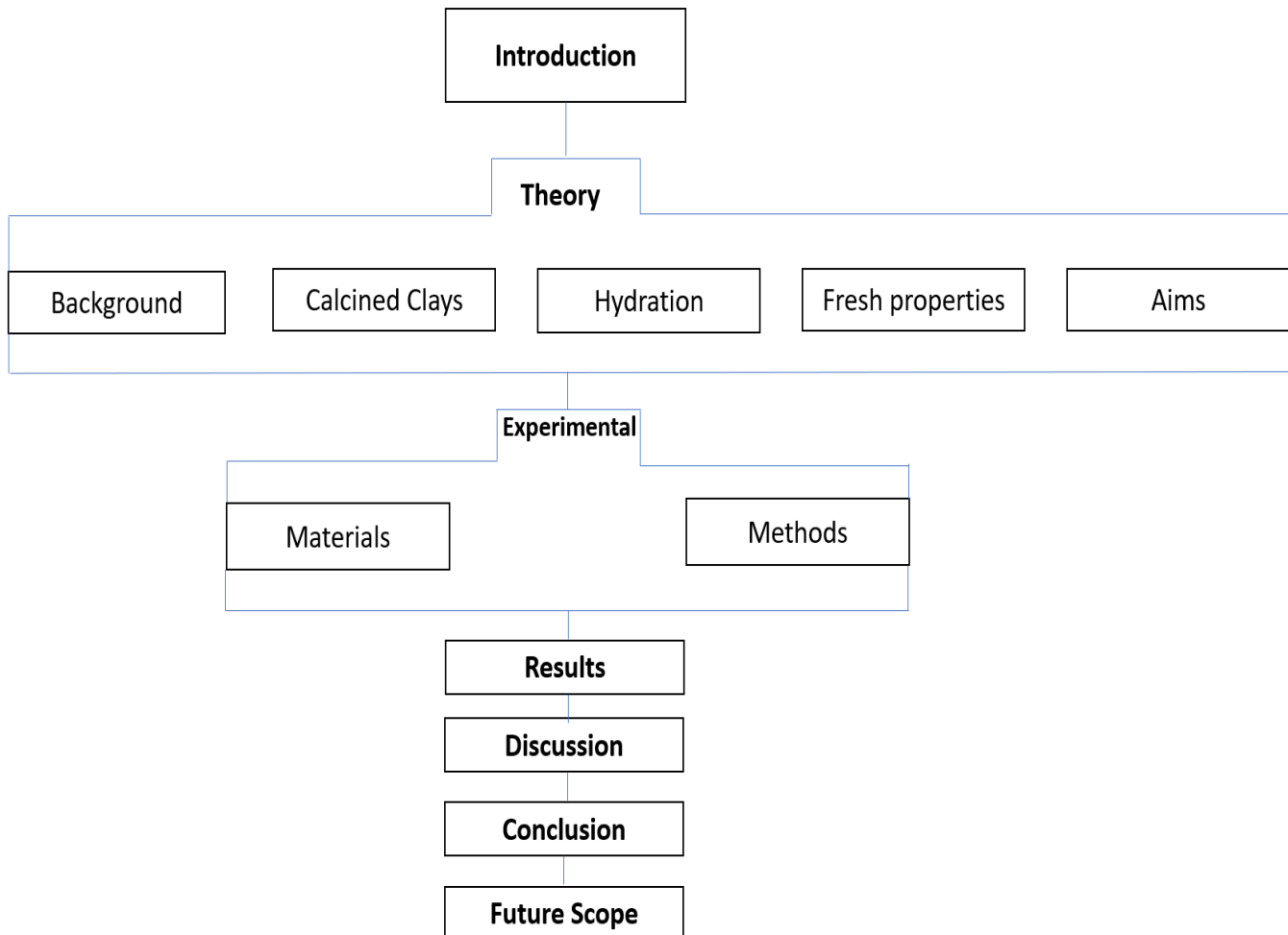


Figure 1: *Flowchart of thesis*

2

MATERIALS AND METHODS

This chapter presents the materials and experimental methods employed to investigate the three goals of the project. This chapter is divided into two parts – the first discusses the clays and their properties. The second part emphasizes on the pre-treatment of clays, their particle size distribution in raw and calcined states, and the rheological tests conducted.

2.1. Materials

The clays that have been used in this experiment are from the regions of Norrköping and Skåne. Norrköping is a city in the province of Östergötland in eastern Sweden and Skåne is a province in the southern tip of Sweden as highlighted in red on the map (Figure 2). From a preliminary XRD study it is found that both clays contain kaolinite, illite and smectite as seen from Figure 3. The Norrköping clay is a marine deposited clay and mostly contains illite and smectite while illite and kaolinite are governing minerals in the clay from Skåne which is a sedimentary type of clay (Plusquellec et al., 2020).

The mineral oxides contained in the two clays are shown in this table 1 where the summation of the major oxides $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ are above 70% wt. which is a necessary criterion to be considered as a natural pozzolan, according to ASTM C 618. The oxide composition is accounted for through ICP (Inductively Coupled Plasma) of the clays conducted by ALS, Global, Piteå. This measurement is a basic step for characterization of clays.

An ordinary Portland cement with 52.5 R from Cementsa is used in this experience as the reference cement.

PCE based Superplasticizers provided by Sika were used as shown in Figure 5. The products are not yet commercially available and were provided to this project for better testing and optimization.



Figure 2: Map of Sweden with the provinces of Östergötland and Skåne highlighted. The 2 clays studied in this project were obtained from these 2 regions.

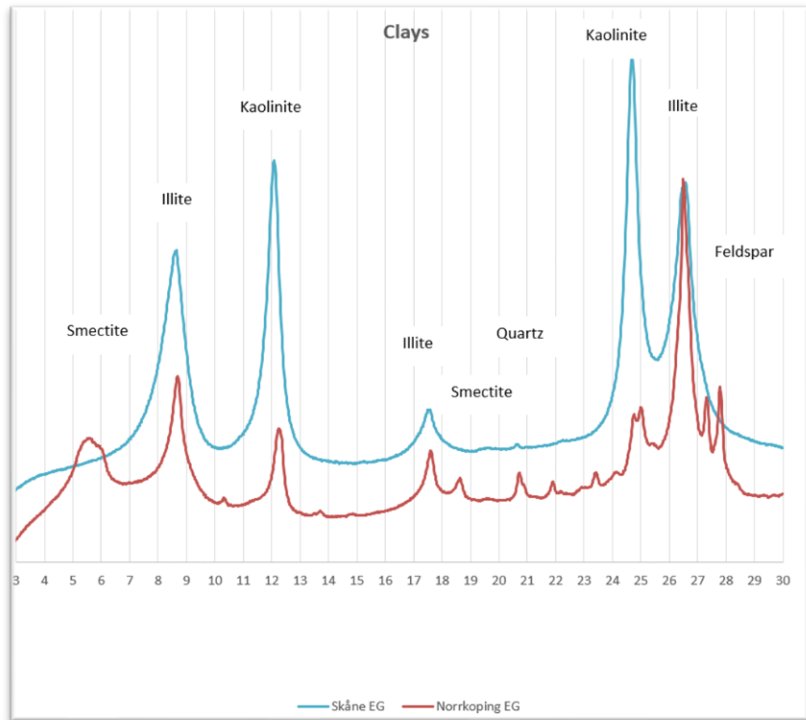


Figure 3: Mineral composition of Skåne and Norrköping clays.

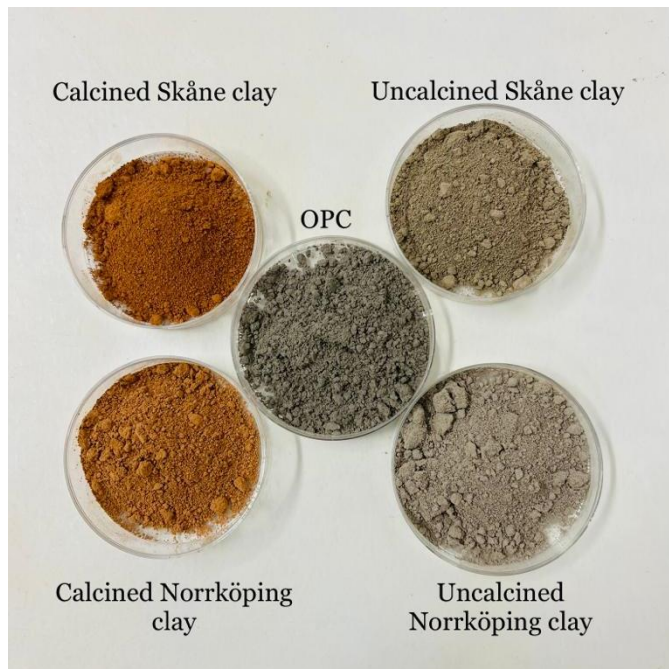


Figure 4: All binders used in the project



Figure 5: PCE type superplasticizers

Table 1: Oxide compositions of the binder material used in the project.

	CEM 1 52.5 R	Clay 1	Clay 2
<i>Origin</i>	<i>Cementa</i>	<i>Norrköping</i>	<i>Skåne</i>
Oxides			
SiO ₂ (wt%)	19.6	51.8	50.5
Al ₂ O ₃ (wt%)	4.5	18.35	15.55
Fe ₂ O ₃ (wt%)	3	9.55	6.7
CaO (wt%)	62.2	1.32	6.62
MgO (wt%)	3.5	3.34	2.63
Na ₂ O (wt%)	0.27	1.7	1.36
K ₂ O (wt%)	1.01	4.42	3.85
TiO ₂ (wt%)	-	0.87	0.77
P ₂ O ₅ (wt%)	-	0.15	0.17
MnO (wt%)	-	0.11	0.09
LOI (wt%)	2.5	8.15	11.2

2.2. Methods

2.2.1. Sample preparation: drying, grinding, calcining of clays

Drying: The preparation of clays starts, first with the pretreatment of the clay before it is mixed with other materials. Clays are initially dried in an oven (LabRum klimat Ab) at 80 °C until it reaches constant mass change. This process usually takes 48 hours. Before the drying, the clays were in a clumpy state, as shown in Figures 6 (a,b) which was difficult to separate. This could create uneven drying. Therefore, in between the drying session (after 24hours), as the clay dried partially, they were taken out of the oven and crushed into smaller bits (> 4 mm) manually with help of hammer, or mechanically with a jaw crusher (Retsch). Thereafter, they were put in the oven for the second time to get homogenously dried as shown in the Figure 7 (a,b).

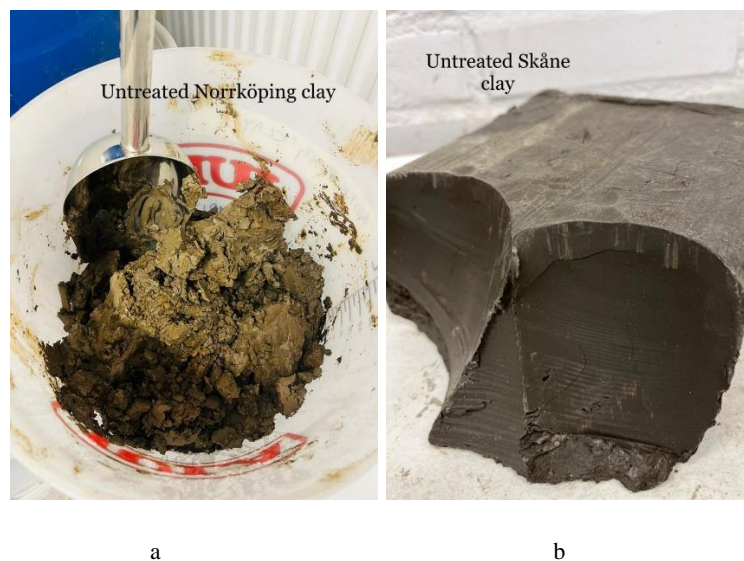


Figure 6: Untreated clays from Norrköping and Skåne

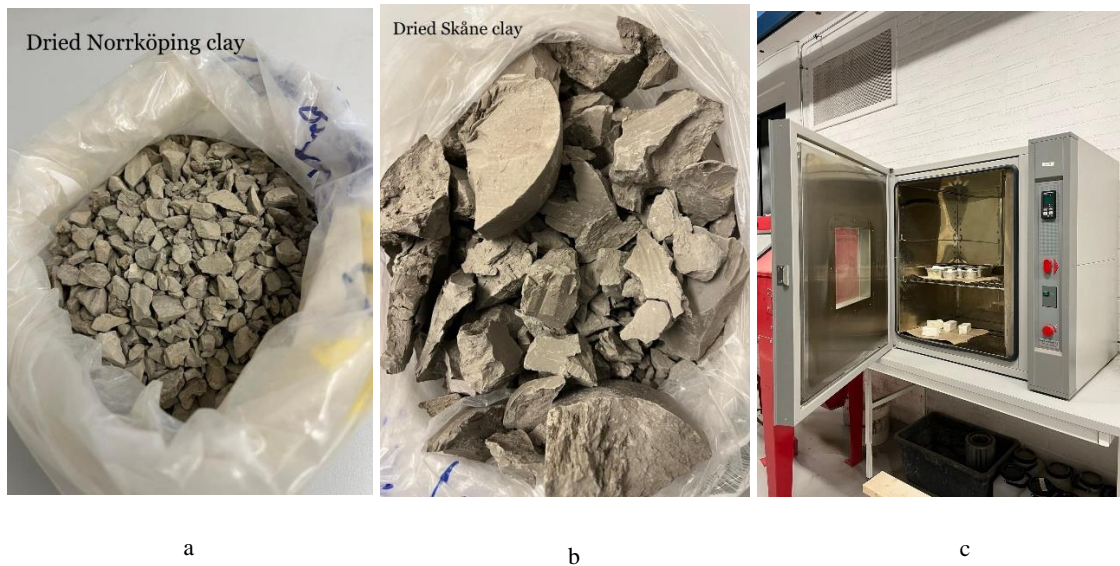


Figure 7: Dried Norrköping and Skåne clays, and the oven used for drying

Grinding: After the drying, clay was ground with jaw crusher (Retch) to particle sizes below 0.5 mm. They were then ground with a knife mill (Retsch GM 200) at 7000 rpm for 6 minutes as shown in the Figures (8 and 9). This was done to get finer clay particles for the subsequent sieving operation. The purpose of first crushing the dried clay before it was fed to a more intensive grinding in the knife mill, was to obtain a homogenous particle size distribution to be fed into the knife mill. If the mix going into the knife mill is too heterogenous in terms of particle size, coarser particles remain concentrated in the coarse fraction while finer ones become much finer. This has been seen to have negative effect on workability (Scrivener et al., 2018).



Figure 8: Knife Mill



Figure 9: Jaw crusher



Figure 10: Furnace



Figure 11: *Ground Norrköping and Skåne clays*

The clay was ground in batches of 240 g so that the ground yield is homogenous every time. The ground clay is shown in Figure 11. The clay was then sieved to obtain clay particles smaller than 0.075 mm (75 microns) for the experiments. Particles below 75 microns are called microfine and their addition in concrete can affect properties like workability, strength, and durability (Norvell et al., 2007).

Calcining: Then the dry material is fed into the furnace (Nabertherm) with the temperature 800 °C for one hour as shown in Figure 10 to activate clay. Figure 12 shows the calcined clays

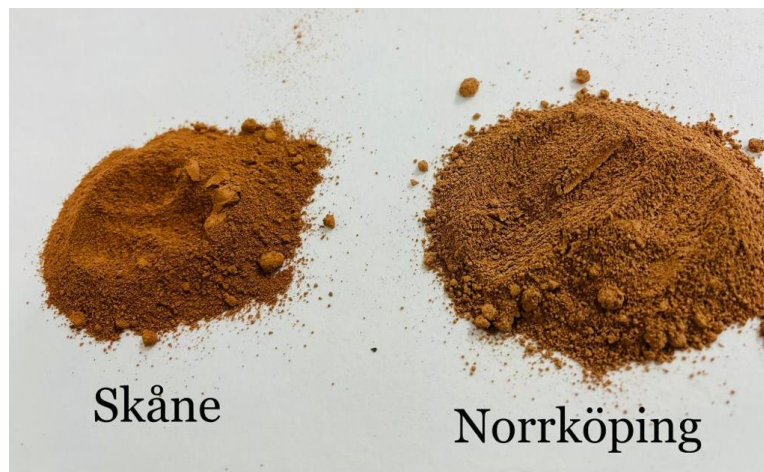


Figure 12: *Calcined Norrköping and Skåne clays*

2.2.2. Gradation of clay particles

To determine raw clay particle size distribution, sieving was conducted with sieve sizes: 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.075 mm (Figure 13). This was done on a laboratory sieve shaker (Pascal engineering) with sieve diameter of 30 cm. Sieving was conducted for 5 mins with 240 g of material each time. The process starts with pouring the sample of the dry raw clay into the top of sieve, the size of the sieve needs to assemble in order of decreasing size of opening from top to bottom.

The purpose of sieving is to grade the clay particles into separate sizes and to have a better control on the particle sizes being used for the tests. For the test of flowability, the particles passing sieve size of 0.075 mm were considered, as they represent the finest size in the clay mix.



Figure 13: Sieves with clay in a shaker

Note: The sieves included the size (4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.075 mm, and the pan). The shaker saved in one close place to reduce the out of the sound when the machine in function.

2.2.3. Particle size distribution (PSD)

The cement properties including the water demand of the paste and the rheology of concrete get affected by the PSD, which depends on the process of grinding and preparations of the material (Perez et al., 2015).

2.2.3.1. Procedure for DLS:

Dynamic Light Scattering (DLS) was used to account for the distribution of particle sizes of clays. conduct the tests. The particle diameter that is measured and shown by DLS is called hydrodynamic diameter (Bianchi et al., 2011).

The Only particles passing the smallest sieve (0.075 mm) was used to be tested as the flow tests were conducted using this size. The steps followed for DLS particle size distribution are as follows:

Step 1: mix 0.1 g of clay in 10 ml water

Step 2: store the solutions for 24 hours

Step 3: Sonicate the solutions for 30 minutes with a sonicator (*Sonorex Mandelin TK52*)

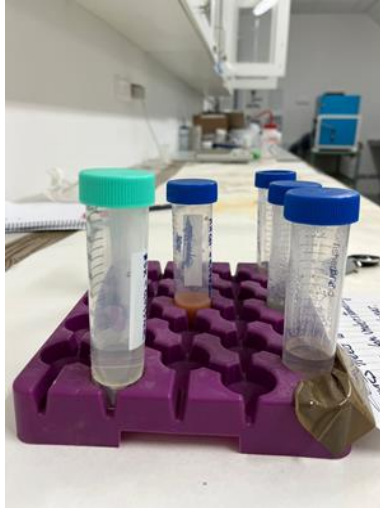
Step 4: Allow sonicated solutions to settle for 30 minutes. These calculation times were obtained from Stoke's law as explained in (Plusquellec et al., 2020)

Step 5: Pipette out 1 ml from the top 3 mm part of the settled solution and fill into the DLS cuvette

Step 6: Conduct DLS measurements (*Litesizer 500, Anton Paar*), which takes 10 minutes as shown in Figure 14.



a: Preparation of suspensions



b: Storing of suspensions



c: Sonication of suspension



d: Settling of sonicated suspension



e: Pipetting 1 ml solution from top 3 mm



f: Filling in cuvette with solution



g: Putting in cuvette in DLS machine



h: Analysing the DLS machine

Figure 14 (a-h): DLS measurement steps

2.2.4. Water demand of clays

It is known that when clays are used in concrete, they have the potential to absorb water and swell (Norvell et al., 2007). This increases the water demand of the clay blended concrete mixes, causing reduction of strength and increase in drying shrinkage (Buth et al., 1966). It is therefore crucial to study the water demand to estimate the potential need for water-reducing agents like superplasticizers in the clay-based mixes.

In this project, the water demand of the 2 types of clays from Norrköping and Skåne was examined. The flow diameter of 100% OPC paste with water cement ratio 1, is taken as the reference consistency. The water demand of 50% and 100% clay substituted pastes were studied, considering both raw and activated states of these clays. Table 2 shows the mixes used in the study and the proportions of the ingredients. The mix designs used have the following variables:

- I. Type of clay: Norrköping or Skåne
- II. Calcined or uncalcined clay
- III. Presence of OPC

Table 2: *Mix designs for the water demand test*

Mix design	Activated clay	Norrköping	Skåne	OPC
1. OPC100 (reference)	-	-	-	100%
2. NK100	-	100%	-	-
3. NKOPC50	-	50%	-	50%
4. NKC100	Yes	100%	-	-
5. NKCOPC50	Yes	50%	-	50%
6. SK100	-	-	100%	-
7. SKOPC50	-	-	50%	50%
8. SKC100	Yes	-	100%	-
9. SKCOPC50	Yes	-	50%	50%

2.2.4.1. Procedure of volume calculation: The first step of the process starts with deciding the volume of a mini cone (height 5.5 cm, bottom diameter 4 cm and top diameter 2 cm), which has been used to test the flowability's of the material as shown in Figure 15. The volume of the cone is calculated with the following formula for a truncated cone:

$V = \frac{1}{3} \pi h (r_1^2 + r_2^2 + (r_1 \times r_2))$, where V is the volume of cone, h is the height of the cone, r_1 and r_2 are the top and bottom open diameters of the mini cone respectively.

Putting the values of h , r_1 , and r_2 , we get

Volume of cone (V) = 40.3 cm³

Density of clay (ρ_{clay}) = 1.6 g/cm³

Density of cement (ρ_{cement}) = 3.08 g/cm³

Density of binder with 50% of cement and 50% clay:

$(\rho_{\text{binder}}) = (\rho_{\text{clay}} \times 0.5) + (\rho_{\text{cement}} \times 0.5) = 2.34$

Water binder ratio used in study = 1

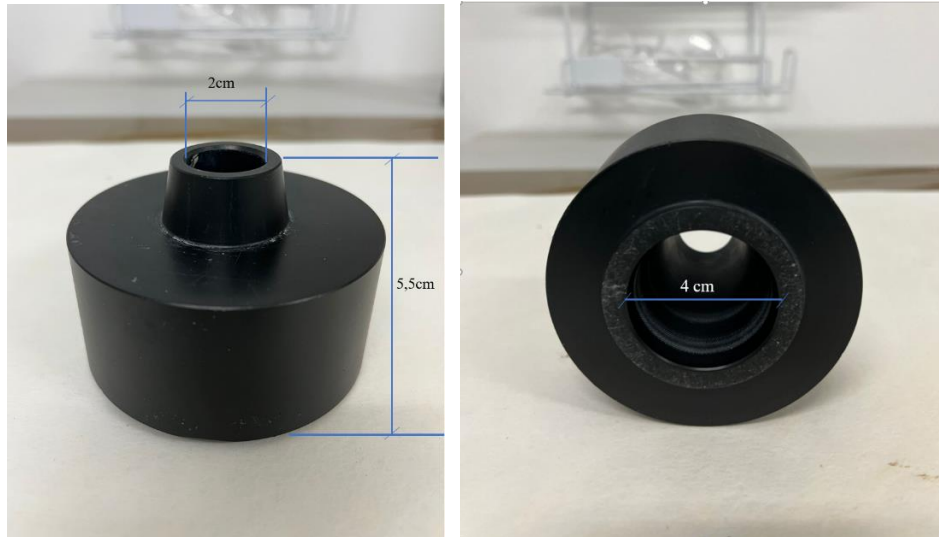
Volume fraction of 1 constituent in binder paste = $\frac{40.3}{1+1} = 20.15$

Amount of binder = $\rho_{\text{binder}} \times 20.15 = 47.15$ g

Amount of water = 1 x amount of binder = 47.15 g

Amount of binder and water when binder consists of 100% cement = $\rho_{\text{cement}} \times 20.15 = 62.06$ g

Amount of binder and water when binder consists of 100% clay = $\rho_{\text{clay}} \times 20.15 = 32.24$ g



a: Mini cone dimensions of height and top diameter

b: Mini cone dimensions of bottom diameter

Figure 15: *Mini cone used for the slump tests*

2.2.4.2. Procedure of flow test for water demand:

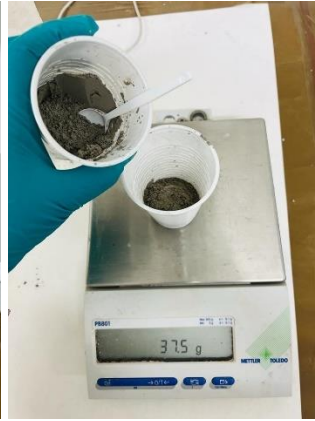
The water demand tests were conducted in the following steps:

1. Different water binder ratios were prepared for the mix designs
2. The mini cone is placed upright on a levelled, smooth surface.
3. The mixes with the new water binder ratios were then filled in the mini cone till the top.
4. The filled cone was tapped on the side with a spoon to ensure that the mix inside is compact. More paste was filled if there is empty volume inside the cone.
5. Once filled, the cone is lifted up at one swift motion, to let the paste fall in a circular pattern.
6. Thereafter, the diameter of the paste spread is measured with a ruler and noted.

In this experiment, the required grams of the raw clay and water were mixed. The paste was blended with spoon approximately for two minutes in the plastic cup until the mix was homogeneous. Then the paste was then poured into the flow cone and placed on a clean and smooth surface, the cone was then removed vertically, and the diameter of the flow was measured with a ruler. If the flow diameter did not match the reference flow measured with OPC paste, the process is repeated with a higher water binder ratio till required flowability was obtained. The same procedure was repeated for clay-cement binders, to understand and show the difference in the flow properties of the clay-cement binder with the same water to binder ratio compared to pure clay or cement mixes. The steps are illustrated through photos as follows.



a: Proportion the binder



b: Weigh the binder



c: Weigh the water



d: Add water in binder



e: Mix paste



f: Prepare cone and rulers



g: Fill cone with paste



h: Tap side of cone to help settle the paste



i: Vertically lift the cone and let the paste fall in a circle

Figure 16 (a-i): Steps for measuring water demand

2.2.5. Flow properties and the effect of superplasticizer

The effects of superplasticizer on flowability were investigated for clays both in uncalcined and calcined status. Superplasticizer needed to use to get 18 cm of flow spread for 100% of the clays and as well when 50% of clay blended with cement was accounted for. The 18 cm of spread was the accounted for as the target flow as it was obtained when the flowability of 100% ordinary Portland cement was measured.

The process of testing the flowability of the material that required superplasticizer started with the calculation of the percentage of PCE that needed to be used with the same water to binder ratio for the following mixes shown in Table 3.

Table 3: *Mix designs for studying the SP demand*

Mix design	Activated clay	Norrköping	Skåne	OPC
1. NK100SP	-	100%	-	-
2. NKOPC50SP	-	50%	-	50%
3. NKC100SP	Yes	100%	-	-
4. NKCOPC50SP	Yes	50%	-	50%
5. SK100SP	-	-	100%	-
6. SKOPC50SP	-	-	50%	50%
7. SKC100SP	Yes	-	100%	-
8. SKCOPC50SP	Yes	-	50%	50%

These mixes were taken after the results observed during the water demand test, where it was observed that certain mixes did not require SP. So only the ones that had a high-water demand and required some SP, were considered. Like the water demand test, the required amount of binder was mixed with water at binder ratio 1 in addition of superplasticizer. The superplasticizer was added in varying dosages as required. The binder with superplasticizer was blended carefully for 2 minutes and the flowability was measured with the help of the mini cone. This test was repeated until the dosage of superplasticizer to get 18 cm of flowability was achieved. The additional steps required to measure SP demand are shown in Figure 17 as follows:



a: Pipette out SP

b: Add in the required amount

Figure 17 (a, b): *Addition of SP in paste*

3

RESULTS

This chapter presents the results observed during the experimental investigations outlined in the last chapter. The results are presented chronologically as observed during the tests.

3.1. Grading of clay particles

The result of gradation process was calculated by using cumulative method. After sieving the material in the shaker as mentioned before the percent of mass retained on each sieve is calculated by $(\text{mass on each sieve}/\text{total mass}) \times 100$. Then the cumulative mass retained was calculated by adding percent mass retained on each sieve with the one above itself. Finally, to get the passing percent, subtracting 100 with cumulative percent of retained amounts on each sieve. The results of gradation calculation are presented in table 4 and Figure18.

Table 4: *Sieve analyses of clay particles*

Sieve sizes (mm)	Mass retained (g)	% Of mass retain on each sieve	Cumulative % retained	% Passing
4	0.5	0.21	0.21	99.79
2	0.1	0.04	0.25	99.75
1	0.2	0.08	0.33	99.67
0.500	0.5	0.21	0.54	99.46
0.250	6	2.5	3.04	96.96
0.125	142	59.1	62.1	37.9
0.075	68	28.3	90.4	9.0
Pan	23	9.6	100	0
Total	240.3	-	-	-

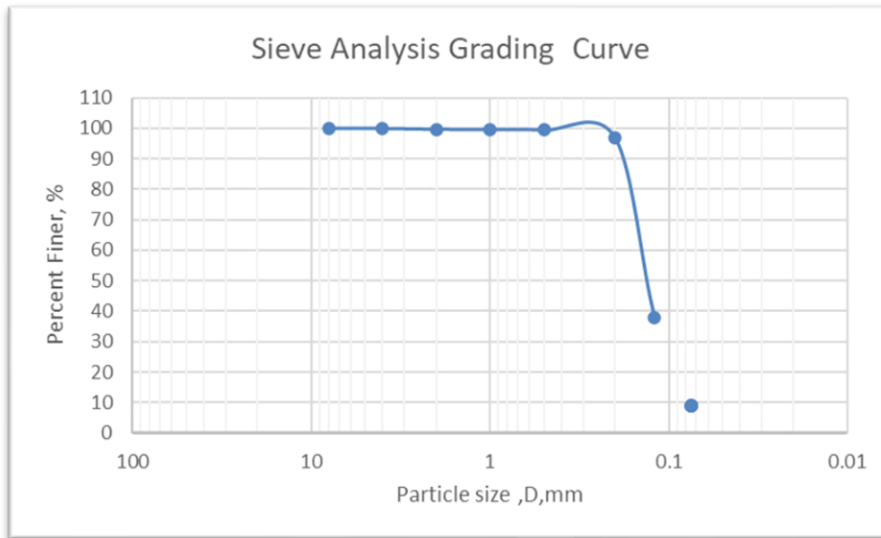


Figure 18: Sieve analysis grading curve result, after the material was sieved and graded.

3.2. Particle size distribution (DLS)

Activated and inactivated clay were used. The purpose of considering only particles passing sieve size of 0.075 mm (the lowest size available in lab) was that the fineness of the material helps to achieve high performance and reaction of the binders (Perez et al., 2015).

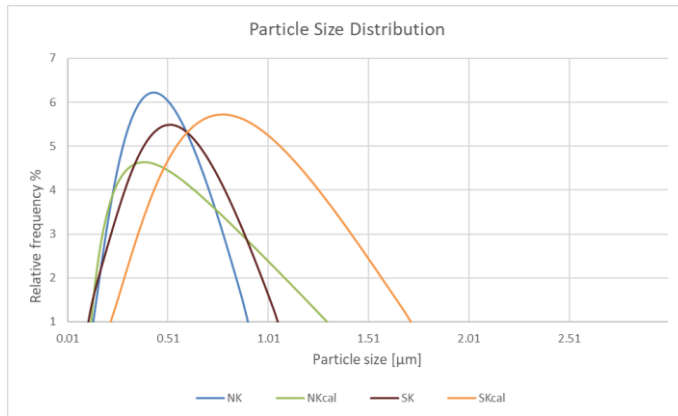
Figure 19 presents the results of the DLS measurement. In this figure, Y-axis of the curve shows the relative frequency and X-axis shows the particle size in μm . From the measurement it was observed that Norrköping (NK) uncalcined clay particle size is between 0.1-0.9 microns, and for NK calcined clay (NKC) the result is 0.1-1.3 μm .

The result for 100% of Skåne uncalcined clay (SK) is between 0.1-1.01 μm , and for SKC is 0.2-1.7 μm . The mix designs used for the DLS tests are shown in Table 5. The average diameters detected by the DLS for each particle suspensions, are presented in Table 6.

Table 5: Mixes used for DLS measurement.

Mix	Activated clay	Norrköping	Skåne
1. NK	-	0.1 g	-
2. NKC	Yes	0.1 g	-
3. SK	-		0.1 g
4. SKC	Yes		0.1 g

Table 6: The hydrodynamic diameter of the mix



Mix type	Hydrodynamic diameter (µm)
1. NK	0.378
2. NKC	0.396
3. SK	0.378
4. SKC	0.785

Figure 19: The particle size distribution curve obtained from DLS. [Norrköping uncalcined clay (NK), Norrköping calcined clay (NKcal), Skåne clay (SK), and Skåne calcined clay (SKcal)].

3.3. Water demand of clays

In general, the water demand of clays was observed to be different for calcined and uncalcined clays. It also varied with the type of clay used. Table 7 and Figure 20 presents the observations.

Table 7: Water demand for various mixes

No.	Mixes	Water demand (For fixed flow diameter of (18 cm))
1	OPC	1
2	NK100	1.8
3	NKOPC50	1.4
4	NKC100	1
5	NKCOPC50	1
6	SK100	1.5
7	SKOPC50	1.3
8	SKC100	1
9	SKCOPC50	1

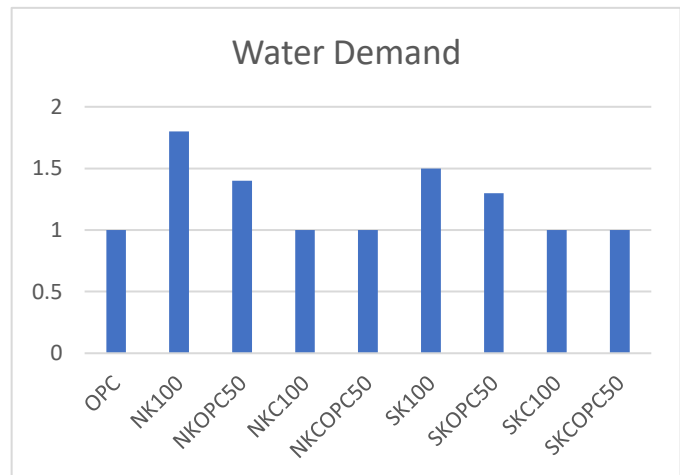


Figure 20: Comparison of water

Cement paste: The flow diameter of the cement paste having a water-binder ratio of 1 was observed to be 18 cm. This is used as a reference consistency for the clay-substituted mix designs. The high water-binder ratio of 1 was accounted for to create possibility of measuring the flow spread and accommodate a comparison study. Lower water-binder ratios will be accounted for in the future studies with consideration of the results obtained in this study.

100% uncalcined clays: The uncalcined Norrköping clay was observed to be significantly less flowable compared to cement. No flow could be observed at w/b of 1. A water demand of 1.8 was observed for 100% raw Norrköping clay and 1.5 for uncalcined Skåne clay.

50% uncalcined clays blended cement: The result was quite changed when half of the clay content was replaced with cement. The pastes were a little bit easier to blend, the flowability of the Norrköping clay blended with 50% OPC was 12 cm while with Skåne was 14 cm at the water-binder ratio of 1. A water demand of 1.4 in case of Norrköping clay and 1.3 in case of Skåne clay was observed respectively to reach the reference consistency.

Calcined clays: For calcined clays, it was seen that the water demand for both the clays significantly dropped. The water demand for both the calcined clays in both substitution percentages (of 50 and 100%) was observed to be 1, which is the same as 100% cement paste (reference).

3.4. The effects of the PCE on flowability

The reaction of raw clay as uncalcined for Skåne and Norrköping was different depending on the dosage of PCE to get the required flow spread.

Two types of PCEs – type 1A and type 1B (Figure 4) provided by Sika were tested and a preliminary flow test revealed slightly better activity and *open time* for one of the PCEs (type 1B). It was observed that immediately upon adding 1A, the paste was initially less stiff and more workable. But it quickly appeared to become stiffer after only a few seconds. This did not allow for a reliable flow test measurement. Type 1B did not have such effects. Therefore, that type was used in the study only.

For 100% of uncalcined Norrköping, 8% of superplasticizer was required to get the reference spread of 18 cm. The amount of SP decreased to 3% when 50% of this uncalcined clay was used with 50% of OPC with the same w/b ratio. On the other hand, for calcined Norrköping clay, no SP was required to get the reference spread. This was consistent for 50% clay blended cement pastes as well.

Skåne uncalcined clay showed reduced flowability with adding more superplasticizer. After a few trials, 15% SP was adjusted to be the right amount to get 18 cm of spread. When this was blended with 50% OPC, 2% SP was required to achieve the required reference flow.

For calcined Skåne clay, no SP was required to obtain the reference spread. When this was blended with 50% cement in the paste, 0.3% SP was required to obtain reference spread. The whole data for the experience are presented in Table 8 and Figure 21.

Table 8: *The amount of superplasticizer that required depends on the mix paste*

Mix design	Activated clay	Norrköping	Skåne	OPC	SP
1. NK100SP	-	100%	-	-	8%
2. NKOPC50SP	-	50%	-	50%	3%
3. SK100SP	-	-	100%	-	15%
4. SKOPC50SP	-	-	50%	50%	2%

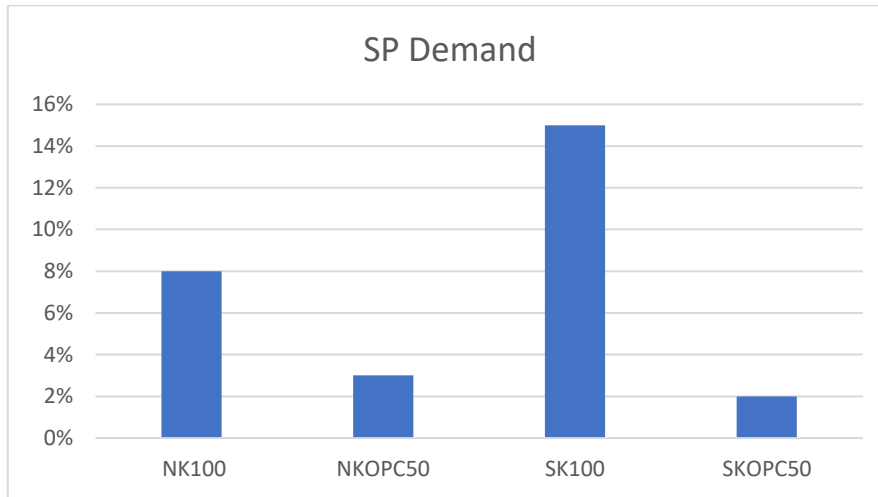


Figure 21: *The SP requirement to prepare the flow spread of the binders.*

4

DISCUSSION

This chapter presents a discussion on the observed test results presented in the previous chapter. It is divided into sections accounting towards answering each aim outlined in the first chapter. For clearer understanding, each section is further divided into questions that are answered through discussions relevant to the observations made.

4.1. Effect of Grading and Particle size distribution on water demand

Several research questions are discussed in the following.

Q1: *What effect was observed upon using mixed particle sizes for the flow test?*

A1: During the investigation, initially the mix designs comprised of clay binders that were made up of a wide variety of particle sizes. There was no homogeneity in the particle sizes used for the pastes. This resulted in variation of flow results obtained from duplicate mixes prepared in the same manner. For some mixes, using mixed particle sizes yielded little to no flow, whereas a more controlled particle size in the same mix design provided better flows (Figure 22). Therefore, to assure repeatability a controlled particle size distribution was needed. This was achieved by following the steps as below:

- I. Crushing the dried clay to a particular size (5 mm) before feeding it to further grinding. This ensures that the ground particles are homogenous in size.
- II. Rapid grinding with knife mill
- III. Sieving to obtain finest size of particles through the available sieve sizes in lab.

Q2: *How did finer and more controlled grading of particles helped to avoid discrepancy in results?*

A2: The particle size of raw clay influences the blended cement properties. By increasing grinding time and using homogeneously distributed small size of particle helps to get better performance of rheology (Zhao et al., 2020). This is because, when mixed particle sizes are used, the bigger particles absorb more water leaving limited water available for lubricating the finer particles.



a: Mix NK100 using mixed particle sizes. This yielded a stiff mix, difficult to work with.

b: Negligible flow registered from mix NK100 using mixed particle sizes.

c: Flow of same mix (NK100) registered upon using controlled particle sizes

Figure 22 (a-c): *Effect of using mixed versus controlled particle size, on the rheology of paste*

Q3: *What was the effect of calcination on the particle size distribution?*

A3: As could be observed from the DLS results, no significant changes could be observed for the particle size distribution upon calcination. This proves that the changes in water demand for calcinated mixes were dependent on the mineralogy of the calcinated clays.

Q4: *Why did we get different water demands for the two different raw clays?*

A4: It is known that water demand of clays is dependent on the crystal chemistry of clay minerals. From previous studies, it is known that at raw conditions, some expandable clays like mixed layer mica/smectite, there is a high-water absorption rate in the mineral structures (He et al., 1995). Swelling and absorbing capacity of clays also depend on the cation exchange capacity. Smectite in particular is known to be a more absorptive mineral than illite or kaolinite, because of their expanding lattices, as illustrated in Figure 23 (Norvell et al., 2007) and (Nehdi, 2014). It could be possible that there is a higher percentage of smectite in the raw clay from Norrköping than the one from Skåne, which could explain the higher water demand for raw NK mixes. From the XRD diagram presented in Figure 3 in chapter 2, it could be seen that the Norrköping clay showed sharp peaks between 5 and 6 2θ and 18-19 2θ angles, which correspond to Smectite. This was not seen in Skåne clay. Future studies can focus on measuring the content of the different minerals present in the clays used, to understand the effect of each mineral on the water demand.

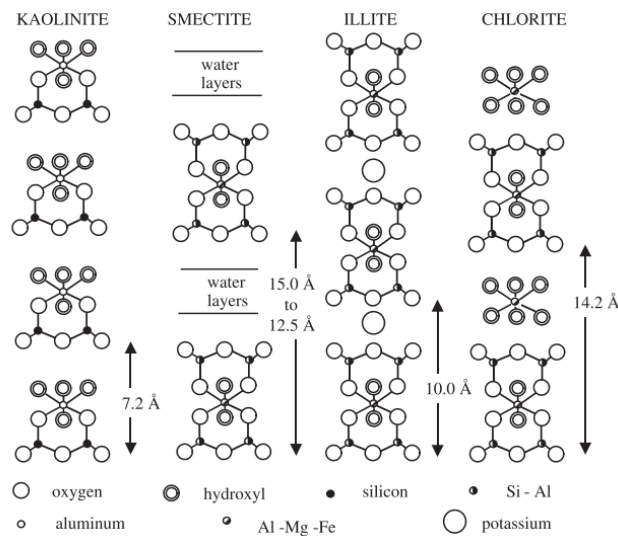


Figure 23: Clay mineralogy showing the layers and distances between the layers of different clay minerals [Hillier S. (1978)]

Q5: Why did we get different water demands for the calcinated and uncalcined clays?

A5: It was further observed that the water demand of the clays decreased drastically upon calcination. According to He et al. (1995) and Grim (1986), raw clay tends to absorb moisture immediately to varying extents depending on their crystal chemistry, but upon calcination, the rehydrating capacities of the clays are substantially destroyed by the high temperatures of dihydroxylations. This explains why the water demand of calcinated clays was highly reduced compared to raw clays.

Q6: What are the possible mistakes that can be encountered while conducting flow test in general?

A6: During mixing, the paste should be stirred rapidly for 2 minutes, and caution should be made to ensure that the binder particles have not stuck at the bottom of the mixing container. The paste should be homogenous while being poured to the mini cone. Otherwise, there will be segregation of the paste binder and the water, and this will result in bleeding, as shown in Figure 24. The flow is then not a reliable measure of the paste rheology.

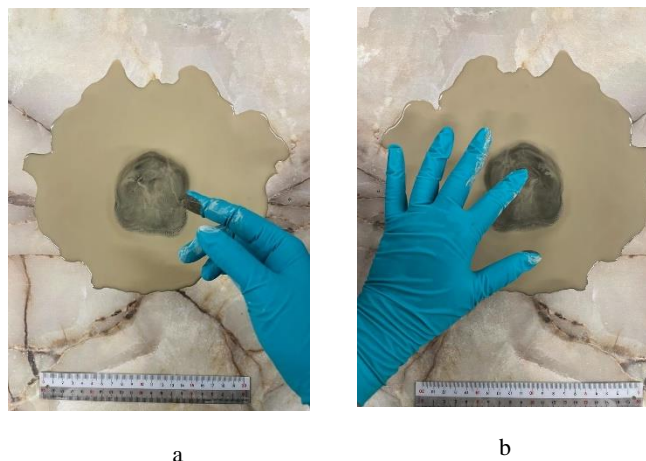


Figure 24 (a,b): Segregation of paste and bleeding

4.2. Effect of clay type on the demand for superplasticizer

On analyzing the SP demand needed by the various mixes, the following research questions could be answered.

Q7: *Why was the SP demand different for different mix designs?*

A7: Similar to the explanation provided previously for the discrepancies observed in the case of water demand, the changes in the minerology of clays govern the demand of superplasticizers. Superplasticizers are water reducing agents, so the demand of water is aligned to the demand of superplasticizers. Greater the water demand, higher the amount of superplasticizers needed to reduce the demand of water, as shown in Table 9. In case of untreated clay, it was seen that higher the water demand, higher was the SP demand which is in line with the expected outcome. In case of activated clays, the SP demand was observed to be in correlation to the water demand, for both types of clays. The high water-binder ratio of 1 which was used in this study is also a contributing factor. Lower water-binder ratios will be accounted for in the future studies with consideration of the results obtained in this study, in which most probably the need for SP should be adjusted.

Table 9: *Water demand of mixes and corresponding SP demand*

Mixes	Water demand	SP demand (at constant w/b =1)
1. OPC100	1	0%
2. NK100	1.8	8%
3. NKC100	1	0%
4. NKOPC50	1.4	3%
5. NKCOPC50	1	0%
6. SK100	1.5	15%
7. SKC100	1	0%
8. SKOPC50	1.3	2%
9. SKCOPC50	1	0%

Q8: *What was the effect of 50% clay substitution with OPC?*

A8: It was also observed that the SP demand dropped drastically upon blending the clay paste with 50% OPC. This is expected since the amount of clay was reduced, which directly reduces the water absorbing particles in the mix. Since there is less water demand, the demand for SP reduces as a consequence.

Q9: *Could raw uncalcined clays be used as partial replacement of OPC?*

A9: From the observations of this study, it is apparent that uncalcined glacial and sedimentary mixed layer clays do not pose a major hindrance to the workability when used up to 50% replacement level in the cement mix. While uncalcined clay does not contribute significantly towards strength development (He et al., 1995), they can make the paste microstructure more compact and help in refining the pore structure. A more compact microstructure will provide higher strength and better resistance against degradation. However, this study was conducted

using high water-binder ratio of 1. It needs to be checked whether higher substitution of clays at lower water-binder ratios provide similar results.

5

CONCLUSION

One of the primary ways to achieve lower carbon emissions in the construction sector is to increase the use of SCMs. However, over the recent years, it is seen that the most used SCMs like fly ash and blast furnace slag, are falling short of meeting demands. Clays on the other hand, have emerged as a promising solution, regarding both performance as cement replacement, as well as availability in the world. In Sweden, recent developments restricting the supply of limestone for cement production has made the push for searching new alternatives an urgent necessity. In the light of this, the current study attempted to examine two Swedish clays for their potential to be used as SCM.

The first criterion to be checked while examining any potential SCM is their effect on concrete fresh properties, or rheology. This is because, rheology governs the ultimate strength performance and durability of the concrete. This project therefore examined the rheological properties of two Swedish clays with varying mineralogies via the water demand and the need for superplasticizers. Both raw and calcined states of the clays were checked, and varying substitution levels were investigated. The following points summarize the findings corresponding to the aims presented in chapter 1:

Aim 1: To account for water demand of calcined and uncalcined mixed layer clays naturally available in Sweden.

Finding: It was found that the water demand of raw and calcinated clays varied. The raw clays needed more water, based on their minerology while the calcinated ones did not demand additional water beyond the reference water-binder ratio of 1. In general, the glacial clay from Norrköping had higher water demand than the sedimentary clay from Skåne. This is owing to the higher amount of expanding minerals like illite-smectite estimated to be present in the glacial clay. Both the clays allowed for a reasonable high substitution with OPC at water binder ratio of 1, without demanding a significantly high dose of SP.

Aim 2: To account for the correlation of ground-particle size distribution and water demand of clays as well as the effectivity of superplasticizers in this context.

Finding: A more controlled particle size distribution provided better workability to the mix and demonstrated better flow properties than a mixed size clay binder. The water demand for mixed particle sized binders were found to be significantly higher than the controlled sized binder. The demand for SP is aligned with that

for water. As a result, the demand of SP was lower when the particle sizes were better controlled. In general, the SP demand declined when the clays were calcinated which is in correlation to the water demand observed.

Aim 3: To investigate and screen the effect of different available types of superplasticizers on workability of calcined clay containing binders.

Finding: Out of the two PCE superplasticizers studied, one type (1B) showed better compatibility with the clay than the other (1A).

These findings point towards reasonable promise of Swedish clays to be used as an alternative cementitious material. Because the rheological properties of binder are fundamental to proper compaction, which in turn leads to required mechanical performance, it can be estimated that higher substitutions of Swedish clays may provide satisfactory strength and durability. The following chapter presents future studies that can be conducted as a continuation to this study.

6

FUTURE SCOPE

This study provided valuable insights into the rheological behavior of treated and untreated clays along with substantial information on the influence of particle sizes. The results obtained through the investigation demonstrate good potential of calcined glacial and sedimentary Swedish clays obtained from the provinces of Östergötland and Skåne respectively, to function as partial replacements of cement. The results also present sufficient promise towards using these clays in their untreated form, for the function of creating a positive compaction effect in the cementitious microstructure. This short investigation opened numerous research questions that future studies can conduct in order to better understand and apply this abundantly available building material in the industrial scale. The following are some of many topics that can be examined in the future studies:

1. The water demand and superplasticizer demand of clays from other regions of Sweden
2. The mechanical performance of the binders studied in this project
3. The effect of varying water-binder ratios (such as those used currently at the industrial level) on the demand of superplasticizers
4. Study the effect of superplasticizers on separation of clay particle sizes > 0.075 mm
5. Study the surface charge effects of varying clay particle sizes blended with cement
6. Study the mechanical and durability performance of varying blended binders containing mixed particle sizes
7. A detailed characterization study of the effect of clay minerals that contribute to the changes observed in the rheological tests
8. A study to understand the chemical characteristics of the superplasticizers used in this study and how it affected the results observed.

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