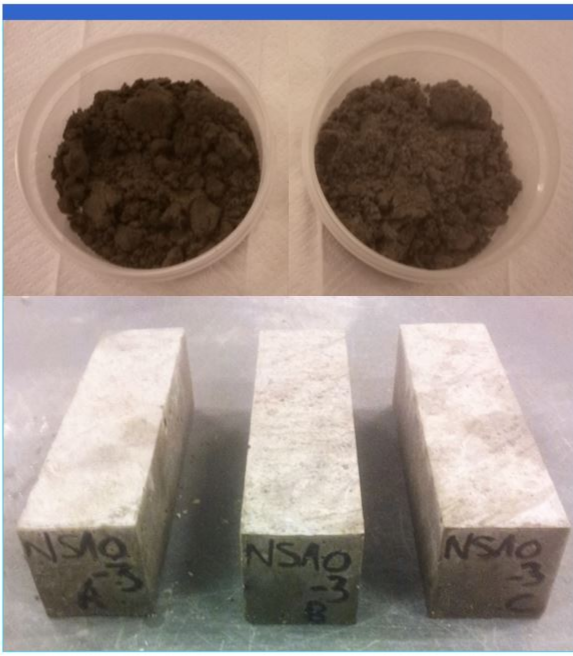
Use of Mine Tailings in Concrete

Zinkgruvan and Nalunaq tailings



Chloé Potier, s151432

M.Sc. Thesis

Department of Civil Engineering
2017

DTU, Kongens Lyngby 2017

DTU Civil Engineering
Department of Civil Engineering

DTU Byg
Department of Civil Engineering
Technical University of Denmark

Preface

This Master thesis was prepared at the department of Civil Engineering at the Technical University of Denmark, in fulfillment of the requirements for acquiring a Master's degree in Civil Engineering. The projects counts for 30 ECTS and was conducted between January 2nd and June 2nd 2017.

This project would not have been completed without the help of a number of people. First, I would like to thank my supervisor Pernille E. Jensen for her constructive and supportive guidance throughout the project. I would also like to thank laboratory technician Malene Grønvold for showing me how to perform the various experiments involved in this project, and for conducting IC analysis of my samples when needed. I also thank laboratory coodinator Ebba C. Schnell for the time she spent conducting ICP analysis on my numerous samples.

Finally, I would like express my gratitude towards my sister Sabia for her enthusiastic support and precious encouragements throughout my student years.

DTU, Kongens Lyngby, June 1, 2017

Chloé Potier (s151432)

Abstract

Every year mining activities generate huge amounts of processing waste known as tailings. Given their high contents in toxic heavy metals, tailings disposal is usually environmentally challenging as contamination of the surrounding environment would threaten biodiversity and human health. This makes tailings disposal costly. Therefore recycling part of this waste by substituting cement or aggregates with tailings in construction materials could be beneficial both environmentally and financially.

The present study investigates the potential use in concrete of mine tailings originating from two mines: the zinc, lead and copper mine located in Zinkgruvan, Sweden, and the gold mine located in Nalunaq, Southern Greenland. This project follows previous research works performed by Nielsen (2017) on the use of the same tailings as cement replacement in concrete. In the present study, replacement in mortar of 5-10% cement and of 5-10% sand with tailings is investigated. The study mainly focuses on the mechanical properties and the leaching behaviour of mortar containing tailings.

First the heavy metals contents in the raw tailings were determined. Limits set by Miljøstyrelsen were used for comparison. Zinkgruvan tailings possess concerning amounts of arsenic, cadmium, lead and zinc, while Nalunaq tailings possess concerning amounts of arsenic, cadmium, nickel and possibly lead. Heavy metals contents in sand and cement were also determined and found to be much lower than that of the tailings. Therefore the main source of heavy metals in mortar originates from the tailings.

Desorption tests investigating leaching of heavy metals from the raw tailings depending on the pH were performed. Desorption in alkaline conditions is of particular interest as pH in concrete is basic. Arsenic, copper, lead and zinc significantly leach out of Zinkgruvan tailings at basic pH, while arsenic leaches out of Nalunaq tailings in alkaline conditions. Substantial leaching rates in acidic conditions were also observed.

Mortar specimens were cast with tailings as 5-10% cement and 5-10% sand substitute.Reference specimens without tailings were also cast for comparison of tests results. The *water-cement* ratio was set to 0.5 for the reference mortar and for mortar mixtures with sand replacement, while the *water-powder* ratio was set to 0.5 for mortar mixtures with cement replacement.

The engineering properties of the fresh mortar mixtures were studied. Flow table tests showed that tailings incorporation significantly reduce mortar consistency. This was attributed to the substantial water absorption of the tailings due to their angular plate-like shape. It was also found that Zinkgruvan tailings delay initial setting, probably due the presence in the tailings of lead and zinc that are known set inhibitors. Meanwhile, Nalunaq tailings delay initial setting when they are used as cement substitute, possibly because of a reduction in cement content, but accelerate setting when they are incorporated as sand substitute. It is suspected that heterogeneous nucleation is responsible for this shortened setting time.

Compressive strength tests were carried out on each mortar mixture after curing times of 7, 14, 28 and 90 days. Results show that cement and sand substitution with tailings can contribute to early age strength but lead to strength losses after 28 days. The observed decrease in fresh mortar consistency is possibly responsible for strength losses. Strength reduction in mortar with cement substitution is also due to a decrease in cement content. Nalunaq tailings possibly act as a filler material, while pozzolanic activity in Zinkgruvan tailings is suspected. Overall, acceptable strengths were observed for mortar mixtures with moderate amounts of tailings. In particular mortar with 5% cement replaced with Zinkgruvan tailings, and mortar with 5% sand replaced with Nalunaq tailings, yielded the highest 28-day compressive strengths after the reference mortar.

Porosity and density tests performed on all the mortar mixtures did not show any appreciable variation.

Leaching tests performed on crushed mortar showed that most metals present in the tailings leach out of mortar, in various proportions. Results were compared with the limits set by Miljøstyrelsen. Leaching of arsenic and lead from mortar with Zinkgruvan tailings, and leaching of arsenic from mortar with Nalunaq tailings are particularly concerning. Overall, lower leaching rates were observed for most elements in mortar with 5% cement replacement. Additional leaching tests should be performed to determine if leaching occurs at such high rates on non-crushed mortar samples, as this scenario would be closer to reality.

Leaching of sulfates was investigated from a reference mortar sample and from a mortar sample in which 10% sand is substituted with tailings. Zinkgruvan and Nalunaq tailings both lead to increased sulfate leaching rates when they are incorporated in mortar, which could be detrimental to concrete strength and reduce construction lifetime.

Overall, the use of Zinkgruvan and Nalunaq tailings in concrete appears to be possible under certain conditions. Tailings contents should be kept low to achieve acceptable workability, setting time and strength, and to restrain leaching of heavy metals. However the ability of the cement matrix to retain enough heavy metals to comply with environmental and public health requirements is questioned. Further leaching tests should be performed to determine the extent of the hazard posed by leaching of toxic elements from mortar containing tailings.

Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

In December 2015 during the COP21, countries agreed to strive to maintain global temperature rise well below 2°C. While carbon dioxide is one of the main drivers of climate change, cement production for the construction industry is responsible for nearly 5% of yearly global CO_2 emissions (World Business Council for Sustainable Development, 2009). Therefore any initiative working towards more sustainability in the construction sector should be encouraged.

Nowadays certain industrial by-products like fly ash or silica fumes are extensively used as partial cement substitutes in concrete, thereby contributing to cut greenhouse gas emissions. Yet other waste materials could be recycled and also incorporated in concrete. Thus the use of mine tailings in construction materials is gaining interest and multiple research projects investigate the feasibility of tailings incorporation in concrete. Mine tailings consist of the solid waste materials generated after an ore has been crushed and processed. They are produced in ever increasing amounts each year, and their disposal is environmentally challenging and costly due to their high contents in toxic elements. Substitution of cement or aggregates with zero-cost tailings in concrete could reduce the needs for disposal of hazardous waste, prevent resource depletion, decrease energy consumption and carbon dioxide emissions. Moreover it could help stabilize hazardous waste by preventing leaching of toxic heavy metals from the tailings. Therefore the use of tailings in concrete gives rise to both financial and environmental benefits.

EU's reference document "for Management of Tailings and Waste-Rock in Mining Activities" recommends the recycling of tailings in construction materials. DTU Byg, the civil engineering department at DTU, wishes to contribute to these developments and to work towards a "Zero Waste" society. Thus a project family has been established, that consists of various research projects investigating the potential use in concrete of different types of tailings.

The present study investigates the potential use of tailings originating from two mines: Zinkgruvan mine, in Sweden, and Nalunaq mine, in Southern Greenland. Zinkgruvan mine is a zinc, lead and copper mine operated since 1857, while Nalunaq mine is a former gold mine that was operated from 2004 to 2013. The present study follows the works of Nielsen (2017) who studied the impact of cement substitution with these tailings in concrete. This project will focus on the potential use of the tailings as partial cement and sand substitute. Cement and sand replacement levels of 5-10% will be considered. Focus is placed on two main aspects: the impact of tailings incorporation on the mechanical properties of mortar, and the leaching behaviour of mortar containing tailings.

Experiments were conducted on the raw materials entering in mortar composition, as well as on mortar mixtures containing tailings. Conducted experiments are listed below.

Water content in the tailings was measured. Tailings, sand and cement were checked for heavy metals contents. Heavy metals desorption tests depending on the pH were performed on the tailings. Mortar mixtures with various amounts of tailings were tested for consistency, setting time, 7-day, 14-day, 28-day and 90-day compressive strength, density, porosity, leaching of heavy metals and of sulfates from crushed mortar samples.

The abbreviations used to designate the various mortar mixtures are summarized in table 1.1 below.

Table 1.1: Abbreviations used for the mortar recipes

Abbreviation	Mortar mixture
REF	Reference mortar with no tailings
ZC5	Mortar with 5% cement substituted with moist Zinkgruvan tailings
ZC10	Mortar with 10% cement substituted with dry Zinkgruvan tailings
ZS5	Mortar with 5% sand substituted with dry Zinkgruvan tailings
ZS10	Mortar with 10% sand substituted with dry Zinkgruvan tailings
NC5	Mortar with 5% cement substituted with moist Nalunaq tailings
NC10	Mortar with 10% cement substituted with dry Nalunaq tailings
NS5	Mortar with 5% sand substituted with dry Nalunaq tailings
NS10	Mortar with 10% sand substituted with dry Nalunaq tailings

CHAPTER 2

Theory

2.1 Mine tailings

2.1.1 Definition

Mining activities generate huge quantities of toxic processing waste called tailings. Tailings consist of residual materials that remain after an ore has been crushed and processed to extract valuable minerals. High contents of heavy metals and residual processing reagents in tailings pose serious environmental threats, making tailings handling and storage challenging and costly. Tailings storage depends amongst other things on the type of mine (open-pit or underground), on the tailings physical and chemical characteristics and on the local environment (Salomons and Förstner, 1988; Ritcey, 1989). Poor tailings management poses serious risks of water and soil contamination through leaching of toxic elements or dust emission, thereby threatening biodiversity and human health (Ritcey, 1989).

2.1.2 Zinkgruvan mine

The Zinkgruvan mine is located in south-central Sweden, about 250 km south of Stockholm. Mining activities began in 1857 and after several expansion programmes the mine is still in use today. In 2014 reserves were estimated sufficient to operate the mine for at least 10 more years. The mine primarily produces zinc concentrate (75 000 - 80 000 tonnes in 2014), and to a lesser extent lead concentrate (27 000 - 30 000 tonnes) and copper concentrate (3 000 - 4 000 tonnes). Silver is also extracted from lead concentrate with grades typically ranging from 1 100 to 1 500 g/t (Meyer, 2013).

Facilities on-site include an underground mine, processing plants for metal concentration, a tailings impoundment for sub-aqueous deposition, and backfill plants. Processing of the ore consists of grinding and successive bulk and selective flotation stages. Concentrates are then thickened and filtered (Meyer, 2013).

Tailings are pumped from the processing plants to a tailings pond in Enemossen area, where the solid fraction settles while decant water is recovered for ore processing. Since 2001 approximately 50% of the tailings are alternatively used as backfill material. Instead of being pumped to the tailings pond, these tailings are sent to a conventional thickener for dewatering, and then to a backfill plant that uses a vacuum disc filter to further dewater the tailings (Malmström et al., 2008). The obtained paste is then mixed with 2-4%

cement and used as backfill material in previously excavated stopes, contributing to the structural integrity of the underground mine (Moore, 2012).

It is expected that the current tailings impoundment in Enemossen will reach full capacity by 2017 and alternative disposal areas are therefore investigated, such as Lake Hemsjön nearby. The Enemossen tailings storage facility will then have to be rehabilitated. (Meyer, 2013).

2.1.3 Nalunaq mine

Nalunaq gold mine is a former underground mine located in South Greenland. It was operated from 2004 to 2008 by Nalunaq Gold Mine A/S and from 2009 to 2013 by Angel Mining A/S. The mine closed in 2013 due to resource depletion and declining gold prices (GEUS/MIMR, 2013). Over the mine's lifetime, 10.66 tons of gold were produced (Naalakkersuisut, Government of Greenland, n.d.).

The ore was initially shipped abroad for processing. Gold extraction was performed in Spain for the first 2 years, then in Canada until 2008 (Secher et al., 2008). When Angel Mining acquired the mine in 2009, an underground processing plant was built on-site for local extraction of gold. Processing consisted of ore crushing and milling followed by gravity concentration and cyanide-based chemical extraction (Bach and Larsen, 2016). Since ore concentration took place abroad until 2008, on-site tailings production began in 2009 after the processing plant started operating. Processing waste originated from gravity concentration and from the cyanide destruction process following cyanide-based gold extraction. Tailings, consisting of a mixture of fines and water, were kept within the underground mine and used as backfill material in previously excavated mine stopes. To ensure proper pumping of tailings from the processing plant to the storage area, additional dilution of the slurry was performed. Tailings were then dewatered during placement (Angel Mining A/S, 2009).

2.2 Concrete and mortar constituents

2.2.1 Definition

Concrete is the most widely used construction material today with an ever increasing production rate. In 2006, an estimated 25 billion tonnes of concrete were consumed (World Business Council for Sustainable Development, 2009). Mortar and concrete compositions are described in figure 2.1. In its simplest form, concrete is a mixture of cement, water, and fine and coarse aggregates, while mortar corresponds to a mixture of cement, water and fine aggregates. Various admixtures can be added to achieve certain physical or chemical characteristics. Mix design is adapted to each project to achieve satisfactory mechanical properties while optimizing costs (Kumar Mehta and Monteiro, 2006).

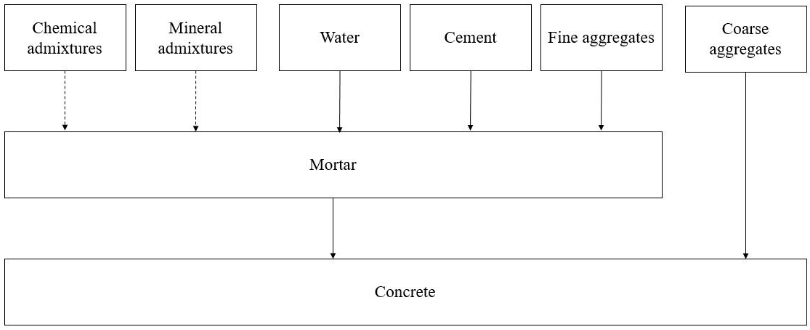


Figure 2.1: Mortar and concrete composition

2.2.2 Cement

Cement is defined as a pulverized material that acquires binding properties when hydrated. When stable under water, it is characterized as hydraulic. The most widely used hydraulic cement is Portland cement. Its main constituents are calcium silicates that can react with water to form calcium silicate hydrates possessing binding properties (Kumar Mehta and Monteiro, 2006). Portland cement results from the pulverization of clinkers containing calcium silicates and calcium sulfates. Clinker consists of a sintered material produced by heating a calcium and silica-rich raw-mix to high temperatures . Typical calcium sources for the raw mix include limestone, chalk, marl and sea-shells, while typical silica sources include clays and shales . Cement production is responsible for nearly 7% of global CO_2 emissions, thereby significantly contributing to global warming (Kumar Mehta and Monteiro, 2006).

2.2.3 Aggregates

Aggregates refer to the rock-like granular materials that are used in concrete and mortar. Aggregates are commonly classified in two categories. Materials with particulates larger than 4.75 mm, such as gravel or stones, are classified as coarse aggregates, while materials with particulate sizes between 4.75 mm and 75 µm, such as sand, are classified are fine aggregates (Kumar Mehta and Monteiro, 2006).

Only fine aggregates are used in mortar, whereas both coarse and fine aggregates are used in concrete.

The workability, durability, strength and cost of concrete or mortar greatly depend on the amount of aggregates used and on their characteristics, such as their shape, surface texture, porosity, absorption, impurities, particle size distribution, mineralogy, bulk density.

2.2.4 Water

Impurities in mixing water can influence the setting time, strength and durability of concrete. Water used in concrete is often fit for drinking. Non-drinkable water such as recycled water from urban systems or from the industry can also be used under certain conditions, if tests show that it does not have a significant impact on concrete properties. In general, contaminants such as chloride, sugar, phosphates, oil or heavy metals should be avoided (Kumar Mehta and Monteiro, 2006).

2.2.5 Chemical admixtures

Admixtures refer to materials other than cement, water and aggregates, that can be incorporated to the mix to improve certain properties of concrete during mixing, transport, placement or curing. Admixtures are widely used throughout the world nowadays, with over 80% of the concrete produced in developed country containing admixtures (Kumar Mehta and Monteiro, 2006). There are five main categories of chemical admixtures, namely air entraining agents, water-reducers, plasticizers, set accelerators and set retarders. The specialty category includes all other chemical admixtures such as shrinkage reducers, corrosion inhibitors or coloring agents (Tange Hasholt, 2016).

Air entraining agents

Air entraining agents are used to improve frost resistance in concrete by modifying the pore structure. However, the entrained air bubbles in concrete results in a loss of concrete strength (Tange Hasholt, 2016).

Water reducers and plasticizers

Water reducers and plasticizers reduce the amount of water required to achieve a certain consistency. Therefore it allows concrete to have a lower water-cement ratio while maintaining a given consistency or alternatively to improve consistency while keeping the same water-cement ratio. A lower water-cement ratio results in a higher strength of hardened concrete, as discussed in 2.3.3.

Set accelerators and retarders

Accelerators and retarders are used to influence the setting time of concrete. Accelerators result in faster setting, which is useful for instance in cold weather conditions or when early strength development is required (Tange Hasholt, 2016). Retarders, on the other hand, slow down cement hydration and therefore delay setting time. They can be used in hot climates or when additional time is needed for placement (Kumar Mehta and Monteiro, 2006).

2.2.6 Mineral admixtures

Mineral admixtures refer to finely ground materials that improve workability, strength or durability of concrete. They are generally used as partial Portland cement replacement with typical substitution rates around 15-20%, hence reducing costs and energy consumption induced by Portland cement production. Mineral admixtures come either from natural sources, like natural pozzolans that derive from volcanic materials, or from by-products of the industry, like fly ash and iron blast-furnace slag. Mineral admixtures can have hydraulic or pozzolanic activity, or be inert materials used as fillers to improve workability in concrete with insufficient fine aggregates (Tokyay, 2016).

Pozzolans

A pozzolan is a silica- or alumino-silica-based material that does not have cementitious properties in itself but that can produce hydrates possessing adhesive properties, when finely ground and placed in the presence of cement and water. This is defined as the pozzolanic reaction (Tokyay, 2016). Fly ash and silica fumes are two examples of pozzolanic materials. Fly ash comes from coal burning while silica fume is a by-product from the silicon and ferro-silicon production (Tange Hasholt, 2016). Amongst other things, pozzolans lead to pore refinement in hardened concrete, thereby improving late age strength and reducing permeability, which is beneficial for concrete durability (Kumar Mehta and Monteiro, 2006).

Fillers

Fillers are inert and very fine grained materials that influence concrete properties. In particular it has been shown that they can improve concrete compressive strength by increasing concrete density and porosity (Jaturapitakkul et al., 2011). Filler materials optimize the pore structure thanks to their fine particles that are able to fill more air voids (Jaturapitakkul et al., 2011). Moreover, thanks to their substantial specific surface, fillers can also accelerate cement hydration rate by providing additional nucleation sites for cement hydrates (Oey et al., 2013).

2.3 Concrete properties

Below are listed the main properties of fresh and hardened concrete that will be of interest in this project.

2.3.1 Workability

Workability is a characteristic of freshly made concrete or mortar. It refers to the ease with which the fresh mix can be handled, placed and compacted, without segregation of the constituents or bleeding. Segregation happens when constituents from fresh mortar or concrete separate and become inhomogeneously distributed, which has adverse effects on concrete strength and durability. Bleeding is a specific type of segregation that occurs when some of the mixing water separates from the solid fraction and "bleeds out" (Kumar Mehta and Monteiro, 2006).

Therefore workability has two aspects: the ease of flow of the mixture, also called consistency, and its resistance to segregation, also called cohesiveness.

Consistency

Consistency refers to the ease of flow of fresh concrete or mortar. Several test methods exist to evaluate consistency, such as the slump test or the flow table test. Consistency mainly depends on the wetness of the mix. Other things being equal, a higher water content in the mix yields a higher slump and flow diameter. Chemical admixtures like water reducers or plasticizers can also be used to improve consistency without increasing the water content. The amount of mixing water required to achieve a given consistency decreases when the aggregates size increases and when the aggregates are rounded rather than angular (Kumar Mehta and Monteiro, 2006).

Cohesiveness

Cohesiveness relates to the ability of fresh mortar or concrete to be compacted and finished without segregation and bleeding. Cohesiveness is in general evaluated by visual judgement. Unlike consistency, cohesiveness tends to decrease when the water content in the mix increases.

2.3.2 Setting time

During cement hydration, chemical reactions occur between cement and water that lead to stiffening, setting and hardening of the plastic mix. These three different stages are defined as follows: stiffening relates to the loss of consistency of the fresh mix, setting refers to its solidification, and hardening refers to the moment when strength gain starts (Kumar Mehta and Monteiro, 2006).

Setting is usually defined in terms of initial setting and final setting. Initial setting marks the moment when the cement paste is no longer workable, while final setting refers to the time when complete solidification is achieved. Initial setting should be long enough to allow sufficient time to place, compact and finish concrete properly. On the other hand, final setting should be early enough to avoid delays in construction works (Kumar Mehta and Monteiro, 2006).

Setting is a relatively long and gradual process. Initial and final setting times are therefore determined arbitrarily and definitions depend on the standard considered. The Vicat apparatus is commonly used to determine the initial and final setting time.

2.3.3 Strength

Strength of hardened concrete is of utmost importance as it ensures the structural integrity of buildings and construction works. Uni-axial compressive strength is commonly used to characterize concrete strength. Concrete compressive strength is significantly higher than other types of strength, such as tensile or flexural strength. It represents the maximum stress that the concrete sample can withstand before failure, when subjected to uni-axial compression. In particular, 28-day compressive strength is usually used as an index of concrete strength (Kumar Mehta and Monteiro, 2006).

Hardened cement is a multiphase material, composed of aggregates, a cement paste matrix and interfacial transition zones between coarse aggregates and the cement paste. The interfacial transition zone consists of a shell-like phase, with a thickness typically ranging from 10 to 50 µm. Although its composition is identical to that of hydrated cement paste, it has a different microstructure and mechanical behavior therefore it is treated as a third phase. The coarse aggregates are generally the strongest constituents of concrete, thus strength-limiting factors mainly lie with the cement paste and the interfacial transition zone. In mortar, no coarse aggregates are present, hence there is no interfacial transition zone and the cement paste will determine the strength. At a given cement content, water-cement ratio and curing time, mortar will usually yield a higher strength than the corresponding concrete (Kumar Mehta and Monteiro, 2006).

Several factors influence concrete strength, including, but not limited to:

- The mix design, and in particular the water-cement ratio and the eventual admixtures content,
- the porosity,
- the curing conditions,
- the specimen geometry,
- the load rate.

The water-cement ratio and the porosity are two of the parameters with the largest influence and will be discussed below.

Impact of the water-cement ratio on concrete strength

The water-cement (w/c) ratio represents the ratio between the weight of water and the weight of cement contained in the concrete or mortar mixture. Concrete strength was found to be inversely related to the w/c ratio. This is described by Bolomey's empirical formula (Aalborg Portland A/S, 2012):

$$f_c = K\left(\frac{1}{w/c} - \alpha\right) \tag{2.1}$$

where f_c is the compressive strength of the mortar or concrete specimen (in MPa), w/c is the water-cement ratio by weight and K andα are parameters depending on the type of cement and the curing time.

Consequently, in order to optimize concrete strength, the w/c ratio should be no more than what is necessary to achieve satisfactory workability (Kumar Mehta and Monteiro, 2006).

Impact of the porosity on concrete strength

In hardened concrete, porosity describes the total volume of concrete that is occupied with voids, also known as pores. In solids, strength is inversely related to porosity. Consequently concrete and mortar strength tends to decrease when the porosity of the cement paste matrix increases (Kumar Mehta and Monteiro, 2006).

2.3.4 Porosity

As mentioned in the previous paragraph, porosity is the ratio of the volume of air voids to the bulk volume of mortar or concrete. The open porosity corresponds to the ratio of the volume of open and interconnected pores to the bulk volume of the mortar specimen. The open porosity is different from total porosity as isolated pores are also taken into account in total porosity determination (Kumar Mehta and Monteiro, 2006). However, total porosity is in practice more difficult to determine than open porosity.

Porosity greatly impacts concrete strength and transport properties (Kumar Mehta and Monteiro, 2006). Therefore porosity determination is of particular interest in this study, as it may influence mortar strength but also the leaching behaviour in mortar mixtures containing mine tailings rich in heavy metals.

2.4 Literature study on the use of mine tailings in construction materials

In this section previous research regarding the use of mine tailings in construction materials will be presented and discussed.

Scope

Industrial activities generate huge amounts of waste materials every year and waste management is becoming ever more challenging. In particular disposal of processing waste that arises from mining activities is of growing concern. As discussed in section 2.1 mine tailings pose a threat to their surrounding environment and to biodiversity, making their disposal is very costly (Sivakugan et al., 2006). Previous research has shown that other industrial wastes such as fly ash or blast furnace slag can be effectively recycled and used in construction materials (see 2.2.6). Similarly, adequate use of mine tailings as cement or aggregates replacement in concrete would be both environmentally and financially beneficial. It would indeed lower the costs associated with tailings disposal, while allowing the use of a ”zero-cost” raw material (Onuaguluchi and Eren, 2012a). Partial substitution of cement with tailings would also reduce the environmental impacts associated with cement production. Previous research projects regarding the use of mine tailings in concrete have mainly focused on two aspects: the impact of tailings incorporation on the mechanical properties of concrete, and the ability of the cement matrix to stabilize the waste by immobilizing heavy metals.

Influence of mine tailings on concrete mechanical properties

Research projects regarding the impact of various tailings on concrete mechanical behavior yielded disparate results. It arises that tailings characteristics are mine-specific and results from studies investigating different tailings cannot be generalized. Yet overall, investigations suggest that acceptable compressive strength can be achieved using moderate amounts of tailings in concrete or mortar (Kundu et al., 2016; Tixier et al., 1997; Onuaguluchi and Eren, 2012a).

Certain studies found that tailings incorporation in concrete mixtures resulted in similar to slightly improved compressive strength compared to a control mixture, for moderate tailings contents. Onuaguluchi and Eren (2012) found that copper tailings from Lefke, Cyprus, used as additives positively affected concrete tensile and compressive strength, especially at an addition level of 5% per mass of cement. Similarly Tixier et al. (1997) observed an increase in concrete compressive strength for partial cement replacement with copper slag. In both studies it was suspected that strength enhancement was due to an optimization of the pore structure thanks to the tailings and slag fine particles that acted as fillers. Improved compressive strength was also observed by Çelik et al. (2006) for mortars containing fly ash and silica fume together with up to 15% gold tailings from Bergama, Turkey, per mass of portland cement. Fine aggregates replacement with tailings also showed positive effects on concrete strength. Lead and zinc tailings incorporated as sand replacement in self compacting concrete were found to slightly enhance the 28-day compressive strength (Jankovic et al., 2015). Strength enhancement together with porosity reduction were also observed at various w/c ratios when copper tailings from Khetri, India, were incorporated in concrete, at sand replacement levels up to 60% by weight (Thomas et al., 2013). However, this should be tempered by another study that found that the same tailings were detrimental to concrete compressive strength when they were incorporated in concrete mixtures with $w/c = 0.45$ (Beniwal et al., 2015).

Other studies found that tailings incorporation in concrete led to a loss of compressive strength. Kundu et al. (2016) investigated cement substitution with copper tailings. Results showed that for a given water-binder ratio, compressive strength of concrete containing tailings decreases as tailings content increases. This was expected as cement content decreases when the tailings substitution rate increases. However acceptable strength was obtained for substitution rates below 10%. Çelik et al. (2006) also observed a significant decrease in compressive strength of mortar containing gold tailings for cement replacement levels over 5%.
Moreover, tailings that come from sulfide ore processing usually have significant sulfide contents. It has been shown that incorporating sulfide-bearing aggregates in concrete can cause sulfate attack during which sulfate ions chemically react with cement hydration products (Neville, 1995). This results in a loss in concrete strength and durability. Thus, the addition in concrete of sulphide-bearing copper tailings from Cyprus was found to result in a minor decrease in concrete sulfate resistance (Onuaguluchi and Eren, 2012b).

Regarding the impact of tailings on fresh concrete or mortar, multiple studies attest that workability is negatively affected by tailings incorporation (Onuaguluchi and Eren, 2012a; B. Kim et al., 2016). Tailings indeed tend to have a substantial water absorption potential, thereby reducing water availability for cement hydration and decreasing consistency. Large water absorption is due to the tailings grains fineness and angular shape, that increase the surface to be wetted (Onuaguluchi and Eren, 2012a; Fall et al., 2005). Onuaguluchi and Eren (2012) also observed a slightly negative impact of copper tailings on setting time of fresh concrete. Certain elements like copper, lead and zinc are known to inhibit the production of calcium hydrates during cement hydration hence delaying setting (Zain et al., 2004). Jang and I. Kim (2000) also believe that heavy metal contained in tailings can adversely affect concrete setting and hardening as their ions may form inactive layers on the surface of cement particles. This could also explain observed strength losses.

Overall, it appears that it is possible to use tailings in concrete while keeping satisfactory strength and workability. In the studies mentioned in this section, tailings were either incorporated as cement replacement, fine aggregates replacement, or as additives. Recommended addition levels and cement substitution rates generally ranged from 5 to 15% by weight of cement (Onuaguluchi and Eren, 2012a; Tixier et al., 1997; Kundu et al., 2016). No clear pattern appears regarding acceptable sand replacement rate, as observed performances were greatly dependent on the tailings characteristics and on the w/c ratio (Jankovic et al., 2015; Beniwal et al., 2015; Thomas et al., 2013).

Leaching behavior of concrete containing tailings

Leaching consists in the transfer of contaminants from a stabilized matrix to a liquid solution. Stabilization-Solidification (S/S) is a treatment method used to immobilize trace elements contained in hazardous waste. Cement-based S/S process relies on chemical and physical encapsulation of leachable elements in a cement matrix, thus preventing leaching of toxic heavy metals and contamination of the surrounding environment (Choi et al., 2009).

Various studies have found that concrete can successfully stabilize mine tailings by retaining heavy metals in the cement matrix (Kundu et al., 2016; Onuaguluchi and Eren, 2012a; B. Kim et al., 2016). Kundu et al. (2016) observed that leaching of heavy metals from concrete containing tailings decreases when tailings amount increases. B. Kim et al. (2016) observed the same trend for arsenic leaching from cementitious low-strength materials containing arsenic-rich tailings. A possible explanation advanced by Kundu et al. (2016) is that tailings contain fine particles that can act as a filler material and reduce pore interconnectivity, thus limiting heavy metals mobility within the cement matrix.

However, although various research projects have examined the potential stabilization of mine tailings through their incorporation in concrete, the mechanisms governing heavy metals leaching from cementitious materials are still investigated and not fully understood (B. Kim et al., 2016).

2.5 Previous research on Zinkgruvan and Nalunaq tailings

Studies specific to the incorporation of Zinkgruvan and Nalunaq tailings in mortar have been performed by Nielsen (2017), who examined the properties of mortar containing tailings at replacement levels of 5 and 10% by weight of cement. When applicable, results obtained in this project will be compared to Nielsen's findings. General conclusions from said study were as follows:

- *Mortar strength:* Cement substitution with Zinkgruvan or Nalunaq tailings results in a loss in mortar compressive strength. Strength decreases when the amount of substituted cement increases. Nalunaq tailings contribute to early age strength development possibly thanks to a filler effect. Zinkgruvan tailings may have pozzolanic activity as after 14 days strength gain is faster for mortars with Zinkgruvan tailings than for reference mortar. Mortar mixtures with Zinkgruvan tailings yield higher 28-day compressive strengths than the corresponding mortar mixtures with Nalunaq tailings.
- *Grain size optimization:* Incorporation of crushed Zinkgruvan tailings to optimize grain size distribution did not increase compressive strength. Therefore these results did not support the presence of pozzolanic materials.
- *Workability:* Workability decreases when the amount of tailings in mortar increases. This is attributed to the large water absorption of the tailings. Mortar strength increases when workability is improved by optimizing the water content.
- *Setting:* Cement substitution with Zinkgruvan or Nalunaq tailings results in slightly delayed setting time for both initial and final setting.

Nielsen did not examine potential sand replacement with tailings or leaching behavior of mortar containing tailings. It will be investigated in the present study.

CHAPTER 3

Materials and Methodology

This chapter documents the tests that have been performed. Materials and methods for the experiments and for mortar casting are described. The tests conducted are listed below:

- Materials characterization
  - Water content in the tailings
  - Heavy metals and sulfur contents in the tailings, sand and cement
  - pH-desorption of heavy metals from the tailings
- Mortar testing
  - Consistency of fresh mortar
  - Setting time
  - Compressive strength (after curing times of 7, 14, 28 and 90 days)
  - Porosity and density
  - Heavy metals and sulfur contents in sand and cement
  - Leaching of heavy metals and sulfur from crushed mortar
  - Leaching of sulfates from crushed mortar

3.1 The tailings

Two types of tailings are investigated in this study: Zinkgruvan tailings and Nalunaq tailings. Figure 3.1 shows a sample of both tailings.

(a) Zinkgruvan tailings (b) Nalunaq tailings

Figure 3.1: Tailings samples

Zinkgruvan tailings

Sampled Zinkgruvan tailings come from a tailings pond near the mine and were less than 2 years old at the time of sampling (Jensen et al., 2016). They were then stored in the laboratory in a closed plastic bucket at ambient temperature.

Nalunaq tailings

Sampled Nalunaq tailings originate from the discharge of the cyanide destruction process that followed gold chemical extraction. Tailings were sampled before placement in the underground tailings storage area. The solid fraction of the slurry, representing 20-22%, was sampled after settlement and decantation (Jensen et al., 2016). The tailings were stored in the laboratory in a closed plastic bucket at ambient temperature.

Tests performed on the tailings

Previous investigations have been carried out by Nielsen (2017) to characterize the tailings. Additional experiments that have been conducted on the tailings in the present study are summarized in table 3.1 and test procedures are described below.

Table 3.1: Tests performed on the tailings

Test	Scope
Water content	The water content in the tailings will impact the w/c ratio in the mortar mixtures containing tailings.
Heavy metals content	Mine tailings contain high amounts of heavy metals, that are toxic to the environment and humans. Thus, to ensure a safe use of tailings in concrete it is crucial to know their heavy metals contents.
pH-desorption of heavy metals	Depending on the pH, heavy metals in tailings can remain bound in the solid matrix or be desorbed and leach out. Mortar is alkaline, therefore desorption of heavy metals at high pH could indicate potential safety hazards associated with the use of tailings in mortar.

3.1.1 Water content

Water content in Zinkgruvan and Nalunaq tailings was determined with triplicate determination, as documented in appendix A.1. The test was carried out twice with three weeks interval between each test. Results reported in 4.1.1 are expressed in % of the weight of the moist tailings and correspond to the average water content obtained from each triplicate determination.

3.1.2 Heavy metals and sulfur contents

Heavy metals contents in the raw tailings were measured with triplicate determination as detailed in appendix A.2. Sulfur content in the tailings was also determined as it may have an influence on concrete properties if it leads to the presence of sulfates in mortar.

To perform the determination, tailings were dried overnight at 105°C and subsequently pre-treated by acidic digestion in accordance with DS 259 (2003). During digestion 1.00 g of tailings and 20 mL of nitric acid at 7.3 M were heated for 30 min to 120°C (200 kPa). After vacuum filtration through a 45 µm filter the liquid phase was recovered and diluted to 100 mL. Concentrations of trace elements in the obtained solution were determined using ICP-OES (Inductively Coupled Plasma with Optical Emission Spectrometer).

In an ICP analysis the tested sample is subjected to plasma energy to place its atoms and ions in an excited state. Emission rays are emitted when the atoms and ions return to their stable state. Based on the wavelength and intensity of the rays, contents in trace elements can be determined (Hitachi, n.d.).

Contents in the following elements were determined: Al, As, Ba, Cd, Cr, Cu, Fe, Ni, P, Pb, S, Zn. The ICP analysis was performed by a laboratory technician.

The results reported in 4.1.2 correspond to the average content in each element obtained from the triplicate determinations.

3.1.3 pH-desorption from the tailings

Release of heavy metals from Zinkgruvan and Nalunaq tailings depending on the pH was investigated as described in appendix A.3, with duplicate determination. Tailings were dried overnight to 105°C prior to the test. Sulfur desorption from the tailings depending on the pH was also determined as it may give an indication on the release of sulfates in mortar.

Concentration in the eluates of Al, As, Ba, Cd, Cr, Cu, Fe, S, P, Ni, Pb, Zn, were determined through ICP-OES analysis. The ICP analysis was performed by a laboratory technician.

Desorption rates were calculated as follows:

$$\%(metal\,released) = \frac{MC}{Mt} \tag{3.1}$$

Where $\%(metal\,released)$ is the desorption rate of the element, MC is the content in the element that leached from the tailings into the eluate (in mg/kg) and Mt is the total initial content of the element in the tailings determined in 3.1.2 (in mg/kg).

The desorption rates reported in 4.1.3 correspond to the average desorption rates obtained from the triplicate determinations.

3.2 Heavy metals and sulfur contents in cement and sand

The impact of tailings incorporation on the leaching behaviour of crushed mortar was investigated further on. The amount of heavy metals in cement and sand was therefore determined to assess the contribution of each mortar constituent to the leaching process. Heavy metals contents in cement and sand used in the mortar mixtures were determined using the same method as in 3.1.2. Sulfur contents were also determined. Details of the procedure are documented in appendix B.2.
The results reported in 4.2 correspond to the average content in each element obtained from the triplicate determinations.

3.3 Mortar casting

This section documents the various mortar mixtures that were cast as well as the materials and methods used for the castings.

3.3.1 Mortar mixtures and mix design

Mortar mixtures

Mortar mixtures with different tailings, cement and sand contents were prepared. Substitution of cement and of sand with mine tailings were studied at replacement rates of 5 and 10% by weight. Additionally, two identical reference mortar mixtures without tailings, called REFa and REF, were cast on 2 different days (see 3.4). Table 3.2 below summarizes the mixtures that were cast and the abbreviation used for their designation.

Table 3.2: Mortar mixtures

Abbreviation	Mortar composition
REF, REFa	Reference mortar (no tailings)
ZC5, NC5	5% cement substitution with Zinkgruvan, respectively Nalunaq tailings
ZC10, NC10	10% cement substitution with Zinkgruvan, respectively Nalunaq tailings
ZS5, NS5	5% sand substitution with Zinkgruvan, respectively Nalunaq tailings
ZS10, NS10	5% sand substitution with Zinkgruvan, respectively Nalunaq tailings

Mix design

The mix design for the reference mortar complies with DS/EN 196-1. The w/c ratio was set to 0.5 for the reference mortar and for mortars with sand replacement. The *water-powder* ratio (w/p), meaning the *water-(cement + tailings)* ratio was set to 0.5 for mortars with cement replacement. Table 3.3 displays the amount of cement, water, sand and tailings in each mortar mixture. Experimental data for each batch is available in appendix C.2.

Table 3.3: Mix design for the various mortar mixtures

	Cement [g]	Water [g]	Sand [g]	Tailings [g]	
REF, REFa	450	225	1350	0	$w/c = 0.5$
ZC5, NC5	427,5	225	1350	22,5	$w/p = 0.5$
ZC10, NC10	405	225	1350	45	$w/p = 0.5$
ZS5, NS5	450	225	1287,5	67,5	$w/c = 0.5$
ZS10, NS10	450	225	1215	135	$w/c = 0.5$

3.3.2 Materials

Cement

CEM II/A-LL:BASIS cement from Aalborg Portland was used in all mortar mixtures.

Sand

Sea sand complying with DS/EN 196-1 (2005) was used in all mortar mixtures. The sand was dried prior to casting as follows:

- Batch 1 (used in REFa, ZC5, NC5, ZS5): sand was left to dry overnight at 105°C
- Batch 2 (used in REF, NS5, ZC10, NC10) : sand was left to dry at 55°C for 3 days
- Batch 3 (used in ZS10, NS10): sand was left to dry at 55°C for 4 days

Dried sand was then stored in buckets at ambient temperature. Casting was performed after the sand had cooled down. The sand was used in mortar mixtures maximum 3 weeks after the drying process.

Tailings

Unmilled tailings were used for each mortar mixture. The first mixtures (NC5 and ZC5) were prepared using moist tailings. However, due to the relatively large and variable water content in the tailings (see 4.1.1) it was decided to use dried tailings further on to better control the water content in mortar.

Tailings were subsequently dried in the oven at 55°C for at least 2 days, and then stored in airtight plastic bags. Casting was performed after the tailings had cooled down to room temperature. The water content in the dried tailings was checked 2 and 3 weeks after the drying process and was found to remain negligible, below 1%.

Water

Distilled water was used in the mixes.

3.3.3 Casting of mortar specimens

Planning

Table 3.4 documents the casting dates for each mortar mixture. More detailed planning including demoulding dates, curing time and tests dates is available in appendix C.1. All batches corresponding to a mixture were cast on the same day. Table 3.5 documents the intended purpose of each batch. For REFa, 3 batches were prepared in one day corresponding to batches 1, 2 and 3 in table 3.5. For all the other mortar mixtures 7 batches were prepared.

Table 3.4: Casting dates and number of batches for each mortar mixture

	Casting date	Batches
REFa	12/01	3
ZC5	16/01	7
NC5	17/01	7
ZS5	25/01	7
REF	30/01	7
NS5	01/02	7
ZC10	06/02	7
NC10	07/02	7
ZS10	08/02	7
NS10	13/02	7

Table 3.5: Intended purpose of each batch

Batch nr.	Purpose
1	7-day compressive strength test
2	14-day compressive strength test
3	28-day compressive strength test
4	90-day compressive strength test
5	Porosity and density test
6	Vicat test
7	Flow table test

Mixing

Mixing of mortar was carried out following the requirements of DS/EN 196-1 (2005), using a mixer from Toni Industri displayed in picture 3.2. The procedure for mixing described in the standard is reminded below:

- Place the cement in the bowl and as soon as the water is added start the mixer at low speed. Start the timer simultaneously.
- Between 30 s and 1 min of mixing, add the sand steadily.

- After 1 min of mixing switch the mixer to high speed for the following 30 s.
- Stop the mixer for 90 s. During the first 30 s, scrape off the mortar from the sides and place it back in the middle of the bowl to ensure homogeneous mixing.
- Start the mixer at high speed for 60 s, then turn it off.

Figure 3.2: Mixer from Toni Industri used for mixing

For mixtures with cement replacement, tailings were incorporated with cement from the beginning of the mixing process. For mixtures with sand replacement, tailings were incorporated together with sand, after 30 s - 1 min of mixing.

The casting time was recorded for each batch (see appendix C.2) and corresponds to the time water is added, to the nearest 5 min.

Moulding

Immediately after mixing fresh mortar was placed in a mould complying with DS/EN 196-1 (2005) as displayed in figure 3.3 .

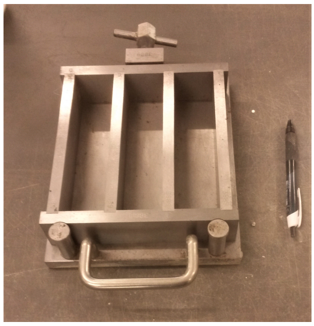


Figure 3.3: Mould used to cast mortar specimens

The mould was placed on a vibrating table and filled in two steps. It was first filled roughly halfway and vibrated for 15-20 seconds at 50 MHz. The mould was then filled up completely and identically vibrated. Excess mortar was scraped off the top of the mould using a metal ruler in a sawing movement.

Due to their lower workability, ZS10 and NS10 were vibrated for a longer time (roughly 15 s more each time) until satisfactory compaction in the moulds. Acceptable compaction was estimated by visual judgement and vibration was stopped before segregation or bleeding were visible.

Specimens were then covered in a plastic sheet to prevent water evaporation from the faces exposed to air, and left to set at room temperature for 20-24 hours.

Demoulding and curing

Between 20 and 24h after moulding specimens were demoulded and submerged in distilled water for curing. Three prism specimens, A, B and C (from left to right as shown on figure 3.4) were cast per batch. Prisms dimensions were 40 x 40 x 160 mm. Reference specimens, specimens containing Zinkgruvan tailings, and specimens containing Nalunaq tailings were left to cure in separate containers.

Figure 3.4: Mortar specimens

3.4 Mortar testing

Procedures for tests performed on fresh and hardened mortar are thereafter documented. Table 3.6 provides an overview of the tests. For each mortar mixture, the following tests were performed:

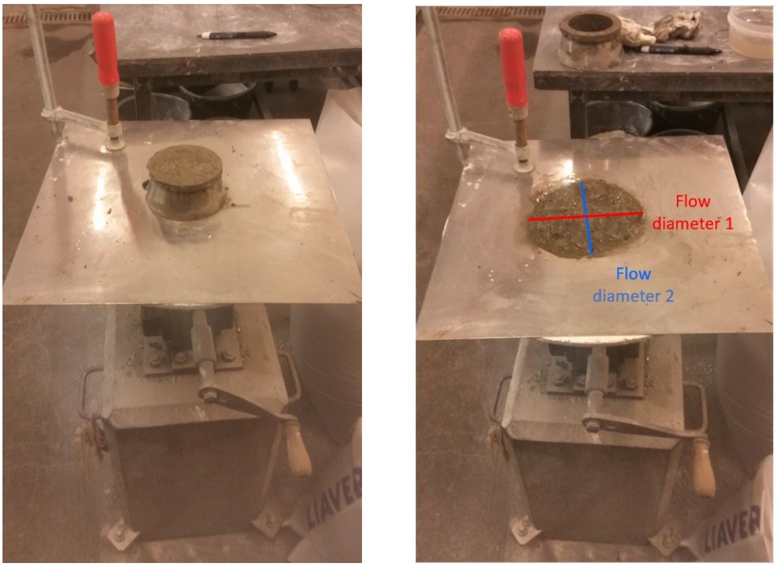
- For REF, ZC5, ZC10, ZS5, ZS10, NC5, NC10, NS5, NS10: consistency, setting time, compressive strength (for curing times of 7, 14, 28 and 90 days), porosity, density and leaching
- For REFa: compressive strength (for curing times of 7, 14 and 28 days). Results were compared with that of REF to assess their consistency.

Table 3.6: Tests performed on mortar

Test	Scope
Consistency	Sufficient consistency is required to allow proper compaction of fresh mortar during the casting. Consistency was determined by conducting flow table tests on fresh mortar.
Setting time	Initial and final setting should remain in a range that allows proper placement of mortar while avoiding delays in construction works. Setting times were determined thanks to a Vicat apparatus.
Compressive strength	Concrete compressive strength is crucial to ensure structural integrity of construction works. Compressive strength tests were conducted on mortar prisms after 7, 14, 28 and 90 days of curing.
Porosity	Porosity can impact mortar strength, durability, and the mobility of heavy metals within the cement matrix. Porosity tests were conducted on mortar prisms that were cured under water for 28 days and subsequently dried until reaching weight consistency.
Leaching from crushed mortar	Leaching of heavy metals from mortar can pose a threat to the environment and human health. Leaching of sulfate can result in a loss of concrete strength and durability. Leaching tests were conducted on crushed mortar samples. Mortar specimens were cured for 28 days and subsequently crushed and dried until reaching weight consistency.

3.4.1 Consistency of fresh mortar

Consistency was determined for each fresh mortar mixture through a flow table test, following the requirements of DS/EN 1015-3 (1999).
A metal mould was placed in the center of the table. The mould had an internal diameter of 100 mm at its base, 70 mm at its top, and a height of 60 mm. It mould was filled halfway with fresh mortar and tapped 10 times using a tamping rod. The mould was then filled up to the top and tapped 10 times again. The surplus mortar at the top of the mould was scraped off and removed. After 15-20 seconds, the mould was removed and the table was jolted 15 times at intervals of 1 s. The diameter of the flowing mortar was finally measured with a caliper, in two directions at right angles of each other as shown on figure 3.5. The reported flow diameter corresponds to the average of the 2 measurements.



(a) Before jolting (b) After jolting

Figure 3.5: Flow table test

3.4.2 Setting time

The initial setting time of each mortar mixture was determined in accordance with DS/EN 193-3 (2016) thanks to the Vicat apparatus displayed in figure 3.6. To determine the setting time, a needle is plunged in fresh mortar at 10 min time intervals and its penetration depth is recorded. The initial setting time refers to the moment when the distance between the needle and the bottom of the mould reaches 6 ±3 mm. The final setting time corresponds to the moment when the penetration depth is no longer greater than 0.5 mm. Setting times are expressed using the casting time as the ”zero-time”.

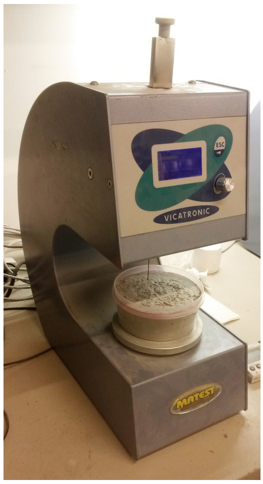


Figure 3.6: Vicat apparatus

3.4.3 Compressive strength

Uni-axial compression tests were carried out following the requirements from DS/EN 196-1 (2005). Tests were executed on hardened mortar specimens at the following ages:

- 7 days $\pm 3\,h$
- 14 days $\pm 3\,h$
- 28 days $\pm 6\,h$
- 90 days $\pm 1\,day$

The prism specimens were placed on the pressure test machine as shown on figure 3.7.

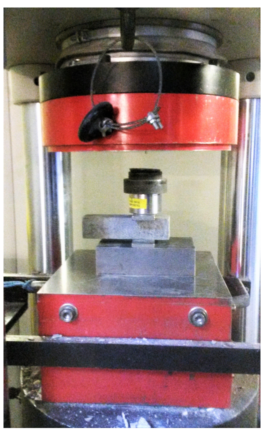


Figure 3.7: Compressive strength test

The compressive strength test was first executed on one half of the specimen, at a load rate of 2.48 kN/s. Subsequent to the breakage of the specimen, the test was carried out again on the other half. Each time three specimens from a same batch were used (A, B and C). Therefore six results were obtained for each determination. The compressive strength was determined as follows (DS/EN 196-1, 2005):

$$R_c = \frac{F_c}{A} \tag{3.2}$$

where R_c is the compressive strength in MPa, F_c is the maximum load at fracture in N and A is the cross-section of the mortar prism in mm^2.

The results reported in 4.3.3 correspond to the average strength calculated based on the six results obtained for each determination. In case one result deviated by more than 10% from the calculated average strength, it was discarded and the average strength was calculated again. In case at least one result still deviated from the average by more than 10%, determination was redone. This means that new specimens were cast and left to cure for the appropriate duration, before being subjected to a new compressive strength test.

Remark for the 90-day compressive strength tests

Due to a practical problem all mortar specimens used for 90 day-compressive strength tests were left to cure out of water for 3 to 4 days. They were indeed left to cure in plastic containers placed on a shelf that collapsed. As a result water leaked out of the containers, leaving the specimens dry. Specimens were placed in new containers and submerged again as soon as the incident was noticed. The specimens may also have collided when the shelf collapsed, although no trace of impact was visible. Specimens had all been curing for at least 70 days when the incident happened, therefore it was assumed that it had little influence on their strength development. Decision was made to document the results for the 90-day compressive strength tests in spite of the incident.

3.4.4 Porosity and density

Porosity and density tests were carried out on three specimens for each mortar mixture. After 28 days of curing under water, mortar specimens from a same batch (A, B and C) were left to dry in the oven at 55°C for at least 4 weeks until reaching weight consistency. They were subsequently subjected to a density and porosity test, as described in appendix B.7. Results reported in 4.3.4 correspond to the average open porosity and the average dry density obtained for each mortar mixture. The dry density of the mortar specimens was calculated as follows:

$$\rho_d = \frac{m_{dry}}{m_{ssd} - m_{sw}} \cdot \rho_w \tag{3.3}$$

where ρ_d is the dry density of the mortar specimen (in kg/m^3), m_{dry} is the specimen mass after drying until weight consistency (in kg), m_{ssd} is the specimen weight over water after vacuum (in kg), m_{sw} is the specimen weight under water after vacuum (in kg), and ρ_w is water density (in kg/m^3).

The open porosity corresponds to the ratio of the volume of open and interconnected pores to the bulk volume of the mortar specimen and it was calculated as follows:

$$p = \frac{m_{ssd} - m_{dry}}{m_{ssd} - m_{sw}} \tag{3.4}$$

where p is the open porosity of the mortar specimen (in %) and m_{dry}, m_{ssd} and m_{sw} are defined as in equation 3.3.

3.4.5 Leaching of heavy metals and sulfur from crushed mortar

Leaching of heavy metals from crushed mortar samples was investigated with triplicate determination as follows. After 28-day compressive strength tests the pieces of the broken mortar specimens were recovered. Mortar samples were dried at 55°C until reaching weight consistency and crushed at 1100 rpm for 30 seconds. Crushed mortar samples were subsequently subjected to batch leaching tests following the requirements of DS/EN 12457-1 (2002) at a Liquid-Solid ratio L/S = 2. Then 20.00 g of crushed mortar samples were introduced in plastic vials together with 40.00 mL of distilled water at pH = 7.0. After agitation on a shaking table for 24h, pH in the eluate was measured and the eluate was separated from the solid fraction by vacuum filtration through a 0.45µm filter. Heavy metals and sulfur concentrations in the eluate were determined by ICP-OES analysis. The ICP analysis was performed by a laboratory technician. The results reported in 4.3.5 correspond to the average concentrations calculated from the triplicate determinations.

3.4.6 Leaching of sulfate from crushed mortar

Sulfate leaching from three mortar mixtures, namely REF, ZS10 and NS10 was investigated, with duplicate determination. ZS10 and NS10 correspond to the mortar mixtures with the highest tailing content.

The procedure was exactly the same as the one described in section 3.4.5. The only difference resides in the final analysis, as sulfate content in the eluates was determined by IC (Ion Chromatography) instead of ICP analysis. The IC analysis was performed by a laboratory technician. The results reported in 4.3.6 correspond to the average concentrations calculated from the duplicate determinations.

CHAPTER 4

Results and Discussion

4.1 The tailings

4.1.1 Water content

The water contents in Zinkgruvan and Nalunaq tailings are displayed in table 4.1. Results are expressed in % of moist matter. Detailed results are available in appendix B.1.

Table 4.1: Water content in Zinkgruvan and Nalunaq tailings, in % ± standard deviation

Test date	Zinkgruvan [%]	Nalunaq [%]
09/01/17	8.2 ± 0.3	13.4 ± 0.2
30/01/17	10.5 ± 0.2	11.4 ± 0.2

The water content of tailings from both Zinkgruvan and Nalunaq mines is relatively high, reaching 10.5% for Zinkgruvan tailings and 13.4% for Nalunaq tailings. It is also significantly changing from one test to the other, with at least 2% difference between the tests for both tailings.
Storage of the tailings in closed buckets at room temperature may explain the water content variability, as evaporation in the top layers may be more important than in the layers beneath.

As explained in part 2.3.3 it is crucial to control the water content in mortar, as the w/c ratio greatly influences the compressive strength. Therefore the tailings water content should be accounted for and the volume of mixing water should be adjusted when incorporating tailings in mortar. The first mortar specimens to be cast, namely ZC5 and NC5, were prepared using moist tailings. For these castings, it was assumed that the water content in the tailings was negligible compared to the total water content. Indeed a water content in the tailings of 13.4% (corresponding to the worst case situation from table 4.1) represents an increase of the total water content in mortar by 1,3%, when the volume of mixing water is 225 mL. It is therefore relevant to neglect the tailings water content for mortar with 5% cement replacement with tailings. However, after acknowledgment of the substantial water content in the tailings and of its variability, it was decided to use dried tailings for the rest of the castings as stated in 3.3.2

4.1.2 Heavy metals and sulfur contents

The trace elements contents in Zinkgruvan and Nalunaq tailings are displayed in table 4.2 below. Previous results obtained by Jensen et al. (2016) are used for comparison. Detailed results are given in appendix B.2.

Results are also compared with the threshold fixed by the Danish Environment Protection Agency for category 1, 2 and 3 materials used in construction. Materials falling under category 2 and 3 are considered more harmful than materials complying with category 1, thus their use in construction materials is more restricted (Miljøstyrelsen, 2010).

Sulfur content in the tailings is also indicated as it may have an influence on concrete properties if it leads to the presence of sulfates in mortar. Indeed, high concentrations of sulfates in mortar will lead to a degradation of cement hydration products through chemical reactions with sulfate ions. This is known as the sulfate attack and would decrease mortar strength and durability (Kumar Mehta and Monteiro, 2006).

Table 4.2: Heavy metals and sulfur contents in the tailings, in mg/kg *dry matter* ± standard deviation, compared with previous results (Jensen et al., 2016) and with the limits for category 1, 2 and 3 materials (Miljøstyrelsen, 2010)

	Zinkgruvan - Present study	Zinkgruvan - Jensen et al.	**Nalunaq - Present study**	Nalunaq - Jensen et al.	Limit - Cat. 1	Limit - Cat. 2 & 3
As	49 ± 6	21 ± 2	529± 15	122 ± 35	<20	>20
Ba	258 ± 9	-	7.0 ± 0.1	-	-	-
Cd	12.6 ± 0.4	11 ± 0.2	2.3 ± 0.2	2.8 ± 0.9	<0.5	>0.5
Cr	3.7 ± 0.2	-	27.4 ± 0.1	-	<500	>500
Cu	94 ± 1	372 ± 28	264 ± 5	105 ± 28	<500	>500
Ni	18 ± 1	24 ± 3	47 ± 1	48 ± 13	<30	>30
Pb	3995 ± 465	3700 ± 233	10 ± 1	59 ± 14	<40	>40
S	5348 ± 170	-	2712 ± 122	-	-	-
Zn	7717 ± 346	7331 ± 322	37 ± 2	45 ± 22	<500	>500

As expected, both Zinkgruvan and Nalunaq tailings have high contents of heavy metals. They both fall under category 2 or 3 materials due to certain heavy metals contents exceeding the category 1 threshold.

Most results from the present study are comparable with the findings of Jensen et al. (2016), although some variations are observed:

- In Zinkgruvan tailings, content in arsenic is twice as high in the present study, while copper content is more than 3 times lower.

- In Nalunaq tailings, arsenic and copper contents are respectively almost 5 times and 2.5 times greater in the present study, while lead content is nearly 6 times lower.

This suggests that some heavy metals may not be homogeneously distributed in the tailings.

Heavy metals in Zinkgruvan tailings

In Zinkgruvan tailings the contents in lead and zinc exceed the threshold for category 1 materials by two orders of magnitude. Lead and zinc are extracted from the Zinkgruvan mine, which can explain the high residual amounts of these two metals. Copper is also extracted but its content remains below the threshold for category 1 waste.

Additionally Zinkgruvan tailings contain significant amounts of arsenic and cadmium, respectively about twice and 25 times greater than the category 1 limit. Substantial arsenic content can be attributed to the occurrence of cobaltite (CoAsS) and chalcopyrite (FeAsS) in the ore deposit (Bjärnborg, 2009). Substitution of zinc for cadmium in sphalerite, the main zinc ore, was also reported (Bjärnborg, 2009), which can explain the high cadmium content.

Chromium, copper, and nickel contents all lie below the category 1 limit.

Heavy metals in Nalunaq tailings

In Nalunaq tailings the contents in arsenic, cadmium and nickel exceed the limit for category 1 waste, with amounts that are respectively over 25, 4 and 1.5 greater than the limit.

According to the present results, the lead content in Nalunaq tailings does not exceed the threshold. This differs from the results of Jensen et al. (2016) who found a lead content exceeding 40 mg/kg. Therefore the presence of lead may also be a concern in Nalunaq tailings.

Contents in chromium, copper and zinc lie below the category 1 limit.

Sulfur content in Zinkgruvan and Naluna tailings

Sulfur content is roughly twice as high in Zinkgruvan tailings as in Nalunaq tailings. The main concern regarding sulfur content in the tailings is that contamination of mortar with high concentrations of sulfates would result in strength loss due to the sulfate attack. Sulfates can form through oxidation of sulfide compounds, for instance if tailings are subjected to weathering (Yin and Catalan, 2003). It was reported that Zinkgruvan and Nalunaq tailings both have low sulfides content compared to other types of mine waste (Lövgren et al., 2011; Bell et al., 2017). However, the digestion test does not provide any information on the compounds formed by sulfur. Sulfate leaching from crushed mortar is investigated in 4.3.6.

Health and environmental concerns

Due to their substantial amounts of arsenic, cadmium, lead and zinc, Zinkgruvan tailings fall under category 2 or 3 waste according to Miljøstyrelsen (2010). Similarly, due to their content in arsenic, cadmium, nickel and potentially lead, Nalunaq tailings also fall under category 2 or 3 waste.

Exposure to arsenic, cadmium, lead and nickel, even at a low level, is correlated with increased risks of cancer, as well as other conditions such as cardiovascular, neurological, respiratory and reproductive diseases (Tchounwou et al., 2012; Chervona et al., 2012). On the other hand, zinc is fairly harmless at low doses, although a high level of exposure can lead to severe intoxication (Fosmire, 1990).

Consequently, considering their respective amount and toxicity, the main environmental and safety concerns regard arsenic, lead and cadmium contents in Zinkgruvan tailings, and arsenic and cadmium contents in Nalunaq tailings.

Tailings should be handled with particular care to avoid contamination of the environment and human exposure especially through dust inhalation or skin contact.

In order to assess the safety of using tailings in concrete, it is essential to determine whether the cement matrix can immobilize the toxic elements they contain, or if these elements can leach out. This was investigated through pH-desorption tests and leaching tests on crushed mortar (see 4.1.3 and 4.3.5).

4.1.3 pH-desorption from the tailings

Results of the pH-desorption tests are documented and discussed below. Detailed results are given in appendix B.3. Desorption rates from the tailings depending on the pH of the leaching medium are expressed in % *metal released*.

Desorption of toxic elements at high pH is of particular interest as concrete is an alkaline material with a pH that usually lies above 12 (Kumar Mehta and Monteiro, 2006). Therefore, leaching from the tailings at high pH could indicate a risk of leaching from mortar containing tailings as well, which would be problematic for environmental and health reasons.

Zinkgruvan tailings

Figure 4.1 displays the results of the pH-desorption tests conducted on Zinkgruvan tailings for arsenic, cadmium, lead and zinc. In section 4.1.2 these elements were found to exceed the limit for category 1 waste (Miljøstyrelsen, 2010). Result for desorption of zinc at pH=1 is not displayed as the measured desorption rate was abnormally high and not coherent, reaching nearly 400%. This measurement should be redone.

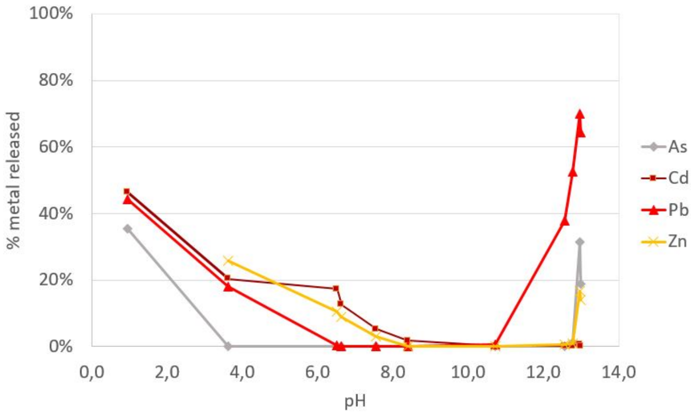


Figure 4.1: pH-desorption of As, Cd, Pb, and Zn from Zinkgruvan tailings

Figure 4.2 displays the results for barium, chromium, copper and nickel desorption. In section 4.1.2 these elements were found to remain below the limit for category 1 waste.

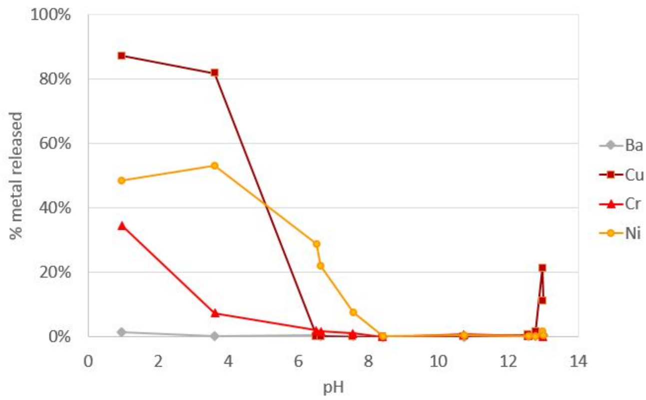


Figure 4.2: pH-desorption of Ba, Cu, Cr, and Ni from Zinkgruvan tailings

From figure 4.1 it is observed that leaching of lead, arsenic and to a lesser extent zinc is significant in alkaline conditions, from pH>10. Leaching of lead reaches the highest level, with a release rate of 70% at pH = 13. Leaching of zinc and arsenic range from 20 to 30%, respectively, at pH=13. From pH=10, desorption rate of arsenic, lead and zinc increases with pH. Desorption of lead appears to begin at pH=11, while leaching of arsenic and zinc start from pH=13. However this should be confirmed with additional measurements for pH= 11-12.

As pH in concrete or mortar usually lies above 12 (Kumar Mehta and Monteiro, 2006), results suggest that leaching of lead at a high release rate may occur in mortar containing Zinkgruvan tailings. Leaching of arsenic and zinc may also occur if the pH is high enough. This is particularly concerning due to the large amounts of these three elements in the Zinkgruvan tailings, as discussed in 4.1.2. In particular lead content is almost 1000 times greater than the limit for category 1 waste (Miljøstyrelsen, 2010).

Cadmium, that is also present in amounts significantly exceeding the limit for category 1 waste (Miljøstyrelsen, 2010), remains bound in the tailings at high pH, indicating that it could be immobilized in the cement matrix when tailings are incorporated in mortar.

From graph 4.2 it is observed that copper is desorbed from the tailings in alkaline conditions, reaching a release rate of 20% at pH = 13. The other elements investigated, namely barium, chromium and nickel, remain bound in the tailings even at high pH.

From figures 4.1 and 4.2 it can be seen that in acidic conditions leaching occurs for all the elements investigated except barium. This is not surprising as acidic environments are known to enhance dissolution of heavy metals (Saria et al., 2006). Desorption of cadmium and nickel occur even at pH= 6-7. This means that particular care should be taken when handling and storing the tailings, as exposure to for instance rainwater could result in leaching of these two elements.

Nalunaq tailings

Figure 4.3 displays the results for the pH-desorption tests performed on Nalunaq tailings for arsenic, cadmium, nickel and lead. In section 4.1.2 these elements were all found to exceed the limit for category 1 waste set by Miljøstyrelsen (2010).

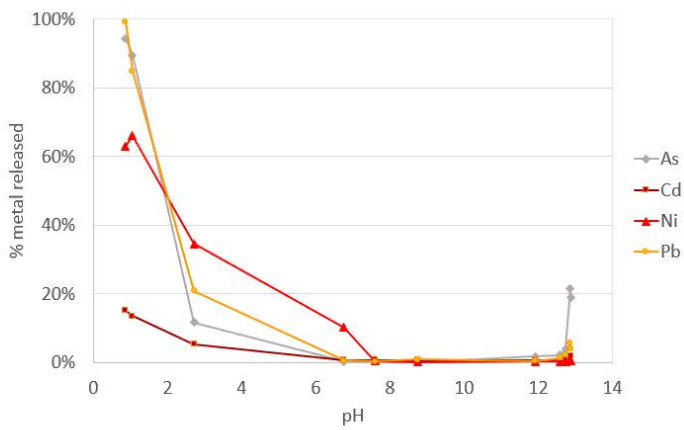


Figure 4.3: pH-desorption of As, Cd, Ni and Pb from Nalunaq tailings

Figure 4.4 displays the results for barium, chromium, copper and zinc. In section 4.1.2 these elements were found to remain below the limit for category 1 waste set by Miljøstyrelsen (2010).

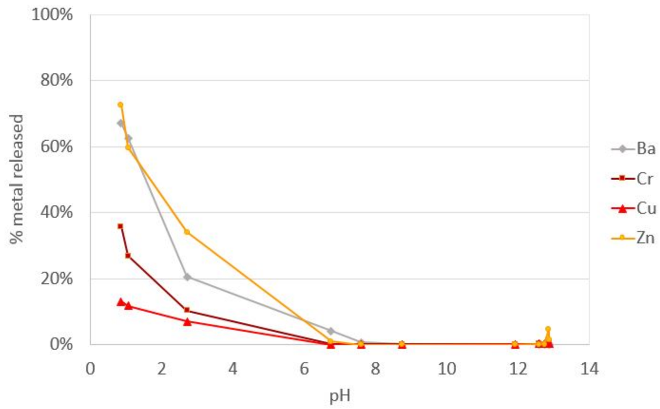


Figure 4.4: pH-desorption of Ba, Cr, Cu, Zn from Nalunaq tailings

From graph 4.3 it appears that for pH>12 leaching of arsenic reaches a maximum release rate of roughly 20%. This is concerning as the arsenic content in Nalunaq tailings is more than 25 times greater than the threshold for category 1 waste (see 4.1.2). It suggests a potentially problematic leaching of arsenic from mortar containing Nalunaq tailings. However it should be noted that leaching of arsenic is close to 0 for 8<pH<12.5. Therefore having pH<12.5 in mortar containing tailings could help prevent arsenic leaching.

Leaching of cadmium, nickel and lead at alkaline pH is low, ranging from 0 to 6%. This indicates that although these elements are present in high amounts in the tailings, they could remain bound and immobilized in the alkaline cement matrix, and thus they will not necessarily pose a threat.

From figure 4.4 it is observed that leaching of barium, chromium, copper and zinc are all negligible at alkaline pH, meaning that these elements could also be successfully immobilized in the cement matrix.

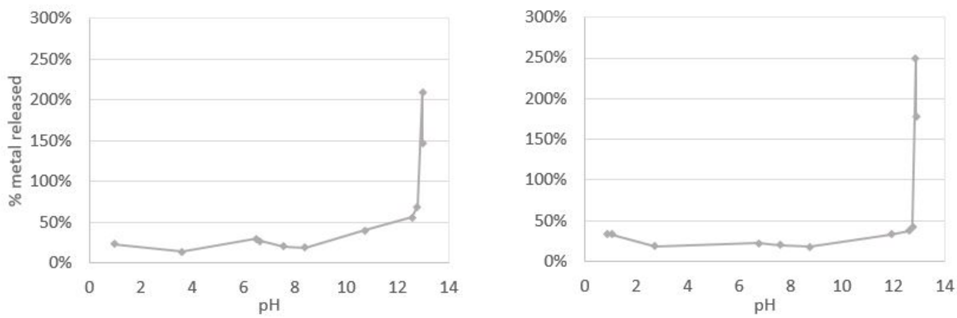
In acidic conditions, leaching occurs for all the elements investigated. The maximum release rates are observed at the lowest pH (pH=0.9), ranging from 13% for copper to 100% for lead. Therefore tailings should not be exposed to acidic conditions to avoid environmental and health issues due to the leaching of toxic elements.

Conclusion on the desorption of heavy metals

Overall, according to the pH-desorption tests, leaching in alkaline conditions of lead, arsenic and zinc from Zinkgruvan tailings and of arsenic from Nalunaq tailings are concerning if tailings are to be used in mortar. Leaching of these elements from mortar containing tailings should be carefully studied to ensure the safety of tailings incorporation. This was investigated in section 4.3.5.

Desorption of sulfur

Figure 4.5 displays the results for sulfur desorption from Zinkgruvan and Nalunaq tailings.



(a) Zinkgruvan tailings (b) Nalunaq tailings

Figure 4.5: pH-desorption of S from Zinkgruvan and Nalunaq tailings

For both Zinkgruvan and Nalunaq tailings, sulfur desorption is highest in alkaline conditions. Significant leaching of sulfur from the tailings indicates potential leaching of sulfates as well, which would be detrimental to mortar sulfate resistance. However no information is provided regarding the compounds in which sulfur occurs. Sulfate leaching was investigated in section 4.3.6.

Sulfur desorption rates from both tailings reach values over 100%, which should not be possible. A first explanation could be that sulfur is not homogeneously distributed in the tailings. It is also possible that all sulfur was not released during the acidic digestion performed on the tailings, as the procedure described in DS 259 (2003) is not designed for sulfur content determination. Therefore sulfur contents obtained in section 4.1.2 and used to determine the percentage of released sulfur may be lower than the reality. Finally, there may have been interferences with other elements during the ICP analysis.

4.2 Heavy metals and sulfur contents in cement and sand

Results regarding the heavy metals contents in sand and cement used in mortar are displayed in table 4.3. Detailed results are given in appendix B.2. Results are compared to the limit set by the Danish Environment Protection Agency for category 1 materials (Miljøstyrelsen, 2010). Results exceeding the threshold are highlighted in red. Unsatisfactory standard deviations, arbitrarily defined as deviations exceeding 20% of the result, are underlined. Results are expressed in mg/kg *dry matter* $\pm$ *standard deviation*.

Table 4.3: Heavy metals contents in cement and sand in mg/kg ± standard deviation

	Sand	Cement	Limit - Cat. 1
As	1.6 ± 0.2	8 ± 1	<20
Ba	3 ± 1	285 ± 14	-
Cd	**1.2 ± 1.4**	0.43 ± 0.03	<0.5
Cr	1.9 ± 0.2	30.6 ± 0.2	<500
Cu	3.0 ± 2.9	98 ± 1	<500
Ni	0.9 ± 0.2	26 ± 1	<30
Pb	3 ± 2	17.2 ± 0.2	<40
S	363 ± 56	14043 ± 336	-
Zn	14 ± 1	37 ± 2	<500

Most standard deviations are acceptable, however five results yielded unsatisfactory deviations. This is possibly due to the detection limit of the ICP-OES analysis as all excessive standard deviations are observed for low amounts of concerned element. Large deviations can be expected when the amount in the element is close to the detection limit. The ICP-OES analysis can detect elements in the eluate from 0.2 mg/L, corresponding to a content of 2 mg/kg.

Overall, heavy metals contents in sand and cement are significantly lower than in the tailings (see 4.1.2). This means that when tailings are incorporated in mortar, they are the primary source of heavy metals.

In sand, apart from cadmium, all metals contents are significantly lower than the limit for category 1 waste (Miljøstyrelsen, 2010). The cadmium content appears to exceed the category 1 threshold. However this threshold is lower than the detection limit of the

ICP-OES analysis and the standard deviation is too large to draw conclusions.

In cement, all elements fall under category 1 waste (Miljøstyrelsen, 2010). Contents in heavy metals are higher in cement than in sand, except for cadmium and zinc. All standard deviations are acceptable.

4.3 Mortar testing

4.3.1 Consistency of fresh mortar

Results of the flow table tests are shown in figure 4.6. The average flow diameter in mm ± standard deviation is displayed for each mortar mixture. Detailed results are given in appendix B.4.

Consistency of mortar containing Zinkgruvan and Nalunaq tailings at 5 and 10% cement replacement has been previously investigated by Nielsen, whose findings will be compared with the present results.

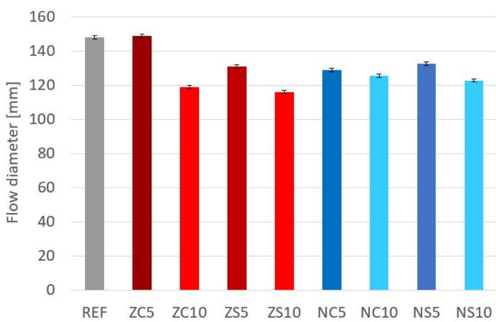


Figure 4.6: Flow diameters

To provide satisfactory workability the consistency of mortar mixtures should remain comparable to that of the reference. Yet, from figure 4.6 it appears that cement and sand replacement with tailings results in most cases in a decrease in the consistency of fresh mortar. Both Zinkgruvan and Nalunaq tailings have a negative impact on the flow diameter.

Flow diameters for REF and ZC5 are almost identical, however for all other mortar mixtures consistency is significantly reduced, with deviations from the mortar mixture ranging from 11 to 22%. A decrease in consistency was also observed by Nielsen (2017) when part of the cement was substituted with Zinkgruvan and Nalunaq tailings. This is possibly due to the angular, plate-like shape of the grains that increases the water absorption potential of the tailings (Nielsen, 2017). The volume of mixing water is identical for all mortar recipes, thus partial absorption of mixing water by the tailings could explain the observed adverse effects. This theory is supported by Onuaguluchi and Eren (2012) who also observed a loss of consistency when studying the impact of copper tailings addition in mortar.

Some differences also exist between the present results and Nielsen's findings (2017). First, unlike in the present study, previous investigations found that the flow diameter increased with cement substitution rate, with both Zinkgruvan and Nalunaq tailings. This result was surprising, as a higher tailings content is expected to result in a higher absorption of water. It should be noted that in the present study, ZC5 and NC5 were cast with moist tailings, while the other mortar mixtures were cast with dry tailings. In Nielsen's study (2017) only dry tailings were used. This could explain the observed differences, as moist tailings may have absorbed less mixing water, resulting in a higher flow diameter for ZC5 and NC5. It is also possible that differences between the two studies are due to the relatively large uncertainty associated with flow table tests, as the results can vary with the instrumentation used, the environment and the person performing the tests (Hinrichs, 2008).

Onuaguluchi and Eren (2012) found that consistency of fresh concrete substantially decreased as the amount of tailings in the mixture increased. This trend is not observed in the present study. Tailings contents in the mortar mixtures are reminded in table 4.4. Apart from ZC5, the flow diameters of mortar mixtures containing tailings are rather similar and an increase in the tailings content does not result in a visible loss of consistency.

Table 4.4: Tailings content in the mortar mixtures

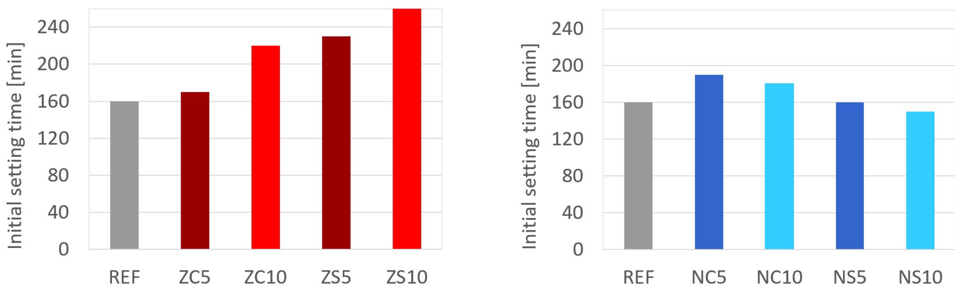
	REF	ZC5, NC5	ZC10, NC10	ZS5, NS5	ZS10, NS10
Tailings content [g]	0	22.5	45	67.5	135

It should be noted that when used as cement replacement, tailings were incorporated from the beginning of the mixing process, whereas when used as sand replacement, tailings were incorporated together with the aggregates after 30 s - 1 min of mixing (see 3.3.3). Delayed addition of tailings may have impacted the consistency as flow diameters of ZC10 and NC10 are respectively lower than that of ZS5 and NS5 although tailings content is higher in the latter. However no literature was found to support this theory.

In order to maintain a satisfactory workability comparable to that of the reference mixture, chemical admixtures such as plasticizers could be added in mortar containing tailings. Thus a higher consistency could be achieved without increasing the volume of mixing water, which would be detrimental to mortar compressive strength. Plasticizers addition in mortar containing tailings was however not investigated in the present study.

4.3.2 Setting time

To determine the setting time of each mortar mixture, a Vicat apparatus was used that measured the penetration depth of a needle plunged in fresh mortar at 10 min intervals. The graphs obtained from the measurements are given in figure 4.8. Detailed results are given in B.5. Figure 4.7 displays the initial setting time in minutes obtained for each mixture, as defined by DS/EN 193-3 (2016). Final setting times are documented in appendix B.5, however they are not discussed here as their determination was judged too unreliable due to the irregular upper surface of the samples. This can be observed on figure 4.8, as large variations subsist for measurements made after 500 min. Setting of mortar mixtures containing tailings as cement replacement was previously investigated by Nielsen, whose findings will be compared with the present results.



(a) Zinkgruvan tailings (b) Nalunaq tailings

Figure 4.7: Initial setting times

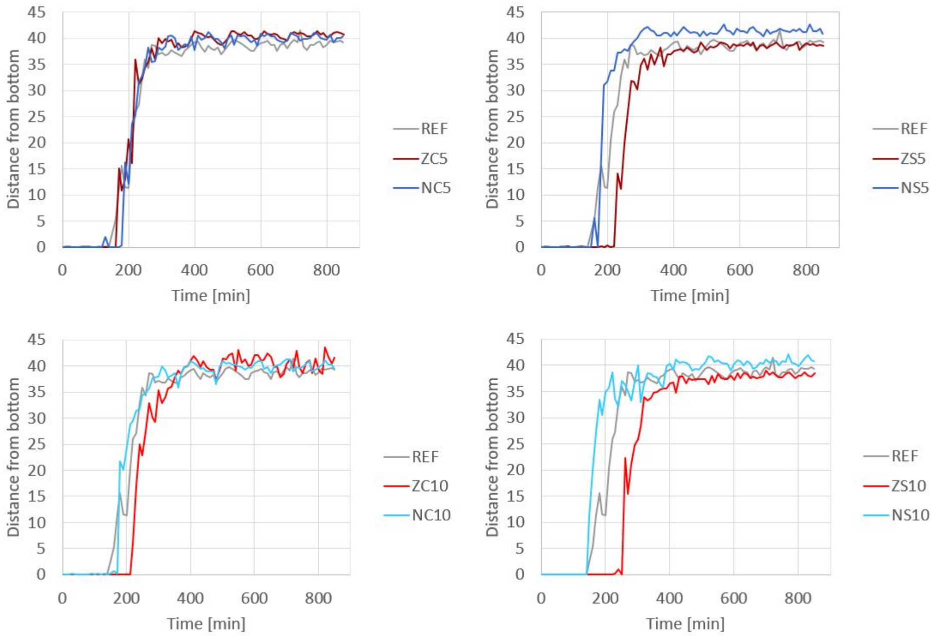


Figure 4.8: Distance between the needle and the bottom of the mould measured by the Vicat apparatus

From figure 4.7 it appears that Zinkgruvan and Nalunaq tailings affect differently the initial setting of mortars. The incorporation of Zinkgruvan tailings results in a delayed initial setting. The delay increases with the amount of tailings in mortar. A decrease in the cement content in ZC5 and ZC10 could contribute to the observed delay for these two mortar mixtures (Mindess et al., 2003). Moreover, previous studies have found that the presence of heavy metals such as copper, lead or zinc delayed cement hydration, thereby increasing setting time (Onuaguluchi and Eren, 2012a; Tashiro et al., 1977). Thus the large amounts of lead and zinc in Zinkgruvan tailings (see 4.1.2) could explain the adverse effects observed on the setting time.

Initial setting times of REF and ZC5 are almost identical, however initial setting of ZC10, ZS5 and ZS10 are significantly delayed, with deviations from the reference ranging from 38 to 63%. Thus, in order to keep the setting time acceptable, tailings content in concrete should remain low. From 4.7 it appears that 5% cement replacement with Zinkgruvan tailings is the optimal solution. Another possibility is to add set accelerators in the mortar mixtures containing large amounts of tailings. However this may have adverse effects on the ultimate strength of mortar (Kumar Mehta and Monteiro, 2006).

Up to a certain amount, Nalunaq tailings delay initial setting of mortar. However, the setting time decreases as the amount of tailings in mortar increases. Compared to the reference, setting is delayed for the mortar mixtures with cement replacement, while it is accelerated for mortar mixtures with sand replacement.

Nielsen (2017) showed that Nalunaq tailings grains are finer than sand but coarser than cement. When sand is substituted with tailings, the proportion of fine particles increases. This may have induced an heterogeneous nucleation effect. This physical process relies on the nucleation of cement hydrates on inert mineral grains. An increase in the specific surface of mineral particles is believed to increase heterogeneous nucleation by providing additional nucleation sites, thereby catalyzing cement hydration (Lawrence et al., 2005). Thus it may explain why mortar mixtures containing Nalunaq tailings as sand replacement see a decrease in their setting time. This explanation is consistent with the fact that setting time decreases as the sand replacement rate increases.

Setting time is however not decreased for mortar with cement replacement. As Nalunaq tailings are coarser than cement particles, cement substitution is not expected to induce heterogeneous nucleation, possibly explaining why the initial setting time is not shortened. Moreover, a decrease in the cement content in NC5 and NC10 could explain why initial setting is delayed compared to the reference mortar (Mindess et al., 2003).

The initial setting time for Basis Cement from Aalborg Portland is 165 min (Aalborg Portland A/S, 2012). This fits the observations as the initial setting time obtained for the reference mortar is 160 min.
Present results are consistent with findings of Nielsen (2017), and the largest deviation observed between the two studies is 20 min. Indeed, a 20 min delay appears in this study for the initial setting time of ZC5 and NC5. Given that measurements were performed every 10 min, this is acceptable.

4.3.3 Compressive strength

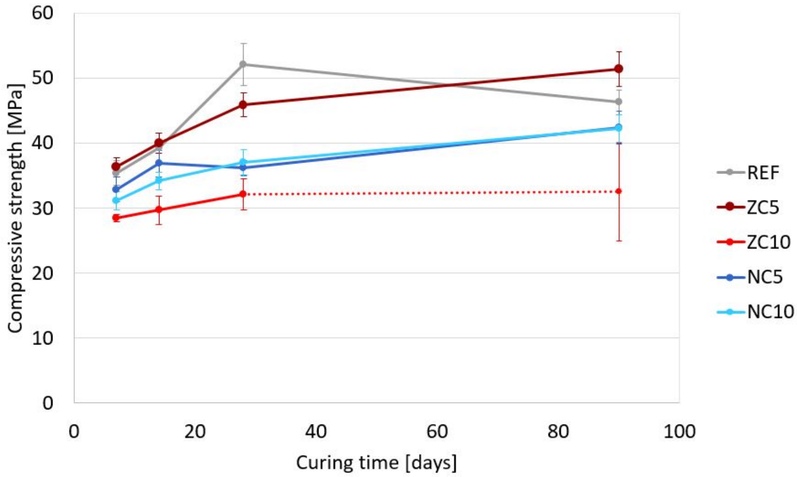
The mortar mixtures were tested for compressive strength after curing times of 7, 14, 28 and 90 days. Results are displayed in figure 4.9. Table 4.5 documents the tests for which one or more results exceeded the 10% margin (see 3.4.3). Detailed results are given in appendix B.6. The impact of cement substitution with Zinkgruvan and Nalunaq tailings on mortar compressive strength has already been investigated by Nielsen (2017). Present results will be compared to that study. Moreover, additional results regarding 90-day compressive strength and the impact of sand replacement with tailings on mortar strength will be discussed.

Table 4.5: Discarded results for the compressive strength tests

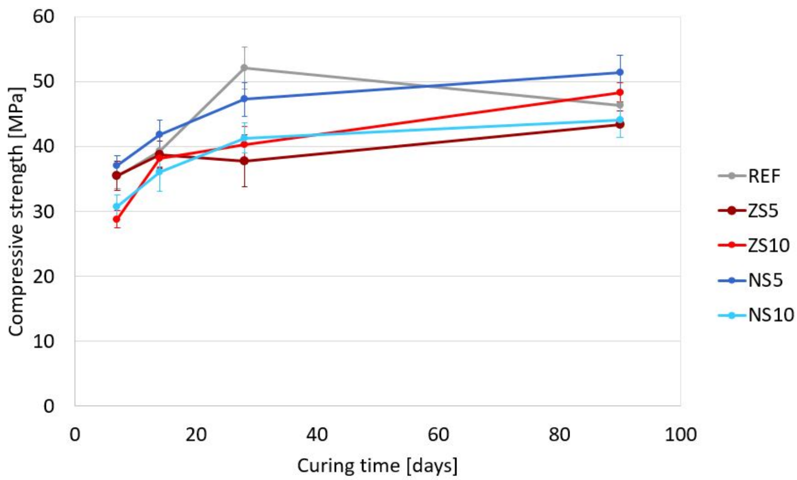
Mortar mixture	Curing time [days]	Discarded results	New determination required
REF	90	1	No
ZC5	28	1	No
	90	1	No
ZC10	7	1	No
	90	4	**Yes**
ZS5	7	1	No
	90	1	No
ZS10	7	1	No
	14	1	No
	90	1	No
NC5	90	1	No
NC10	14	1	No
	90	1	No
NS5	90	1	No
NS10	7	3	**Yes**
	14	1	No
	28	1	No
	90	1	No

Conditions under which results are not satisfactory and strength determination should be carried out again are specified by DS/EN 196-1 (2005) and mentioned in 3.4.3. From table 4.5 it appears that 2 determinations should have been performed again due to excessive deviations of the results. Determination of the 7-day compressive strength NS10 was performed again and new results were satisfactory. However 90-day compressive strength of ZC10 was not determined again due to time constraints. From table 4.5 it also appears that for all mortar mixtures, the 90-day compressive strength tests yielded at least one result that differed by more than 10% from the calculated average strength. Such variations may be due to the incident mentioned in section 3.4.3. However, although determination should be redone for ZC10, all the other tests complied with DS/EN 196-1 (2005).

Figure 4.9 displays the compressive strengths with their respective standard deviations for the various mortar recipes after 7, 14, 28 and 90 days of curing. As the 90-day compressive strength test for ZC10 yielded unsatisfactory results but could not be performed again, the corresponding strength development is plotted in a dotted line.



(a) Cement substitution



(b) Sand substitution

Figure 4.9: Compressive strength for 7, 14, 28 and 90 curing days

Early age strength development

Cement replacement From 4.9(a), considering the results for 7 and 14 curing days, cement substitution with tailings leads in most cases to a loss of compressive strength. This is expected as the w/c ratio increases with the substitution rate. w/c ratios for the different mortar mixtures are reminded in table 4.6. Early age strength development of ZC5 and of reference mortar are very similar while results for NC5, NC10 and ZC10 are noticeably lower. This differs from the findings of Nielsen (2017), who observed a decrease in early age strength for all mortars containing tailings, including ZC5.

In the present study, after 7 and 14 days of curing, NC5 yields a lower strength than ZC5. This is unexpected and also contrasts with Nielsen's findings (2017). Indeed, Nielsen found that Nalunaq tailings have filler properties, complying with the filler limit set to 250 µm. Therefore a higher strength for NC5 than for ZC5 was expected. However, compressive strength of NC10 is higher than that of ZC10 for all curing times, which differs from Nielsen's findings (2017) but corresponds to the expectations.

Sand replacement From 4.9(b), when considering results for curing times of 7 and 14 days, sand substitution with tailings leads to similar to slightly increased compressive strengths at a replacement level of 5%, and to lower to similar compressive strengths at a replacement level of 10%. Variations cannot be explained by a change in the w/c ratio as it is identical for all the concerned mixtures, with $w/c = 0.5$.

The highest 7- and 14-day compressive strength is obtained for NS5. As Nalunaq tailings contain substantial amounts of fine particles compared to sand (Nielsen, 2017), this could indicate that Nalunaq tailings induce a beneficial filler effect optimizing the pore structure, as discussed in the previous paragraph. However this is not supported by the results of the density and porosity tests. Moreover, NS10 yields compressive strengths lower than the reference for 7 and 14 days of curing. This could be due to the lower workability of the mixture that may have adversely affected compaction of mortar in the moulds during casting.

Early age strength developments of ZS5 and REF are almost identical. 7-day compressive strength of ZS10 is significantly lower than that of the reference, but 14-day strengths of REF, ZS5 and ZS10 are almost identical. It was shown that Zinkgruvan tailings are coarser than Nalunaq tailings and that grain size distribution of Zinkgruvan tailings is closer to that of sand than that of cement or fly ash. This may explain why sand substitution with Zinkgruvan tailings has a limited impact on early age strength development of mortar.

28-day compressive strength

The 28-day compressive strength is commonly used as an index of mortar and concrete strength and is therefore of particular interest. 28-day compressive strengths for the various mortar mixtures are displayed in figure 4.10.

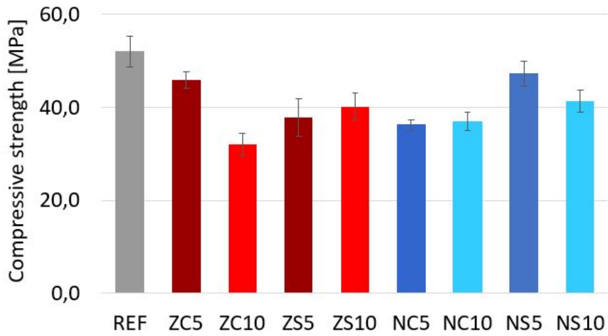


Figure 4.10: 28-day compressive strength

Comparison with Bolomey formula Experimental results can be compared to the theoretical strengths calculated according to Bolomey formula as displayed in table 4.6. Bolomey 28-day strengths were calculated based on the equation stated in 2.3.3. Parameters were set to the values provided by Aalborg Portland A/S (2012) for 28-day strength calculation : $\alpha = 0.5$ and $K = 30$.

From table 4.6 it appears that the experimental 28-day strength of the reference mortar is noticeably higher than its Bolomey strength. However, while ZC5 and NC5 experimental strengths are slighlty higher than their Bolomey strength, all the mortar mixtures containing tailings yielded results lower than their theoretical strength. It should be noted that Bolomey formula is normally intended for concrete containing fine and large aggregates, whereas in mortar only sand is used. Therefore experimental mortar strength results are expected to exceed the Bolomey strength, which is only verified for REF, ZC5 and NS5. Possible explanations for the observed strength losses are discussed below.

Table 4.6: Comparison of 28-day compressive strengths with Bolomey formula

	w/c [-]	$f_{c28\,Bolomey}$ [MPa]	f_{c28} [MPa]	Deviation from $f_{c28\,Bolomey}$ [%]
REF	0,50	45	51.7	+15
ZC5	0,53	42	45.9	+9
NC5	0,53	42	36.2	-14
ZC10	0,56	39	32.1	-18
NC10	0,56	39	37.0	-5
ZS5	0,50	45	37.8	-16
NS5	0,50	45	47.3	+5
ZS10	0,50	45	40.2	-11
NS10	0,50	45	41.3	-8

Cement replacement From figure 4.10 it can be seen that cement substitution with tailings results in a decrease in the 28-day compressive strength for all concerned mortar mixtures (ZC5, ZC10, NC5, NC10). This is expected as the w/c ratio increases when cement is substituted.

After 28 days of curing, a slight decrease is observed in the strength of ZC5, that is 11% lower than that of the reference mortar. Replacement of 10% cement with Zinkgruvan tailings leads to a 38% strength loss compared to the reference mortar. As the w/c ratio increases with the substitution rate, these strengths losses were expected. This substantial decrease is also supported by Nielsen.

Replacement of cement with Nalunaq tailings also results in a decrease in the 28-day compressive strength, as observed by Nielsen, 2017. Compressive strengths of NC5 and NC10 are very similar, unlike strengths of ZC5 and ZC10. Nielsen also observed that the impact of the cement substitution rate was lesser for mortar with Nalunaq tailings than mortar with Zinkgruvan tailings, although variations between the strengths of NC5 and NC10 were more substantial than in the present study. Nielsen (2017) found that mortar with Zinkgruvan tailings used as cement replacement yielded higher 28-day compressive strengths than the corresponding mortar mixture with Nalunaq tailings. This observation is verified when comparing strength of ZC5 and NC5, however in the present study ZC10 yields a lower strength than NC10.

In this study, the strength of NC10 is even slightly higher than that of NC5, with respective compressive strengths of 37 and 36.2 MPa. This is unexpected as the water ratio is higher in mortar with 10% cement substitution than with 5%. It may be due to the filler properties of Nalunaq tailings that increase with the tailings content. However a filler effect should result in a denser and less porous mortar, which was not observed after the density and porosity tests (see 4.3.4).

Sand replacement From figure 4.10 it appears that sand substitution with tailings results in lower 28-day compressive strengths compared to the reference mortar.

ZS5 and ZS10 yield similar results, with respective compressive strengths of 37.8 and 40.2 MPa. These results are significantly lower than the strength of the reference mortar, corresponding to 51.7 MPa. This contrasts with the results for 7 and 14 curing days that showed very similar early age strength development for ZS5, ZS10 and REF.

Sand replacement with Nalunaq tailings causes less substantial strength losses than Zinkgruvan tailings. Compressive strengths of NS5 and NS10 are respectively equal to 46.3 and 41.3 MPa. While NS5 showed higher 7 and 14-day compressive strengths than REF, its 28-day compressive strength is 9% lower than that of the reference mortar. This strength loss remains however acceptable.

Overall strength losses are lower than for mortar in which cement was substituted with tailings. This was expected as the w/c ratio increases when cement is replaced but remains unchanged when sand is replaced. Yet this means that similar strengths for the reference mortar and for mortar mixtures with sand replacement were expected. However substantial strength losses were observed. A possible explanation is that mortar with sand replacement is less workable (see 4.3.1) which may have adversely affected the compaction during casting, creating extra air voids in the specimens and decreasing the strength. However no visible increase in open porosity was observed in section 4.3.4. It is also possible that tailings incorporation caused new chemical reactions in mortar, such as sulfate attack, resulting in detrimental effects on the compressive strength. This is discussed in section 4.3.6.

Previous research on lead and zinc tailings used as sand replacement in self-compacting concrete showed positive effects of the tailings on the 28-day compressive strength (Jankovic et al., 2015). Other studies on copper tailings used as fine aggregates replacement showed that tailings could affect 28-day strength positively at w/c ratios greater than 0.5, but negatively at w/c=0.45 (Beniwal et al., 2015). Therefore it could be beneficial to investigate sand substitution with tailings at different w/c ratios.

90-day compressive strength

Although 28-day compressive strength is commonly used to characterize concrete and mortar strength, it is also relevant to investigate strength development at a later age. Indeed, cement hydration keeps occurring for several years, therefore strength increases over time (Kumar Mehta and Monteiro, 2006). Compressive strength of mortar mixtures after 90 days of curing was determined and results can be seen in figure 4.9. Determination for ZC10 should have been redone as results did not comply with DS/EN 196-1

(2005) but due to lack of time it could not be performed again. Specimens may have been affected by the incident described in 3.4.3, therefore results should be treated with caution. In particular, from figure 4.9 it appears that the 90-day compressive strength of the reference mortar is abnormally lower than its 28-day strength, which may be due to said incident.

Cement replacement From figure 4.9(a) it can be seen that ZC5 yields the highest result with a 90-day compressive strength of 51.3 MPa. This is however lower than the 28-day strength of the reference mortar, namely 51.7 MPa. ZC10 achieves the lowest strength, which is consistent with strength determination at earlier age. However results did not comply with DS/EN 196-1 (2005) and due to the large standard deviation the strength result for ZC10 is unreliable.

Compressive strengths of NC5 and NC10 are almost identical. This is also consistent with the previous investigations that found comparable strengths for these two mortar mixtures after 7, 14 and 28 days.

The rate of strength gain between 28 and 90 days, that can be derived from the slopes on figure 4.9(a), appears to be very similar for ZC5, NC5 and NC10. Previous research found that Zinkgruvan tailings may have pozzolanic activity (Nielsen, 2017). If it was the case, a higher rate of strength enhancement should be observed for ZC5 as pozzolanic materials contribute to long term strength (Kumar Mehta and Monteiro, 2006). Therefore present observations do not support the theory of pozzolanic activity in Zinkgruvan tailings.

Sand replacement As shown on figure 4.9(b), for each mortar mixture with tailings used as sand replacement, the 90-day compressive strength is higher than the 28-day strength. NS5 achieves the highest 90-day compressive strength with 51.3 MPa. This is however lower than the 28-day strength of the reference mortar, corresponding to 51.7 MPa. Compressive strength of NS10 after 90 days is significantly lower than that of NS5. This is consistent with previous investigations regarding compressive strength after 7, 14 and 28 curing days.

ZS10 achieves a higher strength than ZS5. This was also the case after 28 days. One explanation could be that Zinkgruvan tailings have pozzolanic activity, as suggested by (Nielsen, 2017). An increase in pozzolanic materials in the mortar would thus increase the long-term strength. The rate of strength gain between 28 and 90 days, derived from the slopes on figure 4.9(a) is higher for ZS5 and ZS10 than for NS5 and NS10, which could also be explained by a pozzolanic activity in Zinkgruvan tailings. This theory regarding their pozzolanic properties was however not supported by the previous results obtained for the 90-day strength of ZC5 ad ZC10 therefore further investigations are needed to validate this assumption.

Consistency of the compressive-strength results

The operator's skills and therefore the quality of castings may improve after several mortar specimens castings are performed, which can affect mortar compressive strength. In order to ensure results consistency, compressive strengths of reference mortar specimens after 7, 14 and 28 days were determined twice and compared. The first specimens, labelled REFa, were cast on the first casting day. The second specimens, labelled REF, were cast on the fifth casting day (see table 3.4). REF and REFa specimens were both subjected to compression tests after 7, 14 and 28 curing days. Results with their respective standard deviations are displayed in figure 4.11.

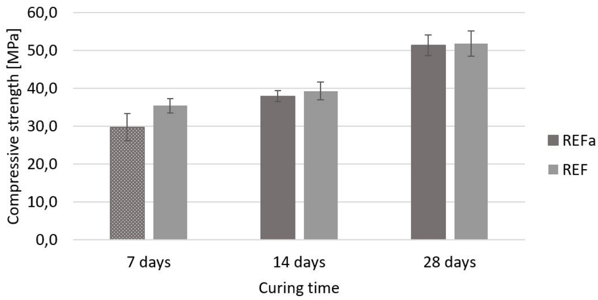


Figure 4.11: Compressive strengths of REFa and REF

According to DS/EN 196-1 (2005), determination of the 7-day compressive strength of REFa had to be redone due to excessive deviation of the results. REF gave satisfactory results for the 7-day strength.

Both 14-day and 28-day compressive strength tests gave very similar results for REF and REFa. This indicates that the quality of castings did not significantly improve over time, thus results can be considered reliable.

It was chosen to report results obtained for REF in section 4.3.3.

4.3.4 Porosity and density

Results of the density and porosity experiments with the standard deviations are given in table 4.7. Mean values for the dry density and open porosity of the mortar specimens are displayed with their respective standard deviations. Porosities are also displayed in figure 4.12 for better visualisation of the results. Detailed results are given in appendix B.7.

Table 4.7: Dry density and open porosity of the mortar mixtures

	Density [kg/m^3]	Porosity [%]
REF	2014 ± 10	20.7 ± 0.9
ZC5	2045 ± 20	21.2 ± 0.7
ZC10	2027 ± 5	21.6 ± 0.1
ZS5	2008 ± 3	22.2 ± 0.1
ZS10	2014 ± 9	22.2 ± 0.3
NC5	2016 ± 5	21.8 ± 0.1
NC10	2002 ± 11	22.6 ± 0.4
NS5	2065 ± 5	20.2 ± 0.1
NS10	2041 ± 7	21.2 ± 0.3

From table 4.7 it appears that densities are very similar from one mortar mixture to the other. They range from 2008 to 2065 kg/m^3, which represents a difference of 2.8%. There is no clear trend indicating an increase or decrease of density due to the incorporation of tailings.

Porosities are also very similar and range from 20.2 to 22.2%. Porosity of mortar containing tailings is in most cases slightly superior to that of the reference mortar. In mortar containing Zinkgruvan tailings porosity increases very slightly with tailings content. However the differences are very small, especially when accounting for the standard deviations. In mortar containing Nalunaq tailings porosities are slightly higher than that of the reference mortar except for NS5. There is not clear trend indicating an increase in porosity

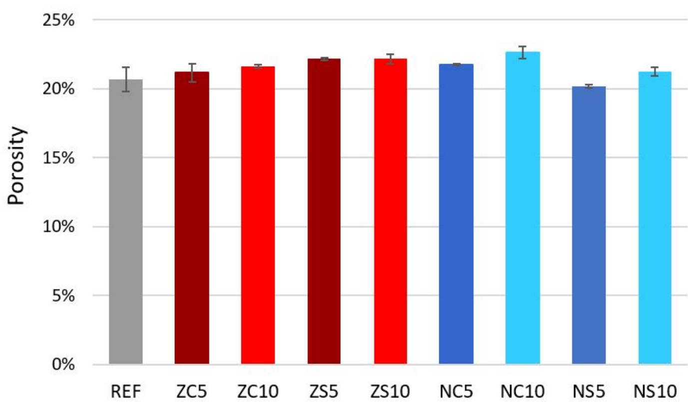


Figure 4.12: Open porosity of the mortar mixtures

with tailings content. Slightly higher porosities in mortar containing tailings may be due to a poorer workability compared to the reference mortar. The loss of consistency of fresh mortar with tailings observed in 4.3.1 may have hindered proper compaction in the moulds, thereby increasing the volume of air voids.

Overall, at the considered substitution rates, neither Zinkgruvan nor Nalunaq tailings seem to have a significant impact on mortar dry density and open porosity. An increase in porosity could have adversely affected mortar strength (see 2.3.3). It could also have increased mortar permeability, thus possibly contributing to leaching of heavy metals by permitting an easier circulation of leachable toxic elements in the interconnected pores network (Galvin et al., 2014).

When investigating copper tailings incorporation in concrete mixtures, Onuaguluchi and Eren (2012) found that porosity slightly increased with tailings content, which is consistent with the present findings concerning Zinkgruvan tailings. This is however not observed in mortar containing Nalunaq tailings.

However it should be noted that the test methods only allowed determination of total open porosity. The experiments performed did not provide information concerning pore size distribution in mortar, although it may have been affected by tailings incorporation. In reality, strength and permeability of concrete are more dependent on the pore size distribution than on the total porosity (Kumar Mehta and Monteiro, 2006). Therefore additional experiments could be beneficial to determine if tailings affect pore size distribution in mortar.

4.3.5 Leaching of heavy metals and sulfur from crushed mortar

Results of the leaching tests performed on crushed mortar samples are given in figure 4.13, for the following elements: As, Ba, Cd, Cr, Cu, Ni, Pb, S, Zn. Concentrations in the eluates with their standard deviation are displayed for each mortar mixture. When it exists, the limit for category 1 waste set by Miljøstyrelsen is plotted in a green line. For a better readability of the graphs, the limit for category 3 waste is only indicated if it is exceeded, and is plotted in an orange line. Detailed results including leaching of Al, Fe and Y are given in appendix B.8.1.

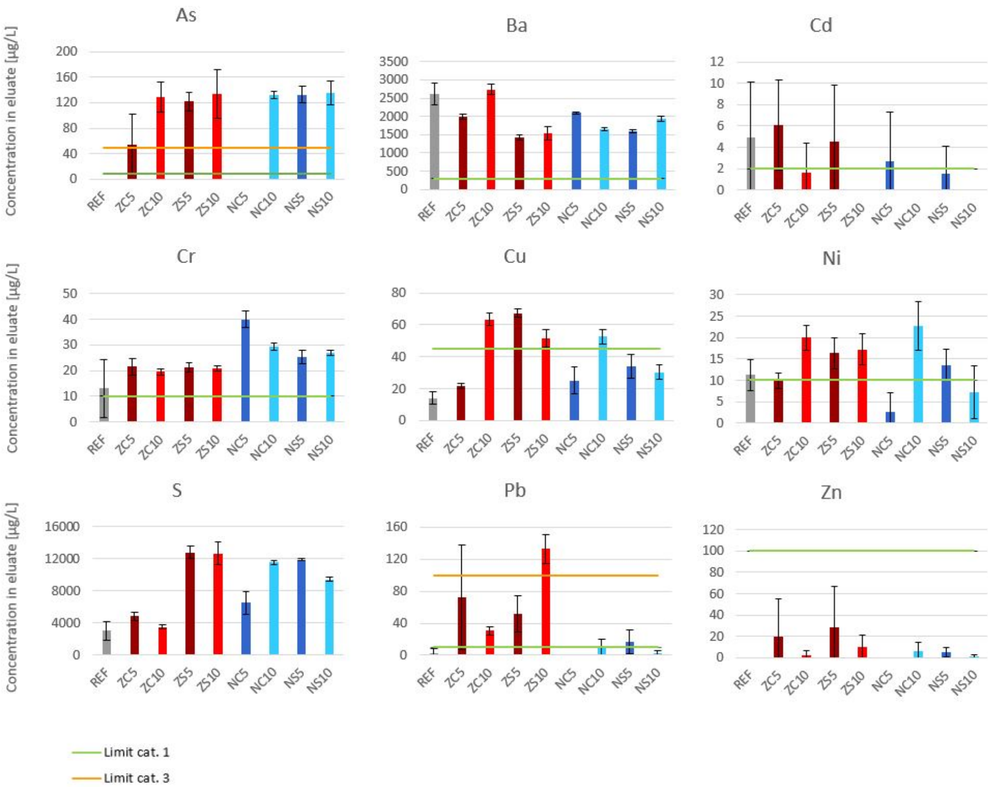


Figure 4.13: Leaching from crushed mortar of As, Ba, Cd, Cr, Cu, Ni, Pb, S, Zn

Leaching of arsenic

There is no leaching of arsenic occurring from the reference mortar. However, the leaching rate of arsenic from mortar containing Zinkgruvan tailings is significant, ranging from 54 to 133 µg/L in the eluate, for ZC5 and ZS10 respectively. Leaching from ZS10 is thus respectively 16 and 2.6 times larger than category 1 and 3 limits set by Miljøstyrelsen (2010) for waste materials used in construction. Standard deviations are relatively large, but results seem consistent as leaching results for ZC10, ZS5 and ZS10 are very close. Arsenic also significantly leaches out from mortar containing Nalunaq tailings. Leaching results from NC10, NS5 and NS10 are very close, ranging from 132 to 135 µg/L, with acceptable standard deviations. These results also exceed the limit for category 1 and 3. No leaching of arsenic was however observed for NC5, which is surprising and may indicate that for an amount of tailings low enough, arsenic can be stabilized by the cement matrix.

Leaching results for mortar containing Zinkgruvan and Nalunaq tailings are very similar except for ZC5 and NC5. Yet the initial arsenic content in Nalunaq tailings is 25 times higher than in Zinkgruvan tailings (see 4.1.2). During the pH-desorption tests, the maximum arsenic release rate in alkaline conditions was only 10% higher for Zinkgruvan tailings than for Nalunaq tailings. Hence a higher leaching from mortar containing Nalunaq tailings than from mortar containing Zinkgruvan tailings was expected. The results suggest that although arsenic leaching is significant, part of the arsenic contained in Nalunaq tailings is successfully immobilized in the cement matrix.

For mortar with both tailings, arsenic leaching seems to be lower at the 5% cement substitution level. Results are almost identical for all the other substitution rates.

B. Kim et al. (2016) determined the leaching fraction of arsenic from cementitious controlled low strength materials containing arsenic-rich tailings. It was found that the leaching fraction of arsenic remained minor, thus the waste was successfully stabilized. The tests methods from B. Kim et al. (2016) differ from tests conducted in the present study, therefore results cannon be quantitatively compared. However present results compared with the limits set by Miljøstyrelsen (2010) suggest the Stabilization-Solidification treatment process is not as successful in the present study and that arsenic leaching from mortar containing Zinkgruvan or Nalunaq tailings is concerning.

Leaching of barium

Leaching of barium is large for all the mortar mixtures investigated, including for the reference mortar. Results range from 1426 µg/L for ZS5 to 2737 µg/L for ZC10, while the limit for category 1 waste is set to 300 µg/L. Standard deviations are acceptable.

Such a significant leaching of barium was not expected as even the reference mortar does not comply with the requirements for category 1 waste. All results remain however below the limit for category 3, that is set to 4000 µg/L (Miljøstyrelsen, 2010). Present results are supported by Hansen (2016) who also found large barium leaching rates reaching around 1000 µg/L in similar experiments. The main source of barium in mortar is cement, with a content of 285 mg/kg (see 4.2. Zinkgruvan tailings contain comparable amounts of barium (257 mg/kg). Barium content in sand and in Nalunaq tailings is negligible. For both tailings barium was not desorbed in alkaline conditions (see 4.1.3). From figure 4.13 it appears that apart from ZC10, all mortar mixtures yielded leaching rates lower than the reference mortar. This suggests that tailings incorporation in mortar may prevent barium leaching, however no literature was found to support this.

Toxicity of barium is characterized as slight to moderate by Choudhury and Cary (2001) and depends on the barium compounds. Barium sulfate is for example used at high doses as an oral radiocontrast medium. Therefore large leaching rayes of barium from mortar may not pose a serious hazard.

Leaching of cadmium

Calculated average concentrations in cadmium in the eluates are all below the detection limit of the ICP analysis, that corresponds to 20 µg/L. Hence standard deviations are very large, making results interpretation unreliable. It is possible that cadmium leaching rate exceeds category 1 limit for waste materials, including for reference mortar. However all results lie below the limit for category 3 waste, corresponding to 40 µg/L.

Overall, cadmium leaching appears lower for mortar with Nalunaq tailings than with Zinkgruvan tailings. This would be consistent with the fact that cadmium content is higher in Zinkgruvan tailings.

Leaching of chromium

Concentrations in chromium in eluates are nearing the detection limit of the ICP analysis that corresponds to 20 µg/L. Standard deviations are acceptable except for the reference mortar. The deviation is probably large because the detection limit exceeds the calculated average concentration in the eluate.

The lowest result is obtained for the reference mortar. All results exceed category 1 limit but remain way below category 3 limit, corresponding to 500 µg/L. For all mortar mixtures containing Zinkgruvan tailings, leaching of chromium lies around 20 µg/L. Leaching results for mortar mixtures containing Nalunaq tailings are slightly higher, with concentrations stretching from 25 to 40 µg/L. This is consistent with the fact that chromium content in Nalunaq tailings is higher than in Zinkgruvan tailings (see 4.1.2).

Chromium toxicity strongly depends on its oxidation state. Cr(VI) is a known carcinogen and poses the most serious threat to human health and to the environment (D. G. Barceloux and D. D. Barceloux, 1999). However the ICP analysis performed on the eluates does not provide information about chromium oxidation state, therefore further investigations would be needed to determine if chromium leaching from mortar is hazardous.

Leaching of copper

Leaching of copper increases when tailings are incorporated in mortar. Leaching rate of the reference mortar is much lower than the category 1 limit. For mortar mixtures containing Zinkgruvan tailings results are all higher than that of the reference, and 3 out of 4 results are above the category 1 limit.
For mortar mixtures with Nalunaq tailings, results are also higher than that of the reference mortar, with leaching from NC5 exceeding the limit. However all results remain far below the limit for category 3 waste, that corresponds to 2000 µg/L. Leaching from mortar with Zinkgruvan tailings is generally more significant than from mortar with Nalunaq tailings. This is coherent with the results of the pH desorption tests as leaching of copper in alkaline conditions was observed for Zinkgruvan tailings, but not for Nalunaq tailings (see 4.1.3). For 5% cement substitution with both tailings leaching only slightly increases compared to REF, suggesting that excessive leaching of copper can be prevented if the tailings content in mortar remains low enough.

Leaching of nickel

Standard deviations are substantial for all results, due to the relatively low concentrations of nickel in the eluates that are in the same range as the detection limit of the ICP analysis. Six out of nine results exceed category 1 limit, however all results remain below category 3 limit set to 70 µg/L (Miljøstyrelsen, 2010).

From figure 4.13 it can be seen that the incorporation of Zinkgruvan tailings seems to lead to an increase in nickel leaching rates, except for ZC5 that contains the lowest amount of tailings. For mortar mixtures containing Nalunaq tailings, the result for NC10 is significantly higher than for the reference mortar. However, the 3 other mixtures with Nalunaq tailings yielded results comparable or below that of the reference. Nickel leaching from mortar with Nalunaq tailings was expected to be lox to moderate, as nickel content in Nalunaq tailings was found to exceed category 1 limit in section 4.1.2, but no desorption of this element was observed in alkaline conditions in section 4.1.3.

Leaching of sulfur

The incorporation of both Zinkgruvan and Nalunaq tailings results in increased sulfur leaching rates compared to the reference mortar. For mortar containing Zinkgruvan tailings, results are slightly higher for ZC5 and ZC10 compared to the reference mortar. When the amount of tailings increases however, sulfur leaching significantly increases and results for ZS5 and ZS10 are over four times higher than for REF. Incorporation of Nalunaq tailings also increases leaching of sulfur from mortar. All replacement rates result in a significant increase compared to the reference mixture. The largest leaching is observed for NS5 with a sulfur concentration that is almost 4 times higher than that of the reference.

This is consistent with the results of the pH-desorption tests that showed that for both Zinkgruvan and Nalunaq tailings, leaching of sulfur in alkaline conditions occurred at high rates.

The present leaching tests do not provide data about the compounds or oxidation states of sulfur. The main concern is that if sulfur occurs as sulfates in mortar, sulfates will attack cement hydration products and affect mortar compressive strength. Therefore it was decided to determine sulfate release from crushed mortar, as presented in section 4.3.6.

Leaching of lead

Standard deviations are large. This may be due to concentrations in eluate that are close to the detection limit for certain samples, especially for the reference mortar and for mortar mixtures containing Nalunaq tailings. Another explanation could be an inhomogeneous distribution of lead in the mortar samples.

Lead leaching from reference mortar is negligible. However, for all mortar mixtures containing Zinkgruvan tailings, results exceed the category 1 limit. Concentration in eluate from ZS10 also exceeds the category 3 limit.

A significant leaching of lead from mortar containing Zinkgruvan tailings could be expected due to the substantial lead content in the raw tailings (see 4.1.2) and due to the high leaching rate of lead from the raw tailing in alkaline conditions (see 4.1.3.

Therefore the cement matrix seems to be unable to satisfactorily stabilize Zinkgruvan tailings by immobilizing lead. However the test method involved crushing the mortar, that may have resulted in the liberation in the eluate of heavy metals that would have otherwise remained bound in mortar if the test had been performed on a bulk mortar sample.

Leaching rate of lead from Nalunaq tailings is generally low. One result exceeds slightly category 1 limit but the standard deviation is large, therefore it can be assumed that the incorporation of Nalunaq tailings does not result in hazardous lead leaching rates from mortar. This is consistent with the previous investigations as lead content in Nalunaq tailings is acceptable and desorption of lead in alkaline conditions is negligible (see 4.1.2 and 4.1.3).

Leaching of zinc

Leaching of zinc is negligible for the reference mortar and for the mortar mixtures containing Nalunaq tailings. Some leaching of zinc occurs from mortar containing Zinkgruvan tailings, however it remains far below the category 1 limit and therefore should not be problematic. In section 4.1.2 Zinkgruvan tailings were found to contain very large amounts of zinc, and during the pH-desorption tests up to 20% of zinc leached out of the tailing in alkaline conditions. Therefore a significant leaching rate could be expected. Present results suggest that the cement matrix succeeded in immobilizing zinc.

Summary and discussion

The main observations deriving from the leaching tests are summarized below. Results from section 4.1.2 and 4.1.3 are mentioned to interprete the present findings.
For mortar containing Zinkgruvan tailings:

- Leaching of arsenic and lead from mortar are of particular concern. This was expected given the significant contents in these two elements in the raw tailings and given the results of the pH-desorption tests.

- Zinc leaching occurs from mortar with Zinkgruvan tailings, however it does not reach concerning levels. Therefore zinc is successfully immobilized in mortar, although zinc content in the raw tailings is high and significant desorption from the tailings was observed in alkaline conditions. Cadmium leaching from crushed mortar occurs as well, but large standard deviations make it challenging to compare the results. It can however be inferred that cadmium leaching rate does not drastically increase with tailings incorporation. Although cadmium content in the raw tailings was found to be concerning, no cadmium desorption was observed in alkaline conditions, which possibly explains why it is successfully stabilized in mortar.

- Although nickel and copper contents are acceptable in the raw tailings, the leaching rates of these two elements significantly increase and reach potentially problematic levels when tailings are incorporated in mortar, except at 5% cement replacement level.
- Sulfur leaching rate substantially increases when 5% sand or more is substituted with tailings, which will be problematic if sulfur occurs in the form of sulfates.

For mortar containing Nalunaq tailings:

- Leaching of arsenic occurs at concerning rates, except in mortar with the lowest tailings content, corresponding to 5% cement replacement. This was expected as arsenic content in the raw tailings was found to be problematic, and substantial desorption from the tailings occurs at alkaline pH. However, part of arsenic appears to be retained in the cement matrix. Leaching results for mortar with Zinkgruvan and with Nalunaq tailings are indeed comparable although Nalunaq tailings contain far more arsenic than Zinkgruvan tailings.
- The leaching rate of nickel from mortar containing tailings at 10% cement replacement level significantly increases compared to that of reference mortar. However all other mortar mixtures yielded comparable or lower results than the reference mortar. Nickel content in the raw tailings is high but desorption of this element in alkaline conditions is negligible therefore low to moderate leaching rates from crushed mortar were expected.
- Cadmium is present in concerning amounts in Nalunaq tailings but it does not leach out at significant rates from crushed mortar containing tailings. Lead content is also potentially problematic in the raw tailings, yet lead leaching rates from crushed mortar are low. Desorption of these two elements in alkaline conditions was negligible, which possibly contributes to their stabilization by the cement matrix.
- Chromium leaching rate increases significantly when tailings are added in mortar, even though chromium content in Nalunaq tailings was found to be acceptable. Further investigations should be carried out to determine if chromium occurs in its most toxic oxidation state, Cr(VI).
- Sulfur leaching rate significantly increases when Nalunaq tailings are incorporated in mortar. This is problematic if sulfur occurs as sulfates.

Hence results show that almost all the heavy metals present in the tailings leach out from mortar, in various proportions. This was also observed by Kundu et al. (2016). Certain studies found that cementitious materials could successfully stabilize mine tailings (Onuaguluchi and Eren, 2012a; B. Kim et al., 2016), which does not appear to be the case in this study. However others expressed concerns regarding leaching of certain metals

(Kundu et al., 2016). Similarly, in the present project, concerns arise due to substantial leaching of arsenic and lead from Zinkgruvan tailings, and leaching of arsenic from Nalunaq tailings.

It should be noted that the tests were performed on crushed mortar samples, which possibly resulted in the release of elements that would have otherwise remained bound in the cement matrix. Therefore the leaching experiments conducted correspond to the worst case scenario of what could happen in practice. In DS/EN 12457-1 (2002) it is stated that materials subjected to leaching tests should not be finely ground prior to the determination. Indeed, crushing the sample will expose new surfaces to the leaching medium, which can influence the leaching behavior. In reality, leaching from mortar exposed for example to rain is expected to occur at inferior rates than the ones observed in the present study. Hence it would be relevant to carry out additional leaching tests on intact mortar samples to determine if leaching rates comply then with the limits set by Miljøstyrelsen (2010). If leaching rates are still concerning in that scenario, removing part of the heavy metals from the tailings prior to incorporating them in concrete could be beneficial. This could be done by electrodialytic remediation (Jensen et al., 2016). However tailings detoxification would increase the costs.

Previous research found that leaching of heavy metals from concrete containing tailings decreased with an increase in the tailings content. This was attributed to modifications in the pore structure of concrete containing tailings. (Onuaguluchi and Eren, 2012a). In the present study, there was no clear trend indicating a reduction in leaching associated with increased tailings contents in mortar. Indeed, as samples were crushed, the impact of mortar porosity could not be observed.

Another parameter of interest is the pH of the leaching medium. In the present study, leaching of heavy metals from mortar was solely investigated using distilled water with a neutral pH. However, pH is a key parameter governing leaching of heavy metals and acidic conditions have been found to increase leaching rates from mortar containing tailings (Kundu et al., 2016). Studying the leaching behaviour of mortar at various pH would be particularly useful to forecast leaching from mortar exposed to acidic rain, for instance.

Curing time is another decisive parameter governing leaching from mortar. Previous studies found that leaching of heavy metals from mortar containing tailings decreases when curing time increases, making tailings use in construction materials safer (Kundu et al., 2016). In the present study, tests were only performed on mortar specimens that had cured for 28 days under water. Further investigations regarding the impact of curing time on leaching from mortar could give insight on how to improve the efficiency of the Stabilization-Solidification treatment performed on the tailings.

4.3.6 Leaching of sulfate from crushed mortar

Leaching of sulfate from crushed mortar was investigated for REF, ZS10 and NS10, that correspond to the mortar mixtures with the highest tailings content. Results are plotted in figure 4.14. Details are given in appendix B.9.

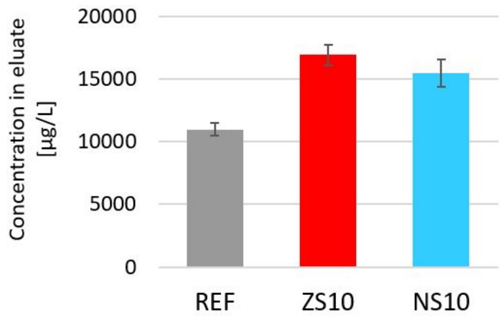


Figure 4.14: Sulfate leaching from crushed mortar

From table **??** it appears that sulfate leaching rate significantly increases when Zinkgruvan or Nalunaq tailings are incorporated in mortar. Substitution of sand respectively with Zinkgruvan and Nalunaq tailings resulted in a 54% and 41% increase in sulfate leaching. All results remain far below the limit for category 1 set by Miljøstyrelsen. However adverse effects on the sulfate attack resistance of mortar mixtures containing tailings may arise, as the limits set by Miljøstyrelsen are not specific to materials destined to be used in mortar or concrete. It is possible that strength losses associated with tailings incorporation in mortar and observed in section 4.3.3 are due to some extent to internal sulfate attack in mortar.

Sulfate leaching results are consistent with sulfur leaching observed in the previous section, where sulfur leaching rates from ZS10 and NS10 substantially increased compared to REF.

The mortar mixtures investigated for sulfate leaching correspond to the mixtures with the highest tailings content. Therefore they should represent the worst case scenario, as sulfate leaching rate is expected to increase with the amount of tailings. This assertion could be verified by investigating the impact of tailings content in mortar on sulfate leaching.

4.4 Suggestions for future research

The investigations conducted in this project have given new insight into the potential use of Zinkgruvan and Nalunaq tailings in concrete. However they have also triggered new questions that would be relevant to answer in order to gain a better understanding of the impact of tailings incorporation in concrete. A few suggestions for future research projects are mentioned below.

First, additional experiments could be performed to improve the mechanical properties of concrete containing tailings. Tailings were found to significantly decrease mortar consistency and strength. Optimizing the mix design to improve fresh mortar workability could contribute to strength enhancement by allowing better compaction during placement. Therefore it could be relevant to investigate tailings incorporation in mortar mixtures with different w/c ratios or with platicizers, that could improve the workability without changing the w/c ratio. Certain studies have also found that tailings incorporation in concrete was most beneficial when they were added together with fly ash and silica fume (Çelik et al., 2006). This could be interesting to investigate with Zinkgruvan and Nalunaq tailings.

Further experiments to determine if Zinkgruvan tailings possess pozzolanic activity could also improve the understanding of the influence of the tailings on concrete strength.

It could also be beneficial to know to if the increase in sulfate leaching rates from mortar containing tailings results in strength losses due to a reduced sulfate resistance.

Regarding the leaching behaviour of mortar containing tailings, the findings from the present study were concerning. Further experiments are therefore needed to validate or disqualify the use of Zinkgruvan and Nalunaq tailings in concrete. Tests measuring leaching of heavy metals from non-crushed mortar samples would provide valuable inputs to assess the hazards posed by these toxic elements. The curing time of the concrete mixtures or the pH of the leaching medium are other parameters that could influence the leaching behaviour and that could be interesting to investigate.

Detoxification of the tailings prior to their incorporation could also be investigated to see if it solves the problems posed by the leaching from mortar of heavy metals present in the tailings.

Pore size distribution is believed to influence both concrete strength and leaching behaviour. Therefore determining if tailings incorporation results in a modification of the pore size distribution could be interesting.

These are just a few examples of potential research projects that could be conducted to contribute to the development of the use of Zinkgruvan and Nalunaq tailings in concrete.

CHAPTER 5

Conclusions

The goal of this project was to evaluate the feasibility of using tailings from Zinkgruvan and Nalunaq mines in concrete, following the works of Nielsen (2017). Incorporation of tailings as 5-10% cement and 5-10% sand substitute were studied. The eligibility of tailings for use in concrete was assessed through a series of laboratory tests investigating the mechanical properties and the leaching behaviour of mortar containing tailings.

Water content measurements in the tailings yielded relatively large results that significantly varied from one test to the other. Thus, while mortar mixtures with 5% cement replacement were cast using moist tailings, it was preferred to cast the other mortar mixtures with dry tailings to have a better control on the total water content in mortar.

Digestion tests performed on the tailings showed that heavy metals contents were generally high. In particular arsenic, cadmium, lead and zinc contents in Zinkgruvan tailings, and arsenic, cadmium, nickel and possibly lead contents in Nalunaq tailings did not comply with the limit for category 1 materials set by Miljøstyrelsen (2010). Thus options for the use of tailings in construction materials are restricted. The same tests performed on cement and sand showed substantially lower metals contents, meaning that the primary source of heavy metals in mortar originates from the tailings.

Desorption of heavy metals from the tailings depending on the pH of the leaching medium was investigated. As pH in concrete is basic, desorption from the tailings in alkaline conditions was of particular interest. Results showed that desorption of arsenic, copper, lead and zinc from Zinkgruvan tailings at basic pH was significant. This is particularly concerning due to the high contents in arsenic, lead and zinc in the tailings. Regarding Nalunaq tailings, desorption of arsenic occurred at a high rate in alkaline conditions, which is worrying due to the large amount of arsenic in Nalunaq tailings. Sulfur desorption from both type of tailings was also determined and found to occur at large rates in alkaline conditions. This can be detrimental to mortar strength and durability if sulfur occurs as sulfates.

Tailings incorporation was found to adversely affect fresh mortar consistency, owing to the angular plate-like shape of tailings particles that induce a large water absorption of the tailings. Setting time increases with the content in Zinkgruvan tailings in mortar. This is probably due to the presence in the tailings of large amounts of lead and zinc, that are known set inhibitors. Setting is also delayed when Nalunaq tailings are incorporated as 5-10% cement replacement, possibly due to a reduction in cement content. Yet setting time is decreased when Nalunaq tailings are used as sand substitute. Heterogeneous nucleation is suspected to contribute to the accelerated setting.

The compressive strength tests performed after curing times of 7, 14, 28 and 90 days showed that although tailings incorporation could slightly increase early age strength, all mortar mixtures containing tailings yielded lower 28-day strengths than the reference mortar. Strength losses are overall lesser when tailings are used as sand substitute than when they are used as cement substitute. Strength losses in mortar mixtures with tailings used as cement replacement are attributed to an increase in the w/c ratio. The decreased consistency observed when tailings are incorporated in mortar probably also contributes to strength losses for mortar with both cement and sand substitution. Mix design optimization to improve fresh mortar workability could lead to strength enhancement. Acceptable 28-day compressive strengths were observed for mortar with moderate amounts of tailings. In particular 5% cement substitution with Zinkgruvan tailings and 5% sand substitution with Nalunaq tailings yielded the highest strengths after the reference mortar. Pozzolanic activity is suspected in Zinkgruvan tailings, however this should be verified in further investigations.

Density and porosity tests were performed on mortar specimens. No visible variation was observed across the various mortar mixtures. Porosity tests only provided data regarding the total open porosity in the specimens, yet it possible that tailings incorporation modified the pore size distribution. This could affect mortar strength and leaching behaviour.

Leaching of heavy metals from mortar was investigated on crushed samples and yielded concerning results. In particular leaching rates of lead and arsenic from certain mortar mixtures containing Zinkgruvan tailings and leaching of arsenic from certain mortar mixtures containing Nalunaq tailings, exceeded the limit for category 3 materials defined by Miljøstyrelsen (2010). Overall, leaching rates were lower for mortar mixtures with the lowest amounts of tailings, corresponding to mixtures with 5% cement replacement. Category 3 exceedance drastically restrains the potential use of tailings in construction and suggests the need for partial removal of heavy metals from the tailings before incorporating them in concrete. However tailings detoxification would increase the costs. It should be noted that excessive leaching rates may have been obtained due to the crushing of mortar samples performed prior to the tests. Thus additional experiments should be performed to assess leaching from non-crushed mortar samples, as this scenario would be closer to reality.

Leaching of sulfates from crushed mortar increases when tailings are incorporated, thereby reducing mortar sulfate resistance and potentially resulting in decrease of strength and durability.

Overall, the use of Zinkgruvan and Nalunaq tailings in concrete appears possible under certain conditions. Tailings content should be kept low to achieve satisfactory consistency, setting time and compressive strength, as well as to restrain leaching of toxic elements. Leaching of heavy metals from mortar containing tailings is particularly concerning and should be further investigated to ensure the soundness of tailings use. Leaching tests on intact mortar specimens containing tailings would thus be relevant to determine if excessive leaching rates were obtained due to the crushing of the samples.

Bibliography

Aalborg Portland A/S. (2012). Cement og beton.

Angel Mining A/S. (2009). Nalunaq gold mine, Nanortalik, greenland -revised environmental impact assessment.

Bach, L. & Larsen, M. (2016). Environmental monitoring at the Nalunaq gold mine, South Greenland, 2015. Aarhus University, DCE -Danish Centre for Environment and Energy.

Barceloux, D. G. & Barceloux, D. D. (1999). Chromium. *Journal of Toxicology: Clinical Toxicology*, *37*(2), 173–194.

Bell, R.-M., Kolb, J., Waight, T. E., Bagas, L., & Thomsen, T. B. (2017). A palaeoproterozoic multi-stage hydrothermal alteration system at nalunaq gold deposit, South Greenland. *Mineralium Deposita*, *52*(3), 383–404.

Beniwal, P., Kuar, E. R., Usman, E. M., & Sangwan, S. (2015). Use of copper tailings as partial replacement of sand in concrete. *International Journal for Research in Applied Science and Engineering Technology*, *3*(12).

Bjärnborg, K. (2009). The copper sulphide mineralization of the zinkgruvan deposit, bergslagen, sweden. Student Paper.

Çelik, Ö., Elbeyli, I. Y., & Piskin, S. (2006). Utilization of gold tailings as an additive in Portland cement. *Waste Management & Research*, *24*(3), 215–224.

Chervona, Y., Arita, A., & Costa, M. (2012). Carcinogenic metals and the epigenome: Understanding the effect of nickel, arsenic, and chromium. *Metallomics: Integrated Biometal Science*, *4*(7), 619–627.

Choi, W.-H., Lee, S.-R., & Park, J.-Y. (2009). Cement based solidification/stabilization of arsenic-contaminated mine tailings. *Waste Management*, *29*(5), 1766–1771. First international conference on environmental management, engineering, planning and economics.

Choudhury, H. & Cary, R. (2001). Barium and barium compounds.

DS 259. (2003). Determination of metals in water, sludge and sediments - general guidelines for determination by atomic absorption spectrophotometry in flame. Dansk Standard.

DS/EN 1015-3. (1999). Prøvningsmetoder til undersøgelse af mørtel til murværk. Del 3: Bestemmelse af frisk mørtels konsistens (rystebord). Dansk Standard.

DS/EN 12457-1. (2002). Characterisation of waste - leaching - compliance test for leaching of granular waste materials and sludges - Part 1 one stage batch test at liquid to solid ratio of 2 l/kg for materials with high solid content and with particle size below 4mm (without or with size reduction). Dansk Standard.

DS/EN 193-3. (2016). Metoder til prøvning af cement - Del 3: Bestemmelse af afbindingstid of volumenbestandighed. Dansk Standard.

DS/EN 196-1. (2005). Methods of testing cement - part 1: Determination of strength. 2nd edition. Dansk Standard.

Fall, M., Benzaazoua, M., & Ouellet, S. (2005). Experimental characterization of the influence of tailings fineness and density on the quality of cemented paste backfill. *Minerals Engineering*, *18*(1), 41–44.

Fosmire, G. (1990). Zinc toxicity. *American Journal of Clinical Nutrition*, *51*(2), 225–227.

Galvin, A. P., Agrela, F., Ayuso, J., Beltran, M. G., & Barbudo, A. (2014). Leaching assessment of concrete made of recycled coarse aggregate: Physical and environmental characterisation of aggregates and hardened concrete. *Waste Management*, *34*(9), 1693–1704.

GEUS/MIMR. (2013). Greenland Mineral Exploration Newsletter.

Hansen, E. Ø. (2016). *Wood ash as a ressource in lightweight concrete blocks and thermal runway as a possible production method for lighweight aggregates, træaske som ressource i letklinkerblokke og thermal runway som mulig produktionsmetode til letklinker.*

Hinrichs, W. (2008). Is sharing of risks a realistic concept in the construction area? In Graubner, Schmidt Proske Editors (Ed.), *6th international probabilistic workshop: Darmstädter massivbauseminar*, November 26, 2008–November 27, 2008 (pp. 461–463). Darmstadt: Darmstadt Technical University.

Hitachi. (N.d.). Description of ICP optical emission spectrometry (ICP-OES). **retrieved** May 9, 2017**from** http://www.hitachi-hightech.com/global/products/science/tech/ana/icp/descriptions/icp-oes.html

Jang, A. & Kim, I. (2000). Solidification and stabilization of Pb, Zn, Cd and Cu in tailing wastes using cement and fly ash. *Minerals Engineering*, *13*(14), 1659–1662.

Jankovic, K., Bojovic, D., Stojanovic, M., & Loncar, L. (2015). The use of mine tailings as a partial aggregate replacement in SCC concrete. *International Conference - Contemporary achivements in civil engineering.*

Jaturapitakkul, C., Tangpagasit, J., Songmue, S., & Kiattikomol, K. (2011). Filler effect of fine particle sand on the compressive strength of mortar. *International Journal of Minerals, Metallurgy and Materials*, *18*(2), 240–246.

Jensen, P., Ottosen, L., Hansen, H., Bollwerk, S., Belmonte, L., & Kirkelund, G. (2016). Suspended electrodialytic extraction of toxic elements for detoxification of three different mine tailings. *International Journal of Sustainable Development and Planning*, *11*(2), 119–127.

Kim, B., Jang, J., Park, C., Ha, O., & Kim, H. (2016). Recycling of arsenic-rich mine tailings in controlled low-strength materials. *Journal of Cleaner Production*, *118*, 151–161.

Kumar Mehta, P. & Monteiro, P. (2006). *Concrete microstructure, properties, and materials.* The McGraw-Hill Companies, Third Edition.

Kundu, S., Aggarwal, A., Mazumdar, S., & Dutt, K. B. (2016). Stabilization characteristics of copper mine tailings through its utilization as a partial substitute for cement in concrete: Preliminary investigations. *Environmental Earth Sciences*, *75*(3).

Lawrence, P., Cyr, M., & Ringot, E. (2005). Mineral admixtures in mortars effect of type, amount and fineness of fine constituents on compressive strength. *Cement and Concrete Research*, *35*(6), 1092–1105.

Lövgren, L., Hedlund, T., Malm, L., & Karlsson, T. (2011). Immobilisation of trace metals in sulfidic mine tailings. *Mine Water - Managing the Challenges*, 387–392.

Malmström, L., Hedström, P., & Syme, D. (2008). Mineral reserves and mineral resources of the Zinkgruvan mine in South-Central Sweden.

Meyer, L. (2013). NI 43-101 technical report for the zinkgruvan mine, central sweden. Wardell Armstrong.

Miljøstyrelsen. (2010). Bekendtgørelse om anvendelse af restprodukter og jord til byggeog anlægsarbejder og om anvendelse af sorteret, uforurenet bygge- og anlægsaffald Danish. Miljø- og Fødevareministeriet, j.nr. MST-7562-00003.

Mindess, S., Young, J., & Darwin, D. (2003). *Concrete*. Prentice Hall,

Moore, P. (2012). The zinc mine. *International Mining*. Great Mines, 26–30.

Naalakkersuisut, Government of Greenland. (N.d.). Mining Projects. **retrieved** April 25, 2017**from** https://www.govmin.gl/minerals/geology-of-greenland/mining-projects

Neville, A. (1995). *Properties of concrete*. Prentice Hall.

Nielsen, M. R. (2017). Anvendelse af mineaffald som delvis cementerstatning i beton. Bsc. Thesis. DTU Byg.

Oey, T., Kumar, A., Bullard, J. W., Neithalath, N., & Sant, G. (2013). The filler effect: The influence of filler content and surface area on cementitious reaction rates. *Journal of the American Ceramic Society*, *96*(6), 1978–1990.

Onuaguluchi, O. & Eren, O. (2012a). Copper tailings as a potential additive in concrete: Consistency, strength and toxic metal immobilization properties. *Indian Journal of Engineering and Materials Sciences*, *19*(2), 79–86.

Onuaguluchi, O. & Eren, O. (2012b). Durability-related properties of mortar and concrete containing copper tailings as a cement replacement material. *Magazine of Concrete Research*, *64*(11), 1015–1023.

Ritcey, G. M. (1989). *Tailings management : Problems and solutions in the mining industry*. Amsterdam : Elsevier Science Publishers ; New York : Elsevier Science Pub. Co. [distributor for U.S. and Canada].

Salomons, W. & Förstner, U. (1988). Springer-Verlag Berlin Heidelberg.

Saria, L., Shimaoka, T., & Miyawaki, K. (2006). Leaching of heavy metals in acid mine drainage. *Waste Management & Research*, *24*(2), 134–140.

Secher, K., Stedal, H., & Stensgaard, B. (2008). The Nalunaq gold mine. *Geology and Ore - Exploration and Mining in Greenland*, (11).

Sivakugan, N., Rankine, R., Rankine, K., & Rankine, K. (2006). Geotechnical considerations in mine backfilling in Australia. *Journal of Cleaner Production*, *14*(12–13), 1168–1175.

Tange Hasholt, M. (2016). Course 11563: Concrete technology - Lecture 2: Concrete constituents. Lecture slides.

Tashiro, C., Takahashi, H., Kanaya, M., Hirakida, I., & Yoshida, R. (1977). Hardening property of cement mortar adding heavy-metal compound and solubility of heavymetal from hardened mortar. *Cement and Concrete Research*, *7*(3), 283–290.

Tchounwou, P., Yedjou, C., Patlolla, A., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In A. Luch (Ed.), *Molecular, clinical and environmental toxicology: Volume 3: Environmental toxicology* (pp. 133–164). Springer Basel.

Thomas, B. S., Damare, A., & Gupta, R. C. (2013). Strength and durability characteristics of copper tailing concrete. *Construction and Building Materials*, *48*, 894–900.

Tixier, R., Devaguptapu, R., & Mobasher, B. (1997). The effect of copper slag on the hydration and mechanical properties of cementitious mixtures. *Cement and Concrete Research*, *27*(10), 1569–1580.

Tokyay, M. (2016). *Cement and concrete mineral admixtures.* CRC Press.

World Business Council for Sustainable Development. (2009). The cement sustainability initiative.

Yin, G. & Catalan, L. J. J. (2003). Use of alkaline extraction to quantify sulfate concentration in oxidized mine tailings. *Journal of Environment Quality*, *32*(6).

Zain, M., Islam, M., Radin, S., & Yap, S. (2004). Cement-based solidification for the safe disposal of blasted copper slag. *Cement and Concrete Composites*, *26*(7), 845–851.

APPENDIX A

Test Methods

A.1 Water content

Apparatus and Materials

- Oven
- Technical scale
- 3 beakers

Procedure
Three empty beakers are weighed and then filled with moist tailings, up to about half their height. The beakers containing moist tailings are weighed again. They are then placed in the oven and left to dry for 2-3 days at 55°C. The beakers containing the dry tailings are then weighed again.

Results
The water content is expressed in percent of the weight of the moist tailings, and is determined as follows:

$$\%_(water\ content) = \frac{m_{wet\ sample} - m_{dry\ sample}}{m_{wet\ sample}}$$

Where $m_{wet\ sample}$ is the weight of the wet sample and $m_{dry\ sample}$ is the weight of the dry sample.

Waste Management
The tailings are collected in the waste dunk marked for heavy metals.

A.2 Heavy metals content

Digestion of soil or ash – DS259

A Principle

This digestion method is a Danish Standard (DS 259) for determining the acid-soluble metals in the soil. Metal concentration is found by this method corresponds to an "overall concentration" of the element in the soil.

A total destruction of the soil will give a higher value of the various metals. The DS 259 will therefore provide a more determined level of a metal concentration of a complete determination of the metal concentration in soil

B Special equipment

Autoclave
For the measurement ICP is used

C Reagents

1) Half-concentrated nitric acid (1: 1) HNO3:
500 mL of concentrated HNO3 measured in a measuring glass and transferred to a 1000.00 mL volumetric flask which is half filled with distilled water. Mix well and add water to the mark. After mixing, transfer to a plastic bottle and labeled

Read chemical instructions before the work begins. www.kemibrug.dk

D Procedure

Weigh 1.00 g of dry, crushed soil on a technical weight in a pyrex glass with screw cap (autoclave glass) and add 20.00 mL 1:1 HNO_3 using a volumetric pipette (Remember to use the fume cabinet).

Autoclave glasses are closed completely, otherwise the HNO_3 will evaporate.

Pour 1.5 L of distilled water in the autoclave and close the lid firmly and lock it with the orange button. The black valve on the lid is opened completely and then rotated one half turn. The autoclave is switched on and it takes about 10-15 minutes until it is warms up. After 3 minutes with steam coming out the valve

has to be closed and the pressure will begins to increase. Take the time when the pressure has reached in the blue mark on the pressure gauge.
Turn off the autoclave after 30 min.

The glasses are then cooled to room temperature.

The samples were filtered with suction through a 0.45 µm filter using the fume cabinet. **Use disposable gloves**. The glasses are rinsed 3 times with distilled water. Filtered must be suck dry between each rinse.

Poured the filter into a 100.00 mL volumetric flask and add distilled water to the mark and mix. The liquid is poured into a 20 mL plastic vial and stored for ICP.

E Calculation of results

Based on the standard curves the metals content of the soil is calculated and expressed in mg / kg.

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

Where
A = extract metal concentration, mg/L = ppm
B = g soil weighed
C = dilution

F Waste management

Reagents and soil is collected in at waste dunk marked heavy metals X 4.41

The filter paper is thrown away in the trash in the fume cabinet.

Soil and Ashes must be collected in container soil waste.

A.3 pH-desorption of heavy metals

Apparatus and Materials

- 22 plastic vials
- Reagents: Sodium hydroxide and nitric acid with concentrations of 1.0 M, 0.5 M, 0.1 M, 0.05 M, and 0.01 M
- Technical scale
- Shaking table
- pH-meter
- For measurement of heavy metals concentrations, ICP is used

Procedure
5.00 g of tailings are weighed on a technical scale and introduced into 22 plastic bottles. Then 25 mL of each reagent listed in table A.1 below are added in two bottles containing tailings. The last two bottles are filled with 25 mL distilled water and will serve as blinds.

Table A.1: Reagents used to determine the pH-desorption of heavy metals in the tailings

Nr	Concentration	Reagent	Nr	Concentration	Reagent
1	1.0 M	HNO_3	6	1.0 M	NaOH
2	0.5 M	HNO_3	7	0.5 M	NaOH
3	0.1 M	HNO_3	8	0.1 M	NaOH
4	0.05 M	HNO_3	9	0.05 M	NaOH
5	0.01 M	HNO_3	10	0.01 M	NaOH

The bottles are securely closed with a lid and placed on a shaking table for a week. After a week, the samples are removed from the shaking table. Once the solutions have had time to decant, their pH is measured. The samples are then filtered through a 0.45 µm syringe filter and placed in 20 mL plastic vials. These are finally sent for ICP in order to determine the heavy metals concentrations.

Following the results of the ICP analysis, the metal content in the eluate is calculated as follows:

$$MC = \frac{0.025 \cdot A}{0.001 \cdot B} \tag{A.1}$$

Where MC is the metal content that leached from the tailings into the eluate (in mg/kg), A is the extract metal concentration obtained in the ICP analysis (in mg/L) and B is the mass of tailings weighed (in g).

Waste Management
Tailings and reagents containing tailings are disposed of in the waste dunk marked for heavy metals.

A.4 Porosity and density test

Porosity and density (LBM standard)

A Princip

The porosity of a material tells us how porous the material is, i.e., how fragile it is. The higher the porosity is, the greater ability the material has to take up water. It also means a good ability to absorb water. The density of the material's mass per unit volume. The mass of a porous material can be a dry mass or a mass of water in the open pores, that is, by finding the density can be calculated mass at different conditions.

B Special equipment

For measurement use the vacuum pump and a technical balance with the possibility to weight under water.

C Procedure

Dry the sample at 105°C until the sample is completely dry i.e. constant weight.

In case of a concrete sample, this has to dry at 50°C for min. 3 weeks. Because drying at high temperature will results in change of the pore structure.

Weighed the sample on a technical balance and note the weight (m_{105}).

Place the sample in a desiccator with lid and tap. Connect the desiccator to the vacuum pump and pumped it down for min. 3 hours.

The distilled water with room temperature is passed into the desiccator using a hose and the under pressure in the desiccator. Close the tap as soon as the water level is 3 cm above the sample. It must be close for 1 hour.

After 1 hour open the tap and let the sample be under water overnight at atmospheric pressure.

First weight the saturated sample under water on a technical balance. The water in box must have room temperature. The weighted is noted as (m_{sw})

The sample is dabbed with a cloth before weighing over water. Note the weight as (m_{ssd})

In order to check whether where was a wash out or not. Dry the samples over night at 105°C and weight it again.

D Calculation of results

Roomtemp: °C	Watertemp: °C	Water density ρ_w= kg/m^3		
Control let: Before: kg After: kg				
Sample nr:				
m_{105}	Kg			
m_{ssd}	Kg			
m_{sw}	Kg			
$V = (m_{ssd}-m_{sw})/\rho_w$	m^3			
$Vpå = (m_{ssd}-m_{105})/\rho_w$	m^3/m^3			
$P_å = V_{på}/V$	Kg/m^3			
$\rho_d = m_{105}/V$	Kg/m^3			
$\rho_f = m_{105}/(V-V_{på})$	Kg/m^3			
$\rho_{ssd} = m_{ssd}/V$	Kg/m^3			
$u_{ssd} = (m_{ssd}-m_{105})/m_{105}$	Kg/kg			

Definitions, concepts and symbols

m_{105} Mass of sample after drying with 105°C (kg)
m_{ssd} Mass of sample over water after vacuum(kg)
m_{sw} Mass of vacuum sample weight in water(kg)
V Volumen of the sample (m^3)
$V_{på}$ Volumen of the open pores (m^3)
ρ_f Soliddensity (kg/m^3)
ρ_d Drydensity (kg/m^3)
ρ_{ssd} Density of sample in the vacuum watersaturated surfacedry cond. (kg/m^3)
$p_å$ Open porosity of the sample (m^3/m^3)
u_{ssd} Water Solids Ratio in vacuum watersaturated surfacedry condition (kg/m^3)

APPENDIX B

Test Results

B.1 Water content

Water content - Tailings							
Sample	Bottle weight (g)	Bottle+ wet sample weight (g)	Bottle+ dry sample weight (g)	Water content (g)	Mean water	Standard deviation	Test date
Zinkgruvan 1	5,01	17,91	16,88	8,0%	**8,2%**	0,3%	9/1
Zinkgruvan 2	5,02	16,72	15,72	8,5%			
Zinkgruvan 3	5,03	16,12	15,21	8,2%			
Nalunaq 1	5,01	20,05	18,00	13,6%	**13,4%**	0,2%	9/1
Nalunaq 2	5,03	17,82	16,14	13,1%			
Nalunaq 3	5,04	18,31	16,53	13,4%			
Zinkgruvan 1	19,18	47,85	44,78	10,7%	**10,5%**	0,2%	30/1
Zinkgruvan 2	19,35	49,32	46,23	10,3%			
Zinkgruvan 3	22,50	52,30	49,20	10,4%			
Nalunaq 1	18,79	51,09	47,34	11,6%	**11,4%**	0,2%	30/1
Nalunaq 2	19,19	49,70	46,29	11,2%			
Nalunaq 3	19,02	49,52	46,07	11,3%			

B.2 Heavy metals content in the tailings

Sample	B - Sample mass	Al 308.215				As 193.696				Ba 233.527			
		A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation
	[g]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]
CP digestion sand 1	1,00	10,6952	1069,52			0,016272	1,6272			0,030371	3,0371		
CP digestion sand 2	1,00	10,4377	1043,77	1025,75	55,03	0,017745	1,7745	1,56	0,25	0,027837	2,7837	3,31	0,71
CP digestion sand 3	1,00	9,63968	963,968			0,012896	1,2896			0,041213	4,1213		
CP digestion cement 1	1,00	194,92	19492			0,075218	7,5218			2,83132	283,132		
CP digestion cement 2	1,00	199,221	19922,1	19538,97	361,94	0,086386	8,6386	7,73	0,82	2,89845	289,845	284,95	4,28
CP digestion cement 3	1,00	192,028	19202,8			0,070423	7,0423			2,81884	281,884		
CP digestion Zinkgruvan 1	1,00	67,2775	6727,75			0,53464	53,464			2,51077	251,077		
CP digestion Zinkgruvan 2	1,00	66,755	6675,5	6701,63	118,04	0,437127	43,7127	48,59	5,81	2,64147	264,147	257,61	9,39
CP digestion Zinkgruvan 3	1,00	69,0101	6901,01			0,540632	54,0632			2,45938	245,938		
CP digestion Nalunaq 1	1,00	102,162	10216,2			5,37346	537,346			0,070501	7,0501		
CP digestion Nalunaq 2	1,00	102,843	10284,3	10286,97	72,14	5,11923	511,923	529,08	14,86	0,06951	6,951	7,05	0,09
CP digestion Nalunaq 3	1,00	103,604	10360,4			5,37958	537,958			0,071383	7,1383		

Sample	B - Sample mass	Cd 228.802				Cr 206.550				Cu 327.395			
		A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation
	[g]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]
CP digestion sand 1	1,00	0,004744	0,4744			0,018829	1,8829			0,064641	6,4641		
CP digestion sand 2	1,00	0,028598	2,8598	1,22	1,42	0,020815	2,0815	1,87	0,21	0,01238	1,238	3,05	2,96
CP digestion sand 3	1,00	0,003166	0,3166			0,016528	1,6528			0,014344	1,4344		
CP digestion cement 1	1,00	0,003996	0,3996			0,30731	30,731			0,973235	97,3235		
CP digestion cement 2	1,00	0,004424	0,4424	0,43	0,03	0,307194	30,7194	30,63	0,17	0,988339	98,8339	97,51	1,24
CP digestion cement 3	1,00	0,004616	0,4616			0,304327	30,4327			0,963665	96,3665		
CP digestion Zinkgruvan 1	1,00	0,12808	12,808			0,03529	3,529			0,949057	94,9057		
CP digestion Zinkgruvan 2	1,00	0,123016	12,3016	12,55	0,36	0,037981	3,7981	3,66	0,22	0,929859	92,9859	93,95	1,43
CP digestion Zinkgruvan 3	1,00	0,129979	12,9979			0,039638	3,9638			0,921129	92,1129		
CP digestion Nalunaq 1	1,00	0,024631	2,4631			0,275098	27,5098			2,59964	259,964		
CP digestion Nalunaq 2	1,00	0,022117	2,2117	2,28	0,16	0,274134	27,4134	27,40	0,12	2,62467	262,467	263,90	4,82
CP digestion Nalunaq 3	1,00	0,021706	2,1706			0,272645	27,2645			2,6928	269,28		

Sample	B - Sample mass	Fe 238.204				Mn 260.568				Ni 231.604			
		A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation
	[g]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]
CP digestion sand 1	1,00	17,415	1741,5	1724,36	55,67	0,539227	53,9227	61,99	7,32	0,006884	0,6884	0,91	0,23
CP digestion sand 2	1,00	17,6944	1769,44			0,682146	68,2146			0,008884	0,8884		
CP digestion sand 3	1,00	16,6213	1662,13			0,638311	63,8311			0,011433	1,1433		
CP digestion cement 1	1,00	198,089	19808,9	19890,87	317,88	1,85189	185,189	186,57	2,92	0,253621	25,3621	25,60	0,57
CP digestion cement 2	1,00	202,417	20241,7			1,89932	189,932			0,262501	26,2501		
CP digestion cement 3	1,00	196,22	19622			1,84596	184,596			0,251769	25,1769		
CP digestion Zinkgruvan 1	1,00	192,741	19274,1	21329,95	2266,99	10,4708	1047,08	1054,40	11,27	0,181391	18,1391	17,83	0,91
CP digestion Zinkgruvan 2	1,00	233,858	23385,8			10,6171	1061,71			0,175118	17,5118		
CP digestion Zinkgruvan 3	1,00	196,752	19675,2			10,6924	1069,24			0,193095	19,3095		
CP digestion Nalunaq 1	1,00	144,756	14475,6	14189,13	292,53	1,39606	139,606	139,50	0,70	0,472201	47,2201	46,71	0,94
CP digestion Nalunaq 2	1,00	138,909	13890,9			1,38759	138,759			0,456252	45,6252		
CP digestion Nalunaq 3	1,00	142,009	14200,9			1,40139	140,139			0,472725	47,2725		

Sample	B - Sample mass	P 214.914				Pb 220.353			
		A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation
	[g]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]
CP digestion sand 1	1,00	1,90916	190,916	248,55	51,41	0,052246	5,2246	3,26	1,71
CP digestion sand 2	1,00	2,89672	289,672			0,021243	2,1243		
CP digestion sand 3	1,00	2,65076	265,076			0,024434	2,4434		
CP digestion cement 1	1,00	10,1026	1010,26	1012,16	9,59	0,171249	17,1249	17,24	0,15
CP digestion cement 2	1,00	10,2256	1022,56			0,174142	17,4142		
CP digestion cement 3	1,00	10,0367	1003,67			0,171742	17,1742		
CP digestion Zinkgruvan 1	1,00	2,97928	297,928	306,94	20,65	35,3857	3538,57	3995,23	465,18
CP digestion Zinkgruvan 2	1,00	3,15952	315,952			44,5189	4451,89		
CP digestion Zinkgruvan 3	1,00	3,39122	339,122			38,4176	3841,76		
CP digestion Nalunaq 1	1,00	2,33984	233,984	227,68	5,82	0,099783	9,9783	9,71	1,01
CP digestion Nalunaq 2	1,00	2,22522	222,522			0,085963	8,5963		
CP digestion Nalunaq 3	1,00	2,26524	226,524			0,105565	10,5565		

Sample	B - Sample mass	S 182.562				Zn 213.857			
		A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation	A - Extract metal concentration	MC - Heavy metal content	MC - Arithmetic mean	Standard deviation
	[g]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/L]	[mg/kg]	[mg/kg]	[mg/kg]
CP digestion sand 1	1,00	3,42303	342,303			1,44613	144,613		
CP digestion sand 2	1,00	4,26659	426,659	362,88	56,38	0,119693	11,9693	56,47	76,33
CP digestion sand 3	1,00	3,19691	319,691			0,128304	12,8304		
CP digestion cement 1	1,00	137,574	13757,4			0,357567	35,7567		
CP digestion cement 2	1,00	144,127	14412,7	14042,93	335,67	0,378179	37,8179	37,46	1,56
CP digestion cement 3	1,00	139,587	13958,7			0,388181	38,8181		
CP digestion Zinkgruvan 1	1,00	53,1664	5316,64			73,7147	7371,47		
CP digestion Zinkgruvan 2	1,00	53,7905	5379,05	5347,85	169,81	80,6169	8061,69	7716,58	346,42
CP digestion Zinkgruvan 3	1,00	56,3695	5636,95			76,6441	7664,41		
CP digestion Nalunaq 1	1,00	28,4936	2849,36			0,357567	35,7567		
CP digestion Nalunaq 2	1,00	26,1671	2616,71	2712,02	121,89	0,378179	37,8179	37,46	1,56
CP digestion Nalunaq 3	1,00	26,7	2670			0,388181	38,8181		

B.3 pH-desorption of heavy metals from the tailings

B.3.1 Raw data - Zinkgruvan tailings

	ZINKGRUVAN TAILINGS							
	Al							
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		0,000E+00	0,000E+00			6701,625
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	1,754E-02	8,771E-02	4,385E-02	0,00%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		2,236E-02	1,118E-01			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	2,469E-02	1,235E-01	1,176E-01	0,00%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		2,027E-01	1,013E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	2,085E-02	1,042E-01	5,589E-01	0,01%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		3,224E+01	1,612E+02			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	3,483E+01	1,742E+02	1,677E+02	2,50%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		2,257E+02	1,128E+03			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	2,278E+02	1,139E+03	1,134E+03	16,92%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		6,801E-02	3,401E-01			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	3,719E-02	1,859E-01	2,630E-01	0,00%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		1,382E+00	6,911E+00			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	9,093E-01	4,546E+00	5,729E+00	0,09%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		1,491E+00	7,455E+00			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	7,272E-01	3,636E+00	5,545E+00	0,08%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		1,034E+00	5,172E+00			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	1,084E+00	5,421E+00	5,297E+00	0,08%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		2,616E+00	1,308E+01			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	2,191E+00	1,096E+01	1,202E+01	0,18%	

ZINKGRUVAN TAILINGS									
As									
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		0,000E+00	0,000E+00			48,58835
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	4,569E-02	2,284E-01	1,142E-01	0,24%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	7,329E-03	3,665E-02	1,832E-02	0,04%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		0,000E+00	0,000E+00			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		3,380E+00	1,690E+01			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	3,527E+00	1,764E+01	1,727E+01	35,54%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		3,493E-02	1,747E-01			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	0,000E+00	0,000E+00	8,733E-02	0,18%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		1,716E-01	8,582E-01			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	5,259E-02	2,630E-01	5,606E-01	1,15%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		1,846E+00	9,230E+00			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	1,802E+00	9,010E+00	9,120E+00	18,77%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		3,132E+00	1,566E+01			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	2,970E+00	1,485E+01	1,525E+01	31,40%	

	ZINKGRUVAN TAILINGS							
	Ba							
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		3,323E-02	1,661E-01			257,612
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	3,093E-02	1,546E-01	1,604E-01	0,06%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		5,962E-02	2,981E-01			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	5,627E-02	2,813E-01	2,897E-01	0,11%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		1,149E-01	5,743E-01			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	1,288E-01	6,439E-01	6,091E-01	0,24%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		2,677E-01	1,339E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	2,436E-01	1,218E+00	1,278E+00	0,50%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		6,010E-02	3,005E-01			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	5,422E-02	2,711E-01	2,858E-01	0,11%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		7,076E-01	3,538E+00			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	7,345E-01	3,673E+00	3,605E+00	1,40%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		3,477E-02	1,739E-01			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	2,622E-02	1,311E-01	1,525E-01	0,06%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		5,058E-02	2,529E-01			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	5,598E-02	2,799E-01	2,664E-01	0,10%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		7,870E-02	3,935E-01			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	9,825E-02	4,913E-01	4,424E-01	0,17%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		2,789E-01	1,394E+00			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	2,669E-01	1,334E+00	1,364E+00	0,53%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		4,384E-01	2,192E+00			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	4,183E-01	2,091E+00	2,142E+00	0,83%	

ZINKGRUVAN TAILINGS								
Cd								
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		4,560E-02	2,280E-01			12,5548
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	4,712E-02	2,356E-01	2,318E-01	1,85%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		1,329E-01	6,644E-01			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	1,333E-01	6,666E-01	6,655E-01	5,30%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		3,242E-01	1,621E+00			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	3,117E-01	1,559E+00	1,590E+00	12,66%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		4,434E-01	2,217E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	4,238E-01	2,119E+00	2,168E+00	17,27%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		5,096E-01	2,548E+00			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	5,147E-01	2,574E+00	2,561E+00	20,40%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		1,157E+00	5,787E+00			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	1,174E+00	5,872E+00	5,829E+00	46,43%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		3,277E-03	1,639E-02			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	4,086E-03	2,043E-02	1,841E-02	0,15%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		3,181E-03	1,591E-02			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	3,623E-03	1,812E-02	1,701E-02	0,14%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		3,394E-03	1,697E-02			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	3,397E-03	1,699E-02	1,698E-02	0,14%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		6,182E-03	3,091E-02			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	4,741E-03	2,371E-02	2,731E-02	0,22%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		1,713E-02	8,567E-02			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	1,884E-02	9,419E-02	8,993E-02	0,72%	

	ZINKGRUVAN TAILINGS							
	Cr							
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		0,000E+00	0,000E+00			3,66355
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		8,804E-03	4,402E-02			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	6,857E-03	3,429E-02	3,915E-02	1,07%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		1,119E-02	5,595E-02			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	1,358E-02	6,792E-02	6,194E-02	1,69%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		1,502E-02	7,508E-02			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	1,478E-02	7,392E-02	7,450E-02	2,03%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		5,353E-02	2,677E-01			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	5,478E-02	2,739E-01	2,708E-01	7,39%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		2,562E-01	1,281E+00			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	2,505E-01	1,252E+00	1,267E+00	34,58%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	1,193E-02	5,964E-02	2,982E-02	0,81%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	5,004E-03	2,502E-02	1,251E-02	0,34%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		3,458E-03	1,729E-02			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	5,034E-03	2,517E-02	2,123E-02	0,58%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		1,971E-02	9,853E-02			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	0,000E+00	0,000E+00	4,927E-02	1,34%	

ZINKGRUVAN TAILINGS — Cu								
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		6,444E-03	3,222E-02			93,9458
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	7,633E-03	3,817E-02	3,519E-02	0,04%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		5,190E-03	2,595E-02			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	1,055E-02	5,275E-02	3,935E-02	0,04%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		3,540E-02	1,770E-01			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	3,417E-02	1,709E-01	1,739E-01	0,19%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		4,384E-02	2,192E-01			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	4,937E-02	2,469E-01	2,330E-01	0,25%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		1,539E+01	7,696E+01			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	1,536E+01	7,680E+01	7,688E+01	81,84%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		1,627E+01	8,135E+01			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	1,650E+01	8,248E+01	8,191E+01	87,19%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		3,092E-02	1,546E-01			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	1,095E-02	5,476E-02	1,047E-01	0,11%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		1,332E-01	6,662E-01			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	1,187E-01	5,935E-01	6,298E-01	0,67%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		2,500E-01	1,250E+00			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	3,316E-01	1,658E+00	1,454E+00	1,55%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		2,142E+00	1,071E+01			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	2,068E+00	1,034E+01	1,052E+01	11,20%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		4,026E+00	2,013E+01			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	3,993E+00	1,996E+01	2,005E+01	21,34%	

ZINKGRUVAN TAILINGS								
Fe								
Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		1,672E-02	8,361E-02			21329,95
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	0,000E+00	0,000E+00	4,180E-02	0,00%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		7,612E-01	3,806E+00			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	3,846E-01	1,923E+00	2,865E+00	0,01%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		1,579E+03	7,895E+03			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	1,604E+03	8,021E+03	7,958E+03	37,31%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		2,541E-02	1,270E-01			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	0,000E+00	0,000E+00	6,351E-02	0,00%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		2,053E-02	1,026E-01			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	1,976E-02	9,881E-02	1,007E-01	0,00%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		1,013E-01	5,067E-01			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	3,446E-02	1,723E-01	3,395E-01	0,00%	

ZINKGRUVAN TAILINGS

Mn

Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt - Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		1,126E+00	5,632E+00			1054,395
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	1,239E+00	6,197E+00	5,914E+00	0,56%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		5,495E+00	2,748E+01			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	5,622E+00	2,811E+01	2,779E+01	2,64%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		1,912E+01	9,562E+01			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	1,845E+01	9,225E+01	9,394E+01	8,91%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		3,499E+01	1,749E+02			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	3,455E+01	1,728E+02	1,738E+02	16,49%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		1,349E+02	6,743E+02			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	1,355E+02	6,776E+02	6,759E+02	64,11%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		2,058E+02	1,029E+03			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	2,090E+02	1,045E+03	1,037E+03	98,35%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		0,000E+00	0,000E+00			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	0,000E+00	0,000E+00	0,000E+00	0,00%	

	ZINKGRUVAN TAILINGS							
	Ni							
Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		6,610E-03	3,305E-02			17,82545
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	1,324E-02	6,619E-02	4,962E-02	0,28%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		2,544E-01	1,272E+00			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	2,957E-01	1,478E+00	1,375E+00	7,71%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		8,063E-01	4,031E+00			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	7,609E-01	3,805E+00	3,918E+00	21,98%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		1,137E+00	5,684E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	9,179E-01	4,589E+00	5,137E+00	28,82%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		1,916E+00	9,582E+00			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	1,882E+00	9,412E+00	9,497E+00	53,28%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		1,709E+00	8,544E+00			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	1,759E+00	8,795E+00	8,669E+00	48,63%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		2,195E-02	1,097E-01			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	2,347E-02	1,173E-01	1,135E-01	0,64%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		2,444E-02	1,222E-01			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	0,000E+00	0,000E+00	6,109E-02	0,34%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		8,417E-03	4,209E-02			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	1,082E-02	5,412E-02	4,810E-02	0,27%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		1,906E-02	9,532E-02			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	1,731E-02	8,657E-02	9,095E-02	0,51%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		5,538E-02	2,769E-01			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	6,453E-02	3,227E-01	2,998E-01	1,68%	

ZINKGRUVAN TAILINGS								
P								
Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		0,000E+00	0,000E+00			306,94
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		1,786E-01	8,929E-01			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	0,000E+00	0,000E+00	4,465E-01	2,50%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		4,040E-02	2,020E-01			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	0,000E+00	0,000E+00	1,010E-01	0,57%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		5,307E-01	2,653E+00			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	5,147E-01	2,574E+00	2,614E+00	14,66%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		3,330E+01	1,665E+02			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	3,306E+01	1,653E+02	1,659E+02	930,59%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		0,000E+00	0,000E+00			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		2,169E-01	1,085E+00			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	2,490E-01	1,245E+00	1,165E+00	6,53%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		7,950E-01	3,975E+00			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	4,761E-01	2,380E+00	3,178E+00	17,83%	

	ZINKGRUVAN TAILINGS							
	Pb							
Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt - Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		1,826E-01	9,130E-01			3995,23
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	1,839E-01	9,196E-01	9,163E-01	0,02%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		3,198E-01	1,599E+00			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	3,240E-01	1,620E+00	1,609E+00	0,04%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		8,008E-01	4,004E+00			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	7,389E-01	3,695E+00	3,849E+00	0,10%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		1,873E+00	9,367E+00			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	5,411E+00	2,705E+01	1,821E+01	0,46%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		1,541E+02	7,706E+02			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	1,328E+02	6,642E+02	7,174E+02	17,96%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		3,550E+02	1,775E+03			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	3,539E+02	1,770E+03	1,772E+03	44,36%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		8,824E+00	4,412E+01			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	1,170E-01	5,849E-01	2,235E+01	0,56%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		2,980E+02	1,490E+03			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	3,070E+02	1,535E+03	1,513E+03	37,86%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		4,139E+02	2,070E+03			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	4,282E+02	2,141E+03	2,105E+03	52,69%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		5,203E+02	2,601E+03			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	5,081E+02	2,540E+03	2,571E+03	64,35%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		5,566E+02	2,783E+03			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	5,637E+02	2,818E+03	2,801E+03	70,10%	

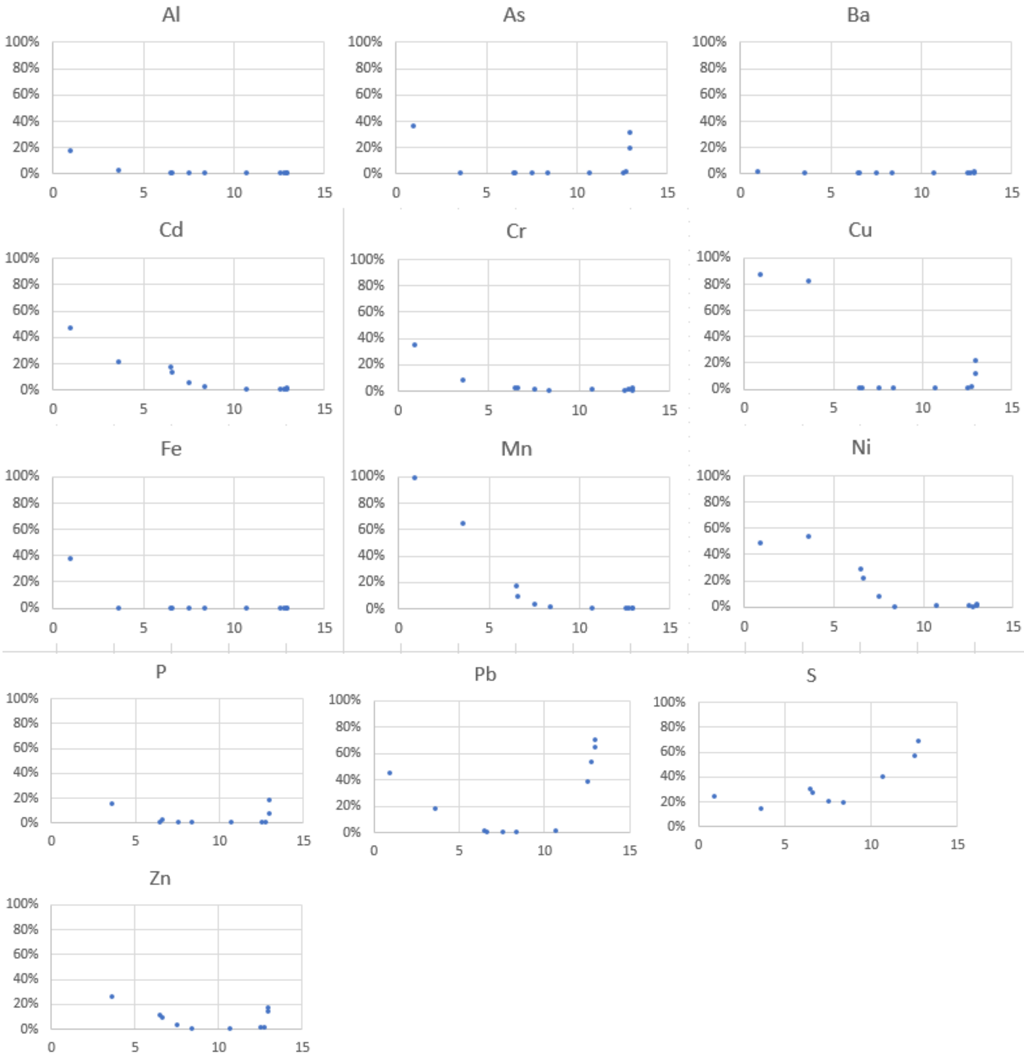
ZINKGRUVAN TAILINGS

S

Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		1,895E+02	9,477E+02			5347,845
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	2,086E+02	1,043E+03	9,954E+02	18,61%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		2,131E+02	1,065E+03			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	2,159E+02	1,080E+03	1,072E+03	20,05%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		3,755E+02	1,877E+03			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	2,046E+02	1,023E+03	1,450E+03	27,12%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		2,142E+02	1,071E+03			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	4,259E+02	2,130E+03	1,600E+03	29,92%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		1,364E+02	6,818E+02			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	1,607E+02	8,034E+02	7,426E+02	13,89%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		2,493E+02	1,247E+03			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	2,517E+02	1,259E+03	1,253E+03	23,42%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		3,966E+02	1,983E+03			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	4,480E+02	2,240E+03	2,111E+03	39,48%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		5,940E+02	2,970E+03			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	6,048E+02	3,024E+03	2,997E+03	56,04%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		8,734E+02	4,367E+03			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	5,938E+02	2,969E+03	3,668E+03	68,59%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		1,556E+03	7,782E+03			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	1,576E+03	7,878E+03	7,830E+03	146,41%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		2,124E+03	1,062E+04			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	2,336E+03	1,168E+04	1,115E+04	208,52%	

ZINKGRUVAN TAILINGS									
	Zn								
Sample	B - Mass of tailings [g]	pH [-]	pH - arithmet [-]	A - Extract metal [mg/L]	MC - Heavy metal content [mg/kg]	MC - Arithmetic mean [mg/kg]	MC/Mt [%]	Mt -Total initial content [mg/kg]
pH-des Zinkgruvan Blind A	5,00	8,48		2,941E+00	1,471E+01			7716,58
pH-des Zinkgruvan Blind B	5,00	8,32	8,4	3,170E+00	1,585E+01	1,528E+01	0,20%	
pH-des Zinkgruvan 0,01M HNO3 A	5,00	7,60		4,750E+01	2,375E+02			
pH-des Zinkgruvan 0,01M HNO3 B	5,00	7,52	7,6	4,895E+01	2,447E+02	2,411E+02	3,12%	
pH-des Zinkgruvan 0,05M HNO3 A	5,00	6,67		1,420E+02	7,101E+02			
pH-des Zinkgruvan 0,05M HNO3 B	5,00	6,60	6,6	1,338E+02	6,691E+02	6,896E+02	8,94%	
pH-des Zinkgruvan 0,1M HNO3 A	5,00	6,30		1,821E+02	9,106E+02			
pH-des Zinkgruvan 0,1M HNO3 B	5,00	6,72	6,5	1,415E+02	7,073E+02	8,090E+02	10,48%	
pH-des Zingruvan 0,5 M HNO3 A	5,00	3,58		3,948E+02	1,974E+03			
pH-des Zingruvan 0,5 M HNO3 B	5,00	3,65	3,6	4,002E+02	2,001E+03	1,987E+03	25,76%	
pH-des Zingruvan 1,0 M HNO3 A	5,00	0,97		5,808E+03	2,904E+04			
pH-des Zingruvan 1,0 M HNO3 B	5,00	0,94	1,0	6,269E+03	3,134E+04	3,019E+04	391,27%	
pH-des Zinkgruvan 0,01M NaOH A	5,00	11,25		3,690E-01	1,845E+00			
pH-des Zinkgruvan 0,01M NaOH B	5,00	10,20	10,7	9,495E-02	4,747E-01	1,160E+00	0,02%	
pH-des Zinkgruvan 0,05M NaOH A	5,00	12,57		8,639E+00	4,319E+01			
pH-des Zinkgruvan 0,05M NaOH B	5,00	12,56	12,6	8,044E+00	4,022E+01	4,171E+01	0,54%	
pH-des Zinkgruvan 0,1M NaOH A	5,00	12,76		1,358E+01	6,788E+01			
pH-des Zinkgruvan 0,1M NaOH B	5,00	12,78	12,8	1,802E+01	9,009E+01	7,899E+01	1,02%	
pH-des Zinkgruvan 0,5M NaOH A	5,00	12,96		2,198E+02	1,099E+03			
pH-des Zinkgruvan 0,5M NaOH B	5,00	13,00	13,0	2,144E+02	1,072E+03	1,085E+03	14,06%	
pH-des Zinkgruvan 1,0M NaOH A	5,00	12,97		2,603E+02	1,301E+03			
pH-des Zinkgruvan 1,0M NaOH B	5,00	12,97	13,0	2,596E+02	1,298E+03	1,300E+03	16,84%	

B.3.2 Graphs- Zinkgruvan tailings



B.3.3 Raw data -Nalunaq tailings

	NALUNAQ TAILINGS							
	Al							
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal concentration [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt - Total initial content [mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		4,287E-02	2,144E-01			10286,97
pH-des Nalunaq Blind B	5,00	8,60	8,8	1,065E-02	5,325E-02	1,338E-01	0,00%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		1,093E+02	5,463E+02			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	1,096E+02	5,482E+02	5,472E+02	5,32%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		4,286E+02	2,143E+03			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	4,215E+02	2,108E+03	2,125E+03	20,66%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		6,106E+02	3,053E+03			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	6,048E+02	3,024E+03	3,039E+03	29,54%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		2,099E+00	1,049E+01			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	2,415E+00	1,208E+01	1,129E+01	0,11%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		3,394E+00	1,697E+01			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	3,964E+00	1,982E+01	1,840E+01	0,18%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		4,088E+00	2,044E+01			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	3,927E+00	1,963E+01	2,004E+01	0,19%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		1,341E+01	6,706E+01			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	1,395E+01	6,976E+01	6,841E+01	0,66%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		1,399E+01	6,994E+01			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	1,390E+01	6,952E+01	6,973E+01	0,68%	

NALUNAQ TAILINGS									
As									
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal concentration [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt - Total initial content [mg/kg]	
pH-des Nalunaq Blind A	5,00	8,90		1,856E-01	9,279E-01			529,0757	
pH-des Nalunaq Blind B	5,00	8,60	8,8	1,515E-01	7,576E-01	8,427E-01	0,16%		
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		1,859E-01	9,294E-01				
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	2,084E-01	1,042E+00	9,856E-01	0,19%		
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		3,756E-01	1,878E+00				
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	3,184E-01	1,592E+00	1,735E+00	0,33%		
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		1,215E+01	6,074E+01				
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	1,244E+01	6,221E+01	6,148E+01	11,62%		
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		9,614E+01	4,807E+02				
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	9,341E+01	4,670E+02	4,739E+02	89,56%		
pH-des Nalunaq 1M HNO3 A	5,00	0,88		9,747E+01	4,874E+02				
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	1,023E+02	5,116E+02	4,995E+02	94,40%		
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		1,462E+00	7,312E+00				
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	2,304E+00	1,152E+01	9,417E+00	1,78%		
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		2,100E+00	1,050E+01				
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	2,671E+00	1,335E+01	1,193E+01	2,25%		
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		4,545E+00	2,273E+01				
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	4,040E+00	2,020E+01	2,146E+01	4,06%		
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		1,955E+01	9,774E+01				
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	2,074E+01	1,037E+02	1,007E+02	19,03%		
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		2,326E+01	1,163E+02				
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	2,242E+01	1,121E+02	1,142E+02	21,58%		

	NALUNAQ TAILINGS							
	Ba							
Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal concentration [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt - Total initial content [mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		1,275E-03	6,375E-03			7,046467
pH-des Nalunaq Blind B	5,00	8,60	8,8	1,626E-03	8,130E-03	7,253E-03	0,10%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		1,245E-02	6,224E-02			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	6,487E-03	3,244E-02	4,734E-02	0,67%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		5,744E-02	2,872E-01			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	6,014E-02	3,007E-01	2,940E-01	4,17%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		2,903E-01	1,451E+00			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	2,890E-01	1,445E+00	1,448E+00	20,55%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		8,842E-01	4,421E+00			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	8,803E-01	4,402E+00	4,411E+00	62,60%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		9,557E-01	4,779E+00			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	9,363E-01	4,682E+00	4,730E+00	67,13%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	2,580E-04	1,290E-03	6,450E-04	0,01%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		4,100E-04	2,050E-03			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	7,470E-04	3,735E-03	2,893E-03	0,04%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		8,200E-04	4,100E-03			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	4,290E-04	2,145E-03	3,123E-03	0,04%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		3,728E-03	1,864E-02			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	4,326E-03	2,163E-02	2,014E-02	0,29%	

NALUNAQ TAILINGS									
Cd									
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		3,365E-03	1,683E-02			2,2818
pH-des Nalunaq Blind B	5,00	8,60	8,8	3,189E-03	1,595E-02	1,639E-02	0,72%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		3,573E-03	1,787E-02			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	3,048E-03	1,524E-02	1,655E-02	0,73%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		3,307E-03	1,654E-02			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	3,549E-03	1,775E-02	1,714E-02	0,75%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		2,386E-02	1,193E-01			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	2,459E-02	1,229E-01	1,211E-01	5,31%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		6,206E-02	3,103E-01			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	6,126E-02	3,063E-01	3,083E-01	13,51%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		7,210E-02	3,605E-01			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	6,667E-02	3,333E-01	3,469E-01	15,20%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		3,531E-03	1,766E-02			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	3,364E-03	1,682E-02	1,724E-02	0,76%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		3,472E-03	1,736E-02			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	3,356E-03	1,678E-02	1,707E-02	0,75%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		2,996E-03	1,498E-02			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	3,210E-03	1,605E-02	1,552E-02	0,68%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		7,546E-03	3,773E-02			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	9,578E-03	4,789E-02	4,281E-02	1,88%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		7,362E-03	3,681E-02			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	7,579E-03	3,790E-02	3,735E-02	1,64%	

	NALUNAQ TAILINGS							
	Cr							
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		6,947E-03	3,474E-02			27,3959
pH-des Nalunaq Blind B	5,00	8,60	8,8	5,058E-03	2,529E-02	3,001E-02	0,11%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		3,989E-03	1,995E-02			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	5,855E-03	2,928E-02	2,461E-02	0,09%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		1,418E-02	7,090E-02			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	1,745E-02	8,724E-02	7,907E-02	0,29%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		5,672E-01	2,836E+00			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	5,613E-01	2,807E+00	2,821E+00	10,30%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		1,487E+00	7,436E+00			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	1,449E+00	7,247E+00	7,341E+00	26,80%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		1,994E+00	9,969E+00			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	1,924E+00	9,619E+00	9,794E+00	35,75%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		1,942E-03	9,710E-03			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	7,558E-03	3,779E-02	2,375E-02	0,09%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		8,958E-03	4,479E-02			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	9,891E-03	4,946E-02	4,712E-02	0,17%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		1,186E-02	5,929E-02			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	2,578E-03	1,289E-02	3,609E-02	0,13%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		2,026E-02	1,013E-01			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	1,989E-02	9,943E-02	1,004E-01	0,37%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		1,679E-02	8,394E-02			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	1,727E-02	8,634E-02	8,514E-02	0,31%	

NALUNAQ TAILINGS									
Cu									
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		3,855E-03	1,928E-02			263,9037
pH-des Nalunaq Blind B	5,00	8,60	8,8	5,469E-03	2,735E-02	2,331E-02	0,01%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		5,458E-03	2,729E-02			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	2,341E-03	1,171E-02	1,950E-02	0,01%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		8,029E-03	4,015E-02			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	6,119E-03	3,060E-02	3,537E-02	0,01%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		3,629E+00	1,815E+01			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	3,707E+00	1,854E+01	1,834E+01	6,95%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		6,386E+00	3,193E+01			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	6,024E+00	3,012E+01	3,102E+01	11,76%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		6,988E+00	3,494E+01			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	6,721E+00	3,361E+01	3,427E+01	12,99%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		3,273E-02	1,636E-01			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	3,476E-02	1,738E-01	1,687E-01	0,06%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		9,606E-02	4,803E-01			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	9,424E-02	4,712E-01	4,757E-01	0,18%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		1,336E-01	6,680E-01			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	1,270E-01	6,349E-01	6,515E-01	0,25%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		2,073E-01	1,037E+00			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	2,112E-01	1,056E+00	1,046E+00	0,40%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		2,255E-01	1,128E+00			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	2,281E-01	1,140E+00	1,134E+00	0,43%	

Sample	B - Mass of tailings [g]	pH [-]	pH - Mean [-]	A - Extract metal concentration [mg/L]	MC - Heavy metal content [mg/kg]	MC - Mean [mg/kg]	MC/Mt [%]	Mt - Total initial content [mg/kg]
NALUNAQ TAILINGS — Fe								
pH-des Nalunaq Blind A	5,00	8,90		1,701E-02	8,505E-02			14189,13
pH-des Nalunaq Blind B	5,00	8,60	8,8	0,000E+00	0,000E+00	4,253E-02	0,00%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		2,711E+02	1,355E+03			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	2,804E+02	1,402E+03	1,379E+03	9,72%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		9,824E+02	4,912E+03			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	9,331E+02	4,665E+03	4,789E+03	33,75%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		1,053E+03	5,263E+03			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	1,068E+03	5,341E+03	5,302E+03	37,37%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		5,991E-01	2,996E+00			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	3,779E-01	1,889E+00	2,442E+00	0,02%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		2,960E-01	1,480E+00			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	2,815E-01	1,408E+00	1,444E+00	0,01%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		3,413E-01	1,707E+00			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	3,172E-01	1,586E+00	1,646E+00	0,01%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		8,440E-01	4,220E+00			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	8,333E-01	4,166E+00	4,193E+00	0,03%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		6,377E-01	3,188E+00			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	5,915E-01	2,957E+00	3,073E+00	0,02%	

NALUNAQ TAILINGS								
Mn								
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		5,274E-03	2,637E-02			139,5013
pH-des Nalunaq Blind B	5,00	8,60	8,8	1,189E-02	5,944E-02	4,291E-02	0,03%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		2,892E-01	1,446E+00			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	9,871E-02	4,936E-01	9,698E-01	0,70%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		2,700E+00	1,350E+01			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	2,716E+00	1,358E+01	1,354E+01	9,70%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		5,566E+00	2,783E+01			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	5,592E+00	2,796E+01	2,790E+01	20,00%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		9,298E+00	4,649E+01			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	9,129E+00	4,565E+01	4,607E+01	33,02%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		1,161E+01	5,803E+01			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	1,137E+01	5,683E+01	5,743E+01	41,17%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		0,000E+00	0,000E+00			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		0,000E+00	0,000E+00			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	1,004E-03	5,020E-03	2,510E-03	0,00%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		0,000E+00	0,000E+00			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	0,000E+00	0,000E+00	0,000E+00	0,00%	

	NALUNAQ TAILINGS							
	Ni							
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		1,510E-02	7,552E-02			46,70593
pH-des Nalunaq Blind B	5,00	8,60	8,8	1,212E-02	6,061E-02	6,806E-02	0,15%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		7,092E-02	3,546E-01			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	2,694E-02	1,347E-01	2,446E-01	0,52%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		9,167E-01	4,583E+00			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	9,846E-01	4,923E+00	4,753E+00	10,18%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		3,207E+00	1,604E+01			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	3,252E+00	1,626E+01	1,615E+01	34,58%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		6,341E+00	3,171E+01			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	6,002E+00	3,001E+01	3,086E+01	66,07%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		5,950E+00	2,975E+01			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	5,837E+00	2,918E+01	2,947E+01	63,09%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		2,463E-02	1,231E-01			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	2,307E-02	1,153E-01	1,192E-01	0,26%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		2,839E-02	1,419E-01			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	2,772E-02	1,386E-01	1,403E-01	0,30%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		2,607E-02	1,304E-01			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	2,398E-02	1,199E-01	1,251E-01	0,27%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		4,775E-02	2,388E-01			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	5,431E-02	2,715E-01	2,552E-01	0,55%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		6,734E-02	3,367E-01			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	7,077E-02	3,539E-01	3,453E-01	0,74%	

NALUNAQ TAILINGS								
P								
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		0,000E+00	0,000E+00			227,6767
pH-des Nalunaq Blind B	5,00	8,60	8,8	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		1,256E+01	6,282E+01			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	1,151E+01	5,756E+01	6,019E+01	26,44%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		4,324E+01	2,162E+02			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	4,221E+01	2,111E+02	2,136E+02	93,83%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		4,349E+01	2,174E+02			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	4,298E+01	2,149E+02	2,162E+02	94,94%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		0,000E+00	0,000E+00			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		0,000E+00	0,000E+00			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	0,000E+00	0,000E+00	0,000E+00	0,00%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		0,000E+00	0,000E+00			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	0,000E+00	0,000E+00	0,000E+00	0,00%	

NALUNAQ TAILINGS								
Pb								
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		1,452E-02	7,258E-02			9,710367
pH-des Nalunaq Blind B	5,00	8,60	8,8	2,080E-02	1,040E-01	8,829E-02	0,91%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		3,577E-03	1,789E-02			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	6,902E-03	3,451E-02	2,620E-02	0,27%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		0,000E+00	0,000E+00			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	2,461E-02	1,230E-01	6,152E-02	0,63%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		4,153E-01	2,077E+00			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	3,935E-01	1,968E+00	2,022E+00	20,82%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		1,684E+00	8,420E+00			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	1,617E+00	8,087E+00	8,254E+00	85,00%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		2,191E+00	1,095E+01			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	1,669E+00	8,346E+00	9,650E+00	99,38%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		4,502E-03	2,251E-02			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	1,210E-02	6,051E-02	4,151E-02	0,43%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		2,593E-02	1,296E-01			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	2,755E-02	1,377E-01	1,337E-01	1,38%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		4,165E-02	2,082E-01			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	5,018E-02	2,509E-01	2,296E-01	2,36%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		4,575E-02	2,287E-01			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	1,107E-01	5,533E-01	3,910E-01	4,03%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		1,271E-01	6,353E-01			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	9,794E-02	4,897E-01	5,625E-01	5,79%	

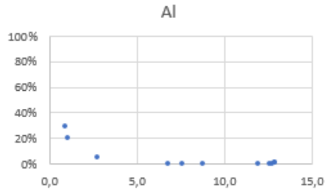
NALUNAQ TAILINGS

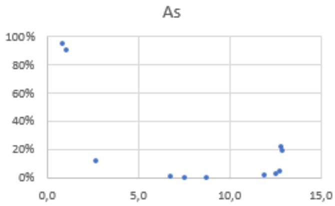
S

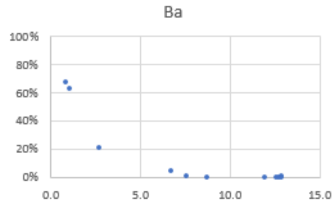
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		9,538E+01	4,769E+02			2712,023
pH-des Nalunaq Blind B	5,00	8,60	8,8	1,020E+02	5,098E+02	4,934E+02	18,19%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		1,056E+02	5,280E+02			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	1,116E+02	5,578E+02	5,429E+02	20,02%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		1,120E+02	5,599E+02			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	1,274E+02	6,370E+02	5,984E+02	22,07%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		9,964E+01	4,982E+02			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	1,018E+02	5,091E+02	5,036E+02	18,57%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		1,749E+02	8,747E+02			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	1,835E+02	9,175E+02	8,961E+02	33,04%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		1,769E+02	8,845E+02			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	1,855E+02	9,277E+02	9,061E+02	33,41%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		1,854E+02	9,272E+02			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	1,735E+02	8,677E+02	8,975E+02	33,09%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		2,045E+02	1,023E+03			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	2,069E+02	1,034E+03	1,028E+03	37,92%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		2,368E+02	1,184E+03			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	2,249E+02	1,125E+03	1,154E+03	42,56%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		9,467E+02	4,733E+03			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	9,808E+02	4,904E+03	4,819E+03	177,68%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		1,382E+03	6,912E+03			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	1,314E+03	6,570E+03	6,741E+03	248,57%	

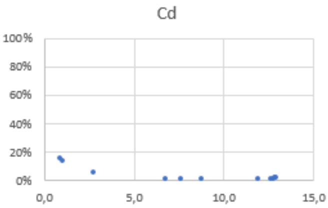
	NALUNAQ TAILINGS							
	Zn							
Sample	B - Mass of tailings	pH	pH - Mean	A - Extract metal concentration	MC - Heavy metal content	MC - Mean	MC/Mt	Mt - Total initial content
	[g]	[-]	[-]	[mg/L]	[mg/kg]	[mg/kg]	[%]	[mg/kg]
pH-des Nalunaq Blind A	5,00	8,90		0,000E+00	0,000E+00			37,46423
pH-des Nalunaq Blind B	5,00	8,60	8,8	4,260E-04	2,130E-03	1,065E-03	0,00%	
pH-des Nalunaq 0,01M HNO3 A	5,00	7,33		1,783E-03	8,915E-03			
pH-des Nalunaq 0,01M HNO3 B	5,00	7,85	7,6	0,000E+00	0,000E+00	4,458E-03	0,01%	
pH-des Nalunaq 0,05M HNO3 A	5,00	6,78		5,433E-02	2,716E-01			
pH-des Nalunaq 0,05M HNO3 B	5,00	6,72	6,8	8,365E-02	4,183E-01	3,450E-01	0,92%	
pH-des Nalunaq 0,1M HNO3 A	5,00	2,72		2,608E+00	1,304E+01			
pH-des Nalunaq 0,1M HNO3 B	5,00	2,72	2,7	2,490E+00	1,245E+01	1,274E+01	34,02%	
pH-des Nalunaq 0,5M HNO3 A	5,00	1,06		4,479E+00	2,239E+01			
pH-des Nalunaq 0,5M HNO3 B	5,00	1,05	1,1	4,467E+00	2,233E+01	2,236E+01	59,69%	
pH-des Nalunaq 1M HNO3 A	5,00	0,88		5,748E+00	2,874E+01			
pH-des Nalunaq 1M HNO3 B	5,00	0,85	0,9	5,137E+00	2,568E+01	2,721E+01	72,63%	
pH-des Nalunaq 0,01M NaOH A	5,00	11,93		0,000E+00	0,000E+00			
pH-des Nalunaq 0,01M NaOH B	5,00	11,90	11,9	1,897E-03	9,485E-03	4,743E-03	0,01%	
pH-des Nalunaq 0,05M NaOH A	5,00	12,58		7,616E-03	3,808E-02			
pH-des Nalunaq 0,05M NaOH B	5,00	12,60	12,6	0,000E+00	0,000E+00	1,904E-02	0,05%	
pH-des Nalunaq 0,1M NaOH A	5,00	12,73		3,244E-03	1,622E-02			
pH-des Nalunaq 0,1M NaOH B	5,00	12,74	12,7	4,117E-03	2,059E-02	1,840E-02	0,05%	
pH-des Nalunaq 0,5M NaOH A	5,00	12,87		1,147E-01	5,734E-01			
pH-des Nalunaq 0,5M NaOH B	5,00	12,88	12,9	1,169E-01	5,843E-01	5,789E-01	1,55%	
pH-des Nalunaq 1,0M NaOH A	5,00	12,82		3,351E-01	1,676E+00			
pH-des Nalunaq 1,0M NaOH B	5,00	12,90	12,9	3,598E-01	1,799E+00	1,737E+00	4,64%	

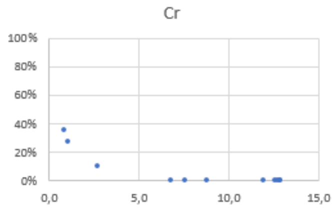
B.3.4 Graphs - Nalunaq tailings

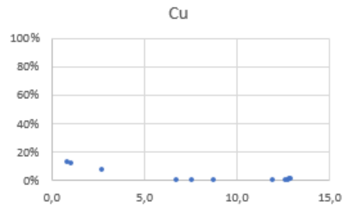


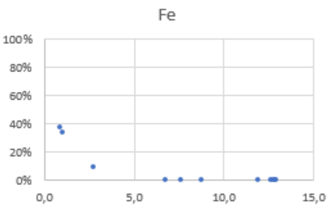


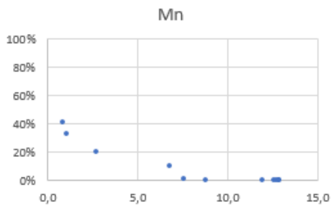


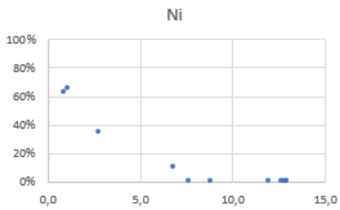


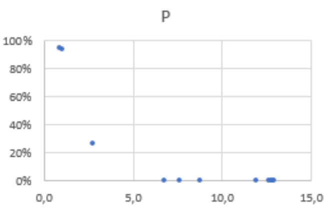


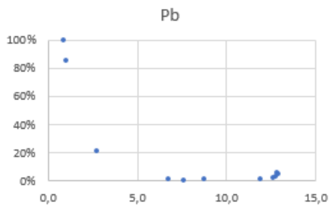


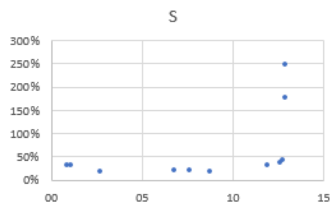


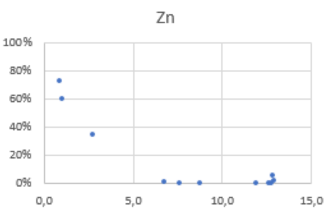












B.4 Consistency of fresh mortar

Mortar recipe	Batch No.	Horizontal diameter (mm)	Vertical diameter (mm)	Mean flow (mm)	Standard deviation (mm)
REF	REF_7	146	151	**148**	4
ZC5	ZC5_7	150	148	**149**	1
ZC10	ZC10_7	120	118	**119**	1
ZS5	ZS5_7	128	134	**131**	4
ZS10	ZS10_7	118	114	**116**	3
NC5	NC5_7	128	130	**129**	2
NC10	NC10_7	128	123	**126**	3
NS5	NS5_7	133	132	**133**	1
NS10	NS10_7	126	120	**123**	4

B.5 Setting time

B.5.1 Results from the Vicat apparatus

$TEST NUMBER : REF
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1________
$SPECIMEN TIME : 11:47:43
$START DELAY[m]: ---
$1ST PEN TIME : 11:47:43
$SPECIMEN T REF_6
$FALL TYPE : FREE
$TIME TYPE : FIXED
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	Time [m,s]
#1	0	0,37
#2	0,1	10,37
#3	0,1	20,37
#4	0	30,37
#5	0	40,37
#6	0	50,37
#7	0,1	60,37
#8	0,1	70,37
#9	0,1	80,37
#10	0	90,37
#11	0	100,37
#12	0,1	110,37
#13	0	120,37
#14	0,1	130,37
#15	0	140,37
#16	2,6	150,37

$TEST NUMBER : ZC5
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1________
$SPECIMEN TIME : 15:51:50
$START DELAY[m]: ---
$1ST PEN TIME : 15:52:50
$SPECIMEN TYPE : ZC5_6
$FALL TYPE : FREE
$TIME TYPE : FIXED
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	Time [m,s]
#1	0	0,48
#2	0	10,48
#3	0	20,48
#4	0	30,48
#5	0	40,48
#6	0	50,48
#7	0	60,48
#8	0	70,48
#9	0	80,48
#10	0	90,48
#11	0	100,48
#12	0	110,48
#13	0	120,48
#14	0	130,48
#15	0	140,48
#16	0	150,48

$TEST NUMBER : ZC10
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1________
$SPECIMEN TIME : 14:31:50
$START DELAY[m]: ---
$1ST PEN TIME : 14:31:50
$SPECIMEN TYPE : ZC10_6
$FALL TYPE : FREE
$TIME TYPE : FIXED
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	Time [m,s]
#1	0,0	0,48
#2	0,0	10,48
#3	0,0	20,48
#4	0,0	30,48
#5	0,0	40,48
#6	0,0	50,48
#7	0,0	60,48
#8	0,0	70,48
#9	0,0	80,48
#10	0,0	90,48
#11	0,0	100,48
#12	0,0	110,48
#13	0,0	120,48
#14	0,0	130,48
#15	0,0	140,48
#16	0,0	150,48

$TEST NUMBER : ZS5
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4.00
$ 24 5.25
$ 18 5.25
$ 12 5.25
$ 2 5.25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1________
$SPECIMEN TIME : 13:26:48
$START DELAY[m]: ---
$1ST PEN TIME : 13:27:48
$SPECIMEN TYPE : ZS5_6
$FALL TYPE : FREE
$TIME TYPE : FIXED
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	Time [m,s]
#1	0	0,47
#2	0	10,47
#3	0	20,47
#4	0	30,47
#5	0	40,47
#6	0	50,47
#7	0	60,47
#8	0	70,47
#9	0,1	80,47
#10	0	90,47
#11	0	100,47
#12	0	110,47
#13	0,1	120,47
#14	0	130,47
#15	0	140,47
#16	0	150,47

$TEST NUMBER : ZS10
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1________
$DATE OF TEST : 08/02/2017
$SPECIMEN TIME : 16:40:45
$START DELAY[m]: ---
$1ST PEN TIME : 16:41:45
$FALL TYPE : FREE
$TIME TYPE : FIXED
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	I [m,s]
#1	0,0	0,51
#2	0,0	10,51
#3	0,0	20,51
#4	0,0	30,51
#5	0,0	40,51
#6	0,0	50,51
#7	0,0	60,51
#8	0,0	70,51
#9	0,0	80,51
#10	0,0	90,51
#11	0,0	100,51
#12	0,1	110,51
#13	0,0	120,51
#14	0,0	130,51
#15	0,0	140,51
#16	0,0	150,51

$TEST NUMBER : REF			$TEST NUMBER : ZC5			$TEST NUMBER : ZC10			$TEST NUMBER : ZS5			$TEST NUMBER : ZS10		
#17	5,3	160,37	#17	0	160,48	#17	0,0	160,48	#17	0	160,47	#17	0,0	160,51
#18	11,5	170,37	#18	15,1	170,48	#18	0,0	170,48	#18	0	170,47	#18	0,1	170,51
#19	15,6	180,37	#19	10,8	180,48	#19	0,0	180,48	#19	0,1	180,47	#19	0,1	180,51
#20	11,5	190,37	#20	12,9	190,48	#20	0,0	190,48	#20	0	190,47	#20	0,0	190,51
#21	11,4	200,37	#21	20,6	200,48	#21	0,0	200,48	#21	0,3	200,47	#21	0,0	200,51
#22	20,4	210,37	#22	16	210,48	#22	0,0	210,48	#22	0	210,47	#22	0,1	210,51
#23	26	220,37	#23	35,9	220,48	#23	6,0	220,48	#23	0,1	220,47	#23	0,0	220,51
#24	27,2	230,37	#24	31,1	230,48	#24	17,0	230,48	#24	14,1	230,47	#24	0,2	230,51
#25	32,9	240,37	#25	32,4	240,48	#25	25,0	240,48	#25	11,1	240,47	#25	1,0	240,51
#26	35,9	250,37	#26	34,3	250,48	#26	22,8	250,48	#26	19,9	250,47	#26	0,1	250,51
#27	34,3	260,37	#27	35,4	260,48	#27	27,5	260,48	#27	25,9	260,47	#27	22,4	260,51
#28	38,7	270,37	#28	38,1	270,48	#28	32,8	270,48	#28	31,9	270,47	#28	15,4	270,51
#29	38,5	280,37	#29	35,9	280,48	#29	30,0	280,48	#29	31,7	280,47	#29	21,2	280,51
#30	36,9	290,37	#30	40,1	290,48	#30	29,3	290,48	#30	30,2	290,47	#30	24,7	290,51
#31	37,2	300,37	#31	39,1	300,48	#31	35,3	300,48	#31	34,8	300,47	#31	26,0	300,51
#32	36,8	310,37	#32	39,8	310,48	#32	32,8	310,48	#32	36,1	310,47	#32	28,3	310,51
#33	36,9	320,37	#33	39,4	320,48	#33	34,0	320,48	#33	33,9	320,47	#33	34,0	320,51
#34	37,7	330,37	#34	39,7	330,48	#34	35,6	330,48	#34	37	330,47	#34	33,3	330,51
#35	37,2	340,37	#35	38,3	340,48	#35	36,0	340,48	#35	34,9	340,47	#35	33,7	340,51
#36	36,9	350,37	#36	39	350,48	#36	37,8	350,48	#36	36,2	350,47	#36	34,7	350,51
#37	36,6	360,37	#37	38,2	360,48	#37	39,1	360,48	#37	38,2	360,47	#37	35,0	360,51
#38	37,8	370,37	#38	38,4	370,48	#38	38,5	370,48	#38	34,6	370,47	#38	35,4	370,51
#39	38,1	380,37	#39	38,9	380,48	#39	39,8	380,48	#39	37	380,47	#39	35,6	380,51
#40	38,8	390,37	#40	39,9	390,48	#40	39,9	390,48	#40	36,9	390,47	#40	35,5	390,51
#41	39,2	400,37	#41	41,4	400,48	#41	40,9	400,48	#41	37,5	400,47	#41	36,5	400,51
#42	39,4	410,37	#42	41,1	410,48	#42	41,8	410,48	#42	37,7	410,47	#42	36,7	410,51
#43	38,3	420,37	#43	40,9	420,48	#43	41,0	420,48	#43	37,9	420,47	#43	34,8	420,51
#44	37,4	430,37	#44	40,4	430,48	#44	39,7	430,48	#44	37,5	430,47	#44	37,8	430,51
#45	38,6	440,37	#45	40,2	440,48	#45	40,9	440,48	#45	38,2	440,47	#45	37,9	440,51
#46	38,1	450,37	#46	40,3	450,48	#46	39,8	450,48	#46	37,7	450,47	#46	36,5	450,51
#47	37,8	460,37	#47	39,7	460,48	#47	39,2	460,48	#47	37,2	460,47	#47	37,6	460,51
#48	38,3	470,37	#48	39	470,48	#48	39,4	470,48	#48	37,6	470,47	#48	37,2	470,51
#49	37	480,37	#49	38,8	480,48	#49	37,3	480,48	#49	39,3	480,47	#49	37,4	480,51
#50	37,8	490,37	#50	39,3	490,48	#50	39,2	490,48	#50	38,6	490,47	#50	37,4	490,51
#51	38,6	500,37	#51	40,1	500,48	#51	41,5	500,48	#51	37,8	500,47	#51	37,3	500,51
#52	39,4	510,37	#52	41,3	510,48	#52	41,2	510,48	#52	38,4	510,47	#52	37,4	510,51

$TEST NUMBER : REF			$TEST NUMBER : ZC5			$TEST NUMBER : ZC10			$TEST NUMBER : ZS5			$TEST NUMBER : ZS10		
#53	39,7	520,37	#53	41,4	520,48	#53	42,1	520,48	#53	38,3	520,47	#53	36,4	520,51
#54	39,4	530,37	#54	40,8	530,48	#54	42,4	530,48	#54	38,5	530,47	#54	38,1	530,51
#55	39	540,37	#55	40,7	540,48	#55	39,1	540,48	#55	39,2	540,47	#55	36,7	540,51
#56	38,6	550,37	#56	41,2	550,48	#56	43,1	550,48	#56	39	550,47	#56	38,4	550,51
#57	38,1	560,37	#57	40,5	560,48	#57	40,6	560,48	#57	38,8	560,47	#57	37,6	560,51
#58	37,5	570,37	#58	40,5	570,48	#58	41,2	570,48	#58	38,1	570,47	#58	37,4	570,51
#59	37,5	580,37	#59	39,9	580,48	#59	39,9	580,48	#59	38,9	580,47	#59	37,4	580,51
#60	38,6	590,37	#60	39,8	590,48	#60	40,3	590,48	#60	38,5	590,47	#60	38,1	590,51
#61	39	600,37	#61	40,3	600,48	#61	42,1	600,48	#61	38,7	600,47	#61	37,2	600,51
#62	39,2	610,37	#62	41,4	610,48	#62	42,1	610,48	#62	38,6	610,47	#62	38,6	610,51
#63	39,5	620,37	#63	40,9	620,48	#63	41,0	620,48	#63	39,1	620,47	#63	37,6	620,51
#64	38,8	630,37	#64	40,7	630,48	#64	41,3	630,48	#64	38,6	630,47	#64	38,6	630,51
#65	38,7	640,37	#65	40,8	640,48	#65	42,4	640,48	#65	39,3	640,47	#65	38,3	640,51
#66	37,5	650,37	#66	40,7	650,48	#66	41,8	650,48	#66	37,8	650,47	#66	37,5	650,51
#67	38,8	660,37	#67	40	660,48	#67	39,7	660,48	#67	38,5	660,47	#67	37,9	660,51
#68	39	670,37	#68	39,8	670,48	#68	40,0	670,48	#68	38,7	670,47	#68	37,5	670,51
#69	38,1	680,37	#69	39,6	680,48	#69	37,7	680,48	#69	38,1	680,47	#69	37,7	680,51
#70	39,1	690,37	#70	40,8	690,48	#70	38,4	690,48	#70	38,6	690,47	#70	37,9	690,51
#71	39,7	700,37	#71	41,2	700,48	#71	40,3	700,48	#71	38,9	700,47	**#71**	**39,0**	**700,51**
#72	39,2	710,37	#72	40,8	710,48	#72	41,2	710,48	#72	39,3	710,47	#72	38,2	710,51
#73	**41,5**	**720,37**	#73	41	720,48	#73	39,7	720,48	#73	38,6	720,47	#73	38,7	720,51
#74	38,4	730,37	#74	40,9	730,48	#74	42,8	730,48	#74	38,1	730,47	#74	38,0	730,51
#75	37,8	740,37	#75	40,4	740,48	#75	39,9	740,48	#75	38,8	740,47	#75	37,7	740,51
#76	38,7	750,37	#76	40,3	750,48	#76	38,6	750,48	#76	38,5	750,47	#76	37,7	750,51
#77	38,7	760,37	#77	40,7	760,48	#77	40,6	760,48	#77	38,7	760,47	#77	38,3	760,51
#78	39,2	770,37	**#78**	**41,4**	**770,48**	#78	41,1	770,48	#78	39,2	770,47	#78	38,7	770,51
#79	39,4	780,37	#79	40,7	780,48	#79	38,7	780,48	#79	37,7	780,47	#79	38,2	780,51
#80	38,3	790,37	#80	41,1	790,48	#80	41,5	790,48	#80	38,6	790,47	#80	37,6	790,51
#81	38,8	800,37	#81	40,2	800,48	#81	39,1	800,48	#81	39	800,47	#81	38,0	800,51
#82	39,5	810,37	#82	40,3	810,48	#82	38,5	810,48	#82	38,7	810,47	#82	38,1	810,51
#83	39,3	820,37	#83	41,1	820,48	**#83**	**43,6**	**820,48**	#83	38,9	820,47	#83	38,7	820,51
#84	39,4	830,37	#84	41,2	830,48	#84	41,7	830,48	#84	38,6	830,47	#84	38,1	830,51
#85	39,6	840,37	#85	41	840,48	#85	40,4	840,48	#85	38,7	840,47	#85	37,8	840,51
#86	39,3	850,37	#86	40,7	850,48	#86	41,5	850,48	#86	38,6	850,47	#86	38,6	850,51

$TEST NUMBER : NC5
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1_________
$DATE OF TEST : 26/01/2017
$SPECIMEN TIME : 12:51:11
$START DELAY[m]: ---
$1ST PEN TIME : 12:52:11
$SPECIMEN TYPE : NC5_71____
$WATER CONT,[%]: 0,5
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	I [m,s]
# 1	0	0,43
# 2	0	10,43
# 3	0	20,43
# 4	0	30,43
# 5	0	40,43
# 6	0	50,43
# 7	0	60,43
# 8	0	70,43
# 9	0	80,43
#10	0	90,43
#11	0	100,43
#12	0	110,43
#13	0	120,43
#14	2	130,43
#15	0	140,43
#16	0	150,43

$TEST NUMBER : NC10
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1_________
$DATE OF TEST : 07/02/2017
$SPECIMEN TIME : 16:26:48
$START DELAY[m]: ---
$1ST PEN TIME : 16:27:48
$SPECIMEN TYPE : NC1005_7__
$WATER CONT,[%]: 0,5
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	I [m,s]
# 1	0,1	0,47
# 2	0	10,47
# 3	0,1	20,47
# 4	0,2	30,47
# 5	0	40,47
# 6	0	50,47
# 7	0	60,47
# 8	0,1	70,47
# 9	0,1	80,47
#10	0,2	90,47
#11	0	100,47
#12	0,2	110,47
#13	0,1	120,47
#14	0,2	130,47
#15	0	140,47
#16	0,2	150,47

$TEST NUMBER : NS5
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1_________
$DATE OF TEST : 01/02/2017
$SPECIMEN TIME : 15:40:39
$START DELAY[m]: ---
$1ST PEN TIME : 15:41:39
$SPECIMEN TYPE : NS5_05_7__
$WATER CONT,[%]: 0,5
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	I [m,s]
# 1	0	0,14
# 2	0	10,14
# 3	0	20,14
# 4	0	30,14
# 5	0	40,14
# 6	0	50,14
# 7	0	60,14
# 8	0	70,14
# 9	0	80,14
#10	0	90,14
#11	0	100,14
#12	0	110,14
#13	0	120,14
#14	0	130,14
#15	0	140,14
#16	0	150,14

$TEST NUMBER : NS10
$KIND OF TEST : EN196-3:2005
$CYCLE TYPE : STANDARD
$POINTS MOVE [mm]
$ 30 4,00
$ 24 5,25
$ 18 5,25
$ 12 5,25
$ 2 5,25
$OPERATOR CODE : CP________
$CUSTOMER CODE : 1_________
$DATE OF TEST : 13/02/2017
$SPECIMEN TIME : 11:57:50
$START DELAY[m]: ---
$1ST PEN TIME : 11:58:50
$SPECIMEN TYPE : ZC5_05_7__
$WATER CONT,[%]: 0,5
$FINAL SETTING : NO
$TIME [m] : 10

ID	PEN,[mm]	I [m,s]
# 1	0	0,48
# 2	0	10,48
# 3	0	20,48
# 4	0	30,48
# 5	0	40,48
# 6	0	50,48
# 7	0	60,48
# 8	0	70,48
# 9	0	80,48
#10	0	90,48
#11	0	100,48
#12	0	110,48
#13	0	120,48
#14	0	130,48
#15	0	140,48
#16	**11,19**	**150,48**

$TEST NUMBER : NC5			$TEST NUMBER : NC10			$TEST NUMBER : NS5			$TEST NUMBER : NS10		
#17	0	160,43	#17	0,8	160,47	#17	5,6	160,14	#17	20,02	160,48
#18	0	170,43	#18	0,2	170,47	#18	0	170,14	#18	27,4	170,48
#19	0,3	180,43	#19	21,8	180,47	#19	17,5	180,14	#19	33,43	180,48
#20	16,3	190,43	#20	20,1	190,47	#20	31	190,14	#20	30,5	190,48
#21	12,1	200,43	#21	24,4	200,47	#21	31,6	200,14	#21	34,99	200,48
#22	23,7	210,43	#22	28,7	210,47	#22	33,8	210,14	#22	35,74	210,48
#23	25,3	220,43	#23	29,4	220,47	#23	33,8	220,14	#23	38,74	220,48
#24	31,7	230,43	#24	31,4	230,47	#24	37,3	230,14	#24	33,678209	230,48
#25	32,8	240,43	#25	31,8	240,47	#25	37,2	240,14	#25	32,17539093	240,48
#26	34,1	250,43	#26	34,3	250,47	#26	37,9	250,14	#26	37,00130434	250,48
#27	38,3	260,43	#27	34,8	260,47	#27	37,5	260,14	#27	36,23324472	260,48
#28	35,5	270,43	#28	35,6	270,47	#28	38,6	270,14	#28	35,11023492	270,48
#29	35,6	280,43	#29	37,7	280,47	#29	39,4	280,14	#29	33,24632049	280,48
#30	38,3	290,43	#30	37,8	290,47	#30	40,1	290,14	#30	36,88415342	290,48
#31	37,7	300,43	#31	37,9	300,47	#31	41,2	300,14	#31	39,99975308	300,48
#32	38,4	310,43	#32	40	310,47	#32	41,8	310,14	#32	32,8804256	310,48
#33	40,4	320,43	#33	39,2	320,47	#33	42,2	320,14	#33	36,53914981	320,48
#34	40,5	330,43	#34	37,8	330,47	#34	41,5	330,14	#34	38,51469543	330,48
#35	40,1	340,43	#35	38,1	340,47	#35	41,3	340,14	#35	38,328756	340,48
#36	37,7	350,43	#36	38,6	350,47	#36	40,5	350,14	#36	37,883473	350,48
#37	38,4	360,43	#37	35,9	360,47	#37	40,5	360,14	#37	37,68215719	360,48
#38	38,9	370,43	#38	38,4	370,47	#38	41	370,14	#38	36,38099919	370,48
#39	38,4	380,43	#39	39,8	380,47	#39	41	380,14	#39	35,66598033	380,48
#40	40,4	390,43	#40	39,9	390,47	#40	40,3	390,14	#40	39,82973075	390,48
#41	37,8	400,43	#41	40,9	400,47	#41	41,2	400,14	#41	40,366802	400,48
#42	40,6	410,43	#42	40,6	410,47	#42	40,5	410,14	#42	39,10451115	410,48
#43	39,7	420,43	#43	40,1	420,47	#43	41,4	420,14	#43	41,06830707	420,48
#44	40,1	430,43	#44	39,5	430,47	#44	42,2	430,14	#44	40,56356695	430,48
#45	41,2	440,43	#45	39,6	440,47	#45	41,5	440,14	#45	40,66977563	440,48
#46	40,7	450,43	#46	38,9	450,47	#46	41	450,14	#46	40,51195527	450,48
#47	39,9	460,43	#47	38,9	460,47	#47	41,2	460,14	#47	40,19923716	460,48
#48	39,9	470,43	#48	39	470,47	#48	41	470,14	#48	38,96634698	470,48
#49	39,2	480,43	#49	36,5	480,47	#49	40,4	480,14	#49	39,41102415	480,48
#50	38	490,43	#50	39,7	490,47	#50	41,3	490,14	#50	39,16058683	490,48
#51	40,1	500,43	#51	40,9	500,47	#51	40,5	500,14	#51	39,9158089	500,48
#52	40,5	510,43	#52	40,5	510,47	#52	41	510,14	#52	40,56452761	510,48

$TEST NUMBER : NC5			$TEST NUMBER : NC10			$TEST NUMBER : NS5			$TEST NUMBER : NS10		
#53	38,7	520,43	#53	40,6	520,47	#53	40,8	520,14	#53	41,82120238	520,48
#54	40,5	530,43	#54	40,3	530,47	#54	40,8	530,14	#54	41,51906468	530,48
#55	40,4	540,43	#55	40,3	540,47	#55	41,6	540,14	#55	40,71721892	540,48
#56	40,5	550,43	#56	39,9	550,47	#56	42,6	550,14	#56	41,03477963	550,48
#57	39,8	560,43	#57	39,8	560,47	#57	41,5	560,14	#57	40,55390241	560,48
#58	39,3	570,43	#58	39,3	570,47	#58	41,4	570,14	#58	40,33678062	570,48
#59	39,7	580,43	#59	39,8	580,47	#59	40,7	580,14	#59	40,24800092	580,48
#60	38,5	590,43	#60	39,6	590,47	#60	41,8	590,14	#60	39,02764096	590,48
#61	40,9	600,43	#61	40,5	600,47	#61	41,3	600,14	#61	40,3968497	600,48
#62	40,3	610,43	#62	40,9	610,47	#62	41,3	610,14	#62	40,94466718	610,48
#63	40,9	620,43	#63	40,9	620,47	#63	41	620,14	#63	40,74003989	620,48
#64	40,3	630,43	#64	39,4	630,47	#64	41,8	630,14	#64	40,03246814	630,48
#65	40,4	640,43	#65	39,8	640,47	#65	42,2	640,14	#65	40,88953521	640,48
#66	39,7	650,43	#66	38,6	650,47	#66	41,4	650,14	#66	40,35119572	650,48
#67	39,4	660,43	#67	39,9	660,47	#67	41	660,14	#67	39,39565255	660,48
#68	39,3	670,43	#68	40,1	670,47	#68	40,4	670,14	#68	39,72574092	670,48
#69	39,6	680,43	#69	40,3	680,47	#69	41,7	680,14	#69	40,56241567	680,48
#70	41	690,43	#70	40,9	690,47	#70	40,9	690,14	#70	40,31166045	690,48
#71	40,7	700,43	**#71**	**41,2**	**700,47**	#71	41,2	700,14	#71	41,17461284	700,48
#72	40,4	710,43	#72	41,2	710,47	#72	41,4	710,14	#72	40,5428454	710,48
#73	39,5	720,43	#73	39	720,47	#73	41,8	720,14	#73	40,99770552	720,48
#74	39,9	730,43	#74	39,8	730,47	#74	41,5	730,14	#74	40,81676684	730,48
#75	39,8	740,43	#75	39,6	740,47	#75	41,3	740,14	#75	40,05894456	740,48
#76	40,1	750,43	#76	39,8	750,47	#76	41,2	750,14	#76	40,73583221	750,48
#77	41,1	760,43	#77	40,5	760,47	#77	41,6	760,14	#77	40,61131356	760,48
#78	40,8	770,43	#78	40,9	770,47	#78	41,4	770,14	**#78**	**42,09387657**	**770,48**
#79	40,1	780,43	#79	38,9	780,47	#79	41,9	780,14	#79	40,5334313	780,48
#80	39,9	790,43	#80	39,3	790,47	#80	41,2	790,14	#80	40,39446799	790,48
#81	39,7	800,43	#81	39,8	800,47	#81	41,2	800,14	#81	39,77803228	800,48
#82	40,7	810,43	#82	40,3	810,47	**#82**	**42,6**	**810,14**	#82	40,46351276	810,48
#83	39,3	820,43	#83	41,1	820,47	#83	41,4	820,14	#83	41,26868995	820,48
#84	40,1	830,43	#84	40,3	830,47	#84	41,3	830,14	#84	41,92427425	830,48
#85	40	840,43	#85	40,3	840,47	#85	41,8	840,14	#85	40,96414868	840,48
#86	40,4	850,43	#86	39,5	850,47	#86	40,9	850,14	#86	40,88047848	850,48

B.5.2 Initial and final setting time

	Initial setting time (min)	Final setting time (min)
REF	160	720
ZC5	170	770
NC5	190	440
ZC10	220	820
NC10	180	700
ZS5	230	480
NS5	160	810
ZS10	260	700
NS10	150	770

B.6 Compressive strength

B.6.1 7-day compressive strength

Specimen data					Geometry						Strength												
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
		[days]	[jj/mm]	[hh:mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[kN]	[MPa]	[kN]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	
REFa	REFa_1A	7	19/1	09:35	40,0 40,0 40,0	40,0	40,5 41 41	40,8	160,5 160,5	160,5	58	35,5	55	33,7	30,7	27,6	33,8	29,7	26,8	32,7	3,6	Determination should be redone (more than 2 results differ of more than 10%)
	REFa_1B	7	19/1	09:45	40,1 40,0 40,0	40,0	40,5 40,8 40,7	40,7	160,0 160,1	160,1	44	27,0	47	28,9								
	REFa_1C	7	19/1	09:50	40,0 40,1 40,0	40,0	40,5 40,5 40,8	40,6	160,0 160,3	160,2	52	32,0	44	27,1								
REF	REF_1A	7	6/2	10:25	40,1 40,0 40,0	40,0	39,3 39,7 39,3	39,4	160 160	160	52	32,9	54	34,2	35,4	31,8	38,9	35,4	-	-	1,9	Reference determination redone; new results are satisfactory
	REF_1B	7	6/2	10:30	40,0 39,9 39,9	39,9	39,8 39,2 39,3	39,4	160,0 160	160,0	58	36,8	54	34,3								
	REF_1C	7	6/2	10:35	40,0 40,0 40,0	40,0	39,3 39,6 39,7	39,5	160,0 160,0	160,0	57	36,0	60	37,9								
ZC5	ZC5_1A	7	23/1	09:45	40,0 40,0 39,9	40,0	41,5 40,2 40,7	40,8	160,1 160	160,05	57	35,0	61	37,4	36,3	32,7	40,0	36,3	-	-	1,5	
	ZC5_1B	7	23/1	09:50	40,0 40,1 40,0	40,0	40 40,3 39,5	39,9	160,2 160	160,1	60	37,5	59	36,9								
	ZC5_1C	7	23/1	09:55	40,0 40,0 40,0	40,0	40,5 39,6 39	39,7	160,0 160,0	160,0	54	34,0	59	37,2								
NC5	NC5_1A	7	24/1	10:40	40,0 40,0 40,1	40,0	40 40,2 40,1	40,1	160,1 160,1	160,1	53	33,0	58	36,1	32,9	29,6	36,2	32,9	-	-	1,9	
	NC5_1B	7	24/1	10:45	40,0 40,0 40,1	40,0	40,6 40,5 40	40,4	160,0 160,1	160,1	50	30,9	51	31,6								
	NC5_1C	7	24/1	10:50	40,0 39,9 40,0	40,0	40,2 40,2 39,7	40,0	160,0 160,1	160,1	54	33,8	51	31,9								
ZC10	ZC10_1A	7	13/2	10:15	40,0 40,1 40,0	40,0	40,1 40 39,3	39,8	160,2 160,1	160,15	45	28,2	45	28,2	27,7	24,9	30,4	28,4	25,6	31,3	0,6	one result discarded
	ZC10_1B	7	13/2	10:20	40,0 40,0 40,0	40,0	40 38,1 39,2	39,1	160,1 160,2	160,2	44	28,1	44	28,1								
	ZC10_1C	7	13/2	10:25	40,1 40,0 40,0	40,0	39,9 40 39,6	39,8	160,2 160,1	160,2	47	29,5	38	23,8								

Specimen data					Geometry						Strength											
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
NC10	NC10_1A	7	14/2	11:25	40,0 40,0 40,0	40,0	40 40,3 39,9	40,1	160,1 160,1	160,1	50	**31,2**	52	**32,4**								
	NC10_1B	7	14/2	11:30	40,0 40,0 40,0	40,0	40 40,5 40,3	40,3	160,0 160,2	160,1	46	**28,6**	51	**31,7**	**31,2**	28,1	34,3	**31,2**			1,4	
	NC10_1C	7	14/2	11:35	40,0 40,0 40,1	40,0	40,5 40 40,3	40,3	160,1 160,0	160,1	50	**31,0**	52	**32,3**								
ZS5	ZS5_1A	7	25/1	09:55	40,0 40,0 40,1	40,0	39,8 39,9 40	39,9	1 160,1	80,55	58	**36,3**	55	**34,4**								
	ZS5_1B	7	25/1	10:00	40,0 40,1 40,0	40,0	39,6 39,2 39,2	39,3	160,0 160,2	160,1	56	**35,6**	48	**30,5**	**34,6**	31,2	38,1	**35,5**	31,9	39,0	2,2	one results discarded
	ZS5_1C	7	25/1	10:05	40,0 40,0 40,1	40,0	39,7 39,7 39,7	39,7	160,1 160,0	160,1	55	**34,6**	58	**36,5**								
NS5	NS5_1A	7	1/2	10:45	40,0 40,1 40,1	40,1	40,5 40,7 40,1	40,4	160 160	160	60	**37,0**	58	**35,8**								
	NS5_1B	7	1/2	10:40	40,0 40,2 40,0	40,1	40,6 40,8 40,8	40,7	160,0 160,1	160,1	60	**36,8**	60	**36,8**	**37,0**	33,3	40,7	**37,0**	-	-	1,6	
	NS5_1C	7	1/2	10:35	40,0 40,0 40,0	40,0	40 39,9 39,8	39,9	160,0 160,1	160,1	57	**35,7**	64	**40,1**								
ZS10	ZS10_1A	7	15/2	11:00	40,0 40,1 40,0	40,0	40,7 40,5 40,4	40,5	160,2 160,2	160,2	46	**28,3**	49	**30,2**								
	ZS10_1B	7	15/2	11:05	40,0 40,1 40,0	40,0	40,3 40,5 40,3	40,4	160,2 160,2	160,2	48	**29,7**	47	**29,1**	**29,9**	26,9	32,9	**28,8**	25,9	31,7	1,4	One result discarded
	ZS10_1C	7	15/2	11:10	40,1 40,0 40,0	40,0	40,3 40,2 40,3	40,3	160,1 160,2	160,2	43	**26,7**	57	**35,4**								

Specimen data					Geometry						Strength													
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
NS10	NS10_1A	7	20/2	10:15	40,0 40,0 40,1	40,0	39,9 40,3 40,3	40,2	160,2 160,2	160,2	48	**29,9**	53	**33,0**	**28,9**	26,0	31,8	**28,9**	26,0	31,8	3,8	3 results are outside the range. Determination should be redone
	NS10_1B	7	20/2	10:20	40,1 40,1 40,0	40,1	40,3 40,2 39,9	40,1	160,2 160,1	160,2	39	**24,3**	50	**31,1**								
	NS10_1C	7	20/2	10:25	40,1 40,0 40,0	40,0	40,6 40,8 40,2	40,5	160,0 160,0	160,0	39	**24,0**	51	**31,4**								
NS10b	NS10b_1A	7	8/3	10:15	40,1 40,0 40,1	40,1	39,9 40,3 40,3	40,2	160 160	160	49	**30,4**	53	**32,9**	**30,6**	27,6	33,7	**30,6**	-	-	1,9	Redetermination: new results are acceptable
	NS10b_1B	7	8/3	10:20	40,1 40,1 40,0	40,1	40,2 40,2 39,9	40,1	160,2 160,1	160,2	53	**33,0**	48	**29,9**								
	NS10b_1C	7	8/3	10:25	40,0 40,0 40,0	40,0	40,5 40,3 40,2	40,3	160,0 160,0	160,0	47	**29,1**	46	**28,5**								

Specimen data					Geometry						Strength											
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
		[days]	[jj/mm]	[hh:mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[kN]	[MPa]	[kN]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	
					40,0		39,9		160													
	REFa_2A	14	26/1	10:10	40,0	40,0	40,1	40,0	160,1	160,05	62	**38,8**	59	**36,9**								
					40,0		40															
					40,0		39,5		160,0													
REFa	REFa_2B	14	26/1	10:15	40,1	40,0	39,5	39,6	160	160,0	62	**39,1**	63	**39,8**	**37,9**	34,1	41,7	**37,9**	-	-	1,5	
					40,0		39,7															
					39,9		40		160,1													
	REFa_2C	14	26/1	10:25	40,0	40,0	39,7	39,8	160,0	160,1	58	**36,5**	58	**36,5**								
					40,0		39,7															
					40,1		39,2		160													
	REF_2A	14	13/2	10:25	40,1	40,1	39,1	39,3	160,1	160,05	64	**40,5**	63	**39,9**								
					40,2		39,7															
					40,0		38,2		160,0													
REF	REF_2B	14	13/2	10:30	40,1	40,0	38,8	39,0	160,1	160,1	59	**37,8**	55	**35,3**	**39,3**	35,3	43,2	**39,3**	-	-	2,3	
					40,0		39,9															
					40,1		40		160,0													
	REF_2C	14	13/2	10:35	40,0	40,0	39,8	39,9	160,0	160,0	65	**40,7**	66	**41,4**								
					39,9		39,9															
					40,0		39,8		160,1													
	ZC5_2A	14	30/1	09:45	40,0	40,0	40,5	40,1	160,1	160,1	66	**41,1**	67	**41,7**								
					40,1		40															
					40,0		39,8		160,0													
ZC5	ZC5_2B	14	30/1	09:50	39,8	39,9	39,5	39,9	160	160,0	64	**40,2**	65	**40,8**	**40,0**	36,0	44,0	**40,0**	-	-	1,5	
					40,0		40,3															
					39,9		40,5		160,1													
	ZC5_2C	14	30/1	09:55	39,9	39,9	40,1	40,4	160,1	160,1	62	**38,5**	61	**37,8**								
					40,0		40,5															
					40,0		40,3		160													
	NC5_2A	14	31/1	10:40	40,1	40,0	39	39,7	160	160	58	**36,5**	58	**36,5**								
					40,0		39,7															
					40,0		39		160,0													
NC5	NC5_2B	14	31/1	10:45	40,0	40,0	39,5	39,4	160,2	160,1	57	**36,2**	53	**33,7**	**36,8**	33,1	40,5	**36,8**	-	-	2,1	
					39,9		39,7															
					40,0		39,7		160,0													
	NC5_2C	14	31/1	10:50	40,0	40,0	39,6	39,7	160,1	160,1	61	**38,4**	63	**39,7**								
					40,0		39,8															
					40,0		39,5		160,1													
	ZC10_2A	14	20/2	10:15	39,8	39,9	39,5	39,5	160	160,05	44	**27,9**	45	**28,5**								
					39,9		39,6															
					40,0		40		160,0													
ZC10	ZC10_2B	14	20/2	10:20	40,0	40,0	39,7	39,9	160,1	160,1	52	**32,6**	51	**32,0**	**29,7**	26,7	32,6	**29,7**	-	-	2,2	
					40,0		40															
					40,0		39,8		160,0													
	ZC10_2C	14	20/2	10:25	39,9	40,0	39,3	39,5	160,0	160,0	47	**29,8**	43	**27,2**								
					40,0		39,4															

Specimen data					Geometry						Strength											
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
NC10	NC10_2A	14	21/2	11:25	40,0 40,1	40,0	39,7 39,7	39,9	160,1	160,1	55	**34,4**	56	**35,1**	**33,2**	29,9	36,5	**34,2**	30,7	37,6	1,4	One result discarded
	NC10_2B	14	21/2	11:30	40,0 40,0 39,9	40,0	39,4 39,6 39,6	39,5	160,1 160,2	160,2	55	**34,8**	45	**28,5**								
	NC10_2C	14	21/2	11:35	40,0 40,0 40,0	40,0	41,3 41,2 40,4	41,0	160,2 160,2	160,2	57	**34,8**	52	**31,7**								
ZS5	ZS5_2A	14	1/2	09:55	40,0 40,0 40,0	40,0	39,5 39,6 39	39,4	160 160	160	67	**42,5**	60	**38,1**	**38,7**	34,8	42,6	**38,7**	-	-	2,1	
	ZS5_2B	14	1/2	10:00	39,9 40,0 39,9	39,9	38,4 39,4 39,4	39,1	160,0 160	160,0	59	**37,8**	59	**37,8**								
	ZS5_2C	14	1/2	10:05	40,0 40,0 40,0	40,0	40 39,8 39,6	39,8	160,0 160,1	160,1	63	**39,6**	58	**36,4**								
NS5	NS5_2A	14	8/2	10:45	40,2 40,0 40,2	40,1	40,1 40,2 40,3	40,2	160,5 160,6	160,55	64	**39,7**	73	**45,2**	**41,9**	37,7	46,0	**41,9**	-	-	2,3	
	NS5_2B	14	8/2	10:40	40,2 40,1 40,1	40,1	40,1 40 40,3	40,1	160,6 160,8	160,7	67	**41,6**	63	**39,1**								
	NS5_2C	14	8/2	10:35	40,2 40,3 40,2	40,2	40,5 40,5 40,2	40,4	160,8 160,8	160,8	70	**43,1**	69	**42,5**								
ZS10	ZS10_2A	14	22/2	11:00	40,0 40,0 40,0	40,0	40,8 40,7 40,8	40,8	160,2 160,1	160,15	70	**42,9**	64	**39,2**	**38,9**	35,0	42,8	**38,1**	34,3	42,0	1,4	One result discarded
	ZS10_2B	14	22/2	11:05	40,0 40,0 40,0	40,0	41 40,4 40,1	40,5	160,2 160,1	160,2	58	**35,8**	62	**38,3**								
	ZS10_2C	14	22/2	11:10	40,0 39,9 40,0	40,0	40,6 40,8 39,8	40,4	160,2 160,2	160,2	62	**38,4**	63	**39,0**								
NS10	NS10_2A	14	27/2	10:15	40,0 40,0 39,9	40,0	39,7 40,1 41,3	40,4	160,1 160,1	160,1	55	**34,1**	53	**32,9**	**37,1**	33,4	40,8	**36,1**	32,5	39,7	3,0	One result discarded
	NS10_2B	14	27/2	10:20	40,0 40,0 39,9	40,0	40 40,4 40,3	40,2	160,0 160,1	160,1	56	**34,8**	63	**39,2**								
	NS10_2C	14	27/2	10:25	40,1 40,1 40,1	40,1	39,9 39,7 40,2	39,9	160,0 160,1	160,1	68	**42,5**	63	**39,3**								

Specimen data					Geometry						Strength											
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
		[days]	[jj/mm]	[hh:mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[kN]	[MPa]	[kN]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	
	REFa_3A	28	9/2	08:50	40,0 40,0 40,3	40,1	39,7 39,3 40,4	39,8	160,0 160,1	160,1	87	**54,5**	83	**52,0**								
REFa	REFa_3B	28	9/2	08:55	40,0 40,1 40,1	40,1	39,7 39,6 39,6	39,6	160,0 160,1	160,1	81	**51,0**	85	**53,5**	**51,3**	46,2	56,4	**51,3**	-	-	2,8	
	REFa_3C	28	9/2	09:00	40,0 40,0 40,0	40,0	39,2 39,6 39,8	39,5	160,2 160,2	160,2	74	**46,8**	79	**50,0**								
	REF_3A	28	27/2	13:40	40,0 39,9 40,0	40,0	38,8 39,4 39,5	39,2	160 160,1	160,1	87	**55,5**	83	**52,9**								
REF	REF_3B	28	27/2	13:45	40,0 40,0 40,0	40,0	39,9 39,3 39,2	39,5	160,1 160	160,1	81	**51,3**	85	**53,8**	51,7	46,6	56,9	**51,7**	46,6	56,9	3,3	
	REF_3C	28	27/2	13:50	40,0 40,0 40,0	40,0	39,6 39,2 39,7	39,5	260,1 160,0	210,1	74	**46,8**	79	**50,0**								
	ZC5_3A	28	13/2	11:00	40,0 40,1 40,0	40,0	40,5 40,2 40,2	40,3	160,1 160,1	160,1	73	**45,2**	78	**48,3**								
ZC5	ZC5_3B	28	13/2	11:05	40,0 40,0 40,0	40,0	40,3 40,1 40,1	40,2	160,1 160,1	160,1	75	**46,7**	70	**43,6**	43,3	39,0	47,6	**45,9**	41,3	50,5	1,8	One result discarded
	ZC5_3C	28	13/2	11:05	40,0 40,0 40,0	40,0	40,7 40,2 40,7	40,5	160,0 160,0	160,0	74	**45,6**	49	**30,2**								
	NC5_3A	28	14/2	10:45	40,0 39,9 40,1	40,0	40,6 40,1 40,1	40,3	160,2 160,1	160,2	58	**36,0**	60	**37,3**								
NC5	NC5_3B	28	14/2	10:50	40,0 40,1 39,9	40,0	39,8 39,8 40	39,9	160,1 159,9	160,0	60	**37,6**	57	**35,7**	36,2	32,6	39,8	**36,2**			1,1	
	NC5_3C	28	14/2	10:55	40,1 40,2 40,0	40,1	40,2 40,3 40,4	40,3	160,0 160,1	160,1	58	**35,9**	56	**34,7**								
	ZC10_3A	28	6/3	13:20	40,0 40,0 40,1	40,0	39,9 39,6 38,6	39,4	160,1 160,1	160,1	47	**29,8**	49	**31,1**								
ZC10	ZC10_3B	28	6/3	13:25	40,3 40,2 40,2	40,2	40,8 40,6 40,6	40,7	160,0 160,1	160,1	57	**34,8**	58	**35,4**	32,1	28,9	35,4	**32,1**			2,4	
	ZC10_3C	28	6/3	13:30	40,0 40,0 40,0	40,0	39,7 39,8 38,5	39,3	160,2 160,2	160,2	49	**31,1**	48	**30,5**								

Specimen data					Geometry						Strength												
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
	NC10_3A	28	7/3	11:25	40,0 40,0 40,0	40,0	40,9 40,3 40,4	40,5	160,2 160,1	160,2	64	**39,5**	63	**38,9**								
NC10	NC10_3B	28	7/3	11:30	40,0 40,1 40,0	40,0	40,8 40,7 40,1	40,5	160,0 160,2	160,1	59	**36,4**	55	**33,9**	37,0	33,3	40,7	**37,0**			2,0	One result discarded
	NC10_3C	28	7/3	11:35	39,9 39,9 40,0	39,9	40,9 40,9 40,2	40,7	160,2 160,1	160,2	59	**36,3**	60	**36,9**								
	ZS5_3A	28	15/2	10:30	40,0 40,0 40,0	40,0	40,2 40,3 40,7	40,4	160,1 160,1	160,1	55	**34,0**	59	**36,5**								
ZS5	ZS5_3B	28	15/2	10:35	39,9 40,0 40,0	40,0	39,9 39,9 40,3	40,0	160,1 160,1	160,1	67	**41,9**	57	**35,6**	37,8	34,0	41,6	**37,8**			4,0	
	ZS5_3C	28	15/2	10:40	40,0 40,0 39,9	40,0	39,8 40,3 40	40,0	160,0 160,0	160,0	56	**35,0**	70	**43,8**								
	NS5_3A	28	22/2	13:30	40,1 40,2 40,1	40,1	40 40,2 40,3	40,2	160,1 160,1	160,1	79	**49,0**	72	**44,7**								
NS5	NS5_3B	28	22/2	13:35	39,9 40,0 40,0	40,0	40,6 40,4 40,3	40,4	160,1 160,1	160,1	72	**44,6**	77	**47,6**	47,3	42,5	52,0	**47,3**			2,6	
	NS5_3C	28	22/2	13:40	39,9 39,9 40,1	40,0	40,6 40,5 40,3	40,5	160,1 160,2	160,2	83	**51,3**	75	**46,4**								
	ZS10_3A	28	8/3	09:05	40,0 40,0 40,2	40,1	40,7 40,9 40,8	40,8	160,1 160	160,1	65	**39,8**	72	**44,0**								
ZS10	ZS10_3B	28	8/3	09:10	40,0 40,0 40,0	40,0	40,2 40,4 40,9	40,5	160,1 160	160,1	60	**37,0**	62	**38,3**	40,2	36,2	44,2	**40,2**			2,9	
	ZS10_3C	28	8/3	09:15	40,0 40,0 40,0	40,0	40,7 40,2 39,7	40,2	160,1 160,1	160,1	62	**38,6**	70	**43,5**								
	NS10_3A	28	13/3	10:15	40,0 40,0 40,0	40,0	40,3 40,2 40,1	40,2	160 160,1	160,1	66	**41,0**	67	**41,7**								
NS10	NS10_3B	28	13/3	10:20	40,0 40,1 40,0	40,0	40 40,3 39,8	40,0	160,1 160	160,1	56	**34,9**	64	**39,9**	40,2	36,2	44,3	**41,3**	37,2	45,4	2,3	One result discarded
	NS10_3C	28	13/3	10:25	40,0 40,1 40,1	40,1	40,2 40,5 40,7	40,5	160,2 160,2	160,2	73	**45,0**	63	**38,9**								

Specimen data					Geometry						Strength											
Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
		[days]	[jj/mm]	[hh:mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[kN]	[MPa]	[kN]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	
	REF_4A	90	1/5	10:25	40,0 40,0 40,0	40,0	39,7 40 40	39,9	160,7 160,6	160,7	73	**45,7**	61	**38,2**								
REF	REF_4B	90	1/5	10:30	40,1 40,0 40,0	40,0	39 39,2 39,3	39,2	160,5 160,4	160,5	69	**44,0**	71	**45,3**	44,9	40,4	49,4	**46,3**	41,6	50,9	1,9	One result discarded
	REF_4C	90	1/5	10:35	40,0 40,1 40,0	40,0	39,4 39,4 39,5	39,4	160,9 160,8	160,9	75	**47,5**	77	**48,8**								
	ZC5_4A	90	17/4	10:40	40,0 40,0 40,0	40,0	40 40 40	40,0	160,8 160,7	160,8	87	**54,4**	80	**50,0**								
ZC5	ZC5_4B	90	17/4	10:45	40,0 40,1 40,0	40,0	39,4 40,4 40,2	40,0	160,8 160,6	160,7	86	**53,7**	81	**50,6**	49,5	44,5	54,4	**51,3**	46,2	56,5	2,6	One result discarded
	ZC5_4C	90	17/4	10:50	40,0 40,0 40,0	40,0	40,9 40,8 40	40,6	160,9 160,9	160,9	78	**48,1**	65	**40,1**								
	NC5_4A	90	17/4	10:00	40,0 40,3 40,2	40,2	39,7 39,6 39,7	39,7	160 160	160,0	65	**40,8**	70	**43,9**								
NC5	NC5_4B	90	17/4	10:05	40,0 40,0 40,1	40,0	39,6 39,6 39,7	39,6	160,1 160	160,1	62	**39,1**	52	**32,8**	40,8	36,7	44,9	**42,4**	38,2	46,6	2,5	One result discarded
	NC5_4C	90	17/4	10:10	40,0 40,1 40,2	40,1	40,3 40,3 39,8	40,1	160,0 160,1	160,1	69	**42,9**	73	**45,4**								
	ZC10_4A	90	8/5	10:30	40,0 40,0 40,0	40,0	40,6 40,6 40,5	40,6	160,2 160,1	160,2	47	**29,0**	43	**26,5**								
ZC10	ZC10_4B	90	8/5	10:35	40,1 40,0 40,1	40,1	40 40,1 40,8	40,3	160,0 160,1	160,1	63	**39,0**	70	**43,4**	32,5	29,2	35,7	**32,5**	29,2	35,7	7,5	4/6 results discarded, determination should be redone
	ZC10_4C	90	8/5	10:40	40,0 40,1 40,0	40,0	41 41 40,1	40,7	160,2 160,1	160,2	39	**23,9**	54	**33,1**								
	NC10_4A	90	8/5	10:45	40,0 40,0 40,2	40,1	40,3 40,5 40,5	40,4	160,2 160,2	160,2	72	**44,4**	72	**44,4**								
NC10	NC10_4B	90	8/5	10:50	40,0 40,1 40,2	40,1	41,8 41,4 41,2	41,5	160,2 160,1	160,2	67	**40,3**	67	**40,3**	40,5	36,4	44,5	**42,2**	38,0	46,4	2,1	One result discarded
	NC10_4C	90	8/5	10:55	40,2 40,2 40,1	40,2	41,3 40,6 40,2	40,7	160,2 160,1	160,2	52	**31,8**	68	**41,6**								

Sample type	Sample name	Curing time	Test date	Test time	Width	Arithmetic mean	Height	Arithmetic mean	Length	Arithmetic mean	Compression 1		Compression 2		Compressive strength - Mean	-10%	+10%	Compressive strength - second mean	-10%	+10%	Standard deviation	Comment
Specimen data					Geometry						Strength											
	NC10_4A	90	8/5	10:45	40,0 40,0 40,2	40,1	40,3 40,5 40,5	40,4	160,2 160,2	160,2	72	**44,4**	72	**44,4**								
NC10	NC10_4B	90	8/5	10:50	40,0 40,1 40,2	40,1	41,8 41,4 41,2	41,5	160,2 160,1	160,2	67	**40,3**	67	**40,3**	40,5	36,4	44,5	**42,2**	38,0	46,4	2,1	One result discarded
	NC10_4C	90	8/5	10:55	40,2 40,2 40,1	40,2	41,3 40,6 40,2	40,7	160,2 160,1	160,2	52	**31,8**	68	**41,6**								
	ZS5_4A	90	18/4	10:00	40,2 40,1 40,3	40,2	40,2 40,5 40,5	40,4	160 160,1	160,1	65	**40,0**	72	**44,3**								
ZS5	ZS5_4B	90	18/4	10:05	40,0 40,0 40,2	40,1	40,2 39,9 39	39,7	160,0 160	160,0	70	**44,0**	60	**37,7**	42,5	38,2	46,7	**43,4**	39,1	47,8	2,0	One result discarded
	ZS5_4C	90	18/4	10:10	40,0 40,0 40,2	40,1	39,6 39,6 39,7	39,6	160,0 160,0	160,0	72	**45,3**	69	**43,5**								
	NS5_4A	90	25/4	10:00	40,0 40,0 40,0	40,0	40,9 40,3 40,8	40,7	160 160	160,0	82	**50,4**	85	**52,3**								
NS5	NS5_4B	90	25/4	10:05	40,0 40,0 40,1	40,0	40,5 40,4 40,5	40,5	160,0 160	160,0	70	**43,2**	79	**48,8**	50,0	45,0	55,0	**51,3**	46,2	56,4	2,8	One result discarded
	NS5_4C	90	25/4	10:10	40,0 40,0 40,0	40,0	40,4 40,4 40,5	40,4	160,0 160,0	160,0	90	**55,6**	80	**49,5**								
	ZS10_4A	90	9/5	10:00	40,0 40,1 40,0	40,0	40,3 40,5 40,5	40,4	160,2 160,é	160,2	79	**48,8**	80	**49,4**								
ZS10	ZS10_4B	90	9/5	10:05	40,1 40,1 40,0	40,1	41,8 41,4 41,2	41,5	160,2 160,1	160,2	76	**45,7**	81	**48,8**	46,2	41,6	50,8	**48,3**	43,5	53,2	1,5	One result discarded
	ZS10_4C	90	9/5	10:10	40,2 40,1 40,0	40,1	41,3 40,6 40,2	40,7	160,1 160,2	160,2	58	**35,5**	80	**49,0**								
	NS10_4A	90	15/5	13:00	40,0 40,0 39,9	40,0	40,7 40,8 40,7	40,7	160,2 160,1	160,2	59	**36,2**	75	**46,1**								
NS10	NS10_4B	90	15/5	13:05	39,9 40,0 40,0	40,0	40 40,3 40,1	40,1	160,1 160,1	160,1	67	**41,8**	66	**41,1**	42,8	38,5	47,1	**44,1**	39,7	48,5	2,6	One result discarded
	NS10_4C	90	15/5	13:10	40,0 40,1 40,0	40,0	40,2 40,3 40	40,2	160,1 160,1	160,1	76	**47,3**	71	**44,2**								

B.7 Porosity and density

	mdry	msw	mssd	V		Vpores			p			rhod			rhof		rhossd		ussd	
					Mean		Mean	Std dev		Mean	Std dev		Mean	std dev		Mean		Mean		Mean
REF_3A	510,78	308,72	560,90	0,25		0,05			0,20			2025,46			2527,86		2224,20		0,10	
REF_3B	511,84	309,57	564,04	0,25	0,25	0,05	0,053	0,003	0,21	0,207	0,009	2011,40	2014,37	9,94	2530,48	2539,43	2216,53	2221,10	0,10	0,10
REF_3C	512,58	312,35	567,84	0,26		0,06			0,22			2006,26			2559,96		2222,55		0,11	
ZC5_3A	527,17	322,84	579,67	0,26		0,05			0,20			2052,60			2579,99		2257,02		0,10	
ZC5_3B	522,82	320,43	578,95	0,26	**0,26**	0,06	0,054	0,002	0,22	0,212	0,007	2022,36	2044,78	19,71	2583,23	**2593,70**	2239,48	**2256,40**	0,11	0,10
ZC5_3C	524,15	323,93	578,45	0,25		0,05			0,21			2059,37			2617,87		2272,71		0,10	
NC5_3A	502,97	308,03	556,90	0,25		0,05			0,22			2021,01			2580,13		2237,71		0,11	
NC5_3B	497,48	303,93	551,34	0,25	**0,25**	0,05	0,054	0,001	0,22	0,218	0,001	2010,75	2016,50	5,24	2570,29	**2577,05**	2228,45	**2234,02**	0,11	0,11
NC5_3C	511,09	313,05	566,35	0,25		0,06			0,22			2017,73			2580,74		2235,89		0,11	
ZC10_3A	519,47	318,56	574,66	0,26		0,06			0,22			2028,39			2585,59		2243,89		0,11	
ZC10_3B	528,59	323,99	585,43	0,26	0,26	0,06	0,056	0,001	0,22	0,216	0,001	2021,84	2026,91	4,51	2583,53	2585,37	2239,25	2242,92	0,11	0,11
ZC10_3C	521,41	319,86	576,65	0,26		0,06			0,22			2030,49			2587,00		2245,61		0,11	
NC10_3A	511,72	314,03	569,40	0,26		0,06			0,23			2003,84			2588,50		2229,71		0,11	
NC10_3B	512,35	314,31	571,71	0,26	0,26	0,06	0,058	0,001	0,23	0,226	0,004	1990,48	2002,10	10,86	2587,10	2587,58	2221,10	2228,37	0,12	0,11
NC10_3C	521,67	320,03	579,31	0,26		0,06			0,22			2011,99			2587,14		2234,30		0,11	
ZS5_3A	510,99	312,93	567,62	0,25		0,06			0,22			2006,32			2579,98		2228,67		0,11	
ZS5_3B	503,47	308,33	559,24	0,25	**0,25**	0,06	0,056	0,000	0,22	0,222	0,001	2006,58	2008,04	2,76	2580,05	**2579,85**	2228,85	**2229,68**	0,11	0,11
ZS5_3C	510,77	312,76	566,72	0,25		0,06			0,22			2011,22			2579,52		2231,53		0,11	
NS5_3A	527,57	323,68	578,62	0,25		0,05			0,20			2069,39			2587,52		2269,63		0,10	
NS5_3B	527,61	323,38	579,60	0,26	0,26	0,05	0,052	0,001	0,20	0,202	0,001	2059,21	2064,86	5,18	2583,41	2586,07	2262,12	2266,41	0,10	0,10
NS5_3C	534,43	327,87	586,55	0,26		0,05			0,20			2065,99			2587,29		2267,47		0,10	
ZS10_3A	521,71	320,15	577,92	0,26		0,06			0,22			2023,94			2588,36		2242,00		0,11	
ZS10_3B	496,44	304,68	552,10	0,25	0,25	0,06	0,056	0,001	0,22	0,222	0,003	2006,47	2013,68	9,12	2588,86	2587,69	2231,43	2235,50	0,11	0,11
ZS10_3C	517,66	317,47	574,93	0,26		0,06			0,22			2010,64			2585,84		2233,08		0,11	
NS10_3A	525,62	322,58	579,21	0,26		0,05			0,21			2048,16			2588,75		2256,98		0,10	
NS10_3B	517,70	317,97	572,36	0,25	0,26	0,05	0,054	0,001	0,21	0,212	0,003	2035,06	2040,69	6,74	2592,00	2590,71	2249,93	2253,00	0,11	0,10
NS10_3C	519,03	318,74	573,31	0,25		0,05			0,21			2038,85			2591,39		2252,07		0,10	

B.8 Leaching of heavy metals from crushed mortar

B.8.1 Results from ICP analysis

REF	pH [-]	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
REFb_1	12,54	1,7E-01	0,0E+00	2,9E+00	1,1E-02	0,0E+00	1,5E-02	1,8E-02
REFb_2	12,54	1,4E-01	0,0E+00	2,3E+00	1,0E-03	2,0E-02	9,8E-03	0,0E+00
REFb_3	12,55	1,7E-01	0,0E+00	2,7E+00	2,8E-03	1,9E-02	1,7E-02	2,0E-02

REF	Mn 260.568 A- Extract metal concentrati on [mg/L]	Na 589.592 A- Extract metal concentratio n [mg/L]	Ni 231.604 A- Extract metal concentratio n [mg/L]	P 214.914 A- Extract metal concentratio n [mg/L]	Pb 220.353 A- Extract metal concentratio n [mg/L]	S 182.562 A- Extract metal concentratio n [mg/L]	Y 377.433 A- Extract metal concentratio n [mg/L]	Zn 213.857 A- Extract metal concentratio n [mg/L]
REFb_1	0,0E+00	1,1E+02	8,4E-03	0,0E+00	0,0E+00	2,6E+00	9,8E-01	0,0E+00
REFb_2	0,0E+00	9,9E+01	1,0E-02	4,6E-02	0,0E+00	4,3E+00	9,8E-01	0,0E+00
REFb_3	0,0E+00	1,1E+02	1,5E-02	0,0E+00	8,5E-03	2,1E+00	9,8E-01	0,0E+00

ZC5	pH	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
ZC5_1	12,54	8,1E-02	8,3E-02	2,1E+00	4,0E-03	1,8E-02	2,3E-02	1,7E-02
ZC5_2	12,54	8,2E-02	8,1E-02	1,9E+00	3,3E-03	2,1E-02	2,1E-02	2,3E-02
ZC5_3	12,54	7,7E-02	0,0E+00	2,0E+00	1,1E-02	2,5E-02	2,0E-02	1,9E-02

ZC5	Mn 260.568 A- Extract metal concentration [mg/L]	Na 589.592 A- Extract metal concentration [mg/L]	Ni 231.604 A- Extract metal concentration [mg/L]	P 214.914 A- Extract metal concentration [mg/L]	Pb 220.353 A- Extract metal concentration [mg/L]	S 182.562 A- Extract metal concentration [mg/L]	Y 377.433 A- Extract metal concentration [mg/L]	Zn 213.857 A- Extract metal concentration [mg/L]
ZC5_1	0,0E+00	1,0E+02	1,1E-02	0,0E+00	1,3E-01	4,2E+00	1,0E+00	6,1E-02
ZC5_2	0,0E+00	1,0E+02	1,0E-02	0,0E+00	0,0E+00	5,2E+00	9,9E-01	0,0E+00
ZC5_3	0,0E+00	1,1E+02	8,0E-03	4,2E-02	9,2E-02	5,2E+00	9,9E-01	0,0E+00

NC5	pH	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
NC5_1	12,58	2,0E-01	0,0E+00	2,1E+00	0,0E+00	3,9E-02	3,4E-02	2,2E-01
NC5_2	12,57	1,4E-01	0,0E+00	2,1E+00	0,0E+00	4,4E-02	1,7E-02	2,7E-02
NC5_3	12,54	1,7E-01	0,0E+00	2,1E+00	8,1E-03	3,7E-02	2,6E-02	1,7E-02

NC5	Mn 260.568 A- Extract metal concentration [mg/L]	Na 589.592 A- Extract metal concentration [mg/L]	Ni 231.604 A- Extract metal concentration [mg/L]	P 214.914 A- Extract metal concentration [mg/L]	Pb 220.353 A- Extract metal concentration [mg/L]	S 182.562 A- Extract metal concentration [mg/L]	Y 377.433 A- Extract metal concentration [mg/L]	Zn 213.857 A- Extract metal concentration [mg/L]
NC5_1	2,1E-02	1,0E+02	7,8E-03	8,7E-02	0,0E+00	7,4E+00	9,5E-01	0,0E+00
NC5_2	1,4E-02	1,0E+02	0,0E+00	8,3E-02	0,0E+00	7,2E+00	9,4E-01	0,0E+00
NC5_3	2,1E-02	9,1E+01	0,0E+00	6,5E-02	0,0E+00	4,9E+00	9,4E-01	0,0E+00

ZC10		Al 308.215	As 193.696	Ba 233.527	Cd 228.802	Cr 206.550	Cu 327.395	Fe 238.204
	pH	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]
ZC10_1	12,52	2,2E-01	1,1E-01	2,9E+00	0,0E+00	1,8E-02	6,8E-02	0,0E+00
ZC10_1	12,54	2,3E-01	1,5E-01	2,6E+00	4,9E-03	2,0E-02	6,2E-02	0,0E+00
ZC10_1	12,54	2,0E-01	1,2E-01	2,7E+00	0,0E+00	2,0E-02	6,1E-02	0,0E+00

ZC10	Mn 260.568	Na 589.592	Ni 231.604	P 214.914	Pb 220.353	S 182.562	Y 377.433	Zn 213.857
	A- Extract metal concentrati on [mg/L]	A- Extract metal concentratio n [mg/L]	A- Extract metal concentratio n [mg/L]	A- Extract metal concentratio n [mg/L]	A- Extract metal concentratio n [mg/L]	A- Extract metal concentratio n [mg/L]	A- Extract metal concentratio n [mg/L]	A- Extract metal concentratio n [mg/L]
ZC10_1	0,0E+00	9,7E+01	2,1E-02	3,3E-01	3,0E-02	3,8E+00	9,3E-01	7,8E-03
ZC10_1	0,0E+00	9,3E+01	2,2E-02	0,0E+00	2,6E-02	3,4E+00	9,4E-01	0,0E+00
ZC10_1	0,0E+00	9,1E+01	1,7E-02	0,0E+00	3,6E-02	3,3E+00	9,4E-01	0,0E+00

NC10		Al 308.215	As 193.696	Ba 233.527	Cd 228.802	Cr 206.550	Cu 327.395	Fe 238.204
	pH	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]	A- Extract metal concentratio [mg/L]
NC10_1	12,57	1,1E-01	1,4E-01	1,7E+00	0,0E+00	3,0E-02	4,8E-02	0,0E+00
NC10_1	12,52	1,1E-01	1,3E-01	1,6E+00	0,0E+00	2,8E-02	5,7E-02	0,0E+00
NC10_1	12,54	1,1E-01	1,3E-01	1,6E+00	0,0E+00	3,1E-02	5,4E-02	0,0E+00

NC10	Mn 260.568 A- Extract metal concentration [mg/L]	Na 589.592 A- Extract metal concentration [mg/L]	Ni 231.604 A- Extract metal concentration [mg/L]	P 214.914 A- Extract metal concentration [mg/L]	Pb 220.353 A- Extract metal concentration [mg/L]	S 182.562 A- Extract metal concentration [mg/L]	Y 377.433 A- Extract metal concentration [mg/L]	Zn 213.857 A- Extract metal concentration [mg/L]
NC10_1	0,0E+00	9,5E+01	2,3E-02	0,0E+00	2,0E-02	1,2E+01	9,1E-01	1,5E-02
NC10_1	0,0E+00	9,2E+01	1,7E-02	0,0E+00	0,0E+00	1,1E+01	9,1E-01	0,0E+00
NC10_1	0,0E+00	8,8E+01	2,8E-02	0,0E+00	7,5E-03	1,1E+01	9,0E-01	3,3E-03

ZS5	pH	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
ZS5_1	12,51	1,4E-01	1,2E-01	1,5E+00	1,0E-02	2,1E-02	7,0E-02	0,0E+00
ZS5_2	12,50	1,2E-01	1,1E-01	1,4E+00	3,4E-03	1,9E-02	6,4E-02	0,0E+00
ZS5_3	12,51	1,2E-01	1,4E-01	1,4E+00	0,0E+00	2,3E-02	6,8E-02	0,0E+00

ZS5	Mn 260.568 A- Extract metal concentration [mg/L]	Na 589.592 A- Extract metal concentration [mg/L]	Ni 231.604 A- Extract metal concentration [mg/L]	P 214.914 A- Extract metal concentration [mg/L]	Pb 220.353 A- Extract metal concentration [mg/L]	S 182.562 A- Extract metal concentration [mg/L]	Y 377.433 A- Extract metal concentration [mg/L]	Zn 213.857 A- Extract metal concentration [mg/L]
ZS5_1	7,6E-02	8,2E+01	1,2E-02	0,0E+00	3,5E-02	1,2E+01	9,5E-01	7,3E-02
ZS5_2	1,4E-03	8,8E+01	2,0E-02	0,0E+00	4,3E-02	1,2E+01	9,3E-01	2,6E-03
ZS5_3	0,0E+00	8,7E+01	1,7E-02	0,0E+00	7,7E-02	1,4E+01	9,3E-01	9,0E-03

NS5	pH	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
NS5_1	12,51	9,3E-02	1,3E-01	1,6E+00	4,5E-03	2,6E-02	3,2E-02	0,0E+00
NS5_2	12,52	7,3E-02	1,2E-01	1,6E+00	0,0E+00	2,7E-02	2,8E-02	0,0E+00
NS5_3	12,51	9,9E-02	1,4E-01	1,6E+00	0,0E+00	2,2E-02	4,2E-02	0,0E+00

NS5	Mn 260.568 A- Extract metal concentrati on [mg/L]	Na 589.592 A- Extract metal concentratio n [mg/L]	Ni 231.604 A- Extract metal concentratio n [mg/L]	P 214.914 A- Extract metal concentratio n [mg/L]	Pb 220.353 A- Extract metal concentratio n [mg/L]	S 182.562 A- Extract metal concentratio n [mg/L]	Y 377.433 A- Extract metal concentratio n [mg/L]	Zn 213.857 A- Extract metal concentratio n [mg/L]
NS5_1	1,2E-03	1,0E+02	1,2E-02	0,0E+00	2,9E-02	1,2E+01	9,6E-01	0,0E+00
NS5_2	0,0E+00	1,0E+02	1,8E-02	0,0E+00	0,0E+00	1,2E+01	9,5E-01	6,4E-03
NS5_3	0,0E+00	1,1E+02	1,1E-02	0,0E+00	2,2E-02	1,2E+01	9,4E-01	8,7E-03

ZS10	pH	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
ZS10_1	12,52	9,7E-02	1,3E-01	1,7E+00	0,0E+00	2,1E-02	4,6E-02	0,0E+00
ZS10_1	12,53	9,5E-02	9,7E-02	1,5E+00	0,0E+00	2,2E-02	5,7E-02	0,0E+00
ZS10_1	12,53	9,7E-02	1,7E-01	1,4E+00	0,0E+00	2,0E-02	5,2E-02	0,0E+00

ZS10	Mn 260.568 A- Extract metal concentration [mg/L]	Na 589.592 A- Extract metal concentration [mg/L]	Ni 231.604 A- Extract metal concentration [mg/L]	P 214.914 A- Extract metal concentration [mg/L]	Pb 220.353 A- Extract metal concentration [mg/L]	S 182.562 A- Extract metal concentration [mg/L]	Y 377.433 A- Extract metal concentration [mg/L]	Zn 213.857 A- Extract metal concentration [mg/L]
ZS10_1	0,0E+00	1,0E+02	1,3E-02	0,0E+00	1,2E-01	1,1E+01	9,4E-01	0,0E+00
ZS10_1	1,0E-03	1,0E+02	2,0E-02	0,0E+00	1,3E-01	1,3E+01	9,4E-01	2,1E-02
ZS10_1	0,0E+00	9,9E+01	1,9E-02	0,0E+00	1,5E-01	1,4E+01	9,4E-01	9,5E-03

NS10	pH	Al 308.215 A- Extract metal concentratio [mg/L]	As 193.696 A- Extract metal concentratio [mg/L]	Ba 233.527 A- Extract metal concentratio [mg/L]	Cd 228.802 A- Extract metal concentratio [mg/L]	Cr 206.550 A- Extract metal concentratio [mg/L]	Cu 327.395 A- Extract metal concentratio [mg/L]	Fe 238.204 A- Extract metal concentratio [mg/L]
NS10_1	12,52	1,2E-01	1,3E-01	1,9E+00	0,0E+00	2,7E-02	3,3E-02	0,0E+00
NS10_1	12,53	9,8E-02	1,6E-01	1,9E+00	0,0E+00	2,8E-02	2,5E-02	0,0E+00
NS10_1	12,53	1,2E-01	1,2E-01	2,0E+00	0,0E+00	2,6E-02	3,3E-02	0,0E+00

NS10	Mn 260.568 A- Extract metal concentration [mg/L]	Na 589.592 A- Extract metal concentration [mg/L]	Ni 231.604 A- Extract metal concentration [mg/L]	P 214.914 A- Extract metal concentration [mg/L]	Pb 220.353 A- Extract metal concentration [mg/L]	S 182.562 A- Extract metal concentration [mg/L]	Y 377.433 A- Extract metal concentration [mg/L]	Zn 213.857 A- Extract metal concentration [mg/L]
NS10_1	5,3E-04	1,0E+02	1,1E-02	0,0E+00	0,0E+00	9,3E+00	9,4E-01	1,6E-03
NS10_1	9,5E-04	8,9E+01	1,0E-02	0,0E+00	6,2E-03	9,8E+00	1,0E+00	0,0E+00
NS10_1	0,0E+00	9,8E+01	0,0E+00	0,0E+00	0,0E+00	9,2E+00	9,6E-01	2,7E-03

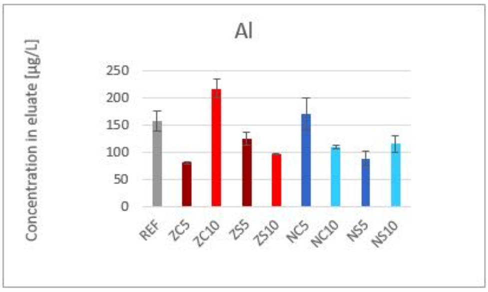
B.8.2 Concentrations in eluates

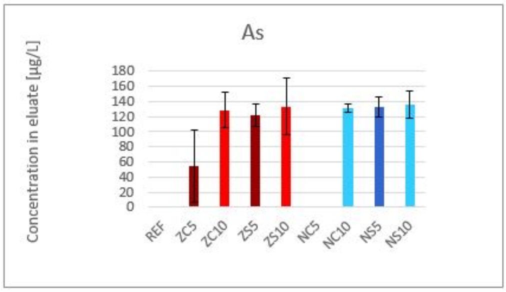
	Limit cat. 1	Limit cat. 3	REF		ZC5		ZC10	
	Concentration in eluate		Average concentration in eluate	Standard devation	Average concentration in eluate	Standard deviation	Average concentration in eluate	Standard deviation
	[µg/L]		[µg/L]	[µg/L]	[µg/L]	[µg/L]	[µg/L]	[µg/L]
Al	-	-	156	18	80	2	217	18
As	8	50	0	0	54	47	129	23
Ba	300	4000	2616	301	1990	78	2737	145
Ca	-	-	730863	14661	671148	18601	623902	13729
Cd	2	40	5	5	6	4	2	3
Cr	10	500	13	11	21	3	19	1
Cu	45	2000	14	4	22	2	64	4
Fe	-	-	13	11	20	3	0	0
K	-	-	139776	5695	146425	1401	131568	3671
Mg	-	-	163	282	0	0	0	0
Mn	150	1000	0	0	0	0	0	0
Na	-	-	105758	5841	104047	1144	93562	3306
Ni	10	70	11	4	10	2	20	3
P	-	-	15	26	14	24	108	188
Pb	10	100	3	5	72	65	31	5
S	-	-	3008	1169	4857	526	3479	265
Y	-	-	981	3	992	6	937	4
Zn	100	1500	0	0	20	35	3	5

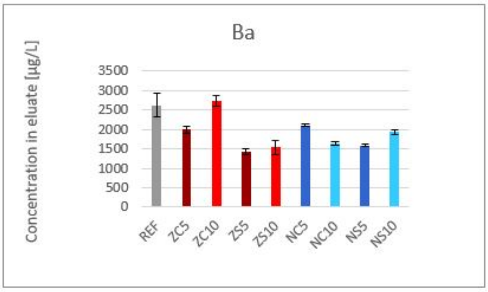
	Limit cat. 1	Limit cat. 3	ZS5		ZS10		NC5	
	Concentration in eluate		Average concentration in eluate	Standard deviation	Average concentration in eluate	Standard deviation	Average concentration in eluate	Standard deviation
	[µg/L]		[µg/L]	[µg/L]	[µg/L]	[µg/L]	[µg/L]	[µg/L]
Al	-	-	125	11	97	1	171	30
As	8	50	122	14	133	38	0	0
Ba	300	4000	1426	68	1535	177	2096	31
Ca	-	-	612642	11125	593423	9676	664265	4351
Cd	2	40	5	5	0	0	3	5
Cr	10	500	21	2	21	1	40	3
Cu	45	2000	67	3	51	5	25	9
Fe	-	-	0	0	0	0	88	114
K	-	-	120593	3045	145959	1818	135904	6010
Mg	-	-	115	200	0	0	100	170
Mn	150	1000	26	44	0	1	19	4
Na	-	-	85863	3109	101154	2103	97543	5965
Ni	10	70	16	4	17	4	3	5
P	-	-	0	0	0	0	78	12
Pb	10	100	52	22	133	18	0	0
S	-	-	12812	733	12685	1467	6511	1432
Y	-	-	939	13	939	3	941	5
Zn	100	1500	28	39	10	11	0	0

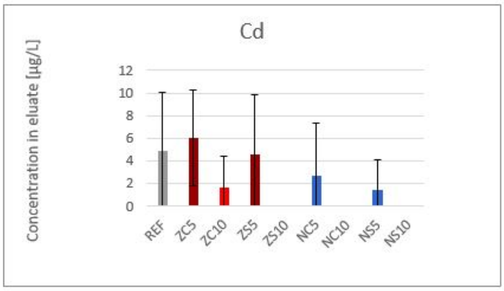
	Limit cat. 1	Limit cat. 3	NC10		NS5		NS10	
	Concentration in eluate		Average concentration in eluate	Standard deviation	Average concentration in eluate	Standard deviation	Average concentration in eluate	Standard deviation
	[µg/L]		[µg/L]	[µg/L]	[µg/L]	[µg/L]	[µg/L]	[µg/L]
Al	-	-	110	3	88	14	115	15
As	**8**	**50**	132	5	132	13	135	18
Ba	**300**	**4000**	1639	40	1591	34	1933	71
Ca	-	-	645120	7373	553866	18554	598197	48486
Cd	**2**	**40**	0	0	2	3	0	0
Cr	**10**	**500**	29	1	25	3	27	1
Cu	**45**	**2000**	53	5	34	7	30	4
Fe	-	-	0	0	0	0	0	0
K	-	-	124078	3428	139805	2713	135265	9795
Mg	-	-	0	0	0	0	0	0
Mn	**150**	**1000**	0	0	0	1	0	0
Na	-	-	91608	3575	103873	2327	95899	6266
Ni	**10**	**70**	23	6	14	4	7	6
P	-	-	0	0	0	0	0	0
Pb	**10**	**100**	9	10	17	15	2	4
S	-	-	11541	204	11913	148	9447	274
Y	-	-	909	4	952	11	964	31
Zn	**100**	**1500**	6	8	5	4	1	1

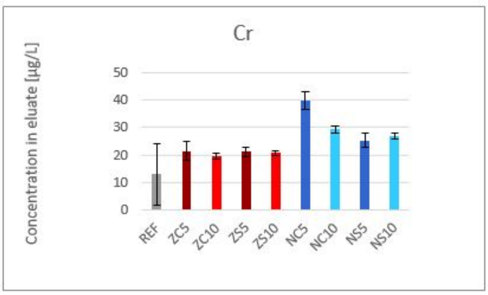
B.8.3 Graphs

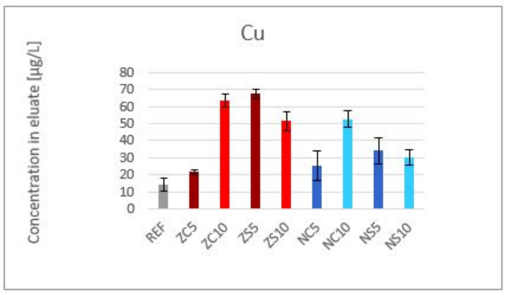

Al
Concentration in eluate [µg/L]
250
200
150
100
50
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

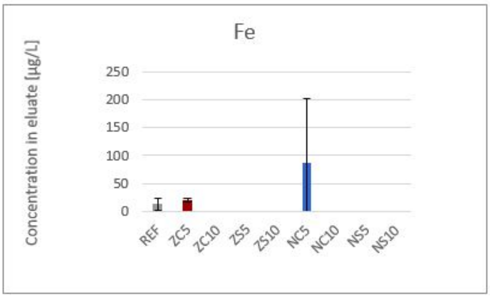

As
Concentration in eluate [µg/L]
180
160
140
120
100
80
60
40
20
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

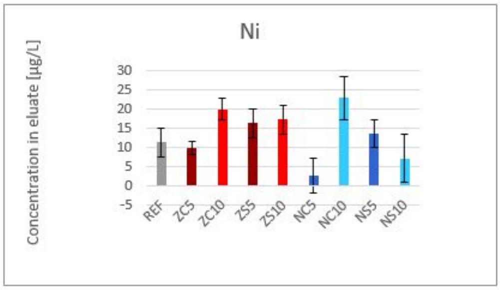

Ba
Concentration in eluate [µg/L]
3500
3000
2500
2000
1500
1000
500
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

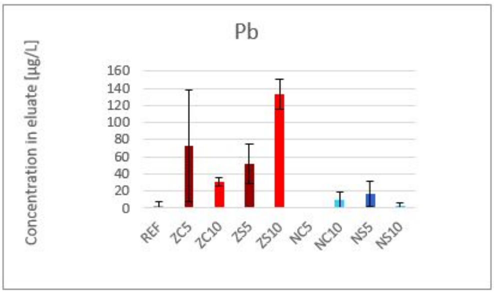

Cd
Concentration in eluate [µg/L]
12
10
8
6
4
2
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

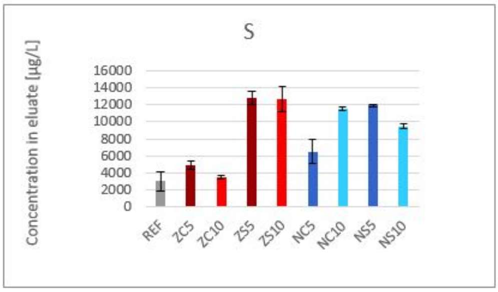

Cr
Concentration in eluate [µg/L]
50
40
30
20
10
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

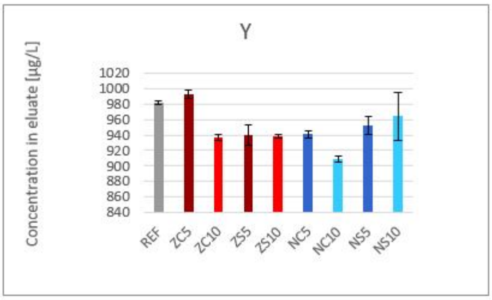

Cu
Concentration in eluate [µg/L]
80
70
60
50
40
30
20
10
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

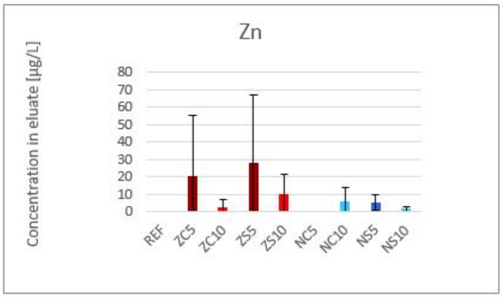

Fe
Concentration in eluate [µg/L]
250
200
150
100
50
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10


Ni
Concentration in eluate [µg/L]
30
25
20
15
10
5
0
-5
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10


Pb
Concentration in eluate [µg/L]
160
140
120
100
80
60
40
20
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10


S
Concentration in eluate [µg/L]
16000
14000
12000
10000
8000
6000
4000
2000
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10


Y
Concentration in eluate [µg/L]
1020
1000
980
960
940
920
900
880
860
840
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10


Zn
Concentration in eluate [µg/L]
80
70
60
50
40
30
20
10
0
REF
ZC5
ZC10
ZS5
ZS10
NC5
NC10
NS5
NS10

B.9 Leaching of sulfate from crushed mortar

	REF			
		Sulfate		
	pH	A - Extract concentration	Concentration in eluate	Std dev
	[-]	[mg/L]	[µg/L]	[µg/L]
REFb_1	12,54	1,1E+01	10945,004	503,658338
REFb_2	12,54	1,1E+01		

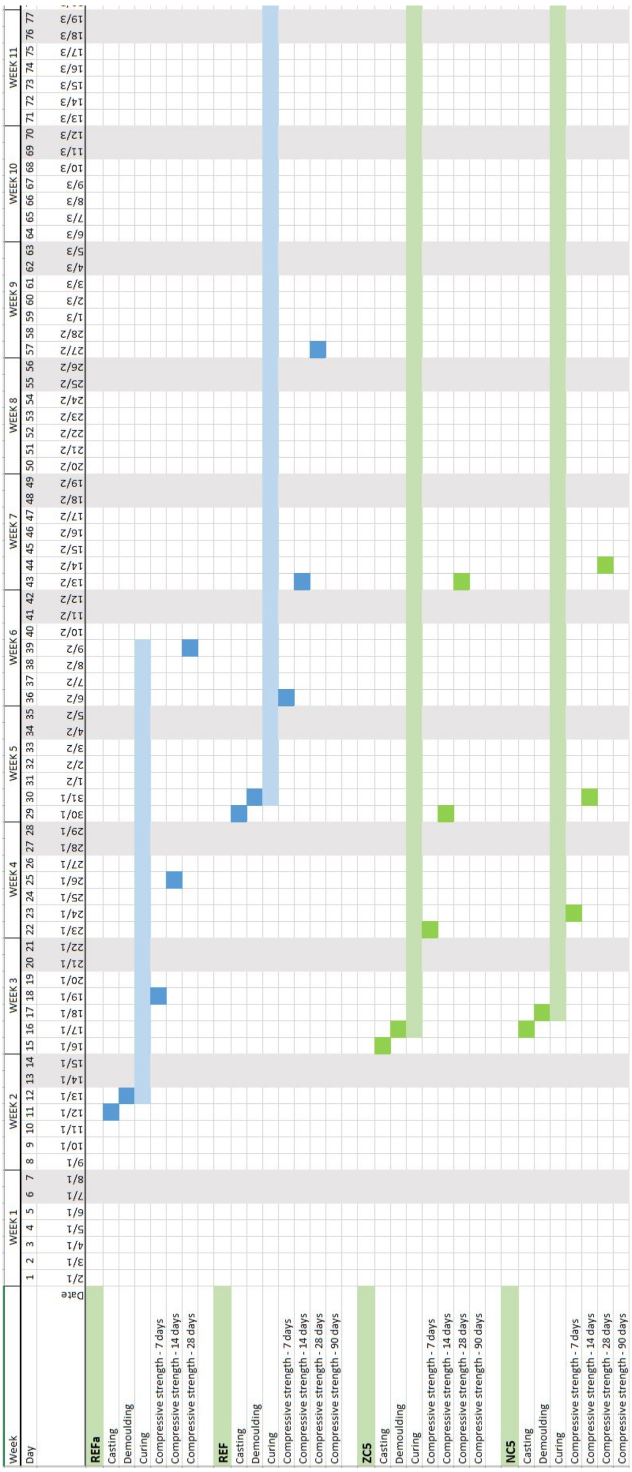
	ZS10			
		Sulfate		
		A - Extract concentration	Concentration in eluate	Std dev
	pH	[mg/L]	[µg/L]	[µg/L]
ZS10_1	12,52	1,6E+01	16900,0626	838,437658
ZS10_1	12,53	1,7E+01		

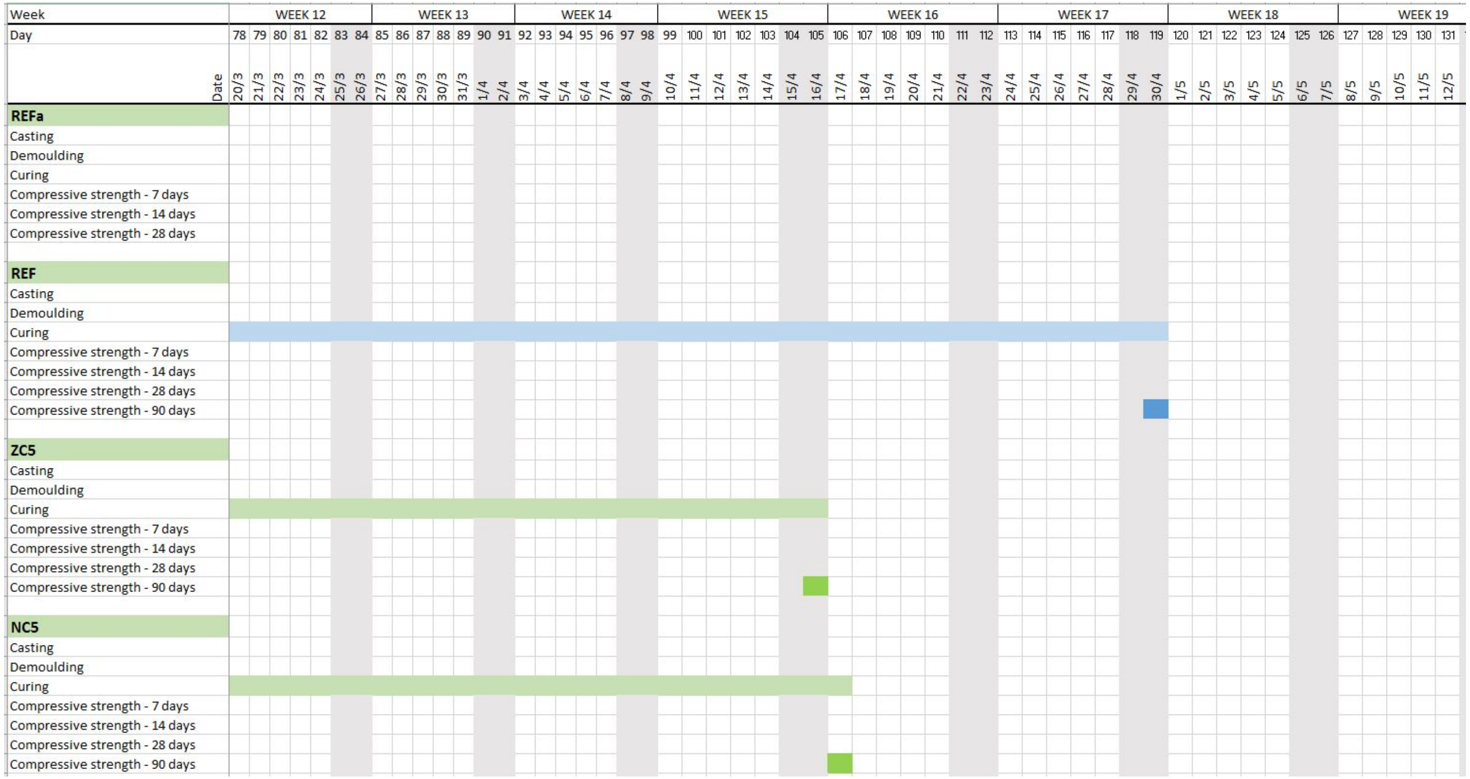
	NS10			
		Sulfate		
		A - Extract concentration	Concentration in eluate	Std dev
	pH	[mg/L]	[µg/L]	[µg/L]
NS10_1	12,52	1,6E+01	15451,8287	1112,33105
NS10_1	12,53	1,5E+01		

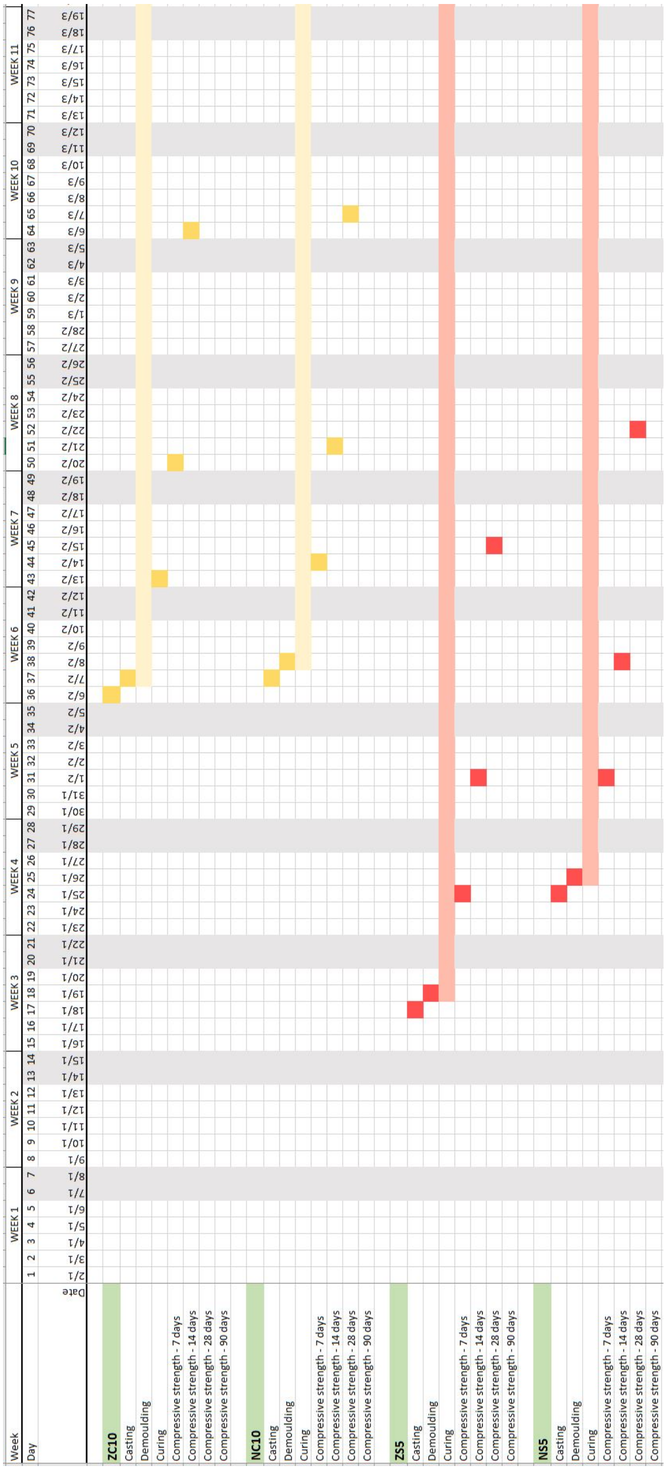
APPENDIX C

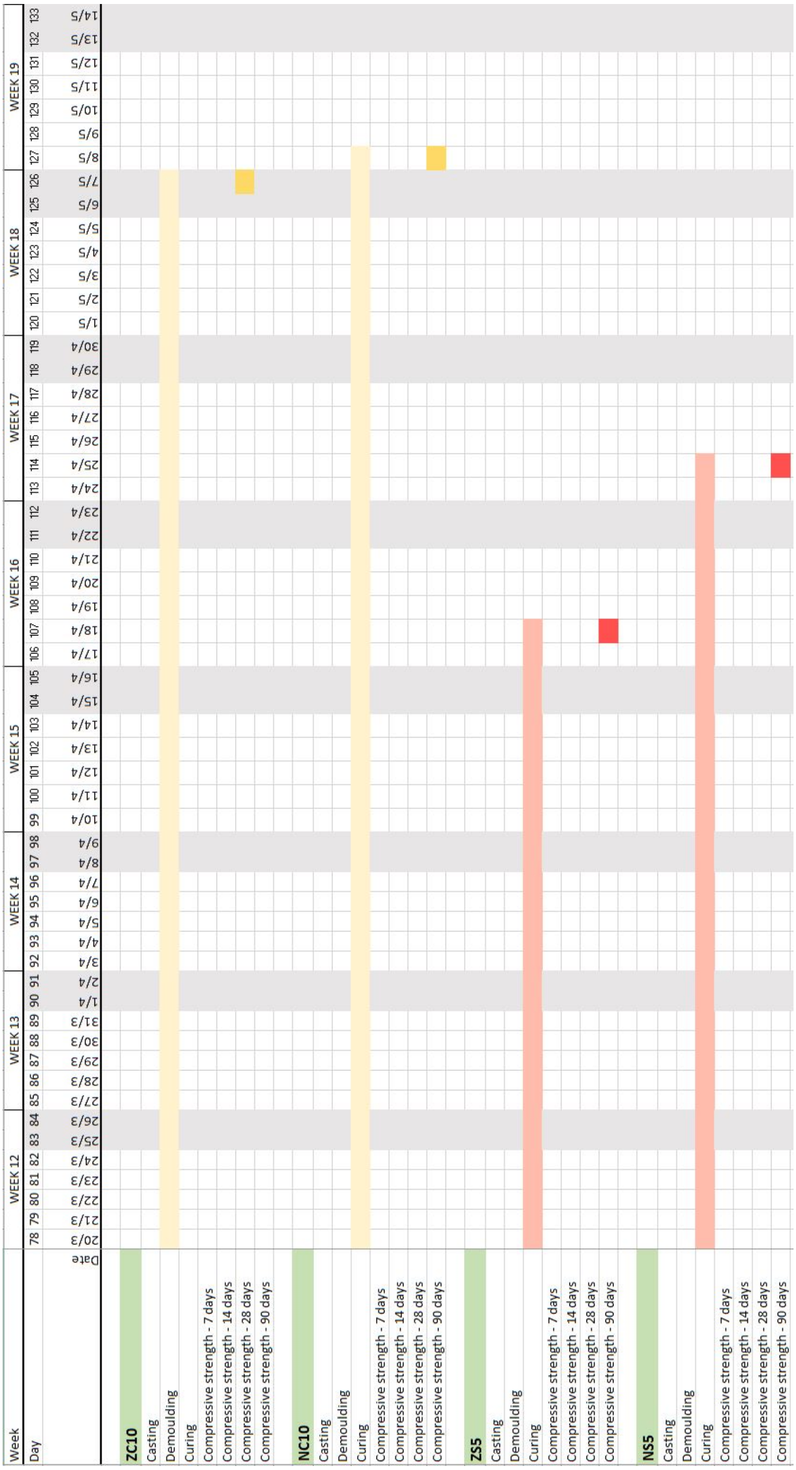
Mortar casting

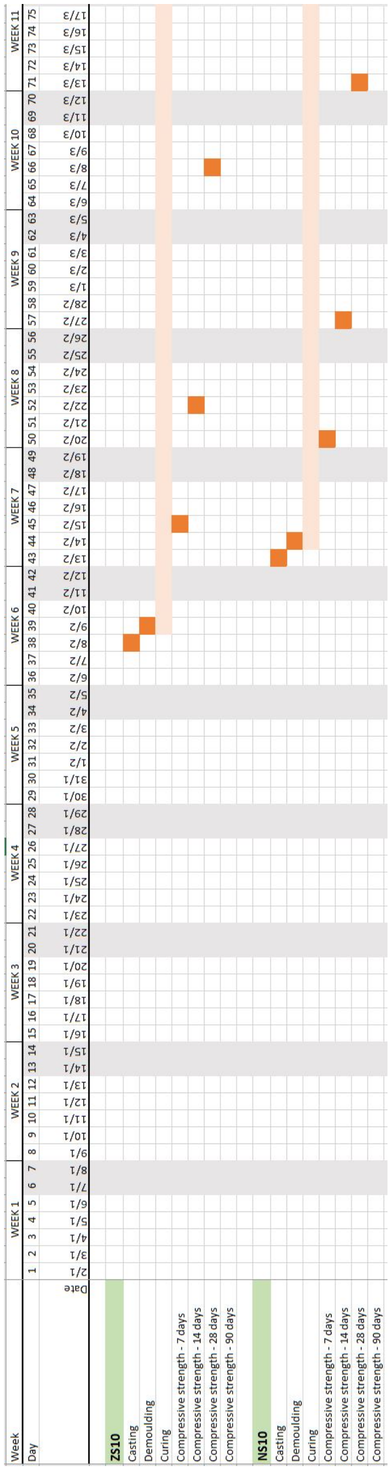
C.1 Planning


Week
Day
Date
WEEK 1
WEEK 2
WEEK 3
WEEK 4
WEEK 5
WEEK 6
WEEK 7
WEEK 8
WEEK 9
WEEK 10
WEEK 11
REFa
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
REF
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
ZC5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NC5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days


Week
Day
Date
WEEK 12
WEEK 13
WEEK 14
WEEK 15
WEEK 16
WEEK 17
WEEK 18
WEEK 19
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131
20/3 21/3 22/3 23/3 24/3 25/3 26/3 27/3 28/3 29/3 30/3 31/3 1/4 2/4 3/4 4/4 5/4 6/4 7/4 8/4 9/4 10/4 11/4 12/4 13/4 14/4 15/4 16/4 17/4 18/4 19/4 20/4 21/4 22/4 23/4 24/4 25/4 26/4 27/4 28/4 29/4 30/4 1/5 2/5 3/5 4/5 5/5 6/5 7/5 8/5 9/5 10/5 11/5 12/5
REFa
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
REF
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
ZC5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NC5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days


Week
Day
Date
WEEK 1
WEEK 2
WEEK 3
WEEK 4
WEEK 5
WEEK 6
WEEK 7
WEEK 8
WEEK 9
WEEK 10
WEEK 11
ZC10
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NC10
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
ZS5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NS5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days


Week
Day
Date
WEEK 12
WEEK 13
WEEK 14
WEEK 15
WEEK 16
WEEK 17
WEEK 18
WEEK 19
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133
20/3 21/3 22/3 23/3 24/3 25/3 26/3 27/3 28/3 29/3 30/3 31/3 1/4 2/4 3/4 4/4 5/4 6/4 7/4 8/4 9/4 10/4 11/4 12/4 13/4 14/4 15/4 16/4 17/4 18/4 19/4 20/4 21/4 22/4 23/4 24/4 25/4 26/4 27/4 28/4 29/4 30/4 1/5 2/5 3/5 4/5 5/5 6/5 7/5 8/5 9/5 10/5 11/5 12/5 13/5 14/5
ZC10
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NC10
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
ZS5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NS5
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days


Week
Day
Date
WEEK 1
WEEK 2
WEEK 3
WEEK 4
WEEK 5
WEEK 6
WEEK 7
WEEK 8
WEEK 9
WEEK 10
WEEK 11
ZS10
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days
NS10
Casting
Demoulding
Curing
Compressive strength - 7 days
Compressive strength - 14 days
Compressive strength - 28 days
Compressive strength - 90 days

Week	WEEK 12							WEEK 13							WEEK 14							WEEK 15						
Day	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105
Date	20/3	21/3	22/3	23/3	24/3	25/3	26/3	27/3	28/3	29/3	30/3	31/3	1/4	2/4	3/4	4/4	5/4	6/4	7/4	8/4	9/4	10/4	11/4	12/4	13/4	14/4	15/4	16/4
ZS10																												
Casting																												
Demoulding																												
Curing																												
Compressive strength - 7 days																												
Compressive strength - 14 days																												
Compressive strength - 28 days																												
Compressive strength - 90 days																												
NS10																												
Casting																												
Demoulding																												
Curing																												
Compressive strength - 7 days																												
Compressive strength - 14 days																												
Compressive strength - 28 days																												
Compressive strength - 90 days																												

Week	WEEK 16							WEEK 17							WEEK 18							WEEK 19						
Day	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133
Date	17/4	18/4	19/4	20/4	21/4	22/4	23/4	24/4	25/4	26/4	27/4	28/4	29/4	30/4	1/5	2/5	3/5	4/5	5/5	6/5	7/5	8/5	9/5	10/5	11/5	12/5	13/5	14/5
ZS10																												
Casting																												
Demoulding																												
Curing																												
Compressive strength - 7 days																												
Compressive strength - 14 days																												
Compressive strength - 28 days																												
Compressive strength - 90 days																												
NS10																												
Casting																												
Demoulding																												
Curing																												
Compressive strength - 7 days																												
Compressive strength - 14 days																												
Compressive strength - 28 days																												
Compressive strength - 90 days																												

C.2 Mix designs - Experimental data

REFa									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
REFa_1	450,22	225,07	1350,23	0,00	12/1	9:20	9:35	7 days compressive strength	19/1
REFa_2	450,30	225,34	1350,35	0,00	12/1	9:45	9:47	14 days compressive strength	26/1
REFa_3	450,00	225,01	1350,09	0,00	12/1	10:05	10:07	28 days compressive strength	9/2

REF									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
REF_1	450,01	225,04	1350,01	0,00	30/1	11:25	10:55	7 days compressive strength	6/2
REF_2	450,01	225,03	1350,01	0,00	30/1	11:40	11:00	14 days compressive strength	13/2
REF_3	450,05	225,02	1350,00	0,00	30/1	13:15	11:05	28 days compressive strength	27/2
REF_4	450,03	225,05	1350,01	0,00	30/1	13:50	11:10	90 days compressive strength	30/4
REF_5	450,00	225,02	1350,00	0,00	30/1	14:30	11:15	Porosity, density	27/2
REF_6	450,01	225,00	1350,04	0,00	30/1	15:40	-	Workability	
REF_7	450,00	225,06	1350,02	0,00	30/1	16:00	-	Vicat	

ZC5									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
ZC5_1	427,58	224,97	1350,03	22,50	16/1	11:50	10:10	7 days compressive strength	23/1
ZC5_2	427,52	225,03	1350,00	22,51	16/1	12:40	10:15	14 days compressive strength	30/1
ZC5_3	427,54	225,03	1350,03	22,48	16/1	13:05	10:20	28 days compressive strength	13/2
ZC5_4	427,54	224,99	1350,01	22,50	16/1	13:20	10:25	90 days compressive strength	16/4
ZC5_5	427,48	225,00	1350,00	22,47	16/1	13:40	11:25	Porosity, density, SEM (28days)	13/2
ZC5_6	427,50	225,03	1350,03	22,51	16/1	14:50	-	Workability	
ZC5_7	427,52	225,04	1349,94	22,50	16/1	12:20	-	Vicat	

NC5									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
NC5_1	427,56	225,04	1350,00	22,54	17/1	11:05	9:30	7 days compressive strength	24/1
NC5_2	427,52	224,99	1350,03	22,51	17/1	11:30	9:35	14 days compressive strength	31/1
NC5_3	427,50	224,98	1350,04	22,53	17/1	11:45	11:00	28 days compressive strength	14/2
NC5_4	427,50	225,02	1350,01	22,48	17/1	12:00	11:05	90 days compressive strength	17/4
NC5_5	427,55	225,00	1349,99	22,52	17/1	12:25	11:10	Porosity, density, SEM (28days)	14/2
NC5_6	427,52	225,02	1350,00	22,50	17/1	10:35	-	Workability	
NC5_7	427,53	225,00	1350,02	22,50	17/1	11:45	-	Vicat	

ZC10									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
ZC10_1	405,02	225,02	1350,03	45,00	6/2	11:00	10:15	7 days compressive strength	13/2
ZC10_2	405,03	225,01	1350,02	45,03	6/2	11:25	10:20	14 days compressive strength	20/2
ZC10_3	405,05	225,03	1350,04	45,05	6/2	11:50	10:25	28 days compressive strength	6/3
ZC10_4	405,03	225,02	1350,07	45,08	6/2	12:15	10:30	Porosity, density, SEM (28days)	7/5
ZC10_5	405,07	225,01	1350,09	45,00	6/2	12:45	10:35	90 days compressive strength	6/3
ZC10_6	405,04	225,03	1350,07	45,02	6/2	13:05		Workability	
ZC10_7	405,09	225,03	1350,06	45,09	6/2	13:25		Vicat	

NC10									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
NC10_1	405,10	225,08	1350,01	45,03	7/2	12:40	11:25	7 days compressive strength	14/2
NC10_2	405,01	225,06	1350,03	45,08	7/2	13:00	11:30	14 days compressive strength	21/2
NC10_3	405,10	225,06	1350,01	45,02	7/2	13:15	11:35	28 days compressive strength	7/3
NC10_4	405,00	225,01	1350,01	45,02	7/2	13:35	11:40	90 days compressive strength	8/5
NC10_5	405,00	225,03	1350,02	45,09	7/2	14:10	11:45	Porosity, density, SEM (28days)	7/3
NC10_6	405,03	225,02	1350,00	45,06	7/2	14:25		Workability	
NC10_7	405,07	225,03	1350,09	45,09	7/2	15:00		Vicat	

ZS5									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
ZS5_1	450,00	225,01	1282,50	67,50	18/1	11:41	10:35	7 days compressive strength	25/1
ZS5_2	450,00	225,06	1282,50	67,50	18/1	11:16	10:45	14 days compressive strength	1/2
ZS5_3	450,00	225,04	1282,50	67,49	18/1	14:10	10:50	28 days compressive strength	15/2
ZS5_4	450,01	225,02	1282,50	67,50	18/1	14:27	10:55	90 days compressive strength, leaching, chloride content	18/4
ZS5_5	450,06	225,03	1282,52	67,50	18/1	14:45	11:00	Porosity, density, SEM (28days)	15/2
ZS5_6	450,00	225,03	1282,50	67,54	18/1	12:25	-	Workability	
ZS5_7	450,01	225,04	1282,52	67,53	18/1	12:25	-	Vicat	

NS5									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Casting time (hh:mm)	Demoulding time (hh:mm)	Purpose	Use day
NS5_1	450,04	225,04	1282,56	67,50	25/1	11:40	9:00	7 days compressive strength	1/2
NS5_2	450,09	225,06	1282,57	67,55	25/1	12:10	9:05	14 days compressive strength	8/2
NS5_3	450,00	225,04	1282,58	67,55	25/1	12:40	9:10	28 days compressive strength	22/2
NS5_4	450,05	225,02	1282,50	67,51	25/1	13:05	9:15	90 days compressive strength, leaching, chloride content	25/4
NS5_5	450,10	225,01	1282,56	67,50	25/1	13:40	9:20	Porosity, density, SEM (28days)	22/2
NS5_6	450,00	225,00	1282,55	67,58	25/1	14:00	-	Workability	
NS5_7	450,00	225,03	1282,50	67,51	25/1	14:35	-	Vicat	

ZS10									
Mix	Cement (g)	Water (mL)	Sand (g)	Tailings (g)	Casting date	Cast time (hh:mm)	Demolded time (hh:mm)	Usage	Use day
ZS10_1	450,04	225,05	1215,01	135,00	8/2	13:05	9:35	7 days compressive strength	15/2
ZS10_2	450,10	225,02	1215,07	135,01	8/2	13:55	9:40	14 days compressive strength	22/2
ZS10_3	450,09	225,06	1215,05	135,09	8/2	14:10	9:40	28 days compressive strength	8/3
ZS10_4	450,03	225,00	1215,09	135,06	8/2	14:25	9:45	90 days compressive strength, leaching, chloride content	9/5
ZS10_5	450,07	225,08	1215,10	135,09	8/2	14:45	9:45	Porosity, density, SEM (28days)	8/3
ZS10_6	450,02	225,07	1215,04	135,05	8/2	15:10	-	Workability	
ZS10_7	450,00	225,03	1215,06	135,07	8/2	15:40		Vicat	

NS10									
Mix	**Cement (g)**	**Water (mL)**	**Sand (g)**	**Tailings (g)**	**Casting date**	**Cast time (hh:mm)**	**Demolded time (hh:mm)**	**Usage**	**Use day**
NS10_1	450,00	225,01	1215,07	135,10	13/2	10:55	9:45	7 days compressive strength	20/2
NS10_2	450,07	225,05	1215,00	135,02	13/2	11:15	9:45	14 days compressive strength	27/2
NS10_3	450,03	225,07	1215,06	135,04	13/2	11:35	9:50	28 days compressive strength	13/3
NS10_4	450,00	225,02	1215,03	135,03	13/2	12:00	9:50	90 days compressive strength, leaching, chloride content	14/5
NS10_5	450,10	225,03	1215,03	135,08	13/2	12:30	9:50	Porosity, density, SEM (28days)	13/3
NS10_6	450,10	225,01	1215,06	135,05	13/2	12:55	-	Workability	
NS10_7	450,02	225,01	1215,01	135,08	13/2	13:25	-	Vicat	
NS10_1b	450,10	225,01	1215,00	135,05	1/3	9:50	9:30	7 days compressive strength	8/3

APPENDIX D

Poster

D.1 Poster made for the mid-term presentation

Use of mine tailings in concrete

DTU Byg - *Master thesis (January-June 2017)*
Chloé Potier – *s151432@student.dtu.dk*
Supervisor: Pernille Erland Jensen

Presentation

Mine tailings (MT) consist of the **waste materials** remaining after mechanical and chemical processing of the ore. Tailings storage is of major concern as MT generally have **high amounts of heavy metals that can** lead to contamination of the surrounding environment through **leaching** or dust emission, thereby posing a threat to biodiversity and human health. It has been shown that incorporating MT in concrete can result in the **immobilization of the leachable elements** in the cement matrix, while providing **satisfying mechanical characteristics** (1). In this thesis, the mechanical properties and leaching behaviour of mortar containing MT from two mines will be studied. The tailings considered come from **Zinkgruvan mine,** in South Sweden (Zn, Pb, Cu extraction) and Nalunaq mine, in South Greenland (Au extraction).

Approach

Mortar

Substitution of cement and sand with mine tailings is investigated in mortar, with replacement rates of 5% and 10% by weight.

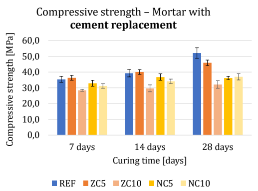
Table 1. Composition of the mortars

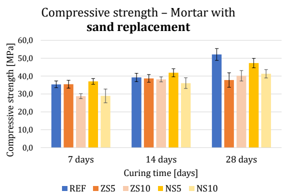
Sample name	Composition	Comment
REF	Reference mortar (no tailings)	w/c* = 0,5
ZC5, NC5	5% cement substitution with Zinkgruvan (respectively Nalunaq) tailings	w/p** = 0,5
ZC10, NC10	10% cement substitution with Zinkgruvan (respectively Nalunaq) tailings	w/p = 0,5
ZS5, NS5	5% sand substitution with Zinkgruvan (respectively Nalunaq) tailings	w/c = 0,5
ZS10, NS10	10% sand substitution with Zinkgruvan (respectively Nalunaq) tailings	w/c = 0,5

*: *w/c = water-cement ratio (by weight)*
**: *w/p = water-powder ratio, meaning water-(cement + tailings) ratio (by weight)*

Compressive strength

Compressive tests are carried out after 7, 14 and 28 days of curing under water, following DS/EN 196-1 (2).





Observations:

Cement replacement: for substitution with both Nalunaq and Zinkgruvan tailings, a loss of strength after 28 days is observed. The more cement is substituted with MT, the more the strength decreases.

Sand replacement: for both tailings, a loss of strength after 28 days is also observed, although it is less significant than for cement replacement.

Workability was also found to decreases with the addition of dry tailings, especially for sand substitution. Increasing workability could improve mortar compaction and result in higher compressive strength.

Leaching behaviour

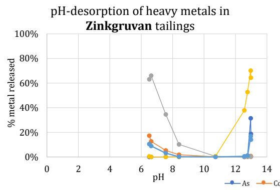
Heavy metals content of the tailings

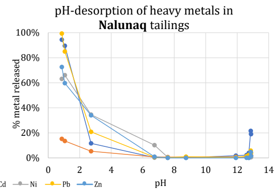
Heavy metals content in the MT is assessed through acidic digestion, in accordance with DS 259 (3).

Table 2. Heavy metals content in Zinkgruvan and Nalunaq tailings (in mg/kg ±std. dev.) and comparison with category 1 waste from Miljøstyrelsen (4)

	As	Cd	Ni	Pb	Zn
Zinkgruvan	49 ± 6	12,6 ± 0,4	18 ± 1	3995 ± 465	777 ± 346
Nalunaq	529 ± 15	2,3 ± 0,2	47 ± 1	10 ± 1,0	38 ± 2
Limit (Category 1)	**20**	**0,5**	**30**	**40**	**500**

pH-desorption of heavy metals in the tailings





Observations: At high pH (>12): significant leaching of Pb, As, Zn (for Zinkgruvan tailings) and of As (for Nalunaq tailings) is observed. This is a concern due to the high content of these metals in the tailings. Concrete is alkaline, therefore this could indicate a risk of leaching of these elements in mortar containing MT.

Leaching of heavy metals in crushed mortar

Mortar samples are crushed and subjected to batch leaching tests at a Liquid-Solid ratio of 2 L/kg (5).

Table 2. Heavy metals concentration in eluate (in µg/L ±std. dev.) and comparison with category 1 waste from Miljøstyrelsen (4)

	As	Ba	Cr (tot)	Pb	Zn
REF	0 ±0	2616 ±300	13 ±11	50 ±44	0 ±0
ZC5	23 ±39	1990 ±78	21 ±3	73 ±65	320 ±554
NC5	0 ±0	2096 ±30	40 ±3	0 ±0	0 ±0
Limit for category 1	**8**	**300**	**10**	**10**	**100**

Observations: Uncertainty is high for the main heavy metals of concern (As, Pb). Some values are significantly above the limit even for the reference mortar (Ba, Pb), possibly due to the crushing of mortar before the leaching test, that releases additional heavy metals. There is also a lack of specific legislation for concrete containing MT.

Conclusion and further prospects

- Cement and sand substitution with both MT lead to a loss of compressive strength. Depending on the concrete use and substitution rate, it could still be satisfactory.
- Leaching tests with crushed mortar yield results significantly above the limit for some elements, including with reference mortar.

Further experiments:

- Batch leaching tests for the other mortar compositions studied
- Porosity and density
- Leaching experiment that does not involve crushing of mortar

(1) *Copper tailings as potential additive in concrete: consistency, strength and toxic metal immobilization properties,* Onuaguluchi, O. and Eren, Ö., 2012, Indian Journal of Engineering and Materials Sciences
(2) DS/EN 196-1
(3) DS 259
(4) Miljøstyrelsen, *Bekendtgørelse om anvendelse af restprodukter og jord til bygge- og anlægsarbejder og om anvendelse af sorteret, uforurenet bygge- og anlægsaffald,* 2010
(5) DS 12457-1

{2.7182818284}