Environmental assessment of mechanically activated fly ash used for soil stabilization

Maria Broberg

ABSTRACT

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Vattenfall AB annually produces approximately 6 Million tonnes of ash from coal, biofuel and municipal waste incineration. Ash from combustion processes is classified as waste. From an environmental and resource as well as an economic perspective, utilization of these materials is desirable. All use of waste needs allowance from the environmental authorities, but the environmental legislation for utilization of waste is vague and this often results in rejections of applications.

Soil stabilization is a cost-effective and flexible method for reinforcement of soil. Conventional binding agents in soil stabilization are lime and cement and the production of them generates huge quantities of CO_2. It is therefore desirable to replace them with material with less environmental impact. Geotechnical properties for soil stabilization with fly ash have been investigated in earlier studies with positive results. Similar studies are currently conducted for mechanically activated fly ash. Mechanical activation of the fly ash increases the reactive properties by crushing the ash into smaller parts.

The aim of this study was to complement these studies with an environmental assessment, in this case leaching tests. Analyzed elements are most metal ions, but also salt ions and dissolved organic carbon. Two type of leaching tests have been performed; Up-flow percolation test prEN14405 and two stage batch test SS-EN 12457-3. The hypothesis was that mechanically activated fly ash leaches more than none activated fly ash due to an increase of reactive sites that are exposed after the mechanical activation. Based on the performed tests the results are positive for using fly ash, both mechanically activated and none activated, in soil stabilization. An extended laboratory study followed by a field study would be appropriate to confirm the primary results.

Key words: Soil stabilization, Mechanical activation, Fly ash, Leaching test

REFERAT

Miljöutvärdering av mekaniskt aktiverad flygaska i markstabilisering
Maria Broberg

Vattenfall AB producerar årligen nära 6 miljoner ton aska från kol-, biobränsle- och kommunal avfallsförbränning. Aska från förbränningsprocesser är klassificerat som avfall. Ur ett miljö-, resurs- samt ekonomiskt perspektiv är det önskvärt att finna en tillämpning för detta avfall. All användning av avfall behöver godkännas, men miljölagarna är vaga och ansökningar avslås därför ofta.

Markstabilisering är en kostnadseffektiv och flexibel metod för att förstärka jorden. Konventionella bindemedel i markstabilisering idag är kalk och cement. Produktionen av dessa genererar höga kvantiteter CO_2 och därför är det önskvärt att ersätta kalk och cement med material som har mindre miljöpåverkan. Geotekniska egenskaper för flygaska i markstabilisering har undersökts i tidigare studier och resultaten är positiva. Liknande studier utförs för närvarande för mekaniskt aktiverad flygaska. Mekanisk aktivering av flygaska ökar askans reaktiva egenskaper genom att askan krossas till mindre partiklar.

Syftet med den här studien är att komplementera dessa studier med en miljöbedömning, i detta fall laktester. Analyserade ämnen är metalljoner, men även saltjoner och löst humus. Hypotesen är att mekaniskt aktiverad aska är bättre för hållfastheten i jorden, men ger mer utlakning än obehandlad flygaska på grund av de färska ytorna som exponeras efter den mekaniska aktiveringen. Resultaten visar på goda förutsättningar att använda flygaska, både mekaniskt aktiverad och icke aktiverad, i markstabilisering. För att bekräfta detta rekommenderas en utvidgad laboratoriestudie och fältstudier.

Nyckelord: Markstabilisering, Mekanisk aktivering, Flygaska, Laktest

PREFACE

This study was supported by the EU-project NextGen BioWaste and the internal research programme for thermal technology, TTP. Vattenfall Research & Development AB was one of the initiators of this four-year integrated EU co-financed project. It is the biggest EU R&D project with focus on renewable fuels. One of the aims with the project is to reduce the costs for waste and biomass combustion power plants that produce heat and electricity. Vattenfall AB annually generates large quantities of waste, such as ash, in these kinds of power plants. Environmental legislation is vague, but according to EU landfilling of waste should be avoided and recycling prioritized without considerable risk for environment and human health. Also considering the economic perspective, utilization of waste is desirable, since landfilling is expensive. The aim of this study, that is the master thesis to conclude the Master of Science program in Environmental and Aquatic Engineering, is to investigate the environmental influence when fly ash is used for soil stabilization.

My supervisor at Vattenfall R&D was Niklas Hansson and my assistant supervisor was Caroline Göthlin, both from department of Civil & Materials engineering, where this study has been performed. My subject reviewer was Dan Berggren Kleja, professor at the Faculty of Natural Resources and Agricultural Sciences at Swedish University of Agricultural Sciences (SLU).

A special thank to both of my supervisors that more than fulfilled their commitment and inspired me with new ideas. Also thanks to my subject reviewer for proof-reading the report and useful contacts. There among Gunilla Hallberg at SLU who was really helpful with the two stage batch tests. Likewise thanks to other people at Vattenfall in Älvkarleby, especially at the concrete laboratory for helping me out with the testing apparatures. Not at least thanks to experienced people in the field which have contribute with their knowledge of leaching tests, there among Cecilia Toornvali from SGI, Eva Lidman from ALS and Britt Aurell from ALControl. Finally, special thanks to people who feel they are forgotten, they are not.

Uppsala February 2009

Maria Broberg

POPULÄRVETENSKAPLIG SAMMANFATTNING

Miljöutvärdering av mekaniskt aktiverad flygaska i markstabilisering
Maria Broberg

Större delen av industrin genererar förutom sina huvudprodukter också avfall, däribland aska från el- och värmeproduktionen. År 2006 var produktionen av aska i Sverige totalt 1.2 miljoner ton (inklusive Vattenfalls produktion); i huvudsak kom den från förbränning av biobränsle och kommunalt avfall. Från ett miljö-, resurs- och även ekonomiskt perspektiv är det angeläget att använda detta avfall. Enligt EU ska återvinning prioriteras och deponering undvikas så länge det inte utgör någon märkbar risk för människans hälsa eller miljön. All användning av avfall ska godkännas av miljömyndigheterna. Lagarna för hur avfall får användas är emellertid vaga och ansökningar om tillämpningar för avfall leder ofta till avslag. Samtidigt ökar efterfrågan på billiga material med en låg miljöpåverkan i många industrier. En typisk sådan industri är produktionen av kalk och cement som genererar stora mängder koldioxid. Både med hänsyn till ekonomin och miljön finns det ett intresse hos stora användare av kalk och cement att delvis ersätta dessa med aska eller andra restprodukter.

Markstabilisering är en metod för att förstärka marken på plats istället för att schakta bort den och ersätta den med nytt material. Med markstabilisering förstärks hållfastheten i jorden genom kemiska reaktioner som uppkommer mellan bindemedlen och jorden. Masstabilisering är när hela jordmassan rörs om med bindemedel. Det kan göras över en större yta, men metoden är svår att tillämpa för djupare lager. Djupstabilisering är en form av markstabilisering där stabiliserande kolonner skapas i marken genom att ett mixerinstrument borras ner på djupet och matar ut bindningsmedel. Konventionella bindemedel i markstabilisering är kalk och cement. Flygaska har emellertid visat sig ge goda resultat för hållfastheten i markstabilisering och har goda förutsättningar att delvis ersätta kalk och cement. Flygaskan har självhärdande egenskaper som börjar verka då askan kommer i kontakt med vatten, så kallade pozzolana reaktioner startar. Mekanisk aktivering av flygaskan kan ytterligare öka den reaktiva förmågan. Tekniken innebär att flygaskan krossas till mindre partiklar och fler aktiva ytor uppstår. I förstudier har denna teknik visat sig ge upp till 25 % högre hållfasthet än obehandlad flygaska. När bindemedlen har tillsatts till jorden uppstår en ny kemisk sammansättning. Ur ett miljöperspektiv är det viktigt att bedöma hur detta påverkar den omgivande miljön.

Syftet med den här studien är att göra en miljöbedömning för mekaniskt aktiverad aska då den används i markstabilisering. Detta har gjorts med laktester som används för att beskriva den naturliga lakningen i laboratorium. Två typer av lakteststandarder har använts; perkolationstest prEN14405 och skaktest EN-SS-12457-3. Genom att använda standardiserade tester underlättas jämförelsen med andra studier. Lakvattnet har analyserats av ett ackrediterat externt laboratorium för de ämnen som det finns gränsvärden för enligt Naturvårdsverkets föreskrifter om deponering, NFS 2004:10. Det rör sig främst om metalljoner, men även klorider, sulfat, fluorider och DOC är analyserade. Dessa gränsvärden används ofta då gränsvärden för den aktuella tillämpningen saknas. Om den stabiliserade jorden med mekaniskt aktiverad flygaska kan klassificeras som inert avfall är

det ändå en indikation på att studien är värd att fortsätta. Utöver dessa gränsvärden finns det en remiss från Naturvårdsverket som handlar om återvinning av avfall i anläggningsarbeten. Remissen är inte direkt applicerbar för den här tillämpningen, men förslaget på riktvärden för avfall i anläggningsbyggande är en intressant grund för jämförelser. Som referens i studien har en stabiliserad jord med bara kalk och cement använts, eftersom detta redan idag är accepterat på marknaden.

Mekanisk aktivering av flygaska ger fler aktiva ytor jämfört med obehandlad flygaska. Mot denna bakgrund är hypotesen att användningen av mekaniskt aktiverad flygaska i markstabilisering förväntas ge en större utlakning än den icke aktiverade flygaskan. För att bekräfta/avslå denna hypotes gjordes även jämförelser mellan flygaska och mekaniskt aktiverad flygaska. Undersökningen har utförts utifrån ett "worst-case-scenario"; Provkroppar har tillverkats med en större mängd bindemedel än vad som anses vara optimalt i fält. Recepten har varierats så att ett recept har större andel aska i sig än vad som är standard i liknande utförda undersökningar. Avsikten är att se hur detta ändrar lakningen. Utfallet från studien är positivt. Mekaniskt aktiverad flygaska ger inte anmärkningsvärt högre utlakning än icke aktiverad flygaska. Vid jämförelse med referensen (stabiliserad jord med kalk och cement) visar vissa ämnen på en större utlakning för referensprovet medan vissa ämnen visar på en större utlakning för prover med flygaska i. Inte i något av proverna överstiger resultaten de använda rikt/gränsvärdena. Detta betraktas som ett positivt resultat, särskilt med beaktande av att studien utfördes utifrån det nämnda "worst-case-scenariot". I denna studie utfördes laktester på provkroppar som lagrats under 7 dagar och 91 dagar. Härdningen fortsätter även efter 7 dagar och för att studera och analysera hur härdningstiden påverkar lakningen behövs därför undersökningar som sträcker sig över en längre tid.

För att ytterligare fördjupa kunskapen om här redovisade resultat bör en komplettering med i första hand en utvidgad laboratoriestudie och därefter en fältstudie genomföras. Laboratoriestudien skulle behöva kompletteras med upprepade laktester för att få fram statistik för att förstärka underlaget till bedömningen. I fältstudien skulle tre kolonner lämpligen installeras under likartade förutsättningar. Alla tre kolonnerna med kalk och cement, men varav obehandlad flygaska kan adderas i en utav kolonnerna och mekaniskt aktiverad flygaska i en annan utav kolonnerna.

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1   INTRODUCTION

1.1   BACKGROUND

Beside the main products most industrial activities produce waste[1]. Ash from combustion processes is classified as waste. In 2006 the total production of ash in Sweden was (including Vattenfall production) 1.2 million tonnes, mainly originating from biofuel and municipal waste incineration (Herbert, 2008). From an environmental and resource as well as an economic perspective, utilization of these materials is desirable. According to EU, recycling of waste should be prioritized and landfilling should be avoided without considerable risk for human health and the environment. Balancing between economization with natural resources and the potential risk that utilisation of waste might imply is often hard. (Egnell et al., 1994)

What also complicates utilization of waste is the fact that there often is a significant variation in the properties of different waste fractions and that the volume of each fraction is proportionately small. Especially ash from biomass combustion exists in small volumes compared to coal ash. In addition all utilisation of waste needs allowance from the environmental authorities and they have a vague legislation to base their decision on which often results in rejections. The complexity in both the properties of many waste fractions and the fact that the legislation is vague put producers of waste in an awkward situation. All this together renders difficulties for the producers to create a market for them.

On the other hand the demand for aggregates from natural resources is increasing. The production of for example cement and lime requires huge quantities of limestone etc. that in turn renders high CO_2 emissions. Both economical and environmental concerns make it advantageous for producers of cement and lime to consider alternative materials such as waste. Due to this fact the concrete industry is the core market for coal ashes. However, ash from biofuel combustion does not fulfil the requirements searched from concrete producers and consequently they are utilized in other areas such as replacement of natural aggregates in bearing layers, e.g. road construction and industrial surfaces. More advanced applications are desirable to widen the market, one such is soil stabilization. It is a method to stabilize especially loose clay and organic soil, before establishing a building construction. Burned lime and cement are the main binding agents in soil stabilization. Earlier studies indicate that fly ash partly can replace lime and cement in soil stabilization with regard to compressive strength. Different methods can be used to enhance desired properties in fly ash, one such method is mechanical activation. Through mechanical activation the fly ash becomes more reactive and primary results illustrates that the activation technology has a positive effect on the compressive strength when used with cement (Hansson, 2008). What still is an area of limited information are environmental concerns when mechanically activated fly ash is used in soil stabilization.

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[1]Waste can be divided into different sub-fractions depending on its properties. Residues can often be equivalent to the word waste.

1.2 PROBLEM DESCRIPTION

Vattenfall AB annually produces approximately 6 Million tonnes of ash from coal, bio fuel and municipally waste incineration. Before ash will be considered for utilisation three general aspects have to be fulfilled (Ecke et al., 2005):

- The residues need to have technical properties for the application, in this case soil stabilization.
- From an environmental aspect, for the actual application, the residues need to be appropriate.
- Show that the limit values set by the environmental authorities are fulfilled.

Geotechnical properties for the soil stabilization application with fly ash have been investigated in a study from 2007 at Vattenfall R&D AB (Hansson, 2007). Similar studies are currently (February 2009) conducted for mechanically activated fly ash. These studies need to be complemented with an environmental assessment. The main research questions in this study are:

1. Does fly ash have larger amounts of leached elements compared to conventional binding agents such as lime and cement?
2. Does mechanically activated fly ash have larger amounts of leached elements than untreated fly ash?
3. Do different leaching test methods give similar results?
4. How does hardening time influence the leaching?

1.2.1 Proceeding

A dominating part of this study has involved development of methods for leaching tests, i.e. decide on appropriate leaching tests for soil stabilization of a clay soil with lime, cement and fly ash as binding agents, both mechanically activated and none mechanically activated fly ash.

This study has been performed mainly in four steps;
1. A literature study with the following issues;
   ◦ Soil stabilization
   ◦ Environmental risks with different binding agents in soil stabilization
   ◦ Chemical analysis
2. Method development of leaching tests
   ◦ Interviews with experienced people in the field
   ◦ Purchase and tests of material
3. Performance of tests
   ◦ Up-flow percolation tests
   ◦ Two stage batch tests
   ◦ Leachate analysis
4. Evaluation of test data according to questions in chapter 1.2.

12.2 Limitations

The study of the environmental assessment of mechanically activated fly ash used for soil stabilization is limited to one type of soil and one type of fly ash, the same fly ash is also mechanically activated. The environmental assessment encompasses soil tests and two types of leaching tests; Up-flow percolation test prEN14405 and two stage batch test SS-EN 12457-3.

Organic substances are considered not to be critical in the investigated materials and the leaching tests for organic substances use completely different methods, therefore environmental assessments are in this study delimitated to inorganic substances and dissolved organic carbon (DOC). The choice of elements is based on available guideline/limit values for waste according to NFS 2004:10 (Naturvårdsverket, 2004).

There are health aspects that are critical when using residues in soil stabilization, as for example dust during the production. There are also technical and economic aspects when transporting residues, but neither of these is discussed in this study.

2 SOIL STABILIZATION & MECHANICAL ACTIVATION

2.1 SOIL STABILIZATION

Building on loose clay or organic soil can be problematic. There is a significant risk of vertical and horizontal deformations (Carlsten, 2000). Soil stabilization is a cost-effective and flexible method for reinforcement of soil. Instead of excavating the loose soils, they are replaced with gravel for example. Life cycle assessments have showed that soil stabilization can be favourable compared to other methods regarding transports and energy consumption (Rydberg & Andersson, 2003). Stabilization can be divided into two main methods; mass stabilization and deep soil stabilization. Mass soil stabilization is when the total mass of soil is mixed with binding agents. With this method it can be hard to stabilize deeper layers, but a larger area can be covered. Deep soil stabilization is made with stabilized columns (Carlsten, 2000). A mixing tool rotates while pressed down in the soil and the binding agents are feed out through it. With soil stabilization the strength of existing soil increases by chemical reactions. The reactions start immediately after installation between binding agents, soil, water and soil particles. The magnitude of the strength is mainly dependent of the original soil material, the binding agents and the amount of binding agents.

2.1.1 Binding agents

Depending on soil properties and purpose with the specific soil stabilization project different amounts and types of binding agents are used. Lime and cement are commonly used, but lately the recycling perspective has brought for example fly ash into the market of stabilization.

2.1.2 Lime

Burnt lime, CaO, is produced by calcinating limestone, $CaCO_3$, at 1100ºC. A problem with the production of lime is the large quantities of CO_2 that are emitted during the calcinations reactions. See Equation 1. (Rogbeck et al., 2006)

$$CaCO_3 + Heat \xrightarrow{yields} CaO + CO_2 \qquad (1)$$

CaO exists in several forms. The form that is easily available for chemical reactions is called $CaO_{reactive}$ and are approximately 90 % of the burnt lime (Hansson, 2007). When it comes in contact with water it reacts and forms hydrated lime, $Ca(OH)_2$. See Equation 2.

$$CaO + H_2O \xrightarrow{yields} Ca(OH)_2 + Heat \qquad (2)$$

The chemical reaction described in equation 2 is essential for soil stabilization. It reduces the water content in soil, hence improves the strength properties. At the same time heat produces which enhance other chemical reactions. It gives an increased pH, which is a condition, in combination with pozzolanic[2] material, for secondary pozzolanic reactions to take place. (Janz & Johansson, 2002)

2.1.3 Cement

Cement is produced by mixing clay and limestone. The mixture is calcinated at 1400ºC. The result is called Portland clinker. This clinker is mixed with for example gypsum, depending of the application for the cement, and grinded to micrometer scale.

Cement reacts with water and chemical reactions starts. C-S-H, cement gel, forms around the cement particle. C-S-H is mostly calcium and silicon and some chemically bound water. It works as a glue and fills the void between the particles, which causes the cement to grow denser and stronger. (Janz & Johansson, 2002)

2.1.4 Ash

Ash is the incombustible rest of a fuel. Ashes can be divided into different categories depending on where in the combustion system they are separated. The most common is to divide it in bottom ash and fly ash. Bottom ash is the fraction that falls to the bottom in a combustion boiler. The ash material that follows the flue gas and is collected in a filter for flue gas cleaning is called fly ash.

Properties of a single ash depend on which fuel that has been used and which type of combustion boiler that is used. For example combustion of hard coal renders more homogeneous ash because the fuel is more homogeneous. Since the volume of ash is much less than the original volume of the fuel, several of the elements are in higher concentrations in the ash than in the original fuel. The dominating elements in ashes are calcium-, silicon-, iron- and aluminium oxides. The combustion is never total and therefore even well combusted ashes have a small amount of organic material.

Many ashes start to harden if water is added and gets more stable both from a physical and a chemical perspective. Depending on the chemical composition different reactions starts when water is added, some of them are pozzolanic, others are hydraulic. Pozzolanic reactions are fortified by silicon, aluminium and iron while organic substances and some

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[2] Pozzolanic can be equivalent to the word self-hardening

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metals, like Pb and Zn, can retard the reactions. Fly ashes generally have enough amounts of CaO and SiO_2 to give pozzolanic reactions.

The reason for using fly ashes in soil stabilization instead of bottom ashes are mainly because that the hardening properties are better for fly ashes since bottom ash go through a water bath and starts to react before it gets in contact with soil. Also bottom ash is not compatible with machines for soil stabilization due to the larger particle size. Unfortunately the amounts of toxic elements are often greater in fly ashes than bottom ashes. (Egnell et al., 2008)

2.2 MECHANICAL ACTIVATION OF FLY ASH

The information on mechanical activation of fly ash is obtained by communication with Andrea Wils, she was a trainee at Vattenfall Research Development in the summer 2008. To increase the reactive properties of ash it is possible to mechanical activate it. Different kind of mills can be used for mechanical activation. One is ordinary ball mill and one is electromagnetic ball mill. Vattenfall AB cooperates in technical issues with EMC in Luleå, who use the ordinary ball mill for mechanical activation of fly ash. Their ball mill has approximately 200 balls with a diameter of 30 mm. See figure 2.1.
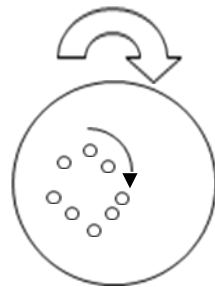
Figure 2.1 Ordinary ball mill

The ash is crushed into smaller parts and the activated surfaces increase, which means that the whole ash reactivity increases. Pre-tests shows that mechanically activated fly ash gives a 25 percent higher strength compared to none mechanically activated fly ash.

In comparison with electromagnetic ball mill, the ordinary ball mill has a lower degree in the reduction of particle size. Thereby it is less efficient, but it also has lower investment costs.

3 ENVIRONMENTAL CONCERNS

3.1 INTRODUCTION

Since clay soil normally has a very low permeability high leaching is not expected, but stabilized columns can be more permeable than the surrounding soil. When binding agents are added to soil, the new soil mixture has a new chemical composition. Some combinations of soil and binding agents give more leaching than others (Håkansson, 2003). Total content includes bound metals that are not necessary available for biological receive or leakage to water (Ecke et al., 2005) and therefore the distribution of contaminants to the surrounding soils and sorption is not at all proportional to total content of elements in soil or binding agents. However, to determine whether a material can pose an environment risk, knowledge of total content is not enough. The leaching behaviour better reflects the environmental influence of a specific material.

3.2 ELEMENTS AND COMPOUNDS

For an organism to function normally small amount of essential elements are necessary. An element that is essential for an organism can be toxic for that organism when the amount of the element is too high.

Metals are a common name for big group inorganic elements. Heavy metals are metals with a density above 5 g/cm^3. There is a common misunderstanding that heavy metals pose a bigger environmental risk than other metals since most heavy metals and their chemical compounds are toxic. Even other metals can be strongly toxic so there is no given correlation between heavy metal and environmental risk (NE, 2008). Metals cannot be created, decomposed or destroyed. They are redistributed or distributed in the ecosystems through biological, geological and hydrological cycles by water. The most important sinks for metals are sedimentation and precipitation as soluble compounds in sediment at the bottom of lakes, seas and wetlands. The concentration of metals in water solution and sediment are in equilibrium, which means there is a continuous exchange between water phase and sediment. Even some organic residuum, such as peat lands, works as a sink for metals and the metal concentration in peat can therefore be very high (Cockerham & Shane, 1994). Most metals can be both free, hydrated ions or in organic/inorganic complex. Normally it is the free, hydrated ion that is the most available (toxic) for leakage to water (Ecke et al., 2005).

Solid and dissolved organic carbon (humus substances) consists of complex molecules with a high affinity to bind metals. Normally the concentration of humus substances is measured by measuring the concentration of dissolved organic carbon (DOC), but this is not a perfect match since DOC also includes other types of dissolved organic carbon. Only small parts of DOC are easily removable. Humus substance can be both dissolved in water, where metal transport occurs through complex forming with metals and it can be as aggregated particles and then bind metals through sorption. (Ecke et al., 2005)

3.3   LEACHING

Residues, as ash, in soil stabilization can be considered as activity of contamination due to the fact that ash contains metals. The transport of contaminants occurs through water, gas or dust. The transport in water is seen as the most dangerous environment risk considering that the contamination plume can reach the ground water (Von Heidestam et al., 1994). The liquid that is in contact with the solid phase is called leachate. Analysing leachates can indirectly cover almost all the other risks, as can be seen in figure 3.1. Therefore an investigation of the leachability can be used as an important indicator in the environment assessment.
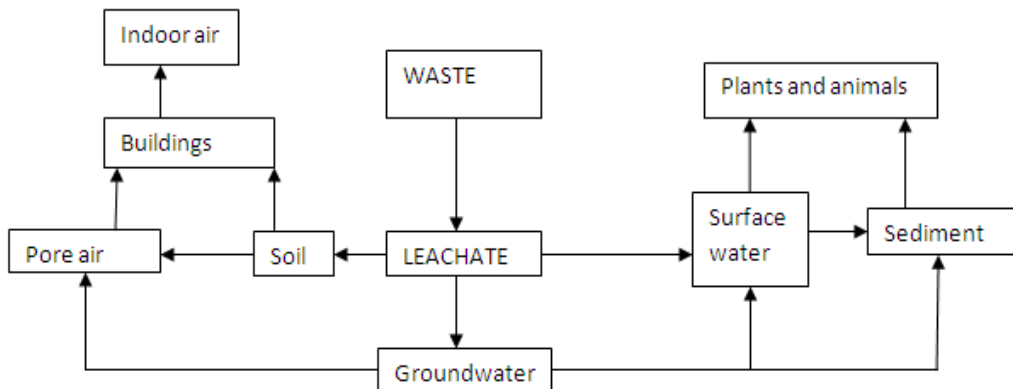
Figure 3.1, This figure clarify how the leachate can be an indicator for the whole environmental risk (Von Heidestam et al., 1994)

3.3.1   Dominant leaching processes

Release of constituents from material to the water phase occurs through several mechanisms, which basically can be divided into two overlaying processes:

1. *Chemical processes*
   Dissolution/precipitation of minerals (solubility controlled processes) Sorption, and ion exchange (sorption controlled processes)
2. *Physical transport processes*
   Advection, surface wash-off and diffusion

In practice it is a combination of 1 and 2 that causes the release of constituents to water phase. (Van der Sloot, 2004)

Release rate and mobilization of different elements are also dependent on chemical factors such as pH, redoxpotential as well as the presences of other substances e.g. chlorides, sulphates, carbonates and DOC. Physical properties such as permeability and porosity are also of importance. (Bjerre-Hansen et al., 2006)

In soils, particles are charged and therefore cations and anions are sorbed/desorbed by these surfaces. Charged soil particles work as ion exchangers. The strength of bindings is dependent on the properties of soil particles. The mechanism is either electrostatic sorption (ion exchange) or surface complex formation. Exchangeable ions are bound weakly by the particle surfaces and not as strong as surface complex that is bound directly to the surface. Therefore, exchangeable ions are more easily desorbed (leached). Examples of ions that normally can be found as exchangeable ions are Na^+ and Ca^+. Cations, as metal ions, can form complex with anions that are common in water, for example fluorine, sulphate and carbonate. (Wiklander, 1976)

There are two types of charging mechanisms in soils; permanent and variable. The permanent charge can be found in some clay minerals, such as illite. Variable charge can be either positive or negative dependent on pH. Soil organic matter, on the other hand, always has a net-negative charge, due to the occurrence of deprotonated carboxylic groups. Humus has a very high charge per kg, which means that a few percent of humus can significantly increase the negative load and thereby the ability to bind cations in the soil. (Wiklander, 1976) Solubility for metals increases with increased amount of humus, depending on the strength of sorption and of the solubility of humus itself (Ecke et al., 2005). However, when pH is around 12, sorption to humus becomes less effective because of the increasing solubility of humus, see figure 3.2, which brings metals in the solution as a complex with humus. So for most metals the solubility is high when pH is low or very high (Bjerre-Hansen, 2006), see figure 3.3. Soluble salts such as Cl is not reactive and therefore not depending on pH.
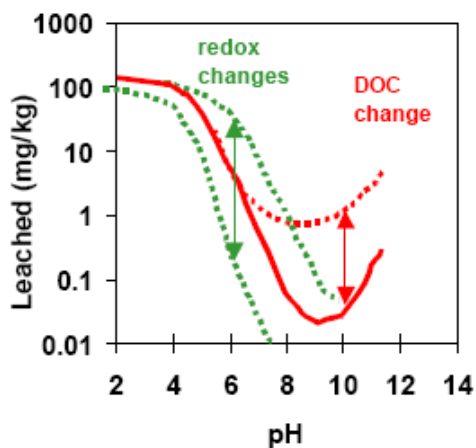
Figure 3.2 Absolute levels for leached DOC and redox depending on pH (Van der Sloot, 2004).

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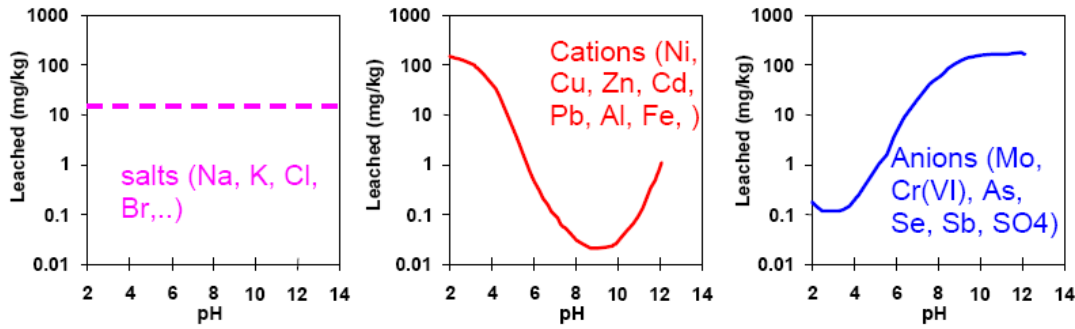
Figure 3.3 General leaching behaviour for three groups of constituents as a function of pH (Van der Sloot, 2004).

A mineral precipitation can form when concentrations of the ions in soil water are sufficient and reverse for dissolution. In Equation 3 an illustrated example;

$$PbCO_3(s) \leftrightarrow Pb2^+ + CO_3^{2-}$$

(3)

The concentration product of lead- and carbonations has to be higher than the ion activity product for these for the formation of $PbCO_3(s)$. (Ecke et al., 2005)

Increased temperature generally leads to faster chemical reactions and even a higher effect of the diffusion transport. If dissolution is endothermic increased temperature leads to higher solubility. Different reactions vary with time. Dissolution of minerals and diffusion are example of slow kinetic reactions. Initially the temperature increase depends on CaO reactions with H_2O. The material or surroundings alter over time. For example, carbonation of alkaline materials changes the precipitation properties for the material. (Van der Sloot, 2004)

3.3.2   Properties of the leached material

When stabilizing soil a material with monolithic properties is obtained. A monolith is a compact material and the permeability is often below 10^{-8} m/s (Egnell et al., 2008). In monolithic and granular material leaching occurs through three mechanisms (Van der Sloot, 1994):

1. *Surface wash-off*
   First flush of the material body. If soluble salt exist on the surface, the surface dissolves quickly and causes a high initial release.
2. *Diffusion*
   The leached amount is dependent on the diffusion of components from the surface to the water phase; the flux depends on the concentration gradient between the surface and the bulk solution. Monolithic material with low porosity can have stagnant water in their pores and if that is the case diffusion is the limiting transport step for advection to occur. Physical erosion (effects of water and frost) has an increasing effect of leaching of the material. Erosion leads to a larger surface area and because of erosion fresh areas are exposed,

9

which leads to a higher concentration gradient and therefore a higher release. Diffusion goes faster for a material with larger exposed surface area per weight unit.

3. *Advection*

    Advection is water percolating through or along the material. Percolation through a material is only possible for a granular material. Particle size determines the distance components have to travel from the centre of the particle to the water phase. Reaction and transport are normally fast for granular material due to the small particle size resulting in more reactive areas per unit area and shorter travel distance.

pH for leaching of a substance depends on pH in the material, surrounding pH and the buffer capacity of the material. Buffer capacity decides how pH changes over time during impact of external factors, e.g. the ability of water to resist acidification (Öman et al., 2000). Materials with a high buffering capacity are generally favouring sorption, thus resulting in a low leaching rate of metal cations.

4   LEACHING TESTS

4.1   INTRODUCTION

A leaching test is used to describe the leaching of contaminants from solid to liquid phase. The test is a way to simulate natural leaching processes. The leaching rate can be accelerated through agitation, modify the chemical conditions (e.g. pH) or increase the liquid to solid ratio, L/S ratio (Aurell et al., 2002). For example L/S 2 means that it is twice as much liquid as mass of dry substance in the sample. Liquid in the solid test sample is removed from the added leachate to achieve the correct L/S ratio, see Equation 4.

$$\frac{L}{S} = \frac{Mass\ of\ leachate}{Mass\ of\ dry\ test\ sample}$$

(4)

By variegate the L/S ratio an estimation of leaching as a function of amount of water that has passed through the material is achieved. L/S 0.1 is used to describe the initial leaching phase and captures the maximum amount of easily soluble contaminants. A percolation of L/S 2 can correspond to up to 20 years of accumulated leaching. L/S 10 is used to describe the leaching in a long term, more than 20 years. Simulation of potential leaching is still a risk, since leaching is dependent on the local hydrology; It depends on the infiltration rate, thickness of the material and dry bulk density and also if the soil is saturated or not. Leaching tests have short contact times between solid material and leachate. Effects of slower kinetic effects are therefore not always seen in laboratory tests.

4.2   LEACHING TEST STANDARDS

European Committee for Standardisation, CEN, develops standardized leaching tests. These are developed for characterization of waste from the beginning and not adjusted for soil applications. The standardization makes it easier to compare results with each other. To simulate several leaching scenarios there are different leaching tests (Aurell et al., 2002). They are developed for different materials and conditions. For monolith material it is recommended to use diffusion tests. This test can determinate whether the leaching is controlled by diffusion or if it is solubility controlled. For leaching under extreme conditions, such as extreme pH, large water amount or full oxidation of the material, availability test can be performed. Test to investigate the buffer capacity of a material is acid neutralisation capacity (ANC) – test. To test the leaching dependency of pH a pH-stat test is recommended. It is important to note that when stabilizing soil, a material with monolithic character is obtained. Also the leaching from it does not have to be dominated by diffusion. Crushing the monolith material into granular material gives more fresh areas and therefore a higher leaching can be expected. In this study two leaching tests for granular material are used. It is the two stage batch test, SS-EN 12457-3, and the up-flow percolation test (column test), prEN 14405, the later is under development as a standard). For both tests de-ionized water is used as leachate. Up-flow percolation test cover more details of leaching (basic characterisation), than two stage batch test, but the later is cheaper and faster to perform (quality controls). If the leached amount between L/S 2 and 10 coincide between the two leaching tests, there is in an economic perspective better to proceed with two stage batch test.

4.3   TWO STAGE BATCH TEST, SS-EN 12457-3

In two stage batch test an L/S ratio of 2 and 10 are obtained. Mainly there are three steps; preparation of test portion, batching and filtration. For preparation the particles for testing need to be less than 4 mm, if this is not the case the sample needs to be reduced in size by crushing. Dry mass of test portion needs to be determined to know the amount of leachate to add in the test bottle. In stage 1, the bottle with test portion and leachate is batched in the end-over-end tumbler, see figure 4.1, for 6 +/- 0.5 hours. In stage 2, the bottle with the same test portion is batched in 18 +/- 0.5 hours. After each stage, the test portion is filtrated and leachate is bundled up. When there are too many small particles centrifugation is needed before filtration. For stage 1 leachate is added in the bottle so that an L/S ratio of 2 is achieved, for stage 2 where an L/S ratio of 8 is achieved, the cumulative L/S ratio for both steps is then L/S 10. The test gives no information about the initial leaching at L/S 0.1.

Figure 4.1, End-over-end tumbler at Swedish University of Agriculture Sciences (SLU), Uppsala.

4.4   UP-FLOW PERCOLATION TEST (COLUMN TEST), PREN 14405

In the up-flow percolation test (column test), prEN 14405, an L/S ratio of 0.1, 2 and 10 are obtained. The test portion (with known dry mass) is packed in a column, see figure 4.2. Particles should be less than 4 mm or 10 mm, if this is not the case the sample needs to be reduced in size by crushing. The size of the column is chosen depending on particle size, 5 cm in diameter for small particles and 10 cm in diameter for larger particles. Before the test starts the column needs to be saturated with the leachate. Leachate is then pumped from the bottom of the column through the material and the leachate is collected at the top at predefined time intervals for each L/S ratio, depending on dry mass of the test portion.
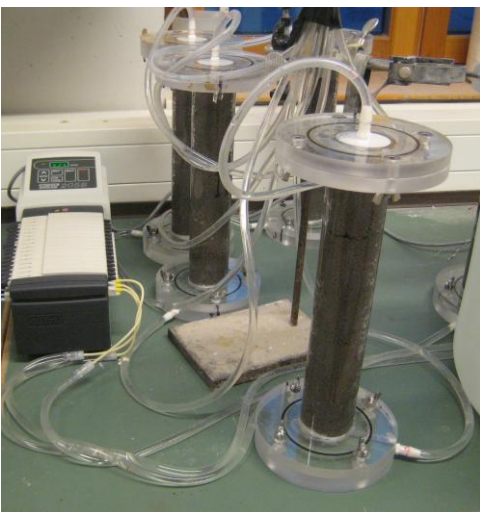

Figure 4.2 Columns with 5 cm in diameter used in up-flow percolation test. To left the flow rate pump.

The process of leaching in a column is supposed to imitate when rain water is filtrating through the soil, but here with a faster rate. The flow rate in the column is expressed in cm/day. A lower flow rate makes it more likely to reach equilibrium and to simulate the natural flow (Aurell et al., 2002).

4.5   LEGISLATION AND GUIDELINE/LIMIT VALUES

Environmental law in Sweden is stipulated to be used for all activities that could impose a risk for the environment. General demands for environment are the same independent of if ashes or other products/materials are used and independent of if the ash is seen as a product or waste. Ashes are normally classified as waste both according to Swedish and European legislation. In Environmental law there is a chapter 9 for fields of activity of using waste for construction purposes. Practically it is a judgement of the contamination level, but it is not obvious how this is done taking different environmental goals into consideration. In this study three different guideline/limit values are used. (Egnell et al., 2008)

For soil stabilization, there are yet no guideline- or limit values set for ash, but there is a referral of criteria's for recycling of waste in construction (Naturvårdsverket, 2007). The referral proposal should be used with caution since the guideline values can change before the final proposal and therefore it is important to also compare with determined limit values, even though these are for another application, namely limit values for landfilling of waste (NFS 2004:10). For both guideline/limit values there are values to compare with for L/S 0.1 and L/S 10. L/S 2 is mainly used for comparison between up-flow percolation test and two-stage batch test. Finally, the total content in fly ash is compared with guideline values for contaminated areas since these are the only guideline values for total content available, there are others but it is still a referral.

4.5.1   Guidelines for recycling of waste in construction

In the referral of guidelines for recycling of waste in construction there are two categories available:
1.   General application (including soil stabilization)
2.   Use on landfills above sealing for non-hazardous and hazardous waste

In this study category 1 is used. It has stricter guideline values than those used in category 2 and also more appropriate for the soil stabilization application.

4.5.2   Limit values for landfilling of waste

For landfilling of waste there are limit values for critical elements (metals), dissolved organic carbon (DOC) and salts in the leachate that has to be fulfilled for the classification of waste as hazardous, non-hazardous or inert waste according to NFS 2004:10 from Naturvårdsverket. In this study limit values for inert waste are used since these are most strict. Also limit values for non-hazardous waste can be discussed for geotechnical applications, even though it is important to remember that waste ordinance is not intended for geotechnical applications of residues (Ecke et al., 2005).

4.5.3 General guideline values for contaminated areas

These guideline values are intended for contaminated areas, also they are for total contents not leached amounts of elements. Background contents mirror the situation before anything is done with the soil and it is not the same as desirable contents. If residues that have values under the guideline values but over the local background content are super induced in a soil area the background content is increased. If this is tolerable have to be decided from case to case dependent on the use of the area. Another argument for why it is not possible to use these guidelines for ash is that the dominating leaching processes for ash are different than for soil, but in geotechnical applications the guideline values can generally be used as a benchmark. (Norman et al., 1996)

4.6   Similar studies

Nordkalk is a company produce and market binding agent for soil stabilization. They have performed tests with lime, cement and ash in soil stabilization with their own ash Terra E, which is an approved product by Vägverket and Banverket. Even if the ash is an approved product they need to fill in a new application for each new usage. In their report "Kalkrik aska som bindemedel i markstabilisering" (Rogbeck et al., 2008), an environmental and geotechnical assessment for fly ash used in soil stabilization are done. They have used different soils than the one used in this study and the ash is as mentioned not the same. Still it is interesting to compare the results from this study with their results since the studies in this area are few. This study used the same leaching tests as this study.

5   LABORATORY STUDY

5.1   INTRODUCTION

Investigation of the environment effect is expensive and time consuming and also implies a risk for the surrounding environment. Therefore it is important to first perform a laboratory study. This study should be well prepared with a test matrix and accurately selected material to test. To facilitate the handling of results it is an advantage to do similar tests as were done earlier or follow standard laboratory instructions. It is also important to include conventional material as a reference.

Laboratory conditions do not reflect natural conditions in a perfect way and it is not always possible to implicate laboratory results in field. For example leaching tests today are carried out using de-ionized water, but lately there are some tests done using $CaCl_2$ as a leachate, which seems to correspond better with the environment in soil. (Aurell et al., 2002)

5.2   INVESTIGATED MATERIAL

In this study one soil and four types of binding agents were used. Lime, cement, fly ash and mechanically activated fly ash were used as binding agents. Background information on materials can be helpful when analysing results.

5.2.1 Soil

The clay soil came from the east coast of Sweden, more precisely from Järva krog in Solna, Stockholm. It was excavated the day before it was sampled and was lying next to the shaft in a pile approximately 1 day; it had been exposed to sun. It had been excavated from a depth of approximately 2 meters and deeper, which is under the dry crust. Undisturbed test specimens were retrieved through pushing down test tubes in the clay pile. The clay soil was shovelled into plastic bags. To avoid evaporation the plastic bags were sealed. The clay soil was brought in 14th October 2008 and was then kept in the plastic bags in a climate room with a temperature of +4 ℃.

5.2.2 Lime

The used lime was burnt lime (CaO) from marble powder, produced by Merck. It was stored in its origin PE bottle of 500g. Several bottles were used.

5.2.3 Cement

The used cement was common construction cement, of type CEM II/42.5 R, produced in Skövde, by Cementa AB. The cement was stored in plastic bottles to restrain the cement from reacting with surrounding air. Chemical composition is shown in Appendix A.

5.2.4 Fly ash

The used fly ash was from a combined heat and power plant. Both electricity and district heating are produced in a pulverized fuel-fired boiler. This kind of boiler can only combust refined biomass fuels like briquettes from peat or grinded wood pellets. The distribution is 80 % of peat briquettes and 20 % of wood pellets. Lime is used to reduce the amount of sulphur and a catalyst is used to reduce the emissions of nitrogen oxide. The particles in the flue gas are removed with textile- and electro filter. Contents of metals in peat ash vary significantly. The chemical composition for the ash used in this study is shown in Appendix B. (Egnell et al., 2008)

5.2.5 Mechanically activated fly ash

The fly ash was treated with mechanical activation. The mechanical activation was performed by EMC in Luleå. At Vattenfall the ash was stored in a closed steel bucket to restrain it from reacting with surrounding air.

5.3 PREPARATION OF TEST SPECIMENS

It is important that all test specimens, see figure 5.2, are prepared, handled and stored in the same way. The preparation was made in accordance with Carlsten (2000). The soil was homogenized in a Hobart mixer, see figure 5.1, for five minutes and the same instrument was used for mixing binding agents with soil. Added amount of binding agents were different for different mixtures. To avoid evaporation, test specimens were sealed with tape and then stored in a temperature of + 7 degrees.

Figure 5.1 The used whisk to the left and the Hobart mixer to the right (Hansson, 2008).
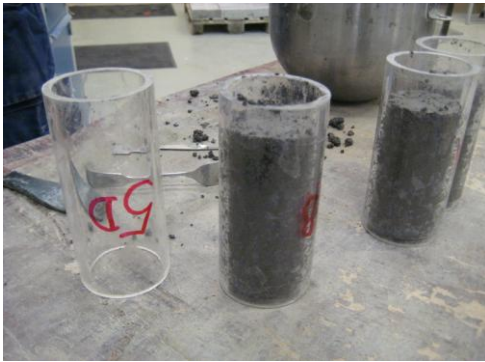
Figure 5.2 Test specimens.

5.4   PERFORMED TESTS

As mentioned in chapter 4.2, a compact material is formed when deep soil stabilization is used. Even though a material has monolithic properties, the leaching from it does not have to be dominated by diffusion. Crushing the monolith material into granular material, as was done in both two stage batch test and up-flow percolation test, gives more reactive sites and therefore a higher leaching was expected. Test specimens formed in this study was crushed and leaching tests on the granular material were performed as a "worst-case scenario". The recipes with more ash in it (in percent of total binding agent amount) are also seen as a "worst-case-scenario". Binding agent amount of approximately 90 kg/m^3 soil is a common amount to use in similar performed studies. The total increase of binding agent amount to 120 kg/m^3 soil is also seen as a "worst-case-scenario", since it is more binding agents than probably necessary for the strength. The mixture with lime and cement was used as a reference. Stabilization with lime and cement is an established method since the 1980s and the method is not an object for environmental tests (Rogbeck et al., 2008). Also leaching tests on unstabilized soil were performed to observe the contribution from the soil itself. Nordkalk (Rogbeck et al., 2008) has performed similar studies with fly ash in soil stabilization and these studies were performed for 7 and 91 days of hardening. A different soil was used in that study, but still it is interesting to compare these results with results

from this study and therefore 7 and 91 days of hardening was used also in this study. The list of mixtures is represented in table 5.1 and the test matrix is showed in table 5.2.

Table 5.1

List of mixtures in performed tests

Mixture	Content
KC 50/50	50 % lime, 50 % cement
KCA 33/33/33	33 % lime, 33% cement, 33 % fly ash
KCAA 33/33/33	33 % lime, 33% cement, 33 % mechanically activated fly ash
KCA 25/25/50	25 % lime, 25 % cement, 50 % fly ash
KCAA 25/25/50	25 % lime, 25 % cement, 50 % fly ash

Table 5.2

Test matrix of performed tests. K is lime, C is cement, A is fly ash and AA is mechanically activated fly ash. Two different recipes are represented, two with equal amount of each binding agent; 50/50 or 33/33/33 and one with increased amount of fly ash; 25/25/50, where 50 % of the binding agent amount is fly ash

	Nr of tests	Duration of hardening [days]	Binding agent amount [kg/m^3 soil]
Soil			
Two-stage batch test	1	-	-
KC 50/50			
Two stage batch test	1	7,91	90
Two stage batch test	1	7,91	120
Up-flow percolation test	1	7	90
KCA 33/33/33			
Two stage batch test	2	7,91	90
Two stage batch test	1	7,91	120
Up-flow percolation test	2	7	90
KCA 25/25/50			
Two-stage batch test	1	7,91	90
KCAA 33/33/33			
Two stage batch test	1	7,91	90
Two stage batch test	1	7,91	120
Up-flow percolation test	1	7	90
KCAA 25/25/50			
Two stage batch test	1	7,91	90

Blank test was performed both on the up-flow percolation test and two stage batch test to determine the contribution from laboratory equipment. For KCA 33/33/33 the double test was performed for verification of the laboratory methods. For a complete list over the mixtures see Appendix C.

An important part of this study was to develop the laboratory methods for leaching tests on the actual materials. The part of the laboratory at Vattenfall R&D AB in Älvkarleby, where the tests favourably should have been performed, was at the moment under construction and not fully operational. Two stage batch tests were mainly performed at Swedish University of Agricultural Sciences (SLU) in Uppsala. Up-flow percolation tests were performed at the concrete laboratory at Vattenfall R&D AB in Älvkarleby, which was not optimal for these tests due to the unclean environment. An external accredited laboratory has performed leaching test on the soil and analyses of leachates.

5.4.1 Tests on soil and binding agents

Dry substance (TS) was measured both on soil and stabilized soil to determine the amount of leachate. To characterize the soil tests were performed to determine the bulk density, yield point, plastic limit, undrained shear strength and sensitivity ratio. Total contents of the fly ash were determined at an accredited laboratory.

5.4.2 Leachate analyses

Metal ions that have limit values for landfilling in Sweden according to NFS 2004:10 (Naturvårdsverket, 1994) were analysed. These are As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se (metal modification) and Zn. DOC and Cl-, F- and SO_4- ions also have limit values for landfilling and effects the presence form of metals and were therefore analysed. For two stage batch test leachate from L/S 2 and 10 were analysed. For up-flow percolation test leachate from L/S 0.1, 2 and 10 are analysed. Since pH is important for the presence form of metals in leachate, pH was measured in every leachate. Electrolytic conductivity was measured as an extra control of leachate analyses.

6   RESULTS

6.1   TOTAL CONTENT OF FLY ASH

The total content of fly ash was compared with guideline values for contaminated soil (Naturvårdsverket, 1997) to give a first hint of which elements that should be observed. Total contents in the ash that exceeded guideline values are marked with grey in table 6.1. Elements that exceeded some of the guideline values were As, Cd and Ni. A list of all analysed elements is shown in appendix G.

Table 6.1

Total content in fly ash compared with guideline values for contaminated soil. MKM is "Less sensitive soil use", MKM G is "Less sensitive soil use with ground water protection" and KM is "Sensitive soil use". Units in the table are [mg/kg TS]

	MKM	MKM G	KM	Ash
As	40	15	15	25,9
Cd	12	1	0,4	0,69
Cr	250	250	120	47
Cu	200	200	100	36,2
Hg	7	5	1	0,418
Ni	200	150	35	46
Pb	300	300	80	22,4
Zn	700	700	350.	74,5

6.2   LEACHING COMPARED TO LIMIT/GUIDELINE VALUES

For the leached amount of all analysed elements in stabilized soil, a complete list is shown in Appendix C. No guideline values for recycling of waste in construction, general application, category 1, (Naturvårdsverket, 1997) or limit values for landfilling as inert waste (NFS 2004:10) were exceeded for any elements in any mixture for 7 days of hardening. The guideline/limit values are shown in Appendix D. Also for 91 days of hardening none of the elements were exceeding any of the guideline/limit values used in this study, except for F. When F was analyzed at the external laboratory, the received leachate was too small for them to analyze all elements and it had to be diluted. The detection limit was increased equal times as dilution was performed. It means that detection limits were increased for 91 days of hardening compared to detection limits for 7 days of hardening, in some cases up to 10 times. That means that it can seems like an element has an increase leaching for 91 days of hardening compared to 7 days of hardening, but in reality it is an effect of the dilution of leachate. This is relevant for elements with values under the detection limit for 91 days of hardening. These elements are especially F and partly SO_4 and DOC.

6.3   COMPARISION BETWEEN LEACHING TESTS

The correlation between two stage batch test and up-flow percolation test was not as good as preferable. This is presented for L/S 2 in figure 6.1 and L/S 10 in figure 6.2.
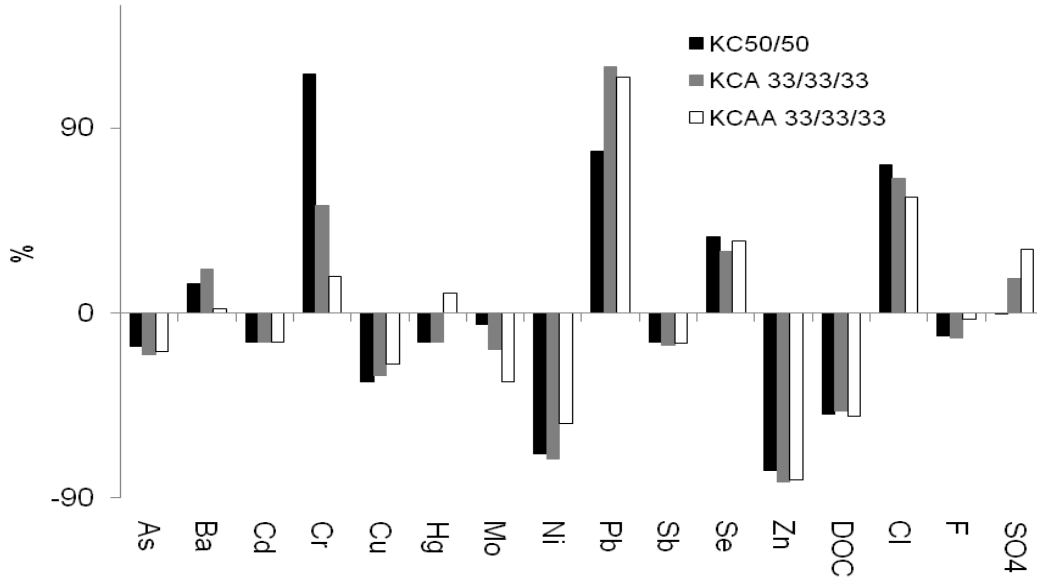
Figure 6.1 Cumulative leaching for L/S 2 of two stage batch test in percent of up-flowpercolation test. 7 days of hardening and binding agent amount is 90 kg/m³ soil.
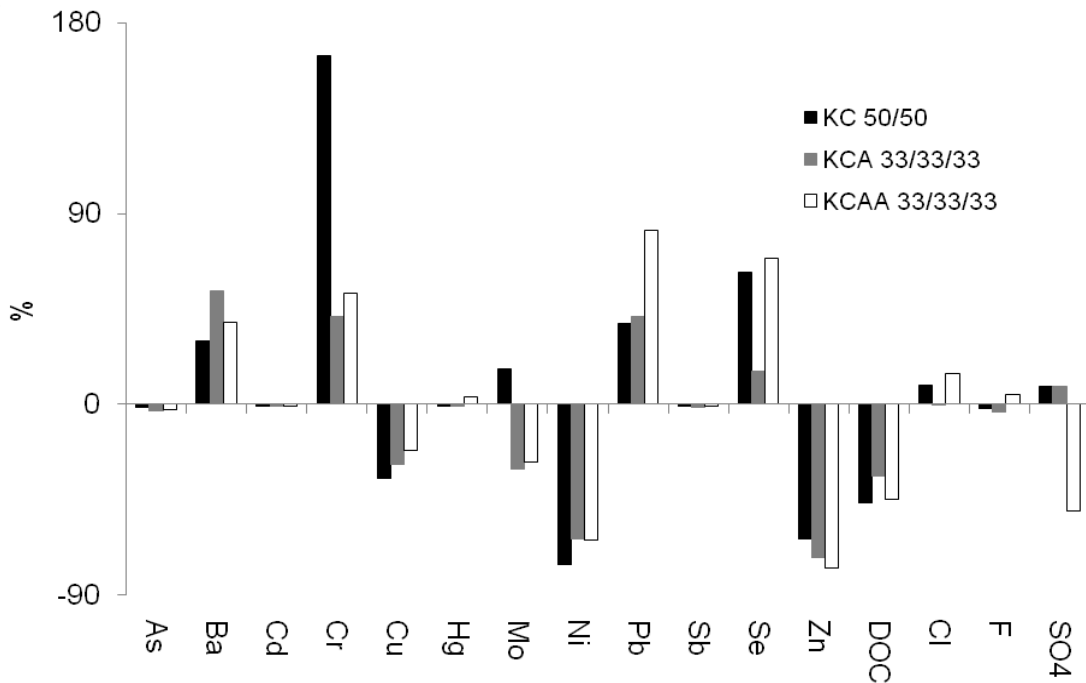
Figure 6.2 Cumulative leaching for L/S 10 of two stage batch test in percent of up-flowpercolation test. 7 days of hardening and binding agent amount is 90 kg/m³ soil.

Another important point is that for some elements the leached amount was increased when fly ash was used, but for some they actually were decreasing when fly ash is added. This and the correlation between the two types of leaching methods are exemplified in figure 6.3 and 6.4. For a complete picture, the cumulative leaching for all mixtures with binding

agent amount 90 kg/m³ soil and 7 days of hardening, since 91 days of hardening was not done for up-flow percolation test, and for all elements that were compared with guideline/limit values are presented in Appendix E. Elements under detection limit for 7 days such as Cd and Hg seemed to have good correlation between the two leaching test methods, but this is because their leached amount was under detection limit.
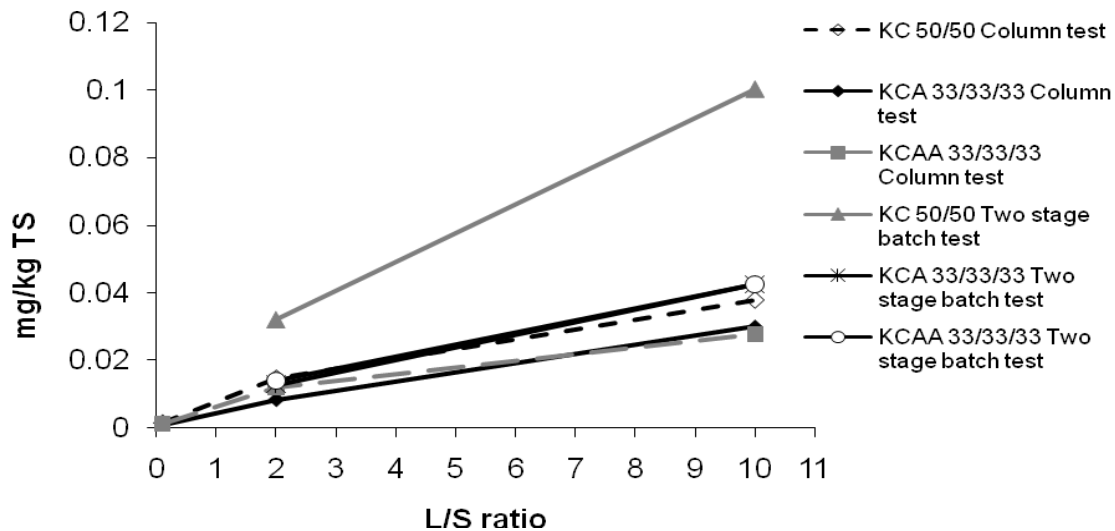
Figure 6.3 The cumulative leaching for Cr, binding agent amount 90 kg/m³ soil and 7 days of hardening.

For Cr there was an increased leached amount when conventional binding agents (lime and cement – KC 50/50) were used compared to when fly ash was added according to figure 6.3. For two stage batch test the lime/cement mixture seemed to deviate, but also for up-flow percolation test there was a pattern that showed increased leaching for Cr with the lime/cement mixture compared to when fly ash was added. Except from the deviating result from two stage batch test for the lime/cement mixture, the correlation between up-flow percolation and two stage batch test was quite good, even if two stage batch test had an increased amount of leached Cr in two stage batch test it was still almost the same slope on the lines in figure 6.3 and that is the most important factor for correlation between the two methods.
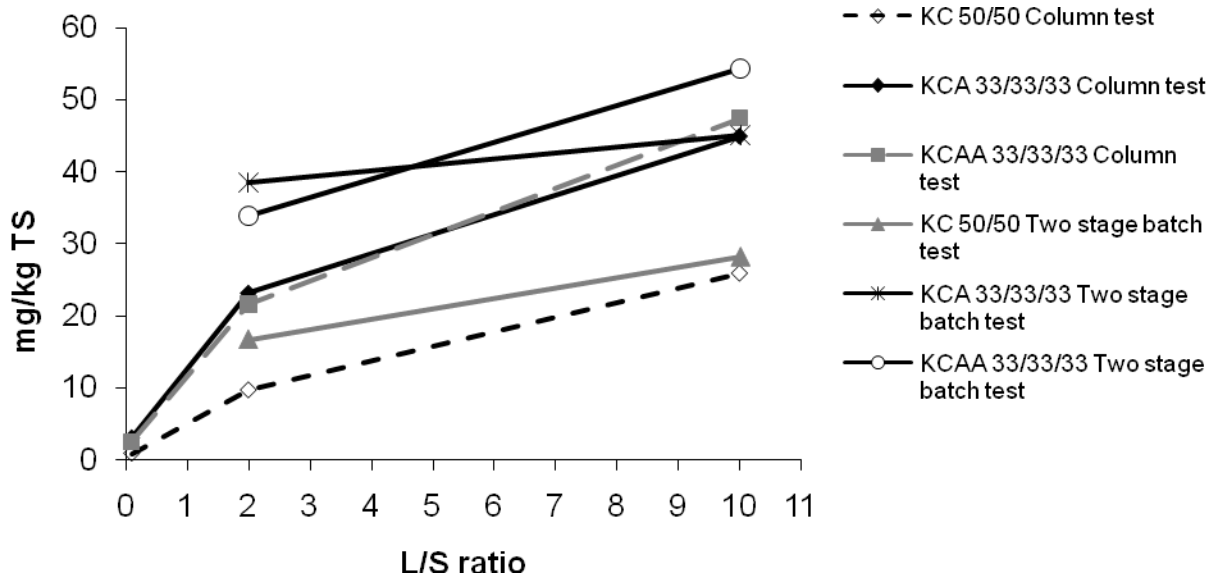
Figure 6.4 The cumulative leaching for Cl, binding agent amount 90 kg/m³ soil and 7 days of hardening.

The amount of leached Cl increases when fly ash is added as binding agent according to figure 6.4. This figure does not show a good correlation between the two leaching test methods, but still for each method there is the same tendency that when fly ash is added there is an increased leaching amount of Cl. The correlation between the two test methods is not good for Cl.

6.4   INFLUENCE OF pH

pH is almost the same in all mixtures with stabilized soil. In figure 6.5 pH is shown for L/S 2 and 7 days of hardening as an example, but regardless which L/S ratio and hardening time, the pH is around 12.5 units.
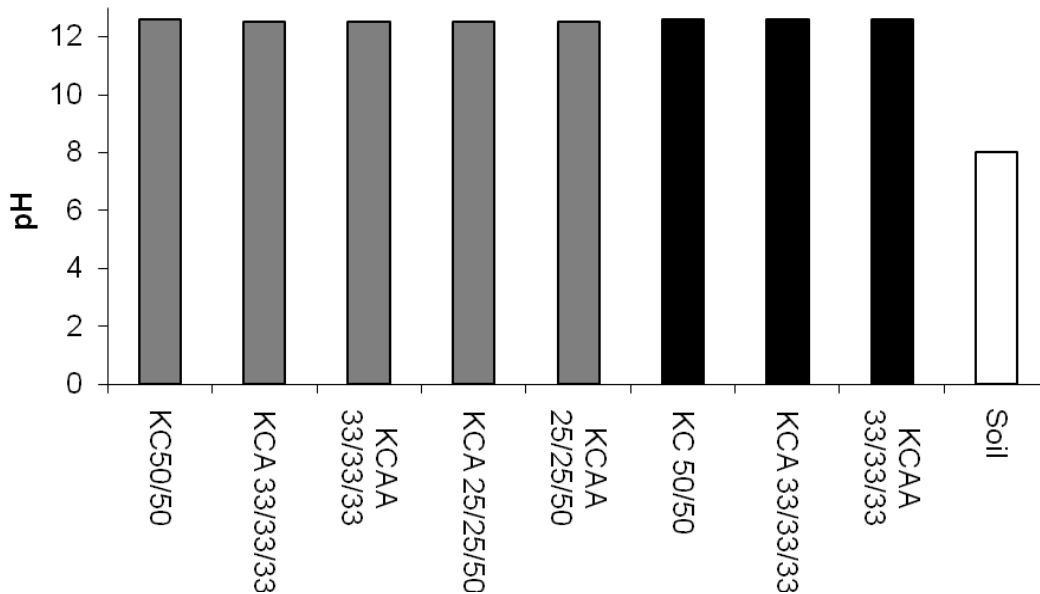
Figure 6.5 pH for L/S 2 in all mixtures. Grey colour represents binding agent amount 90 kg/m³ soil, black colour 120 kg/m³ soil. To the right is pH for the unstabilized soil, marked with white colour. This is for 7 days of hardening.

Since pH is almost the same it is possible to give an indication of which release mechanism that is dominating with help of the cumulative leaching curve, see figure 6.4 above for Cl. If the slope in the cumulative leaching curve has a ratio of 1:1 it is dominated by dissolution of the element. When the slope is decreasing with increasing L/S ratio it is dominated by surface wash-off, this is normally more common for soluble salts as Cl, but this is not the case in figure 6.4 above for Cl. (Van der Sloot, 2004)

6.5   INFLUENCE OF DOC

In chapter 3, it was discussed whether the leached amount of DOC affects the presence form of other elements and also the leaching of DOC is increasing with increased pH. The leached amount of DOC is shown in figure 6.6 for 7 days of hardening, considering no column tests are made for longer hardening time.
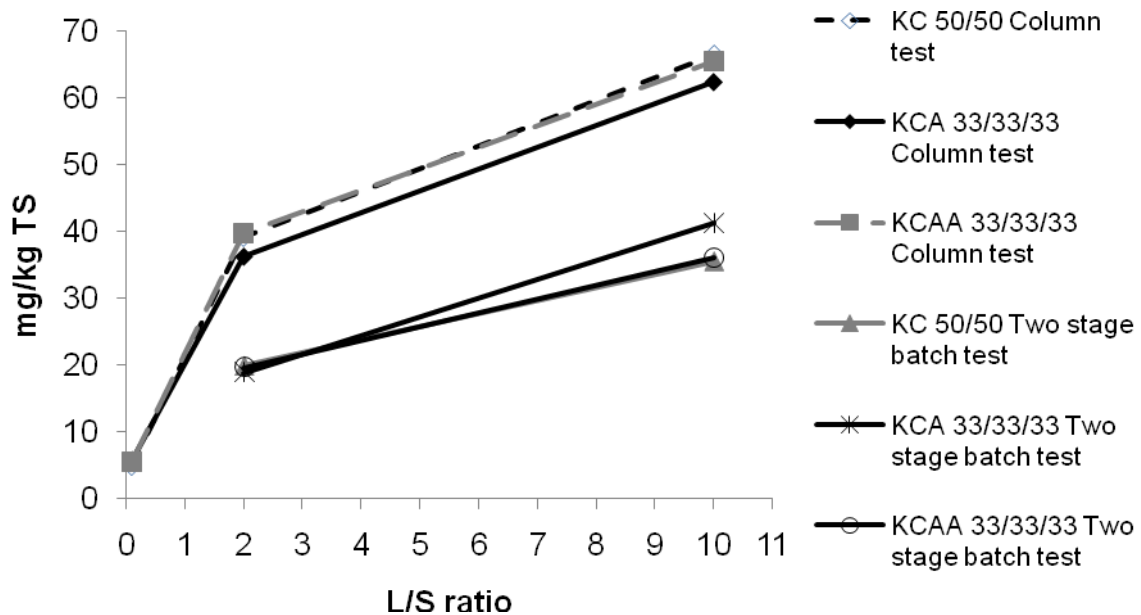
Figure 6.6 Cumulative leached amount of DOC for mixture with lime/cement (KC 50/50), lime/cement/fly ash (KCA 33/33/33) and lime/cement/mechanically activated fly ash (KCAA 33/33/33). The time of hardening is 7 days. Binding agent amount is 90kg/m³ soil.

The most important result in figure 6.6 is that, regardless of which binding agent that is added, the amount of leached DOC is almost the same. In chapter 6.3 it was showed that pH in leachate was almost the same for all mixtures with stabilized soil. Even if increased leaching of DOC occurs due to the increased pH value with stabilized soil compared to unstabilized soil it is regardless which binding agent that are used.

6.6 EFFECTS OF MECHANICAL ACTIVATION ON FLY ASH

To clarify the difference in results between when fly ash is used and mechanically activated fly ash is used, mean value of leaching from all mixtures with mechanically activated fly ash is showed in percent of leaching from mixtures with none activated fly ash in figure 6.7.
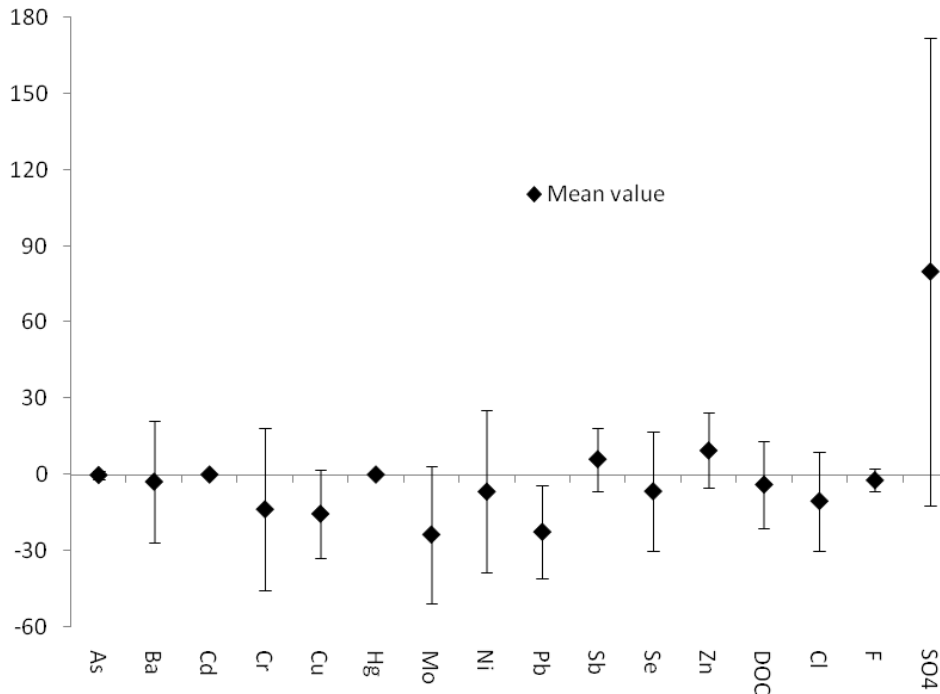
Fig 6.7 Mean value of leached amount for all mixtures with mechanically activated fly ash in percent of leached amount of the same mixtures with fly ash. Standard deviation of mean value from 9 different tests.

Except from SO_4, Sb and Zn mechanical activation actually gives less leaching than mixtures with fly ash when mean value for all mixtures are used.

6.7   EFFECTS OF BINDING AGENT AMOUNT

This part of the study was performed with two stage batch test. Mixtures with a binding agent amount of 120 kg/m^3 soil were compared to mixtures with a binding agent amount of 90 kg/m^3 soil to see if the leached amount of elements is increasing with increased amount of total binding agent. Probably the strength is also increasing with increased binding agent amount, so an increased amount of binding agents does not necessary need to imply an increased leaching since an increase in strength form a more impenetrable material. In fig 6.8, 6.9 and 6.10 this is showed for 7 days and 91 days of hardening. None of the leached amount of elements was exceeding guideline/limit values used in this study. F is not included for 91 days since this element was under the detection limit for analysis.
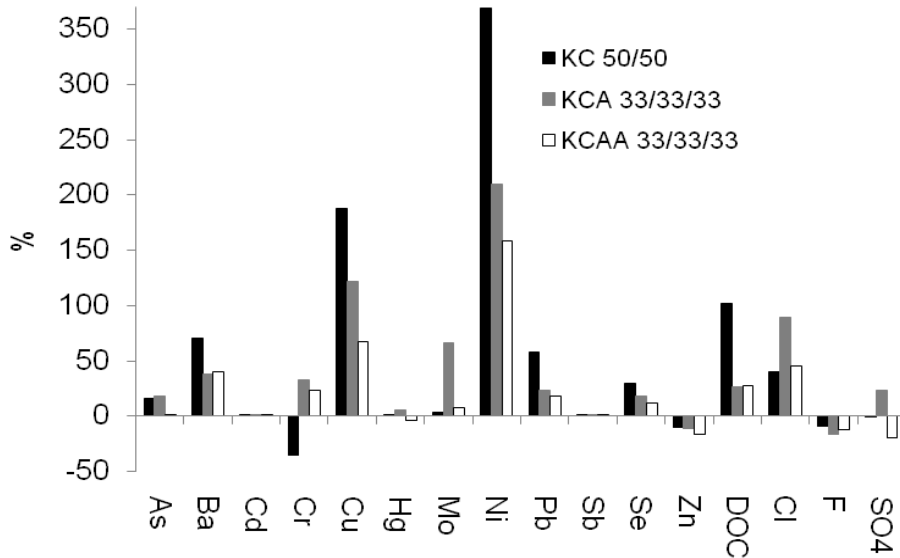
Figure 6.8 Mixtures with lime/cement (KC 50/50), lime/cement/fly ash (KCA 33/33/33) and lime/cement/mechanically activated fly ash (KCAA 33/33/33). Cumulative leached amount for L/S 10 and mixtures with binding agent amount 120kg/m^3 soil in percent of cumulative leached amount of the same mixtures with binding agent amount 90 kg/m^3 soil. Hardening time is 7 days. Two stage batch test.
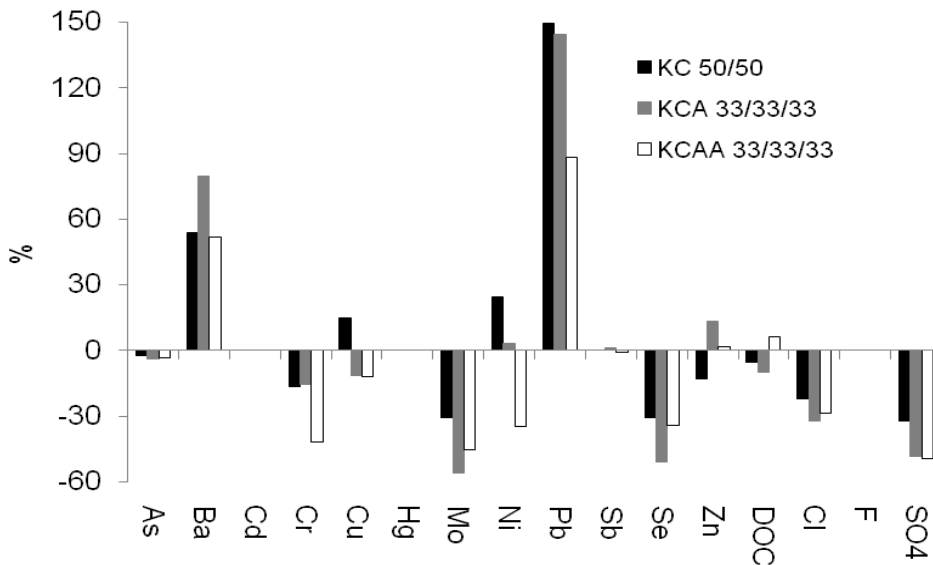
Figure 6.9 Mixtures with lime/cement (KC 50/50), lime/cement/fly ash (KCA 33/33/33) and lime/cement/mechanically activated fly ash (KCAA 33/33/33). Cumulative leached amount for L/S 10 and mixtures with binding agent amount 120kg/m^3 soil in percent of cumulative leached amount of the same mixtures with binding agent amount 90 kg/m^3 soil. Hardening time is 91 days. Two stage batch test.

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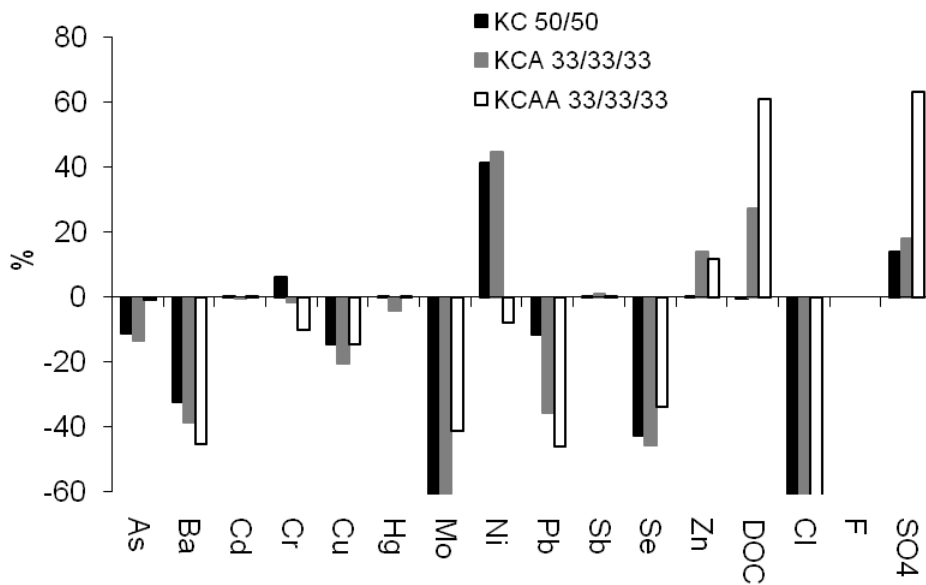
Figure 6.10 Mixtures with lime/cement (KC 50/50), lime/cement/fly ash (KCA 33/33/33) and lime/cement/mechanically activated fly ash (KCAA 33/33/33). Cumulative leached amount for L/S 10 and mixtures with binding agent amount 120kg/m^3 soil in percent of cumulative leached amount of the same mixtures with 7 days of hardening. Two stage batch test.

For 7 days of hardening especially Ni and Cu have a larger leaching, but also Cl, DOC, Ba and Pb. Except for Cl the leached amount is higher for the mixture with lime and cement only (KC 50/50) compared to mixtures with fly ash. Interesting to notice that for Cl, the leached amount is increased for the mixture with fly ash (KCA 33/33/33) compared to the mixture with mechanically activated fly ash (KCAA 33/33/33). In 91 days of hardening the leached amount of elements are almost all decreasing, exception is for Ni, DOC, SO$_4$ and Zn, compared to 7 days of hardening. DOC and SO$_4$ are especially increasing for KCAA 33/33/33, while Ni is decreasing for the same mixture. Zn is increasing for both mixtures with fly ash.

6.8   DIFFERENT RECIPES

This part of the study was performed with two stage batch test. Mixtures with fly ash were compared to the reference mixture with lime and cement only (KC 50/50) in figure 6.11 and 6.12. None of the values for leached amounts were exceeding any of the guideline/limit values used in this study. Several of the elements have values under detection limit for the leachate analysis. It is As, Cd, Hg, Sb, and partly F and Zn. There are some deviations that are hard to confirm without repeating tests, for example the increased leached amount of SO$_4$ in KCAA 25/25/50 for 91 days of hardening and DOC for the same mixture but in 7 days of hardening. An increased leaching of Ni and F is apparent when more fly ash is added compared to reference mixture, mixtures with less fly ash and for 7 days of

hardening. In 91 days of hardening the leached amount of Ni is decreasing in all mixtures with fly ash compared to reference mixture for 91 days hardening, for F no conclusions can be drawn since values of leached amount are under the detection limit for leachate analysis. Leached amount of Cl is obvious increasing more with more fly ash in the mixture; this is obvious both for 7 days of hardening and 91 days of hardening. The most interesting with Cl is that when more mechanically activated fly ash is used (KCAA 25/25/50) the leached amount of Cl is decreasing compared to the mixture with less mechanically activated fly ash (KCAA 33/33/33), for both hardening times. For none activated fly ash the relationship turn out to be the opposite, more fly ash in the mixture (KCA 25/25/50) gives more leaching compared to less fly ash (KCA 33/33/33).
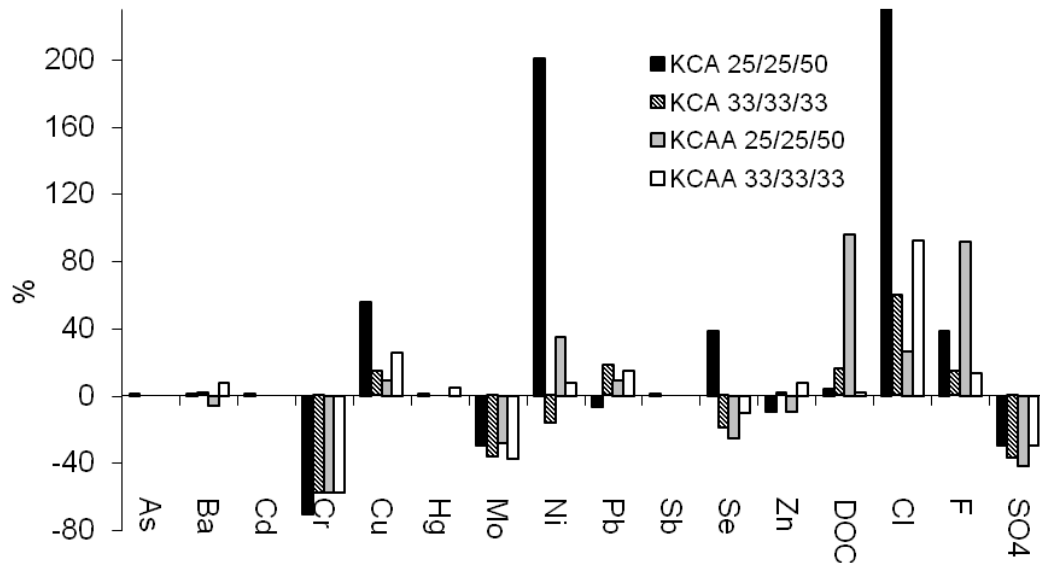
Figure 6.11 The leached amounts for different mixtures of fly ash for L/S 10 in percent of reference mixture KC 50/50. Binding agent amount is 90 kg/m³ soil and hardening time is 7 days. Two stage batch test.

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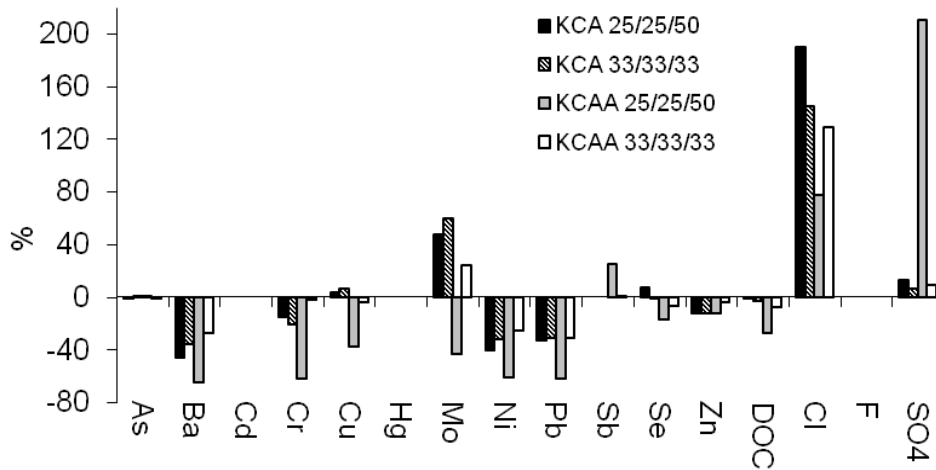
Figure 6.12 The leached amounts for different mixtures of fly ash for L/S 10 in percent of reference mixture KC 50/50. Binding agent amount is 90kg/m³ soil and hardening time is 91 days. Two stage batch test.
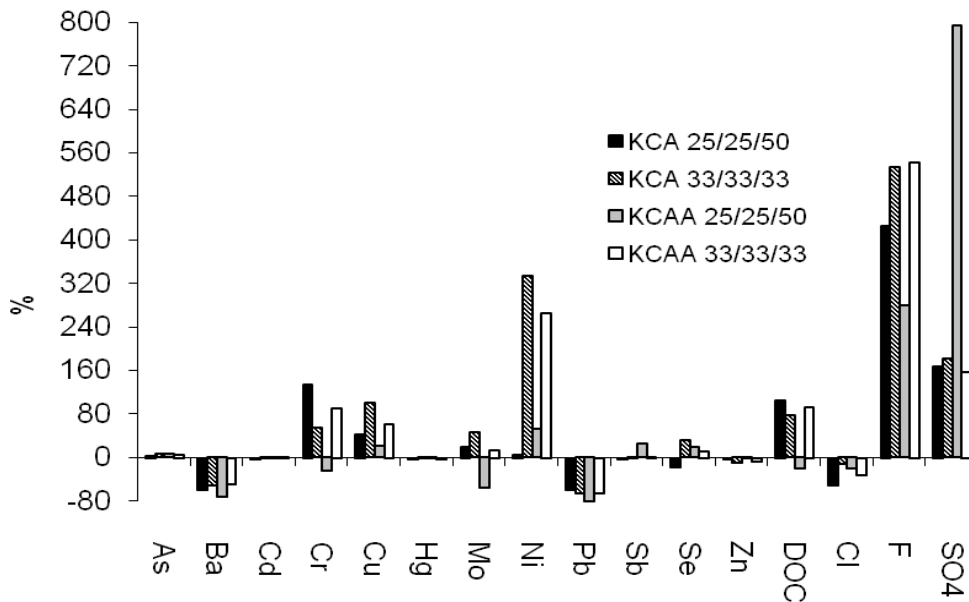
Figure 6.13 The leached amounts for different mixtures of fly ash for L/S 10 and 91 days of hardening in percent of leached amounts for the same mixtures and 7 days of hardening. Binding agent amount is 90kg/m³ soil. Two stage batch test.

In figure 6.13, leached amounts for 91 days of hardening are presented in percent of 7 days hardening. SO_4 and DOC is leaching more in 91 days of hardening for all mixtures, but DOC is leaching less compared to reference mixture for 91 days of hardening. This is also the tendency for Cr and Cu.

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6.9   REPEATABILITY AND BLANK TESTS

To test the two different leaching methods for repeatability two tests each were done for KCA 33/33/33, both for up-flow percolation test and for two stage batch test. The ratio between the two tests is shown in table 6.2 and 6.3.

Table 6.2

Test 1 and 2 for KCA 33/33/33 in two stage batch test, binding agent amount 90 kg/m³ soil and 7 days of hardening. Those values exceeding 40 % in difference between the two repeating tests are marked with grey. The unit is in [mg/kg TS]

ELEMENT	L/S 2		L/S 10		Ratio [%]	
	1	2	1	2	L/S 2	L/S 10
As	0.0023	0.0023	0.0099	0.0099	0.00	0.00
Ba	0.2781	0.2736	0.7433	0.6743	1.65	10.24
Cd	0.0001	0.0001	0.0005	0.0005	0.00	0.00
Cr	0.0116	0.0142	0.0440	0.0411	17.89	6.91
Cu	0.0748	0.0746	0.1534	0.1425	0.30	7.60
Hg	0.0000	0.0000	0.0002	0.0002	0.00	0.00
Mo	0.0225	0.0233	0.0711	0.0669	3.30	6.24
Ni	0.0021	0.0055	0.0066	0.0083	61.76	20.63
Pb	0.0050	0.0057	0.0171	0.0170	11.86	0.84
Sb	0.0002	0.0002	0.0010	0.0010	0.00	0.00
Se	0.0010	0.0011	0.0034	0.0029	5.59	18.79
Zn	0.0045	0.0118	0.0198	0.0253	61.61	21.69
DOC	19.6707	18.0880	36.1975	46.4808	8.75	22.12
Cl	38.4370	38.4370	56.1307	33.9901	0.00	65.14
F	0.4748	0.5200	1.8351	1.9513	8.70	5.95
SO4	2.7132	1.8540	8.8582	7.6344	46.34	16.03

According to table 6.2 there are differences between the two tests and some of them (marked with grey) are over 40%.

Table 6.3

Test 1 and 2 for KCA 33/33/33 in up-flow percolation test. Those values exceeding 40 % in difference between the two repeating tests are marked with grey. The unit is [mg/kg TS]

	L/S 0,1		L/S 2		L/S 10		Ratio [%]		
Element	**1**	**2**	**1**	**2**	**1**	**2**	**L/S 0,1**	**L/S 2**	**L/S 10**
As	0.0004	0.0004	0.0028	0.0029	0.0102	0.0102	7.25	1.05	0.29
Ba	0.0322	0.0324	0.2171	0.2369	0.4628	0.4604	0.62	8.34	0.52
Cd	0.0000	0.0000	0.0001	0.0001	0.0005	0.0005	0.00	0.00	0.00
Cr	0.0010	0.0012	0.0086	0.0083	0.0332	0.0269	17.17	3.33	23.23
Cu	0.0137	0.0153	0.1012	0.1133	0.1963	0.2180	10.33	10.67	9.94
Hg	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.00	0.00	0.00
Mo	0.0027	0.0032	0.0291	0.0267	0.1095	0.0899	15.01	9.10	21.82
Ni	0.0020	0.0025	0.0136	0.0130	0.0216	0.0192	17.05	4.48	12.52
Pb	0.0002	0.0001	0.0026	0.0023	0.0153	0.0087	39.19	12.39	75.90
Sb	0.0000	0.0000	0.0003	0.0003	0.0010	0.0010	11.02	1.12	0.20
Se	0.0001	0.0001	0.0007	0.0008	0.0029	0.0025	37.91	13.32	14.59
Zn	0.0531	0.0195	0.0640	0.0274	0.1205	0.0421	172.55	133.92	186.13
DOC	5.3943	6.1934	37.1588	35.5145	64.4509	60.5937	12.90	4.63	6.37
Cl	2.7970	3.5962	21.3670	25.0983	42.7581	47.2270	22.22	14.87	9.46
F	0.0819	0.0999	0.6439	0.4908	2.1929	1.7448	18.00	31.18	25.68
SO4	0.1958	0.2198	1.7840	2.1256	8.6439	6.5514	10.91	16.07	31.94

For up-flow percolation test Zn is the element that deviated most between test 1 and 2 and when blank test for up-flow percolation test are investigated it is showed that Zn is an element that has the most contribution from the laboratory procedures, see table 6.4.

Table 6.4

Blank test for column test and two stage batch test to show the contribution from the laboratory procedures, no test portion is added, only de-ionized water

Element	Unit	Column test	Batch test
As	µg/l	<1	<1
Ba	µg/l	5.53	1.94
Cd	µg/l	<0.05	<0.05
Cr	µg/l	<0.5	<0.5
Cu	µg/l	1.28	2.33
Hg	µg/l	<0.02	<0.02
Mo	µg/l	<0.5	<0.5
Ni	µg/l	<0.5	0.587
Pb	µg/l	<0.2	<0.2
Sb	µg/l	0.717	<0.1
Se	µg/l	<0.02	<0.02
Zn	µg/l	67.5	3.93
DOC	mg/l	12	2.6
F	mg/l	<0.15	<0.60
SO4	mg/l	<0.50	<0.15
Cl	mg/l	0.89	<0.50

The difference in conductivity between the two column tests confirms that it is not strange that the amount of ions in the solution is varying between the two tests for column test. For two stage batch test it is a good correlation between the two tests, so no explanation to difference in leaching between the two batch tests can be found in conductivity measurements. The conductivity is showed in figure 6.14. Conductivity for all mixtures are seen in Appendix C.
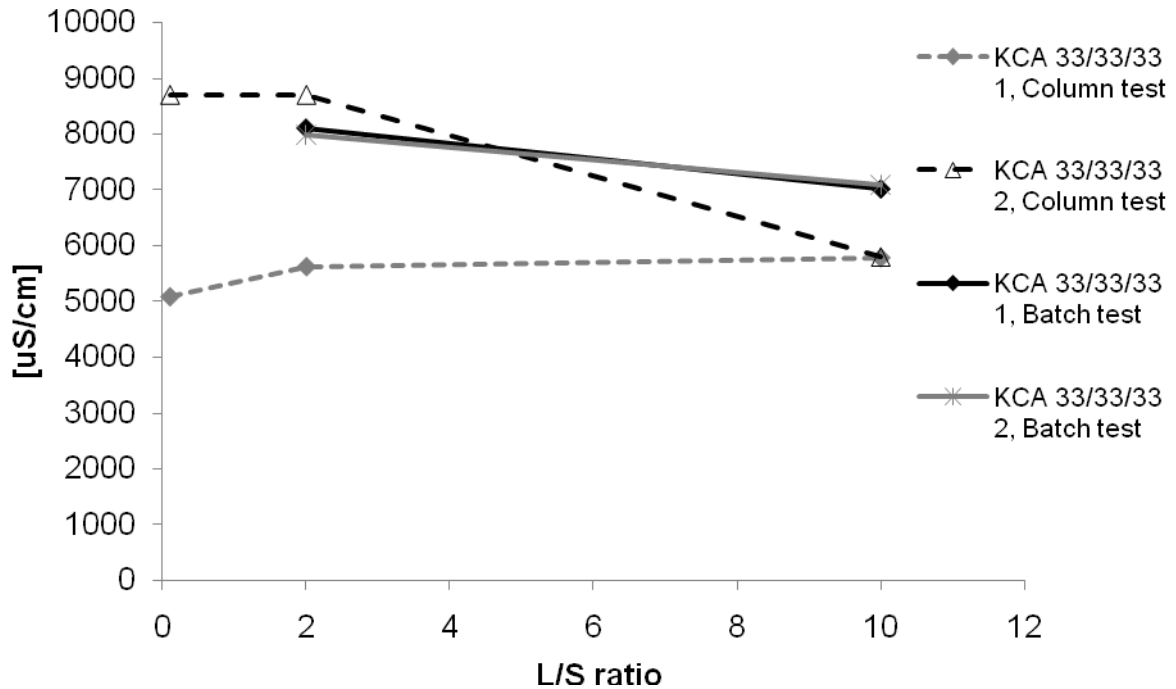
Figure 6.14 Conductivity for up-flow percolation test (column test) and two stage batch test for 7 days of hardening and binding agent amount of 90 kg/m³ soil and mixture KCA 33/33/33. Number 1 and 2 refer to the double test made in each leaching test method.

Except from Cu and Ni the contribution from laboratory equipment seems to be increased for up-flow percolation test compared to two stage batch test, since the leachate analysis is the same for the two type of leaching tests.

6.10 INFLUENCE OF STABILIZATION OF THE SOIL

Leached amount of elements from the soil is compared with stabilized soil. Physical properties of the soil are showed in Appendix F. It is the results from the two stage batch tests since this is the performed test on soil that is showed in figure 6.15, 6.16, 6.17 and 6.19.
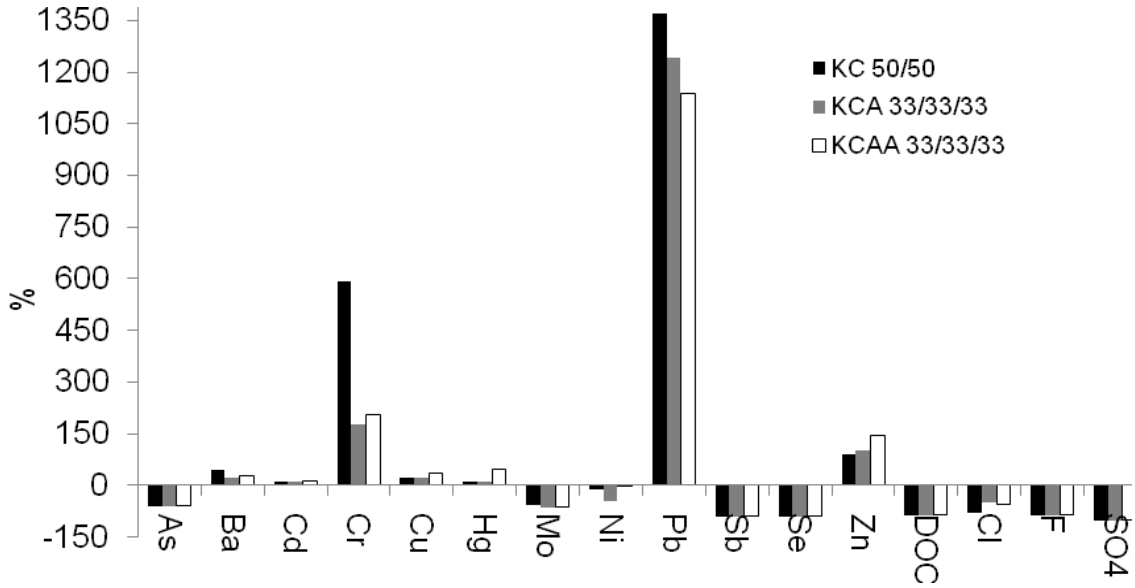
Figure 6.15 Leached amounts of elements in stabilized soil for L/S 2 in percent of leached amounts from unstabilized soil. For 7 days of hardening and with two stage batch test. Binding agent amount is 90 kg/m³ soil.
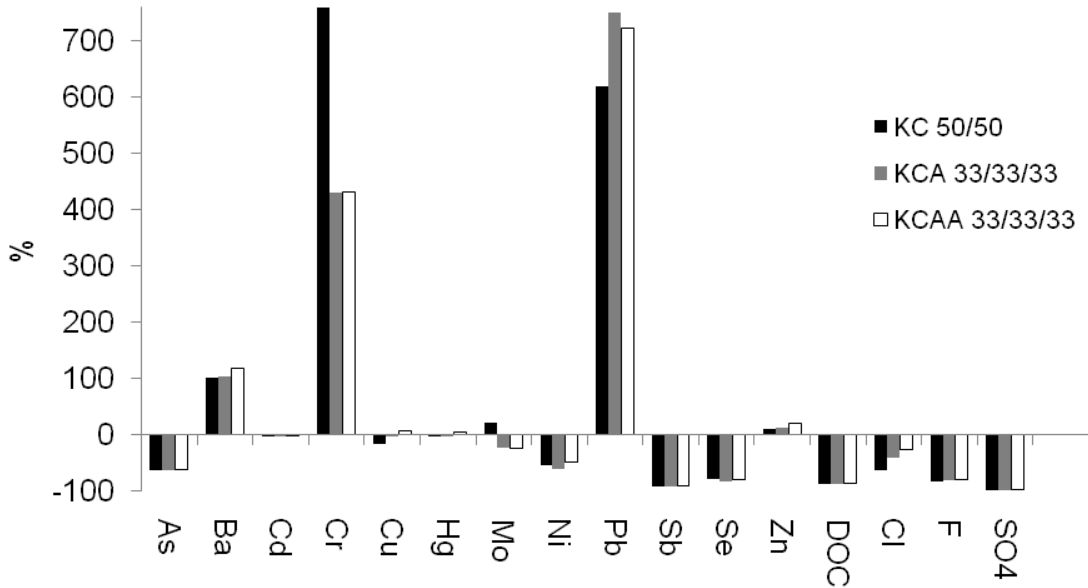
Figure 6.16 Leached amounts of elements in stabilized soil for L/S 10 in percent of leached amounts from unstabilized soil. For 7 days of hardening and with two stage batch test. Binding agent amount is 90 kg/m³ soil.

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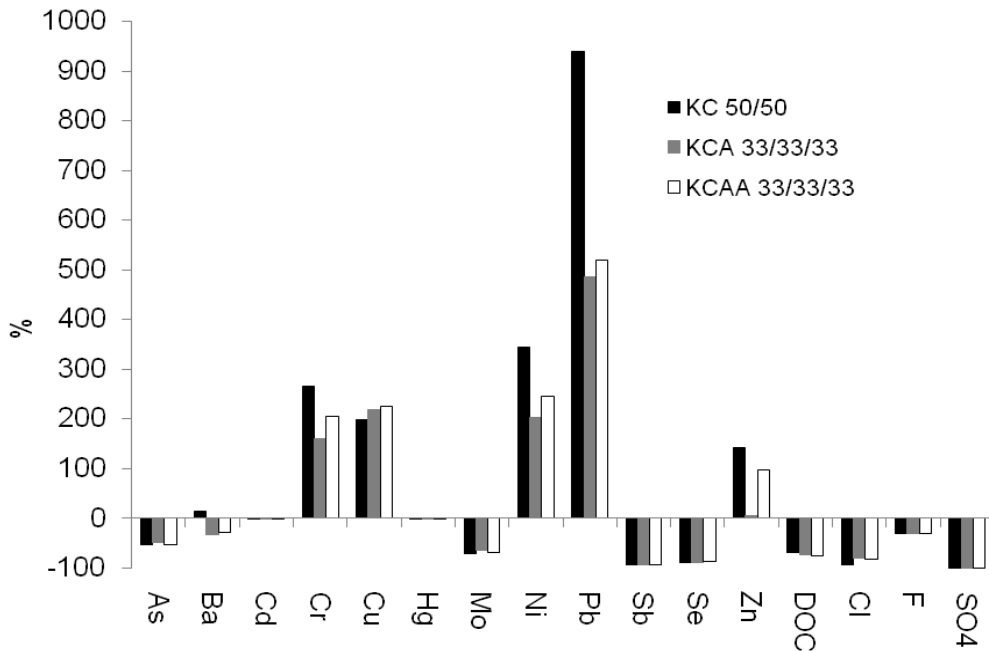
Figure 6.17 Leached amounts of elements in stabilized soil for L/S 2 in percent of leached amounts from unstabilized soil. For 91 days of hardening and with two stage batch test. Binding agent amount is 90 kg/m³ soil.
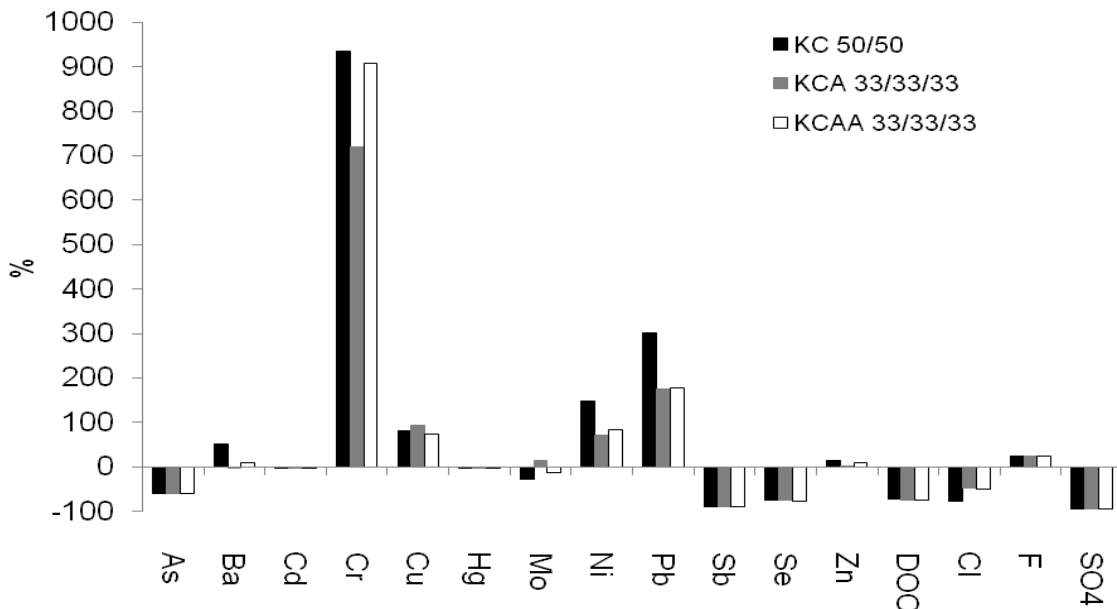
Figure 6.18 Leached amounts of elements in stabilized soil for L/S 10 in percent of leached amounts from unstabilized soil. For 91 days of hardening and with two stage batch test. Binding agent amount is 90 kg/m³ soil.

7   DISCUSSION

7.1   DISCUSSION OF RESULTS

In the fly ash used in this study total content of Ni was high compared to total contents for contaminated soils, also As and Cd. Increased leaching of Ni was observed in some mixtures for soil stabilization, but As and Cd was in the majority of the mixtures under detection limit for analysis. So total contents of fly ash itself does not seemed to be determinant.

Neither limit values for landfilling as inert waste according to NFS 2004:10 nor guideline values for recycling of waste in construction buildings, general application, were exceeded for any of the mixtures or any of the hardening times. Some of the elements, as F in 91 days of hardening, were under detection limit and were therefore hard to analyse. In the study performed by Nordkalk (Rogbeck et al., 2008) some elements were exceeding limit values in NFS 2004:10. Cr was exceeding it with 3.7 times for L/S 0.1 and the mixture with lime, cement and fly ash. It was exceeding the same limit values 2 times for the mixture with only lime and cement and L/S 0.1. In this study Cr was as mentioned not exceeding limit values at all, but the leaching was higher for the mixture with lime and cement and not the mixture with fly ash in it.

In the comparison between the two leaching test methods, the results did not agree perfect at all. This is not typical for this study; Nordkalk (Rogbeck et al., 2008) had also a problem with this. Both for L/S 2 and 10 there were doubts for the correlation between the two leaching methods for a majority of the elements. Also Cr, Pb and Cl leached more in two stage batch test than in up-flow percolation test both for L/S 2 and 10 and for the majority of the mixtures. While Zn, Cu, Ni and DOC leached less in two stage batch test than in up-flow percolation test for both L/S 2 and 10 and for the majority of the mixtures. For a majority of the elements with 7 days of hardening, the accumulated leaching was increasing with increased L/S ratio, for Nordkalk it was the opposite for their mixtures.

Stabilizing soil changes pH in the soil. In this study pH was around 12.5 for all mixtures regardless of hardening time. However, in field pH in the material is affected by surrounding soil, which normally has a lower pH. In this study the pH of the soil was 8. Therefore it is important to investigate the buffer capacity of the material, this is preferably done with an ANC-test. When leaching from an alkaline material occurs pH normally sinks as the material is washed out. So in step two, L/S 2-10, a lower pH should be expected than in step 1, L/S 0-2. In this study this was not the case and an explanation can be that only the surface of the particles has been exposed and most of the material is unchanged. The difference in pH between the soil and other mixtures was probably the main reason for the difference in the results from the mixtures, and not the materials itself. A pH-static experiment should have been performed to determine the leaching dependent on different materials without influence of pH (Håkansson, 2003). Dissolved humus substances are, as mentioned in chapter 3, increasing with increased pH. Even if that is the case, the leaching of DOC was not changing for the different mixtures, at least not for 7 days of hardening. These are interesting aspects.

For the majority of elements, in all mixtures and for both hardening times, leaching was less when mechanically activated fly ash was used in the mixtures compared to when untreated fly ash was used. This was not expected. The exception was SO_4, that increased a lot, but also the standard deviation for SO_4 was particularly high. The standard deviation was also quite high for other elements and therefore more test should be performed to confirm this first positive results.

When increasing the binding agent amount the leaching of 7 days of hardening and 91 days of hardening was different for L/S 10. For 7 days of hardening the majority of elements have an increased leaching for all mixtures with a total increased amount of binding agent. Especially Cu, Ni, DOC, Cl and Pb increased when 7 days of hardening. Except from Cl, the leaching was increasing most for the mixture with lime and cement only. For the leaching of Cl it was the mixture with lime, cement and fly ash that increased most. For 91 days of hardening the leaching was decreasing for most of the elements with a total increased amount of binding agent. However, leaching of Pb and Ba were increasing for 91 days of hardening. Probably the strength was better for 91 days of hardening and therefore the material had been more impermeable. This can be a reason to why less leaching was achieved for most of the elements compared to 7 days of hardening,

With an increased amount of fly ash in the mixture, Ni and F were increasing for 7 days of hardening. Since the total content of fly ash in Ni itself was higher than other elements, this was not a strange result. F is something that should be further observed, it is hard to say more about it without detected values from analysis for 91 days of hardening. SO_4 should also be further observed. It was leaching more for 91 days of hardening than for 7 days of hardening and also more than its reference mixture for 91 days of hardening. Plus it was the deviated value for mixture KCAA 25/25/50 when 91 days of hardening for SO_4. Finally was leached amount of Cl really decreasing with more mechanically activated fly ash, this is an interesting aspect to confirm.

The double test for KCA 33/33/33, both in two stage batch test and up-flow percolation test, indicated that the test in itself can give very different results and therefore repeating test would be to prefer. If more tests were performed, at least three of each, a statistical judgement would be appropriate for every mixture and element, e.i. standard deviation. Repeating the tests several times probably should decrease the deviation numbers.

Leaching from the majority of elements were decreased in stabilized soil compared to the unstabilized soil for all mixtures regardless hardening time. These elements were probably bounded in compounds when binding agents were added to soil. However, for some elements leaching amount increased when the soil was stabilized, for example Cr, Pb and Zn for both of the hardening times and Ni and Cu also for 91 days of hardening time. For Nordkalk the result was the opposite; Stabilization of the soil gave increased amounts of leaching for a majority of the elements compared to leaching of unstabilized soil or ash only. Type of soil and ash has probably significant influence on this. The study from Nordkalk shows that there is a great difference in leaching when stabilizing soil from the west coast and the east coast of Sweden, considering the contents in soil. Tests on different soils should be preferable.

7.2 SOURCE OF ERRORS

There are deviations made from the standard leaching tests in this study. Beside deviations mentioned in 6.10.1 and 6.10.2 there are uncertainties in measurements done by external laboratory, both on elements and pH as well as conductivity.

7.2.1 Deviations from two stage batch test, standard SS-EN 12457-3

Following deviations was made from the two stage batch test;

Following deviations was made from the two stage batch test;

1. Dry mass of test portion was 7,9 g (mean value) more than allowed according to standard, this was compensated with more leachate.

2. Before filtrating centrifugation was needed and at SLU, where two stage batch tests were performed, the only bottles that matched in the centrifugation machine was a bottle with the volume of 1 L. According to standard, the bottle volume should be 0.5 L in first step and 2 L in second step to avoid air space in bottle. Consequences of this were that in the first step it was more air space than necessary. In the second step the test portion had to be halved and even the leachate for receiving the correct L/S ratio. After the first filtration the test portion was halved with a spoon by hand. It is hard to say how this affected the results since no tests were made without this action.

3. The end-over-end tumbler at SLU was faster than standard recommendations. According to standard the rate should be 5-10 rpm, but at SLU the rate was approximately 60 rpm. This was compensated by a shorter batch time, namely 4 hours in the first step instead of 6 +/- 0.5 hours. The second step was only shorted with half an hour. According to people in field the consequence of this should not be a problem for the results.

4. Added leachate was in some of the bottles miscounted by a misunderstanding of standard. In the results measured L/S ratio 2 actually was L/S 2.3 (mean value). L/S 10 was correct. Limit values used were L/S 2, if limit values were available for L/S 2.3 it probably should have been higher than for L/S 2 due to the longer leaching time; therefore this should not be a problem when handling the results.

7.2.2 Deviations from up-flow percolation test, prEN14405

The following deviations were made from the up-flow percolation test;

1. During test, the de-ionized water to the pump was ending during the weekend and it is hard to say how long time the columns were standing without water refilling. 24 hours were approximately removed from the test period when L/S ratios were calculated. Wires to the columns were lying on different levels in the can for water refilling and therefore the water can have ended at different times for different columns, but this is also hard to estimate.

2. Dry mass of test portion was approximately decided after the beginning of the tests.

3. After the test begun, the columns were leaching and columns had to be turned up-side down for repairing. This made voids in the test portions and the leaching can have been effected.

4. The above factors resulted in more than allowed deviations of L/S ratios according to standard. L/S 0.1 in results was calculated to L/S 0.2. L/S 2 was calculated to L/S 2.44 and L/S 10 was correct. How this affected the comparison with guideline/limit values for L/S 0.1, L/S 2 and L/S 10 it is hard to say, but more would probably leach than with the correct L/S ratio since more leachate was in contact with the solid material. If equilibrium was reached, the longer leaching time did not have any effect.

8   CONCLUSIONS & RECOMMENDATIONS

8.1   CONCLUSIONS OF THE STUDY

Leaching properties between mixtures with lime and cement only and mixtures where fly ash is added are not distinct. Some element leaches more for mixture with lime and cement only, for example Cr. For other elements the scenario is reversed; elements leach more for mixtures where fly ash is added, for example Cl. If there is an obvious increased risk for the surrounding environment when fly ash is used in soil stabilization compared to when conventional binding agents only are used is hard to estimate from the result in this study.

Mechanically activated fly ash does not have larger amounts of leached elements than untreated fly ash, which is unexpected due to treatment of the fly ash. This is for a majority of elements when a mean value was determined for all mixtures with mechanical activated fly ash in. Still the standard deviation is quite big so more tests are preferable. Still a conclusion from the results in this study is that mechanically activated fly ash used in soil stabilization compared to untreated fly ash does not seem to increase the risk on surrounding environment.

Different type of leaching methods, in this case two stage batch test and up-flow percolation test gave different results of leaching. In this study especially Cr, Pb and Cl leached more when two stage batch test were used, but for a majority of elements the leaching of elements were increased in up-flow percolation test. A conclusion could be that up-flow percolation tests overestimate the leached amount of elements in this study.

A longer hardening time gave mainly a decrease in leaching for all elements and mixtures, except for leaching of Pb, Ba and SO_4. Leaching in a long perspective does not seem to be a problem for the surrounding environment according to these primary results, for a majority of the elements.

In addition to this there is the effect of the soil itself. In this study leaching test on unstabilized soil gave more leaching of a majority of elements. Elements with an increased leaching when the soil was stabilized were Cr, Pb, Zn, Ni and Cu. Of those there is more leaching from the mixture with lime and cement only, except for Cu, Zn and Pb. These had more leaching when fly ash was added to the mixture. Type of soil used in the study is determinant for the leaching of elements.

From the results in this study, both the mechanically activated fly ash and the untreated fly ash can be used in soil stabilization with lime and cement considering the leaching aspect. This is further supported when we take into consideration that the study is based on a "worst-case-scenario". Also parameters affecting leaching like pH and DOC are almost the same for all mixtures, which is a good result since the mixture with lime and cement already is in use on the market.

8.2   RECOMMENDATIONS

Based on these primary results an extended laboratory study is recommended. Buffer capacity should be determined with an ACN-test. PH-static test should be performed for the knowledge of leaching at different values of pH. Also several tests should be performed to decrease the standard deviation values and the difference in results between different leaching tests.

For future research a life cycle assessment should be performed and also a field study. The regional effects, for example a change in transport behaviour, can be included in a life cycle assessment. In the field study it would be appropriate to analyze groundwater from two similar areas with different columns, one with cement and lime and one with cement, lime and ash, activated and non-activated.

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10   APPENDICES

Appendix A   Physical and chemical properties of construction cement
CEM II/A-LL 42,5 R, Skövde.

Appendix B   Chemical composition of fly ash used in this study.

Appendix C   Leached amount of elements in every mixture, including pH & conductivity

Appendix D   Guideline/limit values

Appendix E   Cumulative leaching for analyzed elements

Appendix F   Soil data

Appendix G   List of analyzed element

Appendix A Physical and chemical properties of construction cement
CEM II/A-LL 42,5 R, Skövde.

Fysikaliska data

Egenskap		Riktvärde Skövde	Riktvärde Slite	Spann	Sort	Krav	Gällande Standard
Specifik yta		430	460	± 30	m²/kg		
Bindetid		140	160	± 30	min	≥ 60	EN 197-1
Tryckhållfasthet	1d*	23	21	± 3	MPa		
Tryckhållfasthet	2d*	35	33	± 3	MPa	≥ 20,0	EN 197-1
Tryckhållfasthet	7 d*		44	± 4	MPa		
Tryckhållfasthet	28 d*	55	56	± 4	MPa	≥ 42,5 och ≤ 62,5	EN 197-1
Kompaktdensitet		3 080	3 080	± 20	kg/m²		
Skrymdensitet		1 250	1 250	± 250	kg/m²		
Ljushet		26	30	± 1	%		

* Mätt på normbruk

Kemiska data

Egenskap	Gränsvärden Skövde	Gränsvärden Slite	Sort	Krav	Gällande Standard
Magnesiumoxid, MgO	1,1–1,3	2,3–2,7	%	≤ 5,0 %	EN 197-1
Sulfathalt som SO_3	3,4–4,0	3,1–3,7	%	≤ 4,0 %	EN 197-1
Klorid, Cl^-	0,02–0,04	0,03–0,07	%	≤ 0,10 %	EN 197-1
Vattenlöslig Cr^{6+}	0–2	0–2	ppm	≤ 2 ppm (enl. EG 2003/53 och KIFS 2004:6)	

Appendix B Chemical composition of fly ash used in this study.

TS	%	99.5
SiO2	% TS	19.2
Al2O3	% TS	4.16
CaO	% TS	43.2
Fe2O3	% TS	11.1
K2O	% TS	0.651
MgO	% TS	5.08
MnO	% TS	0.115
Na2O	% TS	0.216
P2O5	% TS	0.841
TiO2	% TS	0.202
Summa	% TS	84.8
LOI	% TS	7.3
As	mg/kg TS	25.9
Ba	mg/kg TS	483
Be	mg/kg TS	1.67
Cd	mg/kg TS	0.69
Co	mg/kg TS	9.13
Cr	mg/kg TS	47
Cu	mg/kg TS	36.2
Hg	mg/kg TS	0.418
La	mg/kg TS	13.4
Mo	mg/kg TS	<6
Nb	mg/kg TS	<6
Ni	mg/kg TS	46
Pb	mg/kg TS	22.4
S	mg/kg TS	25300
Sc	mg/kg TS	3.9
Sn	mg/kg TS	1.68
Sr	mg/kg TS	407
V	mg/kg TS	58.7
W	mg/kg TS	<60
Y	mg/kg TS	21.7
Zn	mg/kg TS	74.5
Zr	mg/kg TS	87.1

Appendix C Leached amount of elements in every mixture, including pH & conductivity

Up-flow percolation test, binding agent amount 90 kg/m^3 soil, 7 days of hardening, Cumulative leaching [mg/kg TS]

L/S 0.1

ELEMENT	KC 50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33
As	0.0002597	0.0003836	0.0004136	0.0003396
Ba	0.0363614	0.0321658	0.0323656	0.0333646
Cd	0.0000100	0.0000100	0.0000100	0.0000100
Cr	0.0015883	0.0010229	0.0012347	0.0013166
Cu	0.0134857	0.0137054	0.0152838	0.0126066
Hg	0.0000040	0.0000040	0.0000040	0.0000040
Mo	0.0028170	0.0027171	0.0031966	0.0030767
Ni	0.0019000	0.0020378	0.0024574	0.0018960
Pb	0.0003177	0.0002058	0.0001480	0.0002857
Sb	0.0000200	0.0000262	0.0000236	0.0000204
Se	0.0000895	0.0000863	0.0001395	0.0000957
Zn	0.0237748	0.0531436	0.0194993	0.0205781
DOC	4.9946959	5.3942716	6.1934229	5.5940594
Cl	0.9190240	2.7970297	3.5961810	2.5972419
F	0.0939003	0.0819130	0.0998939	0.0978960
SO4	0.2397454	0.1957921	0.2197666	0.2397454

L/S 2

ELEMENT	KC 50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33
As	0.0027031	0.0028270	0.0028570	0.0027831
Ba	0.2855905	0.2171330	0.2368801	0.2774625
Cd	0.0001322	0.0001322	0.0001322	0.0001322
Cr	0.0148317	0.0085975	0.0083206	0.0119211
Cu	0.1129330	0.1011800	0.1132650	0.1093662
Hg	0.0000529	0.0000529	0.0000529	0.0000529
Mo	0.0284729	0.0291061	0.0266779	0.0316648
Ni	0.0202257	0.0135708	0.0129885	0.0156769
Pb	0.0032986	0.0025857	0.0023007	0.0023064
Sb	0.0002643	0.0002705	0.0002679	0.0002647
Se	0.0008323	0.0007289	0.0008407	0.0007628
Zn	0.0328887	0.0640168	0.0273671	0.0530757
DOC	39.2026167	37.1587694	35.5144979	39.8019802
Cl	9.7153465	21.3670438	25.0983027	21.6559406
F	0.5092822	0.6439003	0.4908416	0.5377122
SO4	3.1718529	1.7840170	2.1256365	2.2433522

L/S 10

ELEMENT	KC 50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33
As	0.0100794	0.0102033	0.0102332	0.0101593
Ba	0.5349074	0.4627617	0.4603801	0.5400566
Cd	0.0005010	0.0005010	0.0005010	0.0005010
Cr	0.0379931	0.0331604	0.0269087	0.0278537
Cu	0.1992350	0.1963335	0.2180076	0.2074701
Hg	0.0002004	0.0002004	0.0002004	0.0002004
Mo	0.0935314	0.1095071	0.0898923	0.0929613
Ni	0.0368222	0.0216109	0.0192067	0.0267412
Pb	0.0104167	0.0153466	0.0087254	0.0090262
Sb	0.0010019	0.0010081	0.0010055	0.0010023
Se	0.0023813	0.0028902	0.0025225	0.0020462
Zn	0.0611397	0.1205188	0.0421196	0.1059633
DOC	66.4946959	64.4508487	60.5937058	65.6188119
Cl	25.9430693	42.7581330	47.2270156	47.4727723
F	1.6894802	2.1929102	1.7448020	1.7916726
SO4	12.0233380	8.6439180	6.5513791	18.4710750

Up-flow percolation test, binding agent amount 90 kg/m^3 soil, bold font when under detection limit for analysis, 7 days of hardening, Concentration in solution

L/S 0-0.1

ELEMENT	SAMPLE	KC50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33
As	µg/l	1.3	1.92	2.07	1.7
Ba	µg/l	182	161	162	167
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	7.95	5.12	6.18	6.59
Cu	µg/l	67.5	68.6	76.5	63.1
Hg	µg/l	**0.02**	**0.02**	**0.02**	**0.02**
Mo	µg/l	14.1	13.6	16	15.4
Ni	µg/l	9.51	10.2	12.3	9.49
Pb	µg/l	1.59	1.03	0.741	1.43
Sb	µg/l	**0.1**	0.131	0.118	0.102
Se	µg/l	0.448	0.432	0.698	0.479
Zn	µg/l	119	266	97.6	103
DOC	mg/l	25	27	31	28
Cl	mg/l	4.6	14	18	13
F	mg/l	0.47	0.41	0.5	0.49
SO4	mg/l	1.2	0.98	1.1	1.2
pH		12.5	12.5	12.5	12.5
Conductivity	mS/cm	818	508	871	826.2

L/S 0.1-2

ELEMENT	SAMPLE	KC50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33
As	µg/l	**1**	**1**	**1**	**1**
Ba	µg/l	102	75.7	83.7	99.9
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	5.42	3.1	2.9	4.34
Cu	µg/l	40.7	35.8	40.1	39.6
Hg	µg/l	**0.02**	**0.02**	**0.02**	**0.02**
Mo	µg/l	10.5	10.8	9.61	11.7
Ni	µg/l	7.5	4.72	4.31	5.64
Pb	µg/l	1.22	0.974	0.881	0.827
Sb	µg/l	**0.1**	**0.1**	**0.1**	**0.1**
Se	µg/l	0.304	0.263	0.287	0.273
Zn	µg/l	3.73	4.45	3.22	13.3
DOC	mg/l	14	13	12	14
Cl	mg/l	3.6	7.6	8.8	7.8
F	mg/l	0.17	0.23	0.16	0.18
SO4	mg/l	1.2	0.65	0.78	0.82
pH		12.4	12.4	12.5	12.4
Conductivity	mS/cm	579	562	871	56

L/S 2-10

ELEMENT	SAMPLE	KC50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33
As	µg/l	**1**	**1**	**1**	**1**
Ba	µg/l	33.8	33.3	30.3	35.6
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	3.14	3.33	2.52	2.16
Cu	µg/l	11.7	12.9	14.2	13.3
Hg	µg/l	**0.02**	**0.02**	**0.02**	**0.02**
Mo	µg/l	8.82	10.9	8.57	8.31
Ni	µg/l	2.25	1.09	0.843	1.5
Pb	µg/l	0.965	1.73	0.871	0.911
Sb	µg/l	**0.1**	**0.1**	**0.1**	**0.1**
Se	µg/l	0.21	0.293	0.228	0.174
Zn	µg/l	3.83	7.66	**2**	7.17
DOC	mg/l	3.7	3.7	3.4	3.5
Cl	mg/l	2.2	2.9	3	3.5
F	mg/l	0.16	0.21	0.17	0.17
SO4	mg/l	1.2	0.93	0.6	2.2
pH		12.4	12.4	12.4	12.4
Conductivity	mS/m	634	578	579	612

Two stage batch test, binding agent amount 90 kg/m³ soil, 7 days of hardening, Cumulative leaching [mg/kg TS]

L/S 2

ELEMENT	KC 50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023
Ba	0.3256	0.2781	0.2736	0.2826	0.2778	0.2600
Cd	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Cr	0.0321	0.0116	0.0142	0.0140	0.0060	0.0121
Cu	0.0751	0.0748	0.0746	0.0818	0.1207	0.0676
Hg	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
Mo	0.0269	0.0225	0.0233	0.0211	0.0246	0.0240
Ni	0.0063	0.0021	0.0055	0.0072	0.0179	0.0052
Pb	0.0059	0.0050	0.0057	0.0050	0.0047	0.0050
Sb	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Se	0.0011	0.0010	0.0011	0.0010	0.0017	0.0009
Zn	0.0077	0.0045	0.0118	0.0098	0.0046	0.0049
DOC	19.8968	19.6707	18.0880	19.6707	18.2148	16.7314
Cl	16.7314	38.4370	38.4370	33.9150	68.3055	49.7420
F	0.4522	0.4748	0.5200	0.5200	0.6147	0.5879
SO4	3.1654	2.7132	1.8540	2.9393	2.2769	2.0123

L/S 10

ELEMENT	KC 50/50	KCA 33/33/33 1	KCA 33/33/33 2	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	0.0099	0.0099	0.0099	0.0099	0.0100	0.0099
Ba	0.6956	0.7433	0.6743	0.7476	0.7033	0.6542
Cd	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Cr	0.1005	0.0440	0.0411	0.0425	0.0297	0.0421
Cu	0.1293	0.1534	0.1425	0.1628	0.2014	0.1405
Hg	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Mo	0.1089	0.0711	0.0669	0.0676	0.0768	0.0782
Ni	0.0089	0.0066	0.0083	0.0096	0.0267	0.0119
Pb	0.0144	0.0171	0.0170	0.0165	0.0134	0.0157
Sb	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Se	0.0039	0.0034	0.0029	0.0035	0.0053	0.0029
Zn	0.0222	0.0198	0.0253	0.0238	0.0200	0.0201
DOC	35.5485	36.1975	46.4808	36.1975	36.9573	69.6008
Cl	28.2344	56.1307	33.9901	54.3507	93.1097	35.7055
F	1.6540	1.8351	1.9513	1.8693	2.2851	3.1619
SO4	13.0543	8.8582	7.6344	9.1932	9.1677	7.5442

Two stage batch test, binding agent amount 120 kg/m^3 soil, 7 days of hardening, Cumulative leaching [mg/kg TS]

L/S 2

ELEMENT	KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	0.0042	0.0045	0.0024
Ba	0.4326	0.3802	0.3825
Cd	0.0001	0.0001	0.0001
Cr	0.0224	0.0160	0.0167
Cu	0.1783	0.1633	0.1346
Hg	0.0000	0.0001	0.0000
Mo	0.0312	0.0344	0.0226
Ni	0.0232	0.0122	0.0125
Pb	0.0063	0.0059	0.0054
Sb	0.0002	0.0002	0.0002
Se	0.0017	0.0014	0.0016
Zn	0.0046	0.0046	0.0046
DOC	45.5370	27.3222	22.7685
Cl	18.2148	54.6444	47.8139
F	0.3415	0.4554	0.5237
SO4	5.0091	2.5045	2.5045

L/S 10

ELEMENT	KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	0.0115	0.0117	0.0101
Ba	1.1878	0.9778	1.0457
Cd	0.0005	0.0005	0.0005
Cr	0.0652	0.0563	0.0524
Cu	0.3724	0.3288	0.2731
Hg	0.0002	0.0002	0.0002
Mo	0.1121	0.1145	0.0725
Ni	0.0416	0.0230	0.0248
Pb	0.0227	0.0209	0.0194
Sb	0.0010	0.0010	0.0010
Se	0.0050	0.0037	0.0039
Zn	0.0200	0.0200	0.0200
DOC	71.7205	52.1283	46.1966
Cl	39.4381	85.2377	79.2343
F	1.4992	1.5855	1.6372
SO4	12.8921	10.1671	7.3556

Two stage batch test, binding agent amount 90 kg/m³ soil, bold font when under detection limit for analysis, 7 days of hardening, Concentration in solution

L/S 0-2

ELEMENT		KC 50/50	KCA 33/33/33	KCA 33/33/33	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	µg/l	**1**	**1**	**1**	**1**	1	**1**
Ba	µg/l	144	123	121	125	122	115
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	14.2	5.14	6.26	6.21	2.62	5.36
Cu	µg/l	33.2	33.1	33	36.2	53	29.9
Hg	µg/l	**0.02**	**0.02**	**0.02**	0.0256	**0.02**	0.02
Mo	µg/l	11.9	9.96	10.3	9.32	10.8	10.6
Ni	µg/l	2.79	0.937	2.45	3.2	7.88	2.28
Pb	µg/l	2.61	2.23	2.53	2.19	2.07	2.22
Sb	µg/l	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Se	µg/l	0.504	0.439	0.465	0.456	0.763	0.376
Zn	µg/l	3.4	**2**	5.21	4.34	**2**	2.17
DOC	mg/l	8.8	8.7	8	8.7	8	7.4
Cl	mg/l	7.4	17	17	15	30	22
F	mg/l	0.2	0.21	0.23	0.23	0.27	0.26
SO4	mg/l	1.4	1.2	0.82	1.3	1	0.89

L/S 2-8

ELEMENT		KC 50/50	KCA 33/33/33	KCA 33/33/33	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	µg/l	1	1	1	1	1	1
Ba	µg/l	54.8	65	57	65.1	59.6	55.8
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	9.29	4.29	3.71	3.89	3.05	4.02
Cu	µg/l	8.85	11.8	10.5	12.3	13.3	10.9
Hg	µg/l	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Mo	µg/l	10.8	6.59	6.01	6.3	7.03	7.32
Ni	µg/l	**0.5**	0.607	**0.5**	**0.5**	1.58	0.98
Pb	µg/l	1.21	1.62	1.54	1.55	1.19	1.45
Sb	µg/l	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Se	µg/l	0.366	0.323	0.252	0.327	0.487	0.273
Zn	µg/l	2	**2**	**2**	**2**	**2**	**2**
DOC	mg/l	2.5	2.6	4	2.6	2.8	3.9
Cl	mg/l	1.9	3.3	**0.6**	3.5	5	4.3
F	mg/l	**0.16**	0.18	0.19	0.18	0.22	0.2
SO4	mg/l	1.3	0.83	0.76	0.85	0.9	0.92

Two stage batch test, binding agent amount 120 kg/m³ soil, bold font when under detection limit for analysis, 7 days of hardening, Concentration in solution

L/S 0-2

ELEMENT		KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	µg/l	1.85	1.96	1.05
Ba	µg/l	190	167	168
Cd	µg/l	**0.05**	**0.05**	**0.05**
Cr	µg/l	9.85	7.02	7.33
Cu	µg/l	78.3	71.7	59.1
Hg	µg/l	**0.02**	**0.025**	**0.02**
Mo	µg/l	13.7	15.1	9.91
Ni	µg/l	10.2	5.38	5.48
Pb	µg/l	2.75	2.59	2.39
Sb	µg/l	**0.1**	**0.1**	**0.1**
Se	µg/l	0.734	0.618	0.681
Zn	µg/l	**2**	**2**	**2**
DOC	mg/l	20	12	10
Cl	mg/l	8	24	21
F	mg/l	**0.15**	0.2	0.23
SO4	mg/l	2.2	1.1	1.1

L/S 2-8

ELEMENT		KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	µg/l	**1**	**1**	**1**
Ba	µg/l	104	83.4	91.4
Cd	µg/l	**0.05**	**0.05**	**0.05**
Cr	µg/l	5.83	5.34	4.81
Cu	µg/l	28.7	24.8	20.7
Hg	µg/l	**0.02**	**0.02**	**0.02**
Mo	µg/l	10.7	10.7	6.7
Ni	µg/l	2.9	1.66	1.85
Pb	µg/l	2.17	1.99	1.85
Sb	µg/l	**0.1**	**0.1**	**0.1**
Se	µg/l	0.453	0.319	0.325
Zn	µg/l	**2**	**2**	**2**
DOC	mg/l	4.5	3.8	3.5
Cl	mg/l	3.1	5.3	5.2
F	mg/l	**0.15**	0.15	0.15
SO4	mg/l	1.1	1	0.66

Conductivity and pH for 7 days of hardening and two stage batch test

	L/S 2		L/S 10	
	pH	Cond. [mS/m]	pH	Cond. [mS/m]
KC 50/50 90 kg/m^3 soil	12.55	774	12.47	623
KCA 33/33/33 90 kg/m^3 soil, 1	12.49	811	12.53	717
KCA 33/33/33 90 kg/m^3 soil, 2	12.54	798	12.53	702
KCAA 33/33/33 90 kg/m^3 soil	12.52	785	12.53	709
KCA 25/25/50 90 kg/m^3 soil	12.53	770	12.43	565
KCAA 25/25/50 90 kg/m^3 soil	12.54	762	12.5	659
KC 50/50, 120 kg/m^3 soil	12.57	844	12.55	798
KCA 33/33/33 120 kg/m^3 soil	12.57	839	12.55	752
KCAA 33/33/33 120 kg/m^3 soil	12.58	823	12.54	743
Soil	8	1059	8	20.1

Two stage batch test, binding agent amount 90 kg/m^3 soil, 91 days of hardening, Cumulative leaching [mg/kg TS]

L/S 2

ELEMENT	KCA 50/50	KCA 33/33/33	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	0.0027	0.0030	0.0027	0.0025	0.0029
Ba	0.2541	0.1528	0.1630	0.1116	0.1320
Cd	0.0001	0.0001	0.0001	0.0001	0.0001
Cr	0.0169	0.0121	0.0141	0.0110	0.0106
Cu	0.1824	0.1948	0.1982	0.1746	0.1980
Hg	0.0000	0.0000	0.0000	0.0000	0.0000
Mo	0.0172	0.0218	0.0189	0.0200	0.0232
Ni	0.0314	0.0214	0.0244	0.0134	0.0172
Pb	0.0042	0.0023	0.0025	0.0021	0.0022
Sb	0.0002	0.0002	0.0002	0.0002	0.0002
Se	0.0011	0.0010	0.0012	0.0010	0.0009
Zn	0.0097	0.0042	0.0079	0.0040	0.0040
DOC	46.0115	40.0100	38.0095	34.0085	34.0085
Cl	5.0013	15.4039	13.8035	24.0060	22.0055
F	2.4006	2.4006	2.4006	2.4006	2.4006
SO4	3.8010	3.2008	5.8015	2.4006	3.2008

L/S 10

ELEMENT	KC 50/50	KCA 33/33/33	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	0.010381	0.010505	0.01035	0.010268	0.010492
Ba	0.520907	0.333386	0.375416	0.281693	0.180835
Cd	0.0005	0.0005	0.0005	0.0005	0.0005
Cr	0.08281	0.065686	0.080652	0.069886	0.031456
Cu	0.276833	0.295771	0.264323	0.287177	0.171692
Hg	0.0002	0.0002	0.0002	0.0002	0.0002
Mo	0.062608	0.099944	0.077437	0.092199	0.035136
Ni	0.047191	0.032269	0.034978	0.028045	0.0183
Pb	0.008034	0.005501	0.005555	0.005387	0.003017
Sb	0.001	0.001	0.001009	0.001	0.001248
Se	0.00415	0.004128	0.003882	0.004439	0.003442
Zn	0.022943	0.020094	0.022017	0.020001	0.020001
DOC	75.69433	73.50581	69.78566	75.80325	54.85914
Cl	16.02932	39.32175	36.70451	46.43619	28.51519
F	12.0006	12.0006	12.0006	12.0006	12.0006
SO4	21.69253	23.17834	23.61829	24.5613	67.37513

Two stage batch test, binding agent amount 120 kg/m^3 soil, 91 days of hardening, Cumulative leaching [mg/kg TS]

L/S 2

ELEMENT	KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	0.0022806	0.0021605	0.0020005
Ba	0.2820705	0.256064	0.24006
Cd	0.0001	0.0001	0.0001
Cr	0.0157439	0.0162441	0.0117629
Cu	0.1914479	0.1716429	0.1488372
Hg	4.001E-05	4.001E-05	4.001E-05
Mo	0.0122631	0.0144836	0.0124631
Ni	0.032008	0.0195049	0.0149437
Pb	0.0050213	0.0043011	0.003981
Sb	0.0002001	0.0002201	0.0002001
Se	0.0010703	0.0006802	0.0007802
Zn	0.004001	0.0089422	0.008122
DOC	40.01	34.0085	34.0085
Cl	3.2008	8.002	8.60215
F	2.4006	2.4006	2.4006
SO4	4.001	2.4006	2.4006

L/S 10

ELEMENT	KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	0.010161	0.010092	0.010001
Ba	0.80155	0.599797	0.569396
Cd	0.0005	0.0005	0.0005
Cr	0.069315	0.055428	0.047022
Cu	0.317526	0.261924	0.232951
Hg	0.0002	0.0002	0.0002
Mo	0.043499	0.043882	0.042462
Ni	0.058765	0.033287	0.022798
Pb	0.020052	0.013441	0.010459
Sb	0.001	0.001011	0.001
Se	0.00287	0.002018	0.002554
Zn	0.020001	0.022824	0.022355
DOC	71.57418	66.37408	74.34596
Cl	12.45774	26.71554	26.17263
F	12.0006	12.0006	12.0006
SO4	14.68641	12.0006	12.0006

Two stage batch test, binding agent amount 90 kg/m³ soil, bold font when under detection limit for analysis, 91 days of hardening, Concentration in solution

L/S 2

ELEMENT		KC 50/50	KCA 33/33/33	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	µg/l	1.37	1.49	1.34	1.26	1.43
Ba	µg/l	127	76.4	81.5	55.8	66
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	8.46	6.03	7.06	5.49	5.28
Cu	µg/l	91.2	97.4	99.1	87.3	99
Hg	µg/l	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Mo	µg/l	8.62	10.9	9.43	10	11.6
Ni	µg/l	15.7	10.7	12.2	6.68	8.58
Pb	µg/l	2.08	1.17	1.24	1.05	1.09
Sb	µg/l	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Se	µg/l	0.572	0.498	0.599	0.495	0.47
Zn	µg/l	4.86	2.09	3.96	**2**	**2**
DOC	mg/l	23	20	19	17	17
Cl	mg/l	2.5	7.7	6.9	12	11
F	mg/l	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
SO4	mg/l	1.9	1.6	2.9	**1.2**	1.6
pH		12.5	12.4	12.3	12.3	12.3
Kond.	mS/m	722	564	563	521	511

L/S 2-8

ELEMENT		KC 50/50	KCA 33/33/33	KCAA 33/33/33	KCA 25/25/50	KCAA 25/25/50
As	µg/l	**1**	**1**	**1**	**1**	**1**
Ba	µg/l	43.5	28.4	32.5	25	11.9
Cd	µg/l	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Cr	µg/l	8.26	6.63	8.18	7.16	2.87
Cu	µg/l	20.4	21.8	18.1	22	6.61
Hg	µg/l	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Mo	µg/l	5.99	9.89	7.55	9.13	2.47
Ni	µg/l	3.46	2.37	2.5	2.36	0.959
Pb	µg/l	0.657	0.479	0.477	0.48	**0.2**
Sb	µg/l	**0.1**	**0.1**	0.101	**0.1**	0.128
Se	µg/l	0.397	0.403	0.364	0.438	0.328
Zn	µg/l	**2**	**2**	**2**	**2**	**2**
DOC	mg/l	5.8	5.9	5.6	6.5	4
Cl	mg/l	1.5	3.5	3.3	3.8	1.8
F	mg/l	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
SO4	mg/l	2.2	2.4	2.3	2.6	7.4
pH		12.2	12.2	12.2	12.1	11.8
Kond.	mS/m	418	340	338	303	148

Two stage batch test, binding agent amount 120 kg/m^3 soil, bold font when under detection limit for analysis, 91 days of hardening, Concentration in solution

L/S 0-2

ELEMENT		KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	µg/l	1.14	1.08	**1**
Ba	µg/l	141	128	120
Cd	µg/l	**0.05**	**0.05**	**0.05**
Cr	µg/l	7.87	8.12	5.88
Cu	µg/l	95.7	85.8	74.4
Hg	µg/l	**0.02**	**0.02**	**0.02**
Mo	µg/l	6.13	7.24	6.23
Ni	µg/l	16	9.75	7.47
Pb	µg/l	2.51	2.15	1.99
Sb	µg/l	**0.1**	0.11	**0.1**
Se	µg/l	0.535	0.34	0.39
Zn	µg/l	**2**	4.47	4.06
DOC	mg/l	20	17	17
Cl	mg/l	1.6	4	4.3
F	mg/l	**1.2**	**1.2**	**1.2**
SO4	mg/l	2	**1.2**	1.2
pH		12.5	12.5	12.5
Kond.	mS/m	844	755	728

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L/S 2-8

ELEMENT		KC 50/50	KCA 33/33/33	KCAA 33/33/33
As	µg/l	**1**	**1**	**1**
Ba	µg/l	72.3	51.2	48.8
Cd	µg/l	**0.05**	**0.05**	**0.05**
Cr	µg/l	6.81	5.21	4.55
Cu	µg/l	23.5	18.5	16.7
Hg	µg/l	**0.02**	**0.02**	**0.02**
Mo	µg/l	4.12	4.02	3.99
Ni	µg/l	4.57	2.5	1.61
Pb	µg/l	1.94	1.24	0.924
Sb	µg/l	**0.1**	**0.1**	**0.1**
Se	µg/l	0.255	0.184	0.238
Zn	µg/l	**2**	**2**	**2**
DOC	mg/l	5.5	5.3	6.2
Cl	mg/l	**1.2**	2.5	2.4
F	mg/l	**1.2**	**1.2**	**1.2**
SO4	mg/l	1.4	**1.2**	**1.2**
pH		12.5	12.4	12.3
Kond.	mS/m	703	582	502

Two stage batch test for soil, bold font when under detection limit, Cumulative leaching [mg/kg TS]

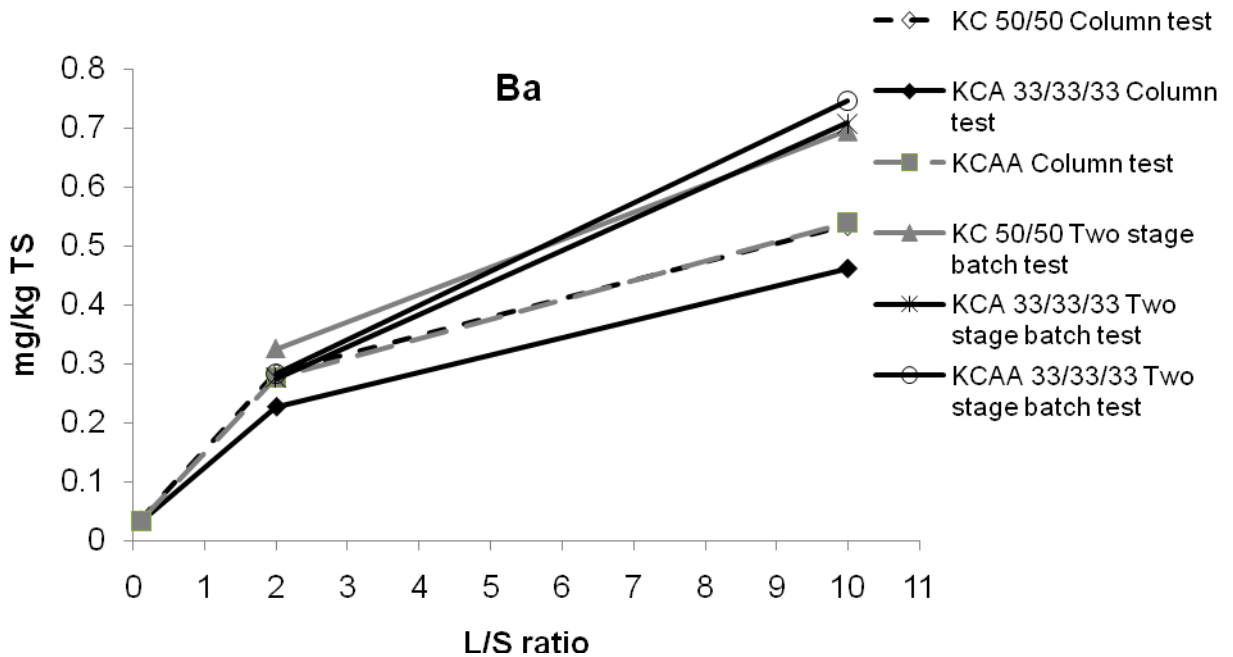| ELEMENT	L/S 2	L/S 10
As	0.0057	**0.0266**
Ba	0.2240	0.3450
Cd	**0,0001**	**0,0005**
Cr	0.0046	**0,008**
Cu	0.0610	0.1530
Hg	**0,00004**	**0,0002**
Mo	0.0592	0.0883
Ni	0.0071	0.0190
Pb	**0,0004**	**0,002**
Sb	0.0026	**0.0103**
Se	0.0094	0.0167
Zn	0.0040	**0.0200**
DOC	148.0000	288.0000
Cl	74.0000	74.0000
F	3.4000	9.6600
SO4	564.0000	542.0000

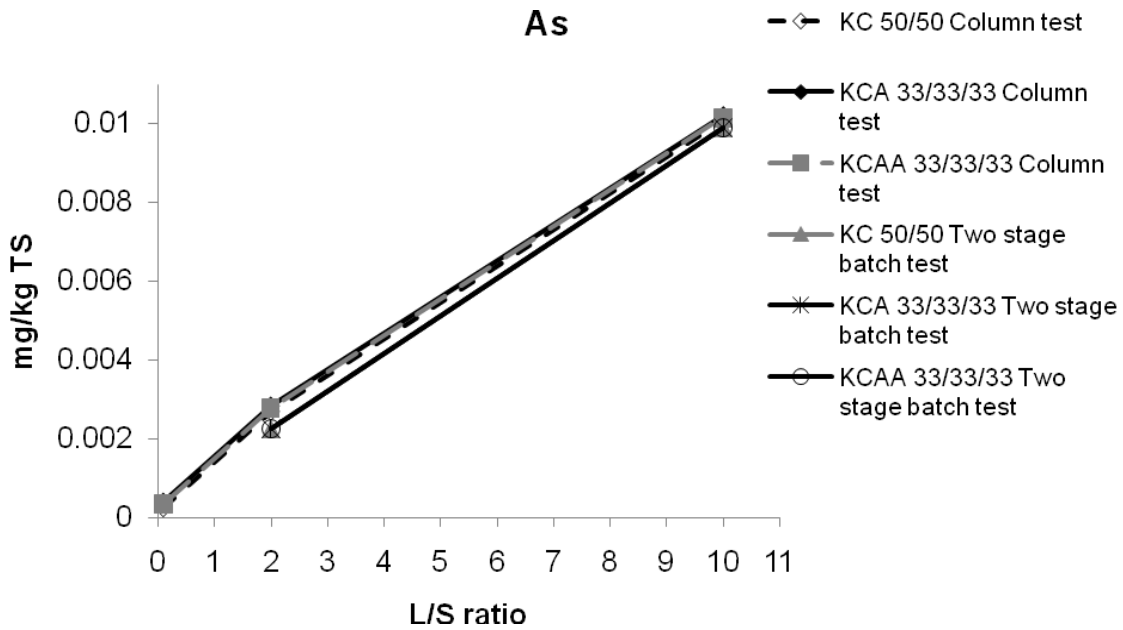**Appendix D** Guideline/limit values

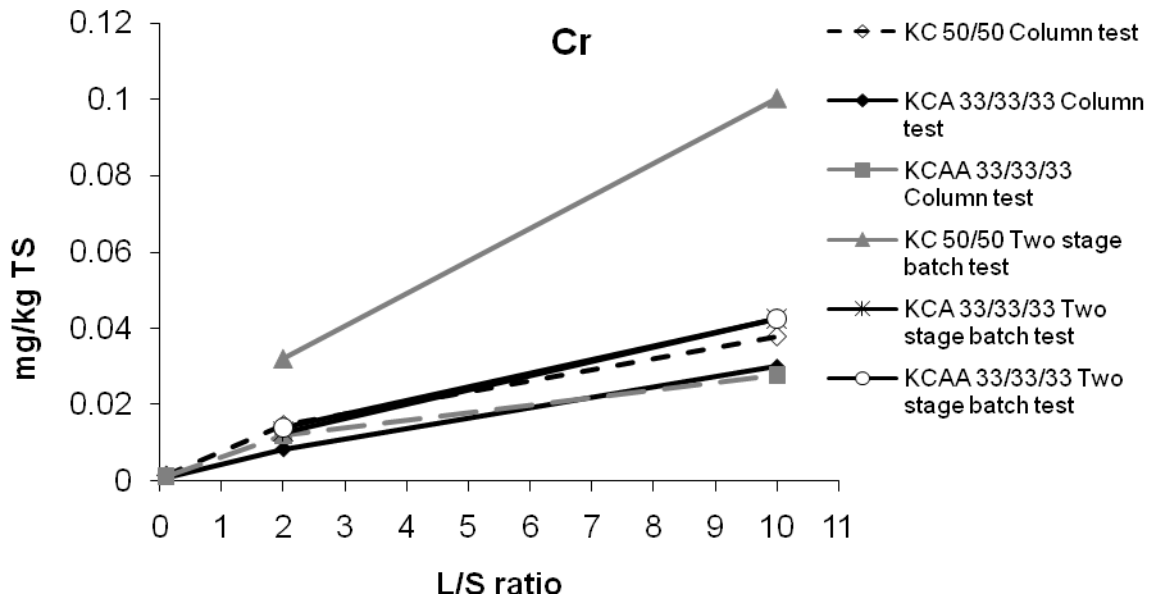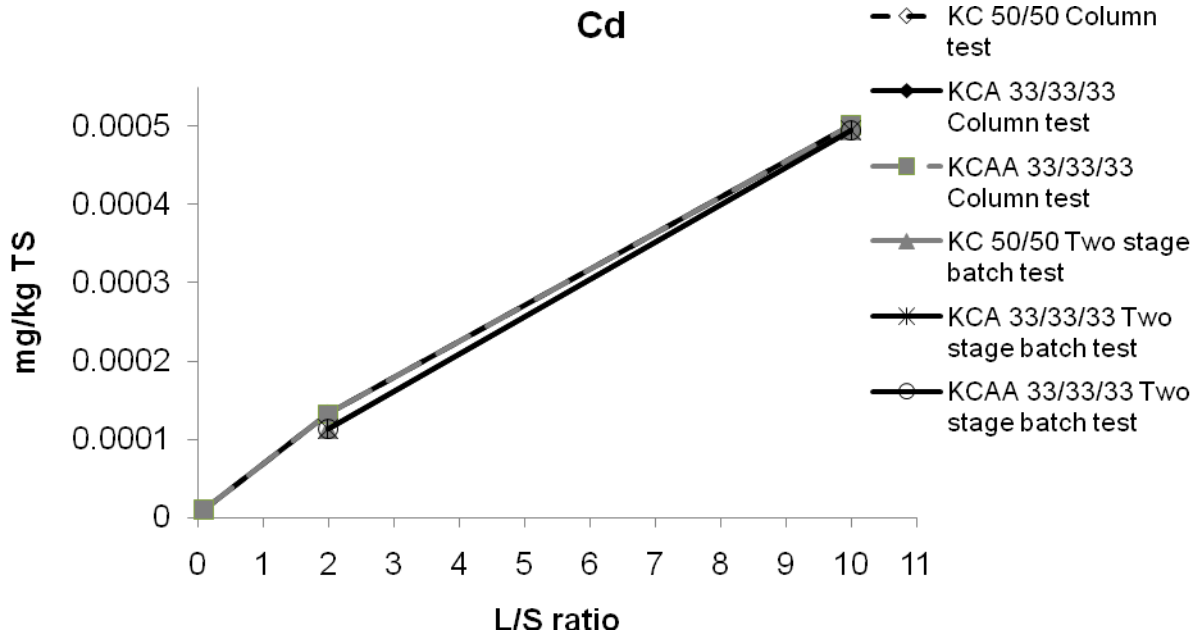1 = Limit values for landfilling of waste, classified as inert waste
2 = Guideline values for recycling of waste in construction buildings, category 1
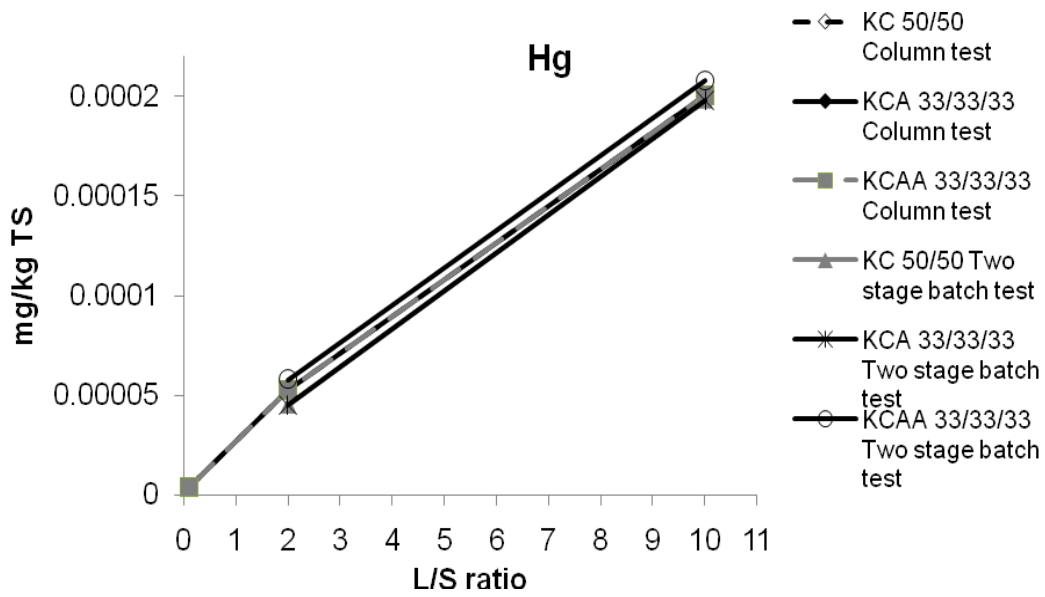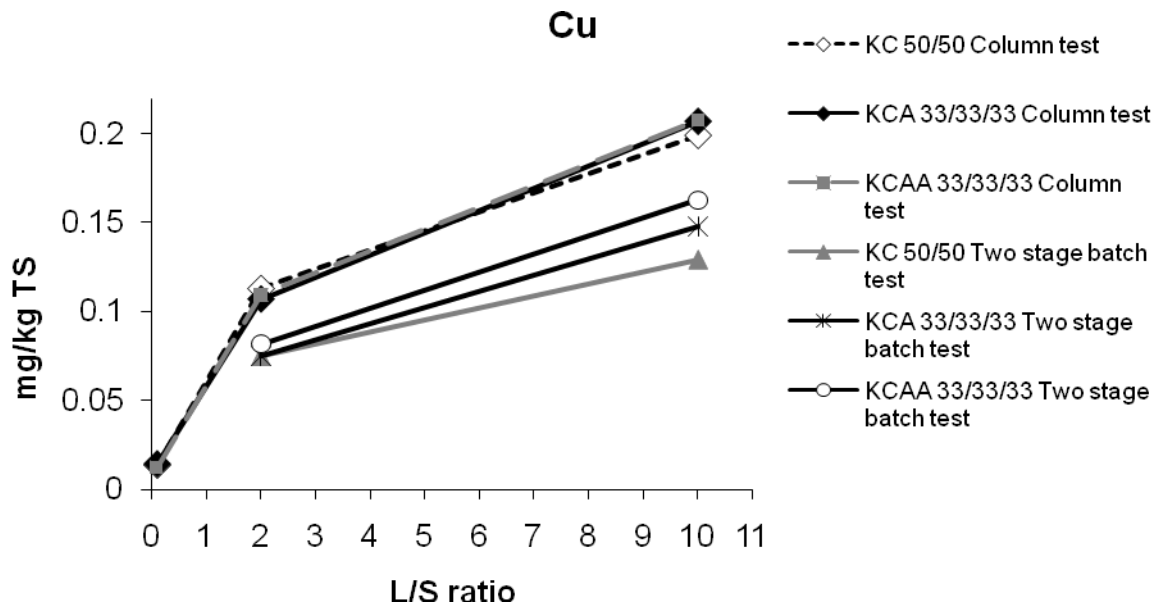
L/S 0.1	[mg/l]	
ELEMENT	1	2
As	0.06	0.016
Ba	4	
Cd	0.02	0,004
Cr	0.1	0.09
Cu	0.6	0.09
Hg	0.002	0,001
Mo	0.2	
Ni	0.12	0.18
Pb	0.15	0.09
Sb	0.1	
Se	0.04	
Zn	1.2	0.64
DOC	160	
Cl	460	84
F	2.5	
SO_4	1500	78

L/S 10	[mg/kg TS]	
ELEMENT	1	2
As	0.5	0.13
Ba	20	
Cd	0.04	0.01
Cr	0.5	0.42
Cu	2	0.31
Hg	0.01	0.004
Mo	0.5	
Ni	0.4	0.6
Pb	0.5	0.31
Sb	0.06	
Se	0.1	
Zn	4	2.2
DOC	500	
Cl	800	147
F	10	
SO_4	1000	227

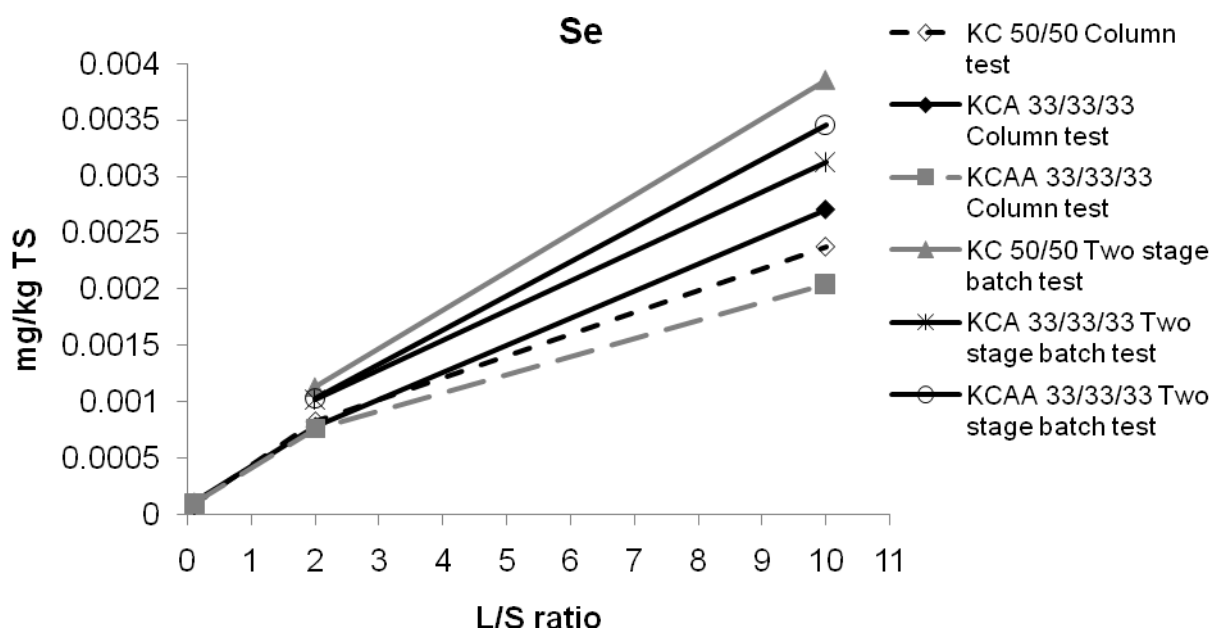**Appendix E** Cumulative leaching for analyzed elements

Cd

Legend:
- KC 50/50 Column test
- KCA 33/33/33 Column test
- KCAA 33/33/33 Column test
- KC 50/50 Two stage batch test
- KCA 33/33/33 Two stage batch test
- KCAA 33/33/33 Two stage batch test

Cr

Legend:
- KC 50/50 Column test
- KCA 33/33/33 Column test
- KCAA 33/33/33 Column test
- KC 50/50 Two stage batch test
- KCA 33/33/33 Two stage batch test
- KCAA 33/33/33 Two stage batch test

Cu

Legend:
- KC 50/50 Column test
- KCA 33/33/33 Column test
- KCAA 33/33/33 Column test
- KC 50/50 Two stage batch test
- KCA 33/33/33 Two stage batch test
- KCAA 33/33/33 Two stage batch test

Hg

Legend:
- KC 50/50 Column test
- KCA 33/33/33 Column test
- KCAA 33/33/33 Column test
- KC 50/50 Two stage batch test
- KCA 33/33/33 Two stage batch test
- KCAA 33/33/33 Two stage batch test

Pb

- KC 50/50 Column test
- KCA 33/33/33 Column test
- KCAA 33/33/33 Column test
- KC 50/50 Two stage batch test
- KCA 33/33/33 Two stage batch test
- KCAA 33/33/33 Two stage batch test

Sb

- KC 50/50 Column test
- KCA 33/33/33 Column test
- KCAA 33/33/33 Column test
- KC 50/50 Two stage batch test
- KCA 33/33/33 Two stage batch test
- KCAA 33/33/33 Two stage batch test

Se

Zn

DOC

Cl

F

SO$_4$

Appendix F Soil data

Bulk density	[t/m³]	1.59
Water ratio	[%]	65
Undrained shear strength, undisturbed	[kPa]	12.1
Undrained shear strength, disturbed	[kPa]	1.7
Sensitivity ratio	[-]	7
Cone yield point	[%]	74
Plastic limit	[%]	39
Plasticity index	[-]	35

Appendix G List of analyzed elements

As	Arsenic
Ba	Barium
Cd	Cadmium
Cr	Chromium
Cu	Copper
Hg	Mercury
Mo	Molybdenum
Ni	Nickel
Pb	Lead
Sb	Antimony
Se	Selenium
Zn	Zinc
DOC	Dissolved Organic Carbon
Cl	Chloride
F	Fluoride
SO₄	Sulphate