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Water filtration with mineral-based byproducts as a sustainable treatment technology

Vattenfiltrering med mineralbaserade restprodukter som reningsteknik för hållbara samhällslösningar

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Preface

The potential of metallurgical slags as water and wastewater treatment materials has been known for almost three decades. Despite the fact that knowledge has been built up over the years, different types of slag have not yet come into full-scale and commercial use. The project “MINRENT” presented in this report aimed to elaborate further on new knowledge of Swedish steel slags and show possible real-life solutions where slag material fits in the context of sustainable water purification.

The applied research was performed under the umbrella of a consortium consisting of three universities and twelve companies, which are listed below:

KTH Royal Institute of Technology (coordinator)
Luleå University of Technology
Örebro University
AB Sandvik Materials Technology
Outokumpu Stainless AB
Höganäs Sweden AB
Ovako Sweden AB
SSAB Merox AB
Team Wåhlin Mark- & Asfalt AB
Alnarp Cleanwater Technology AB
Ramson AB
Flexiclean AB
Swerock AB
NCC AB
Vargön Alloys AB

The project time was 2016-09-01–2018-12-31 (later extended to 2019-06-30) and financial support was obtained from the Swedish Government Agency Vinnova, corporated co-financing by the industry and the Swedish iron and steel producers' association Jernkontoret.

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Summary

The aim of the project was to investigate whether the 200 000 ton slag, that is not used optimally or deposited every year, can be alternatively applied as water treatment materials, ensuring future outlets and providing added value for the steel industry and society. Five goals had been set and could be met: test of filter material for purification in small sewage plants, testing of mineral filters for industrial wastewater and stormwater, new technology to build road shoulders on busy roads with slag that simultaneously cleans stormwater, laboratory-tested filter products, and two graduated doctors.

Slag's properties can be modified in the furnace to contain minerals that have properties to bind phosphorus or metals from water. Slags can separate both cations and anions from contaminated water, anions even at pH value 10. Furthermore, slag and bark in combined filters are able to remove PFAS and also fluorine by modifying of AOD slag. Some types of slag are recommended to replace sand in soil beds for sewage treatment. Stormwater wells in cities and industry can be equipped with slag filters. Storm water from traffic-intensive roads can be cleaned in the road shoulder with certain types of slag.

R&D has been conducted in clear collaboration between industry and academia. The research has been conducted in the laboratory, at the companies and in the field. Implementation has been possible through researchers and companies starting pilot facilities and studying their function and utility to achieve sustainability goals. The analysis made is that different types of Swedish-produced slag are useful by-products, after simple reprocessing or after modifications, in water purification applications. These applications can be of several different types and be interesting for several end users.

Sammanfattning

Målet för projektet var att undersöka om de 200 kton slagg som inte används optimalt eller deponeras varje år kan utnyttjas varaktigt i nya applikationer och därmed säkerställa framtida avsättningsmöjligheter och ger ett mervärde för stålindustrin och samhället. Fem mål fanns och kunde uppfyllas; test av filtermaterial för rening av små avlopp, test av mineraliska filter för industriellt avloppsvatten och dagvatten, ny teknik att bygga stödremsor vid trafikerade vägar med slagg som samtidigt renar dagvatten, laboratorietestade filterprodukter, två doktorer utexaminerade.

Med kunskaper från ett föregående projekt (I-slag) har tillämpade försök hos Ovako i samarbete med Luleå tekniska universitet kunnat påvisa hur slaggers egenskaper kan modifieras i ugnen så att de innehåller mineral som har egenskaper att binda fosfor eller metaller från vattenfaser. I laboratoriemiljö har det bevisats att slagger kan avskilja både katjoner och anjoner från förorenat vatten, anjoner även vid pH-värden över 10. Vidare kan slagg och bark avskilja PFAS och fluor tas bort genom en modifikation av AOD-slagg. Pilotförsök i fält har bevisat att testade slagger har förmåga att reducera fosfor och metaller i olika typer av förorenat vatten. Vid småskalig avloppsrening kan vissa slagger användas som utbytbara filter för fosforrening och fosforåtervinning. De konventionellt byggda markbäddarna med sand för avloppsrening kan med fördel byggas med flera typer av slagg varvid en avsevärt bättre och långsiktig fosforrening erhålls. Dagvatten från industriområden och i städer kan renas effektivare än tidigare med kombinationsfilter, t ex slagg och bark. Större vägar genererar via avrinningen stora mängder föroreningar som i projektets försök visat sig kunna bindas effektivt i vägens stödremsa om lämpliga slagger används istället för grus.

Vissa typer av slagger rekommenderas att ersätta sand i markbäddar för avloppsrening. Dagvattenbrunnar i städer och industri kan utrustas med slagg-filter. Dagvatten från trafikintensiva vägar kan renas i stödremsan med vissa typer av slagg.

FoU har bedrivits i tydlig samverkan mellan industri och akademi. Forskningen har bedrivits i laboratorium, vid företagen och i fält. Genomförandet har kunnat ske genom att forskare och företag startat pilot-anläggningar och studerat deras funktion och nytta för att uppnå hållbarhetsmål. Den analys som gjorts är att olika typer av svenskproducerad slagg är biprodukter som kan användas efter enkel upparbetning eller efter modifieringar i vattenreningsapplikationer. Dessa tillämpningar kan vara varierande och vara intressanta för flera slutanvändare.

Key words: Filter material, steel slag, minerals, water purification, reprocessing, modification

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1 INTRODUCTION

In the previous project I-slag, two Swedish research groups have together with the industry proved, that many slags from Swedish steel mills can be processed for the purpose of water treatment and achieve quality and criteria that are interesting for exploitation in the society. The technology to control slag processes to form the material with excellent phosphorus-binding and metal separation properties and the water treatment processes coupled to that have come so far by projects in the I-slag that it is now time to open up the value chain. The new project MINRENT therefore aimed to explore the specific minerals in industry residues that can serve as seeds for the separation of substances that we do not want to get into the environment, such as phosphorus released to the Baltic Sea or metals leaking into groundwater. The goal is to develop metallurgical slag into complete filter products for water purification and that they can be part of a sustainable cycle with strong societal relevance.

Commercialization and availability in the market of selected slags for the removal of phosphorus and metals was one of the key indicators for a successful project. The primar~~il~~y application of the results by the Swedish metal industry is the use of slags in water treatment businesses. End-users are SMEs, which designs and build systems for small sewage plants in rural areas, manufacturer of compact filter bed solutions, industries (including mining) of local water pollution problems and the company that builds major thoroughfares including the clients of those.

The major portion of iron and steel is produced via pyrometallurgy. In 2016 the world crude steel production was 1,630 million tonnes and a significant amount of residues are produced along with the steel. The largest residue by weight is slag, which in Sweden corresponded to 71 percent of the steel residues in 2015. In Sweden, crude steel production in 2015 amounted to 4.7 million tonnes, while, slag production reached 1.35 million tonnes. The different iron-making and steel-making slag types, with different mineral composition, make slag suitable for a wide diversity of applications. The different applications and minerals are therefore not limited to the examples given for each slag type.

The European Union encourages utilization of products such as slag as raw material in order to conserve natural resources in accordance with Directive 2006/12/EC. In Sweden most iron- and steelmaking slags have been registered in REACH to be considered as by-products instead of residues. Slag usage in Sweden has increased in recent years; about 80 % of the slag produced in 2015 was used either internally by the steel plants or externally. The slag utilization in Sweden is still lower than in many other European countries. The lower usage in Sweden is coupled to abundance of natural resources and lack of sinter plants to recharge the by-products to the process.

2 AIMS AND DELIVERABLES

2.1 Aims

After completion of the project MINRENT, the steel companies have developed the offer to use metallic residual products up-graded to filter bed materials for water purification. The steel companies should have started delivery of filter products for all parts of the value chain with great environmental benefits and at competitive prices.

2.2 Performance targets and deliverables

Specific performance targets and deliverables were as follows:

1. At least two prototypes of soil beds (with selected slag) for wastewater treatment were put into operation and evaluated for at least one year.
2. Test of at least four applications of advanced mineral filters in full-scale for the purification of industrial wastewater (incl. stormwater from industrial areas).
3. At least one road section of 25 m was fitted with road shoulder support strips containing slag designed to block the spread of pollutants to groundwater. Field tests and evaluation have been performed for six months, including technical ideas on how to replace support strips when they are saturated with pollutants.
4. At least four trade-marked filter products based on slag and slag mineral has been developed with originality in the form of manufacturing method and application.
5. Two doctors have graduated (LTU, KTH) and one postdoc (Örebro) have obtained associate professor competence (equivalent) with specialization on mineral residues in water treatment.

The project delivered on three levels, academic, industrial and end customer adapted:

1. Scientific articles / reports produced by participating researchers and where the majority are published in journals with a high IF.
2. Methods to control processes in steelmaking so that slag properties achieve environmental and commercial advantages in e.g. final production of filter products (may be covered by IPR).
3. Two prototypes of treatment plants, two technical solutions and two manuals that can be used in several stages of end users (small to large companies, decision makers, environmental control authorities, teachers, etc.).

2.3 Impact objectives and contributions to the objectives of the program

The business benefits are clear for the Steelwork companies, which can expand their portfolio with manufacturing of filter products and for the small and large companies that have a cost-effective product to use in their filter applications.

The project contributes to the fulfilment of several of the environmental quality goals (e.g. no eutrophication, good groundwater quality) set by the Swedish Parliament. To replace natural gravel with specially crushed and processed slag in soil beds for wastewater treatment is in line with the national environmental targets for reduced virgin materials and increased use of alternative materials. This also satisfies many of intentions of the EU Resource Efficiency Strategy. In addition, as carbon dioxide emissions from steel and slag production is allocated to steel, the use of slag also contributes to reduced carbon dioxide emissions compared with quarrying. The new filter products produced from the slag and their minerals are tested already during the project once in full scale and evaluated by both researchers and those who practically use the results. It provides opportunities to adjust or improve in any further research but especially in the implementation phase. The new possibility of water purification for phosphorus or metal separation shall be implemented within environmental protection control bodies, e.g. county administrative boards and municipalities. The impetus for using slag designed for water purification comes from that need society today has to reduce the outflow of phosphorus to water systems and to the Baltic Sea.

Through the use of by-products, reuse of internal materials and recycling of metal content, the extraction of virgin raw materials is significantly reduced, both in internal and external use. The metallurgical industry works to ensure optimal use of the materials where different properties are utilized in different applications with the goal of substituting some of the traditional virgin materials with alternative materials and thereby reducing raw material extraction. Metallurgical slags used and developed in project MINRENT meet eminently program goals and outcome targets.

3 BACKGROUND

Research shows that many types of slag from steel mills can be processed for the purpose of water purification and achieve quality and criteria that are interesting for exploitation in this area. Based on the studies that have been carried out, we now know roughly what properties a number of minerals contribute. However, the results illustrate how small variations in chemical composition and variations in e.g. cooling processes can affect the composition of the individual minerals and thereby also their properties (Engström et al., 2013; Strandkvist et al., 2015). Slag is a multi-crystalline material whose properties (water purification ability, hydration ability, leaching ability) are determined by its mineral composition. Which minerals are found in each slag depends in turn on a number of parameters, including chemical composition, cooling rate but also how the slag is treated after it has cooled. Research on how the individual minerals contribute to the above-mentioned properties is still scarce. At Luleå University of Technology (LTU), studies on individual minerals and their dissolution and cement-binding properties have been ongoing since 2000. Within the I-slag project, these studies have been continued and broadened to also include the minerals' water purification ability with a focus on phosphorus. Swedish universities, led by LTU and KTH, are today world leaders in research on individual minerals with this focus. Additional knowledge should be gathered about a number of minerals and how small variations in the composition of the mineral can affect its properties. This should be done at the same time as practical application under real conditions. The conviction is that this knowledge ultimately makes it possible to industrial i.e. already during the metallurgical process, design the mineral composition of the slag in an optimal way for the purpose. But even *in situ*, slag can be manipulated to obtain improved properties (Zuo et al., 2015). Increased capacity to remove e.g. phosphorus can be achieved by combining different slags of different properties (Zuo et al., 2016).

Previous projects have shown that several slag has excellent properties for fixing phosphorus (P) or metals. Results from other projects with filter materials also indicate that drug residues and organic substances are broken down in metallurgical slag. Tests in the field for separation of P from wastewater and metals in run-off water from motorways (E18) have shown that scaling up is possible and that the metallic materials can be used all the way to sustainable use.

The function of a filter material depends partly on its element composition and structure and partly on the properties of the aqueous phase with which it is in contact and which grain fraction it is produced in. It will thus develop a dynamic balance with its surroundings, and it is the combined properties that determine its function. Given that the surface properties of the material are known, the effect of the aqueous phase can be calculated, or at least estimated. This applies both to its ability to sorb dissolved components in an aqueous phase and its tendency to go into solution (Sou et al., 2014). One consequence of this is that it is probably not possible to find an individual material that quantitatively sorbs both an- and cations at the same time as it binds organic substances with varying polarity. The material properties of a filter mass must therefore be adapted to a priority group of pollutants, based on their chemical properties, so a broad filter function will always be a compromise (Sjöberg & Karlsson, 2015). However, by optimizing the properties of the material, suggest also good retention also for components that are not the primary targets.

Steel slag with their combined physical and chemical properties is one such group of materials described above. The physical properties include mechanical stability and porosity. Chemical stability is also important because the environment in which they are used must not lead to the material dissolving or ceasing to function (Navarro et al., 2010). It is thus of utmost importance to ensure the external chemical limits of the material. Society often has major problems finding cost-effective solutions for water purification. Many types of slag have the opportunity to fill these gaps and become branded products. This particular approach was applied in MINRENT where researchers refined and further developed slag to finished products together with the steel industry while feedback was obtained from end customers responsible for construction of treatment plants.

4 MATERIALS AND METHODS

4.1 General execution of the project in work packages

The MINRENT project managed seven work packages (WP).

WP 1 consisted of project administration and management while the others had specific topics related to the goals of the project (Fig. 1).

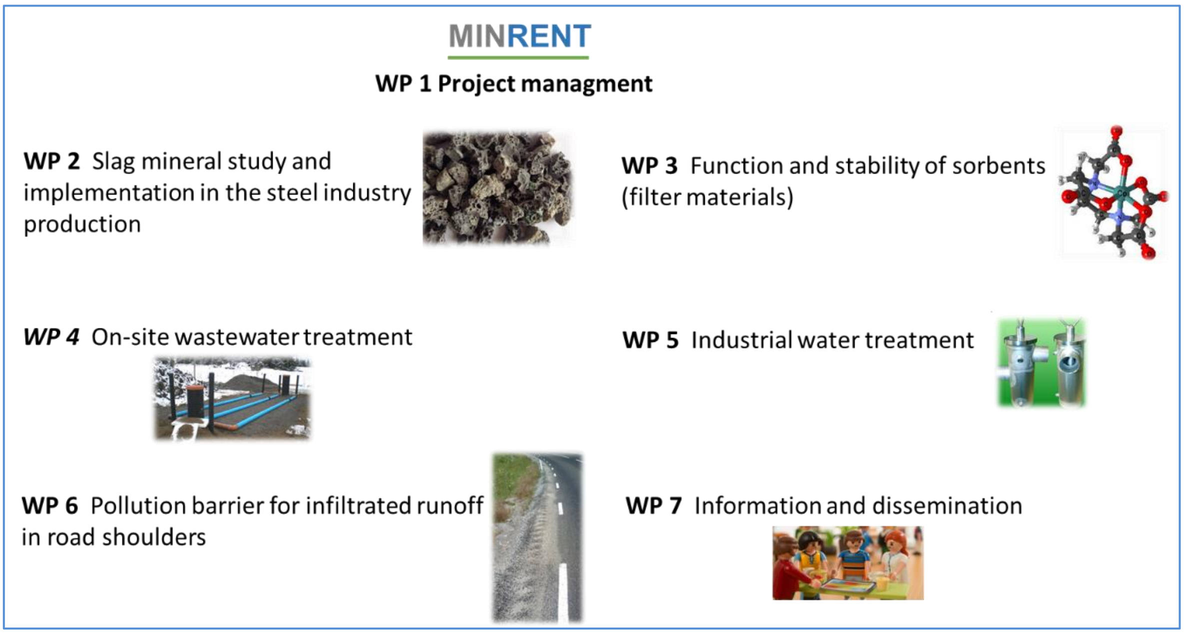


Figure 1. Illustration of the six Work Packages in the MINRENT project.

WP 2 worked with the production of new minerals and evaluation of its properties for water purification based on the experience obtained in project I-slag and the new knowledge achieved in MINRENT where full-scale experiments were applied. It was suggested that the properties of the slag are designed already during the metallurgical process in a way that is optimal for the purpose with respect to its mineral composition and appropriate application. WP leader was Luleå University of Technology (LTU).

In **WP 3** of the project two overarching objectives were included; i) the potential release of toxic elements and ii) the materials suitability to sorb (retain) toxic elements from contaminated water. In order to establish this information a series of tests under controlled conditions as well as realistic on-site tests were performed. WP leader was Örebro University (ÖRU).

WP 4 aimed to test, evaluate and show slag's potential for phosphorus reduction in wastewater generated at small-scale facilities. One facility (prototype design) of soil-bed type with slag mineral is built with the participation of Wåhlins AB and was studied in detail scientifically by the researchers. Alnarp Cleanwater Technology and Höganäs AB studied the performance of two facilities with slag material using replaceable filter bags and included also a study of plant availability of phosphorus sorbed to slag. WP leader was the Royal Institute of Technology (KTH).

WP 5 focused on the use of filter slag media for industrial filters (Ramson AB) and stormwater treatment (Flexiclean AB). Ramson is a high-tech company that manufactures filtration systems for everyone types of industrial processes. Flexiclean manufactures filter cassettes that can be used, for example, in stormwater wells at gas stations, large parking lots and industrial areas. Within WP 5, filters were tested to separate mainly metals (at e.g. landfill sites) but also organic substances. Results from WP 2 and WP 3 added the basis for which slag minerals to be tested in a full-scale test at each company. WP leader was ÖRU.

The purpose of the work in **WP 6** was to show in full scale how certain types of slag can be used to bind metals and organic compounds in road stormwater and hence prevent the contaminants from reaching the groundwater adjacent to the road. The technology can also be adapted for use with treatment of contaminated soil, contaminated dredged material and landfills. Participating company was Swerock AB whose role is to test the slag material properties for use as road shoulder material and pollution barrier. NCC AB had the role of preparing a road section where one pollution barrier with slag mineral can be tested. WP leader was KTH.

4.2 Specific methods and materials used in the work packages

<u>WP 2</u>

The experiments had the following protocol:

- Synthesis and dissolution of individual minerals
- Thermodynamic calculations
- Laboratory-scale experiments on real systems
- Full-scale verifications at Ovako in Hofors

The elemental analysis of the slag was performed by Ovako in Hofors using boron melts with x-ray fluorescence or ICP if the metallic iron content was too high. Other instruments and tests were performed at LTU using X-ray diffractometers, Scanning electron microscope (SEM), laboratory furnaces, and titration and leaching tests (EN 12457-2 where slag at 95 wt-% within the size 0–4mm is submerged in water at a liquid/solid, L/S, ratio of 10);.

The leaching test does not account for ageing and particle size distribution, which might be a problem, since they are known to influence the leaching. The impact of these parameters on the leaching of low-alloy EAF slag was investigated.

The ageing effect on chromium leaching of low-alloy EAF slag was investigated by crushing low-alloy EAF slag into different size fractions. The slag was aged outdoors in piles of different size fractions as one of the methods to test ageing and chromium leaching.

<u>WP 3, WP 5</u>

The experiments had the following protocol:

- Batch and column tests
- Sorption, release (leaching) and reconditioning
- Pilot-scale tests at landfill

Batch equilibrium tests were performed in 50 ml polycarbonate test tubes (Sarstedt) having a L/S (liquid to solid ratio) of either 10 or 100. The equilibrium time was set to 24 hours, according to preliminary tests. The samples were kept on a rotary tumbler during equilibration. All experiments were made in triplicates and with analysis of a minimum of three sub samples from each. Column tests were performed in 150 mm polycarbonate tubes, using gravity as driving force. Both desorption and adsorption experiments were conducted with constant flow as well as stopped flow in order to mimic real conditions when in use.

Since there is a potential release of harmful elements these experiments were made by extraction with 18.2 MΩ water at L/S 10 and 100. Both batch equilibration and column tests, including stopped flow, were used. In addition, the release in the sequential leaching tests were used to evaluate the chemical end points for metal release. Concerning reconditioning, the release of sorbed metal species was studied with the emphasis of metal recovery using solution properties.

Metal analysis was made with ICP-MS (Agilent 7500cx) or MP-AES (Agilent MP 4210). Principal inorganic anions were quantified with ion-exchange chromatography using a Dionex AS12A separation column. Electrical conductivity, Eh and pH were measured with conventional potentiometry. In the batch experiments, including the sequential extraction, a combination with centrifugation (9000 rpm, 30 minutes) followed by syringe filtration (polycarbonate, 0.20 µm) was used to separate the "dissolved" phase from the solids. For column experiments, only filtration was necessary.

In addition to the experiments with controlled test solutions the suitability of the different materials was also evaluated under future operational conditions. Two examples with challenging matrices were selected as they were close to the endpoints for the materials. Ground water that had been contaminated with high levels of metals and hydrophilic organic molecules were selected to evaluate the multi functionality of the sorbents. The function of the slags was evaluated with batch as well as column experiments. The feeding solution consisted of brines from washing of incineration ashes at different dilutions in order to determine the highest concentration that would interfere with element adsorption. Both original and metal spiked brines were used to determine the adsorption specificity and capacity under different conditions.

<u>WP 4</u>

The experiments had the following protocol:

- Full-scale tests for small-scale wastewater treatment
- Pot experiment in green-house for plant availability test

The focus was on phosphorus removal of the systems that were constructed (soil-slag bed) or installed (package treatment plant) but also other parameters such as nitrogen removal, bacteria reduction, organic matter removal (BOD_7), pH and hydraulic loading were included in the studies.

Measurements were made in the field and/or laboratory. Field equipment used was Hach Multimeter HQd with sensors for pH, electrical conductivity, temperature, redox and oxygen. Phosphorus and nitrogen analysis were performed at KTH laboratory using SEAL autoanalyzer instrument or samples were sent to accredited laboratory.

The pot experiment was performed in cooperation with the Swedish Agricultural University in Alnarp.

WP 6

The experiment had the following protocol:

- Full-scale test in the field

The ISCO automatic water sampler was used to collect flow-proportional road runoff and filtered water at the study site E18, Vreta, Norrtälje. The physical parameters pH, electrical conductivity and temperature were measured in the field when collection of samples took place after each rainfall/snowmelt event. The Hach HQd instrument in WP 4 methodology was also used here.

Samples for metal analyses with ICP-MS were delivered to accredited laboratory ALS Scandinavia.

5 RESULTS

5.1 Leaching of elements from the slag matrix – modifying the minerals to avoid release

The aim was to minimise the chromium leaching of low-alloy electric arc furnace (EAF) slag by modifying the minerals and/or mineralogy in the slag so that the chromium-containing minerals do not dissolve. In low-alloy electric arc furnace slag there are three chromium containing minerals: spinel $(Mg,Fe)Cr_2O_4$, magnesiowüstite (Mg,Mn,Fe)O and brownmillerite $Ca_2(Al,Fe)_2O_5$. Among these minerals, the spinel has already been determined to be stable.

Instead of indirectly examining the chromium leaching from magnesiowüstite and brownmillerite by comparing chromium leaching from slag samples, individual investigation of the dissolution properties of the minerals were performed. Dissolution of different compositions of magnesiowüstite and brownmillerite were studied at pH 7 and pH 10 for 40 hours. It was found that increased iron content decreased the dissolution rate of both magnesiowüstite and brownmillerite. Magnesiowüstite (Mg,Fe)O did not dissolve at pH 10 when it contained 60 wt-% FeO and did neither dissolve at pH 7 or pH 10 at higher FeO content. According to thermodynamic calculations, the FeO content in the magnesiowüstite can be affected and this was investigated. Laboratory and full-scale experiments showed that chromium leaching had no correlation to the composition of magnesiowüstite in slag. The conclusion was that magnesiowüstite was not the main mineral leaching chromium.

Brownmillerite composition is difficult to control in slag and had a significant impact on the dissolution rate. Therefore, brownmillerite in slag should be avoided to minimise leaching of chromium. From thermodynamic calculations, two options to avoid brownmillerite formation were identified: decreasing the basicity (CaO/SiO_2 ratio) or increasing the cooling rate. Both methods were tested in laboratory scale using low-alloy electric arc furnace slag. When the basicity was decreased by SiO_2 addition, the chromium leaching of the slag decreased (Fig. 2). The chromium leaching was correlated to the brownmillerite content, the chromium leaching decreased with the decreasing basicity until brownmillerite was no longer detected by XRD analysis. After that, the chromium leaching did not decrease significantly, indicating a correlation between basicity, brownmillerite and chromium leaching. When cooling of slag, the slower cooling rates increased the chromium leaching and fast cooling rates decreased the chromium leaching. The full-scale trials with different cooling methods confirmed that the faster-cooled water-sprayed slag had lower chromium leaching (0.3 mg Cr/kg slag) than slag that had cooled by its own (1.4 mg Cr/kg slag).

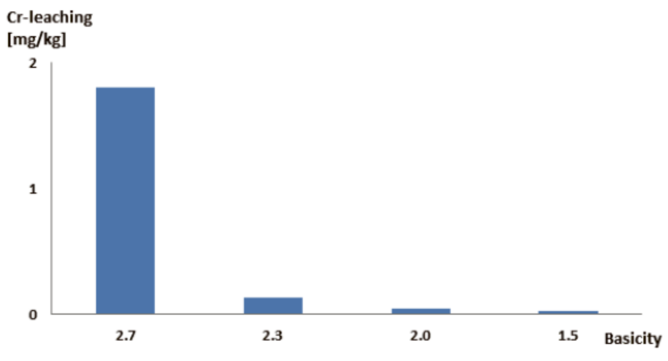


Figure 2. Chromium leaching of slag with different basicity caused by SiO_2 additions

Si-sand addition was used to decrease the basicity to 2.2, which would prevent brownmillerite formation according to thermodynamic calculations. The targeted basicity of 2.2 was difficult to achieve, as the basicity varied between batches since the scrap composition and other parameters changed. Batches from other experiments were included for more data. The chromium leaching of batches below basicity 2.2 did not reach the same magnitude as the batches above basicity 2.2.

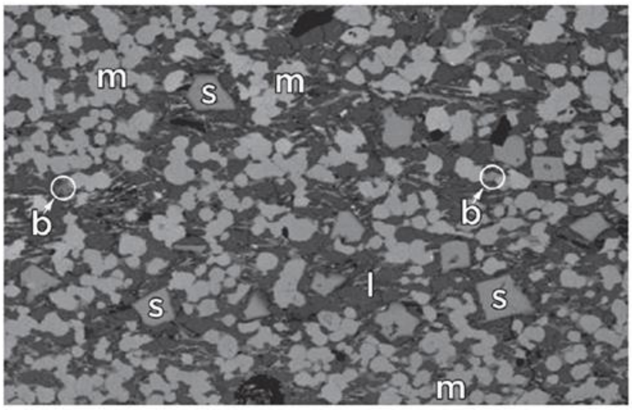


Figure 3. SEM image of low-alloy EAF slag with modified basicity from Ovako Hofors. The minerals present are spinel (s), magnesiowüstite (m), larnite (l) and brownmillerite (b).

Moreover, it was discovered that ageing of low-alloy electric arc furnace slag increases the chromium leaching and it is related to the particle size of the material (Fig. 4). The chromium leaching issue was carefully investigated by Strandkvist (2020).

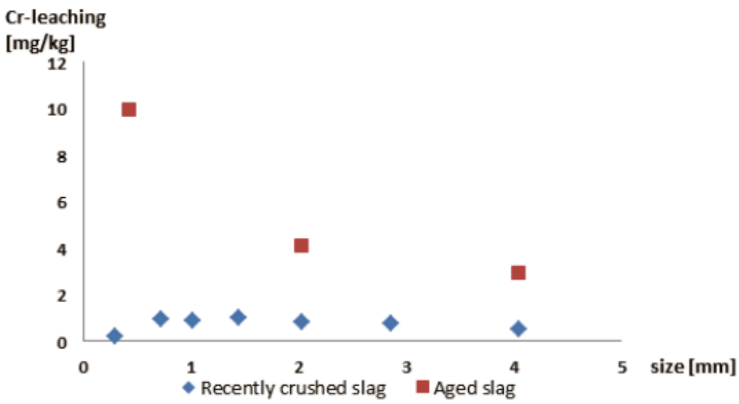


Figure 4. The chromium leaching of recently crushed and aged slag samples from different size fractions.

5.2 Dissolution of matrix minerals – implications for slags used in water treatment

Reactive filters for treating domestic wastewater or water polluted from landfills, roads and urban areas are usually having a starting pH of 11 or more. The dilution of phosphorus and metal-binding minerals from the material´s matrix is crucial for the further precipitation and sorption to the material. In figure 5 the dissolution of four calcium silicate minerals are shown from an EAF-slag. The fast and constant high dissolution rate of Larnite (Ca_2SiO_4) is visible and a lower but also constant with time dissolution at 15–20 % for the other three minerals Merwinite ($Ca_3Mg(SiO_4)_2$, Monticellite ($CaMgSiO_4$) and (pseudo)wollastonite ($CaSiO_3$).

The total oxide composition of the minerals vary concerning reactive calcium oxide (CaO) from 65.12 % for Larnite, 51.18 % for Merwinite, 48.28 % for Wollastonite to 35.84 for Montecellite.

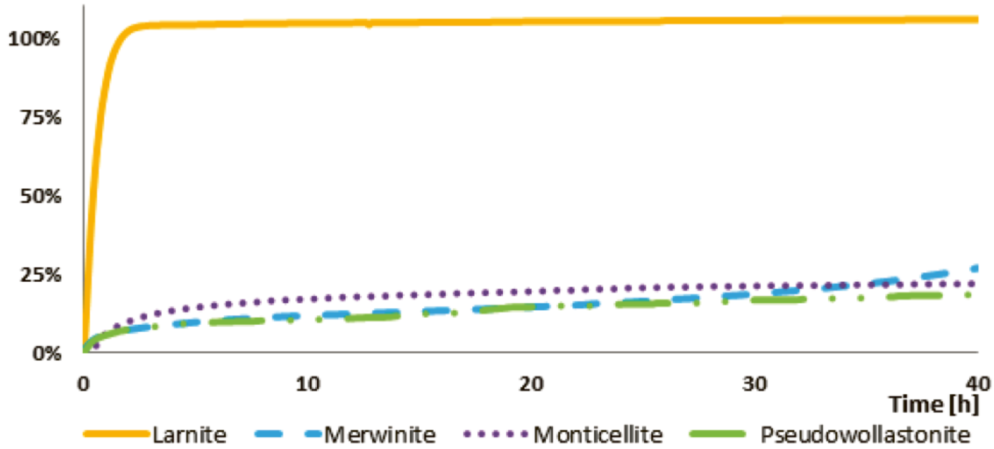


Figure 5. Dissolution (%) of matrix minerals at pH 10.

5.3 General impact on the solution phase

Equilibrium concentrations of four selected elements

The equilibrium conditions were determined upon contact with 18.2 MΩ water in column experiments. According to the aqueous concentrations of the principal metals the pH-buffering is highly related to the release of calcium (Fig. 6), which is most pronounced for the Al-red AOD slag. For this slag the equilibrium concentration is found at some 20 mg/l while the Si-red reached 10 mg/l. Aluminium behaves in a different fashion where the Si-red gives an equilibrium concentration of 3 mg/l and the Al-red some 1 mg/l. It is also interesting to note the almost three-fold increase for the Si-red slag as a response to stopped flow. This observation in combination with higher equilibrium concentrations both indicate the presence of aluminium mineral phases with higher solubilities in Si-red than in Al-red slag. Both iron and manganese have equilibrium concentrations below 1 µg/l and have rather unsystematic relations to volume, except for iron being released from the Si-red. The concentrations for these elements are however not of any significance for the use of the slags for metal retention purposes.

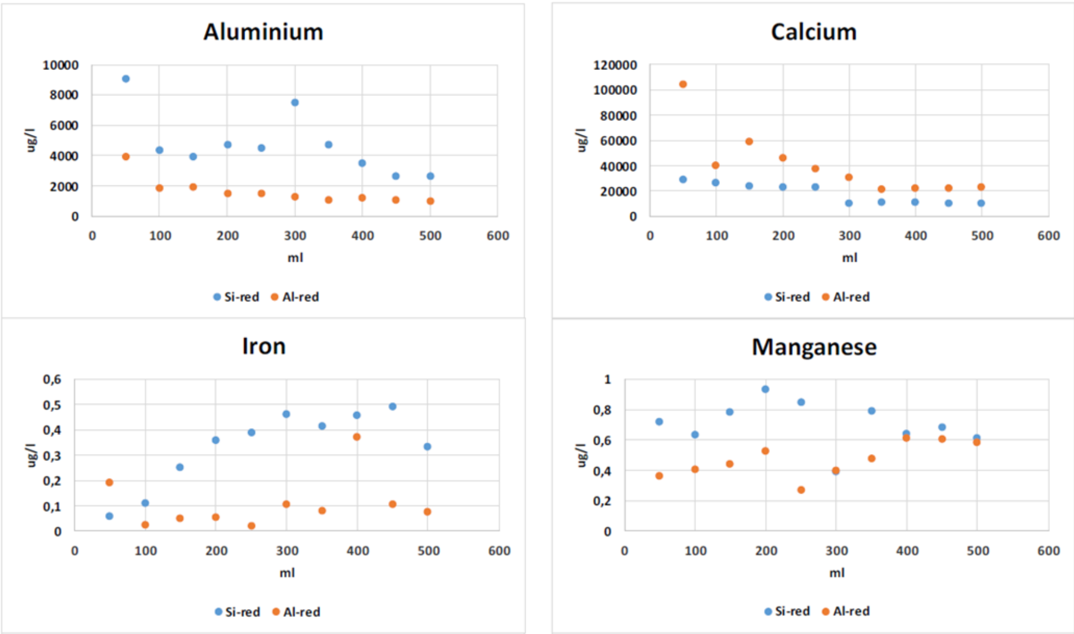


Figure 6. Concentrations (µg/l) of four principal elements in the aqueous phase as a function of accumulated volume (ml) during column tests of Si-red and Al-red AOD slag from Avesta Outokumpu. Stopped flow for 30 minutes at 300 ml.

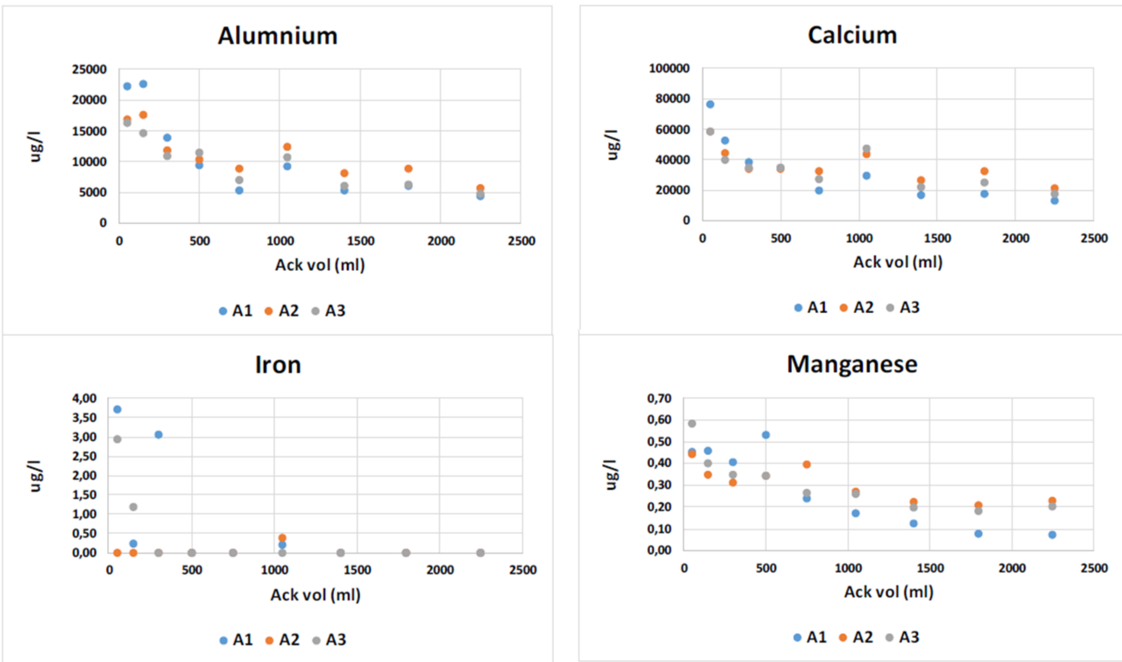


Figure 7. Concentrations (µg/l) of four principal elements in the aqueous phase as a function of accumulated volume (ml) during column tests of EAF slag from Höganäs. Stopped flow for 30 minutes at 1000 ml. Data presented for three separate replicates A1–A3.

The column tests of the Höganäs EAF slag gave steady state concentrations of some 0.5 mg/l aluminium, 20 mg/l calcium, and 0.5 µg/l iron, and 0.2 µg/l manganese (Fig. 7). When the flow was stopped the concentrations of aluminium and calcium increased, which is a clear indication that the system was not in equilibrium during the flow test. For all elements, there was a high wash out of these elements during the initial volumes that reached 22 mg/l for aluminium, 80 mg/l calcium, 4 µg/l iron, and 0.5 µg/l manganese.

According to the acid dissolution of the solid phase of the slag sample from Vargön, the principal elements are aluminium, calcium, iron followed by manganese (Fig. 8). After an initial release of up to 1000 µg/l calcium, the concentrations of the other elements stabilised at quite low steady state concentrations. They were some 5 µg/l aluminium, 100 µg/l calcium, 0.5 µg/l iron, and 2 µg/l manganese. The stopped flow test did not result in any significantly increased concentrations. Hence, these data all indicate that the material is quite inert and does not readily react with water.

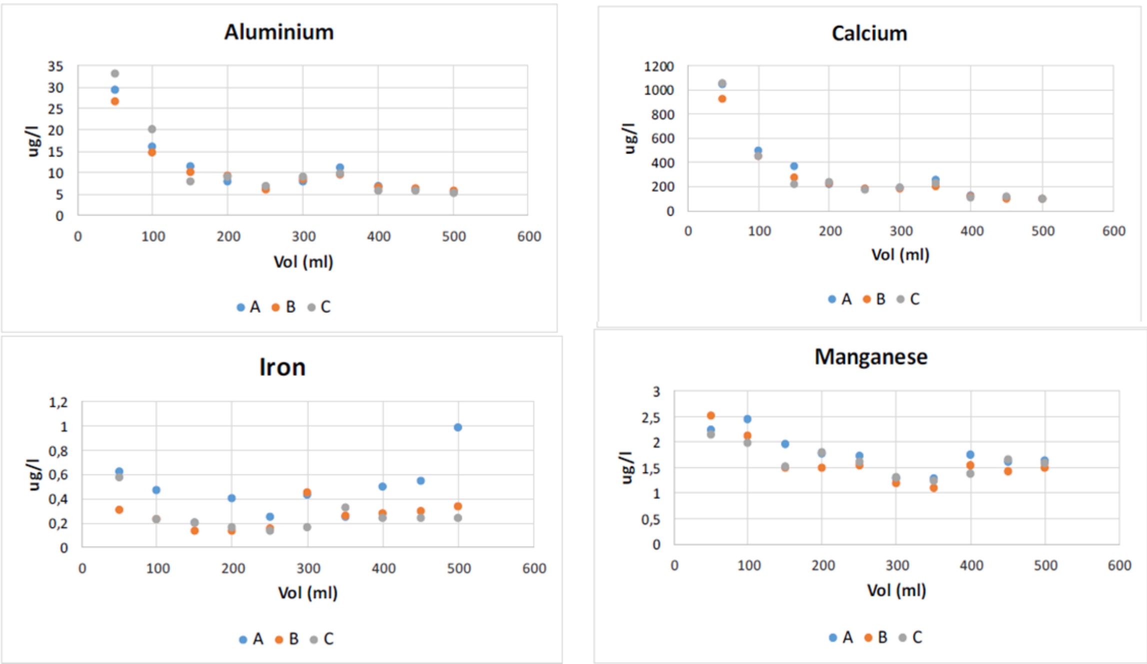


Figure 8. Concentrations (µg/l) of four principal elements in the aqueous phase as a function of volume (ml) during column tests of slag from Vargön. Stopped flow for 30 minutes at 350 ml. Data presented for three separate replicates A1–A3.

<u>Sequential leaching of four selected elements</u>

The release of major elements is generally supported by the results from the sequential leaching that was used to determine under which chemical conditions the materials are destabilized.

For the AOD slag from Avesta Outokumpu, small qualitative differences were found between the two types of slag. Only potassium and sodium were easily released when the slags were extracted with deionized MQ water (ultra pure Milli-Q). For the aluminium reduced slag some 20 % potassium and 40 % sodium were leachable whereas this corresponded to 20 % and 25 % for the silicon reduced variety. These two elements were extractable in all the other treatments, which indicate that they will influence the ionic strength of water in contact with these solids. The rest of the major elements all shared a high reducible fraction and a smaller oxidative release. For aluminium and iron only these two solid species were dominating in both slag types. The reducible treatment (fraction Red) released some 60 % and 80 % of the aluminium in the aluminium and silicon reduced slags, respectively. This is a clear indication that aluminium is included in a reducible phase of another element since it is not reducible under the conditions of the treatment. Both slag types also contained some 20–30 % aluminium that was released in the oxidative treatment (fraction Ox). According to the redox chemistry of aluminium this phase must have another primary element.

Concerning the Höganäs sample, the sequential extraction indicated that reducing species were the single most important fraction of the extractable principal elements, except for potassium. Notable releases upon treatment with MO water was found for sodium (13 %), potassium (2 %), calcium (2 %) and aluminium (2 %). For aluminium and calcium these findings are somewhat surprising considering the high steady state concentration in the column experiment and might indicate a phase transformation as the material comes into contact with water. In contact with ammonium acetate at neutral pH (Ac7) there was a release of potassium (35 %), sodium (10 %) and calcium (10 %) while no of the others had any detectable releases. Upon leaching with ammonium acetate at pH 5 (Ac5) some 20 % was released for all elements except aluminium (5 %) and iron (10 %). These responses indicate that the slag is sensitive to particularly the impact of acid, since the matrix elements were mobilised. In addition, the release of calcium, potassium and magnesium indicate the presence of non-specific sites of retention.

Concerning the Vargön slag, the solid species, as determined with sequential leaching, of the principal elements are being mobilised in the reducing treatment (Red) for all elements (Figure 5.2.3.3). The release in the water treatment (MQ) was highest for sodium (30 %) followed by potassium (10 %), calcium (5%) and aluminium (2 %). No detectable release in water was found for iron, magnesium and manganese. Ammonium acetate (Ac7) mobilises some 10 % calcium, 5 % potassium and 5 % manganese. Upon extraction with ammonium acetate at pH 5 (Ac5) some 5 % aluminium, 2 5% calcium, 35 % iron, 10 % potassium, 30 % magnesium and 45 % manganese were released. Hence, the material is susceptible to a lowered pH, possibly through dissolution of carbonates and poorly ordered oxides. Hence, the if the slag is used as a sorbent it seems to be less suitable for systems that are acidic and at low redox potential.

5.4 Sorption of cationic and anionic metal species

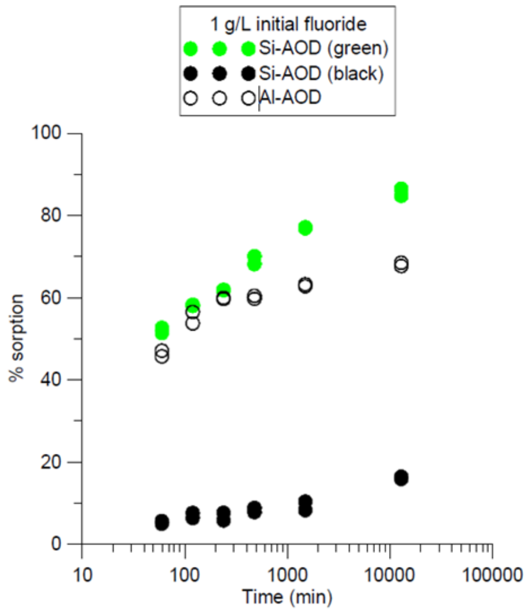
Concerning the Avesta AOD slag, capacities exceeding 200 µg/g were found for barium, cadmium, copper, nickel and zinc. The most surprising result was the efficient retention of arsenic since the test was made with arsenate ions (AsO_4^{3-}). This negatively charged species would not be retained by simple adsorption mechanisms since the pH of the system was 11.1, which is far above the estimated pH_{ZPC}. In fact, the capacity of both slags for arsenic was in the range of 400 µg/g. Chromium is the second element of interest since the tests were performed with chromium(VI) in the form of chromate ions (CrO_4^{2-}). For this element the aluminium reduced slag retained 60–75 µg/g whereas the silicon reduced only reached 20 µg/g. The different behaviour for the slags concerning the retention of chromium is also valid for molybdenum. That is, a retention capacity of some 25 µg/g for the aluminium reduced slag and just 5 µg/g for the silicon reduced one. Vanadium has a complex aqueous speciation with a number of oxy anions as well as simple cations, as a function of redox potential and pH in the solution. The high capacity of aluminium reduced slag of some 150 µg/g and some 90 µg/g for the silicon reduced one is an indication on a behaviour and aqueous speciation that is similar to arsenic.

The Höganäs EAF slag was an efficient scavenger for the majority of cations in the test. The approximate capacities were barium 35 µg/g, cadmium 45 µg/g, copper 50 µg/g, lithium 35 µg/g, nickel 35 µg/g, lead 40 µg/g and zinc 45 µg/g. The slag had a capacity for arsenic of some 45 µg/g.

The Vargön slag had in general a very low retention capacity, usually below 0.1 µg/g and for many of the elements not any significant retention at all. No anion adsorption was identified at capacities exceeding 0.01 µg/g.

Removal of fluoride ions

In a series of tests the retention of fluoride ions were made with three different slag types from Outokumpu with respect to capacity under different hydrochemical conditions. Both batch and column tests were performed. The tested slags were: i) green Si-AOD, ii) black Si-AOD and iii) Al-AOD. The results identified the green Si-AOD as the most responsive material with respect to equilibrium time (Fig. 9) as well as capacity (Fig. 10). On average, the adsorption capacities were found to be 65.5 mg/g for Al-AOD; 20 mg/g for black Si-AOD and 77 mg/g for green Si-AOD.



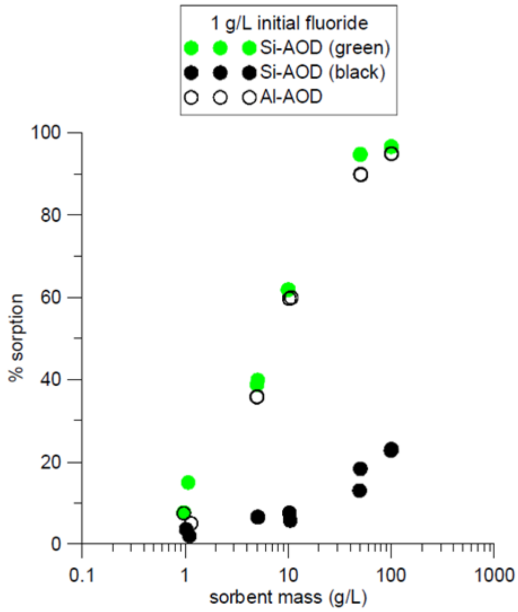


Figure 9. (left) and 10 (right). Adsorption of fluoride to AOD slag as a function of time. Adsorption of fluoride to AOD slag as a function of initial fluoride concentration.

5.5 Metal removal from industrial water and urban stormwater

Purification of water with AOD slag used to clean combustion ashes

In an effort to produce a clean brine from water used to clean combustion ashes the slag was evaluated for its potential use. In a study with brines the aluminium and silicon reduced slags from Outokumpu, respectively, were selected. Experiments were made both in batch mode and as column tests with a serial dilution of the brine and focus on copper, zinc, cadmium and lead. These ions all form stable neutral or negatively charged chloride complexes under the conditions in the brine. In order to cover a worst case scenario, the highest concentrations were set at 10 mg/l for each element.

The results from both batch and column experiments confirmed a high retention capacity of both slags, with a slight preference for the aluminium reduced one. A dilution experiment of the matrix showed that there was an almost quantitative removal of the selected metals up to a 50 % dilution. In these experiments the capacities for these elements exceeded those found in those where their capacities were determined. It was also clear that there was no competition between these ions why this high efficiency was retained at different concentration ratios of contaminating metals. For the concentrated brine, the efficiency dropped to some 80 % for copper and lead while zinc and cadmium reached some 55–60 %. No significant improvements were obtained by increasing the contact time or lowering the liquid to solid ratio. However, by using a pre-filter that contained another optimized waste product the combined retention efficiency was quantitative for the metals in question.

Treatment of multi-contaminated groundwater

AOD slag was used for treatment of groundwater contaminated with cations (Cu, Zn, Pb) anions (As, Cr) and polyfluorinated organic compounds. The suitability of slag was evaluated within the frame of the present project together with bark adsorbents. According to the general hydrochemistry at the site, the Outokumpu aluminium reduced slag was selected as the primary material. Batch adsorption studies with a 11 compounds mixture of PFAS had demonstrated a retention in the range of 30–35 % from a 5 µg/l solution. This result was not too impressive why the slag was combined with bark adsorbents that adsorbed similar fractions on its own. With this combination an increase of the high molecular PFAS mixture was found, reaching up to some 55 %. The low molecular weight material remained at 30 %. Increasing the bark ratio did not alter the efficiency. During these experiments the retention of cationic metals was quantitative, but it went down for the anionic metal ions. Following the results from the batch experiments where different proportions were evaluated the trials were extended to flow through systems where the bark and slag were mixed together. With this design the retention efficiency increased slightly and some 60 % of the high molecular weight fraction was retained. However, without any improvement for the low molecular weight fraction. A positive response was, however that the retention of anionic metal ions increased to some 80 % of the expected capacity.

Water purifying of leachate water from landfill area

The trial was made in IBC-containers filled with Petrit E (Fig. 10), where the water was pumped into the bottom of the container where it was evenly distributed over the whole bottom surface. The water then starts to flow upwards through Petrit E as filter media to the outlet valve at the top of the IBC-container. In these tests the Petrit E had a particle size distribution of 5 – 10 mm. As shown in Fig. 11, the results were in general very good and in some cases even better than expected. Copper, zinc and nickel have been tested in lab scale before the field trials with good results, which also were confirmed in these trials. The other evaluated elements (lead, cadmium, chromium and arsenic) were not analysed or evaluated before. The most positive and unexpected result was the very good purification of lead, which also then has been a subject of great interest from other partners.

Figure 10. Experiment with treatment of landfill leachate in IBC-containers filled with Petrit E.

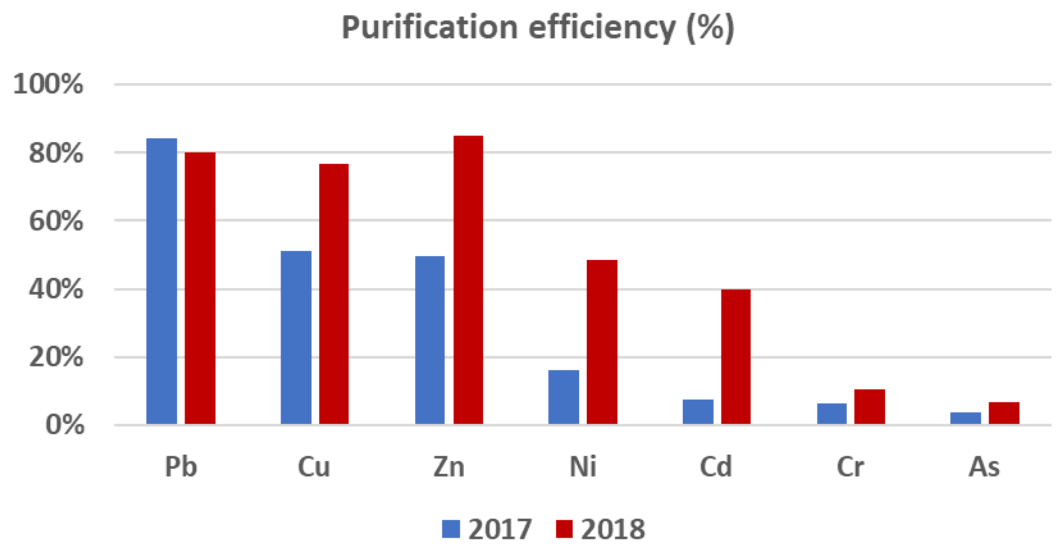


Figure 11. Metal removal efficiency of Petrit E from landfill leachate during two test trials.

<u>Water purification of internal wastewater from Höganäs steel plant</u>

The reason for these trials was not an actual problem with the outlet water today but instead that a) there might be stricter future regulations on outlet waters and b) it is much easier to conduct and follow up tests internally compared to do that on external sites. The preliminary results of using Petrit E for metal removal from industrial wastewater is shown in Fig. 12.

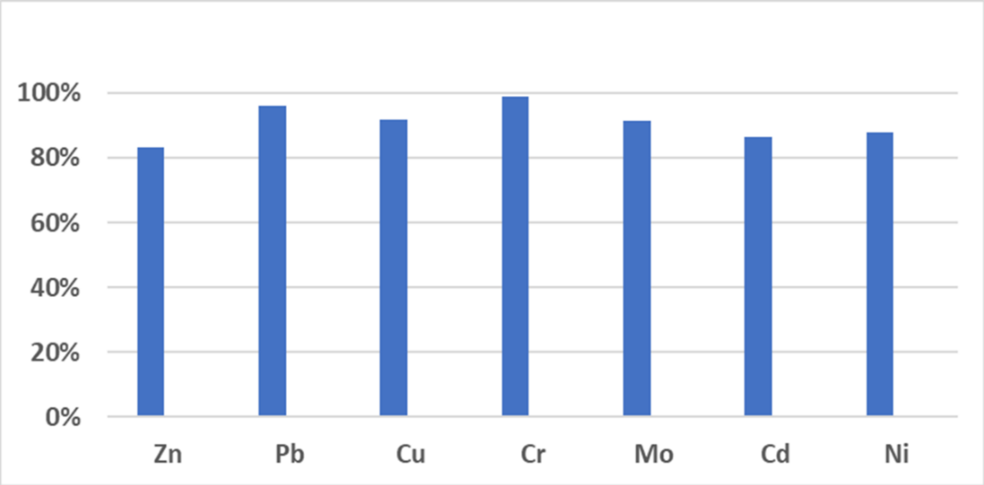


Figure 12. Results of water purification of industrial water (based on only a few analyses).

5.6 Phosphorus removal in slag filters used in on-site wastewater treatment systems

<u>Package treatment plant with phosphorus trap</u>

The site chosen for the trial was a system that handles sewage water from three households. The system consisted of the Alnarp Cleanwater Technology (ACT) treatment system followed by a filter well with a replaceable bag. In this case the big bag with 700 kg of standard mineral (particle size 2–6 mm) was replaced with a bigbag with a little more than 1000 kg Petrit E screened to the same particle size. The system is shown in Figure 13.

Figure 13. The ACT wastewater treatment system. The photo to the left shows the filter well with a bag filled with Petrit E.

The filter well with Petrit E operated for a period of one and a half year and the test period obtained very good results in terms of P removal efficiency (Fig. 14). After the end of the evaluation period the system continued to give high and stable results. But after some time, the effectiveness of the Petrit E material started to decrease, due to saturation of the filter media. As expected, the pH-level started to decrease at the same time, which is an effect that can be seen in other filter materials used for the purpose of phosphorus removal in onsite systems.

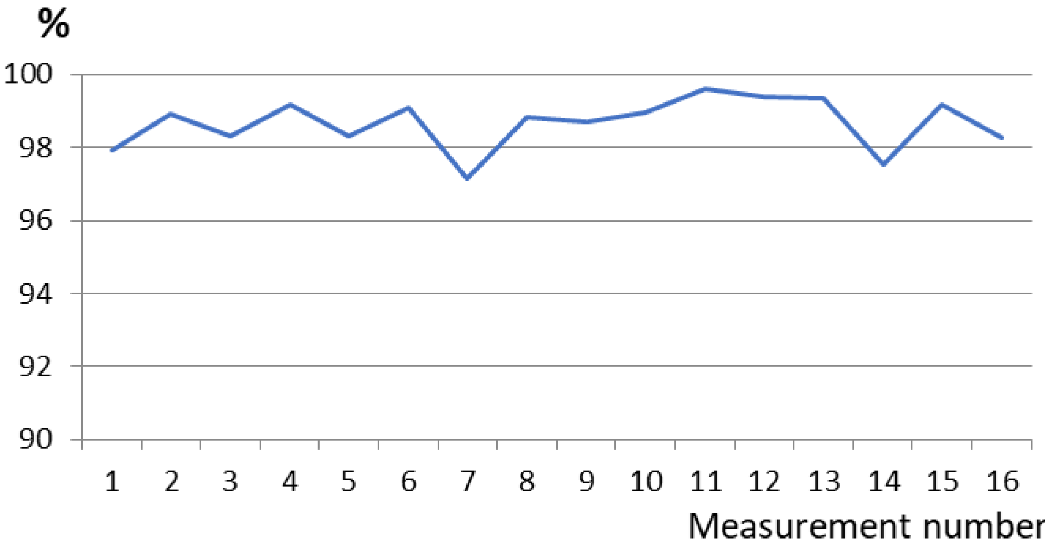


Figure 14. Phosphorus removal during 1.5 year based on influent and effluent grab water samples taken at irregular intervals.

Previous performed research, in e.g. the I-slag project, has observed cementation in CaO rich slags. This process might have influence on the porosity and hydraulic conductivity when filter slag is used in wastewater treatment. For this purpose an investigation was performed where samples of different fractions of Petrit E (EAF slag) were divided into two similar parts and tested in two ways. One part was held in water during the whole testing period and the other part was one to two times a week varied between being wet and dry, where the drying was carried out in ambient conditions indoors. During a test period of six months, the slag that varied between wet and dry slowly started to "burn" and became more and more homogenous. The slag held in constant water saturated conditions did not form a hard crust. There was also a clear difference in the color of the material. The material that had started to burn got a white surface, most certainly depending on carbonation of the lime (see fig. 15).

After the Petrit material was used in a filter system, a pot cultivation trial with spring wheat was performed to investigate the P-fertilization effect. No negative effect on the plants could be demonstrated with the amounts used in the experiment. The higher proportion of dry matter for the plants that have received sewage-treated slag may indicate that the sewage-treated slag may have a potentially positive effect on growth. Further evaluation is needed to evaluate the long-term effect of slag as a fertilizer.

Figure 15. Color of slag that had been regularly wet and dry (left pic.) and slag that constantly had been held in water (right pic.).

Soil treatment system amended with AOD slag

An on-site wastewater treatment system was constructed for the first time with AOD slag (Avesta Outokumpu) as a phosphorus removal barrier in a soil treatment system (drainfield). The construction of the soil treatment system is shown in Figure 16.

Figure 16. Construction of filter bed. The grey material in the trench is ”masgrus”, AOD-slag. This phosphorus-binding layer is covered by sand (red-brown color) on which the distribution pipe from the septic tank will be placed. The red-colored pipe that stands out connect to a perforated pipe in the bottom of the filter bed, which transports the treated water out to the receiver (ground water or open ditch).

The phosphorus removal was monitored over a period of 18 months by grab sampling. The wastewater discharge was in average very low to this system (80 L/d) why the efficiency showed high performance with an average phosphorus removal of 98.5 %. Soil filters with only sand shows much lower removal efficiency, usually around 40 %.

5.7 Removal of pollutants from road run-off with road shoulder slag filters

A selected section of the road E18 between Norrtälje and Kapellskär studied a new technology developed in the project MINRENT for road run-off purification. The construction of the so-called road shoulder filter (RSF) took place in August and beginning of September 2018. Figure 17 show the completed system, consisting of a water impermeable plastic liner attached below the edge of the asphalt and forming two individual filter beds with drainage pipes at the bottom. A well for collecting water from the filter beds was installed in the road slope. The filter media used was locally available gravel from crushed granitic bedrock (8–32 mm), usually applied in the road shoulder, and AOD-slag (2–8 mm) delivered from Avesta Outokumpu, Avesta). Length, width and depth of each trench was 25 x 1.1 x 0.4 m.

The measurements of the RSF ran from 2018-09-13 to 2018-12-18. A number of seven rain/snow melt events were studied, which represented 32 % of the total precipitation for the study period. Grab and automatic sampling (ISCO) took place for water analyses, primarily metals. The results presented in figure 18 show that the AOD-slag filter had better removal performance than the filter with crushed bedrock. However, removal of metals in that medium is clearly visible. For AOD-slag, no removal of molybdenum (Mo), vanadium (V) and chromium (Cr) was observed when it appeared in the influent road runoff. Copper that mostly appear in particle-bound form, was probably removed by physical filtration in the gravel filter.

Figure 17. The RSF with crushed gravel in the foreground, followed by that with AOD-slag (left picture). Winter conditions (December) at the RSF site.

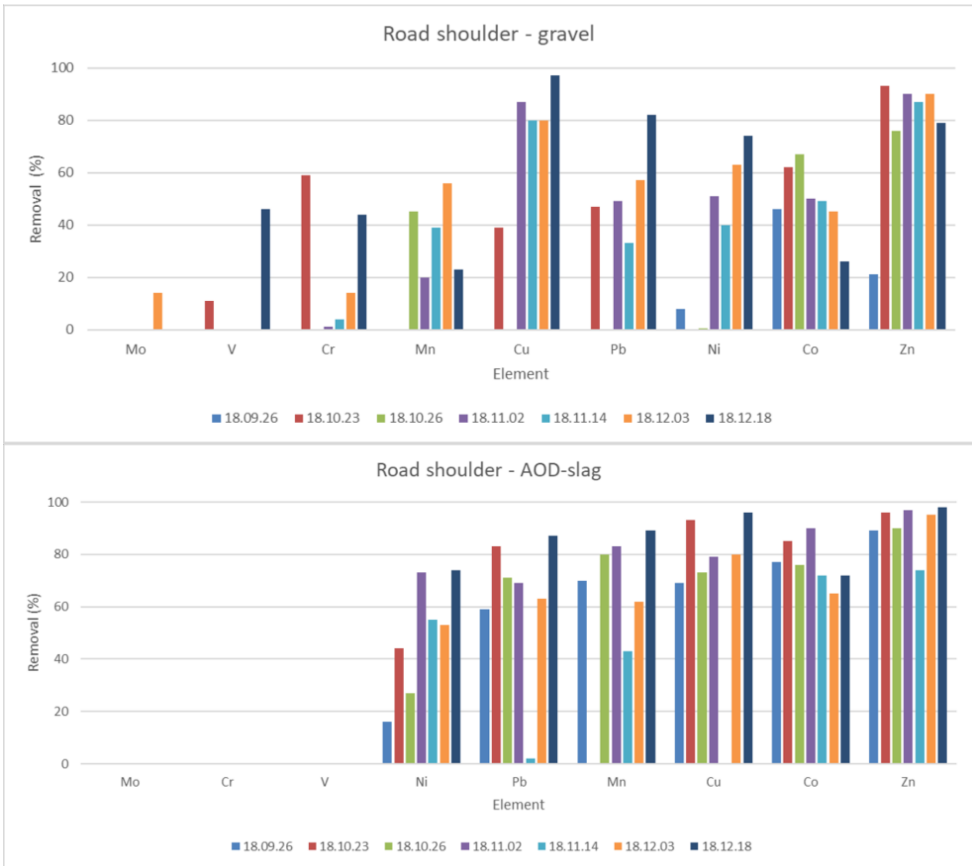


Figure 18. Removal efficiencies (RE) for the first four months in use of the RSF system. RE calculated from sampled influent runoff and effluent flow-proportional runoff.

6 DISCUSSION

The studies within project MINRENT has demonstrated that slags can be used for the removal of both cationic and anionic elements from polluted waters. Retention of cations follows an anticipated sequence of mechanisms based on adsorption and surface precipitation. Anionic species are retained even at pH 10 through the formation of surface precipitates where the dissolution of cationic reactants is essential. The most efficient slags have capacities in mg/g range for both cat- and anionic species. The choice of slag depends on its stability under the chemical conditions it is to be used, i.e. its chemical stability and ability to retain pollutants. For the materials tested in this study pH and redox potential were found to be the single most critical parameters. Particularly the combination of low pH and low redox potential limited the functionality and could in fact result in a net release of elements. Fortunately, the slags with high functionality also are self-buffering why a suitable pH is maintained as long as the consumption by the contaminated water does not exceed the buffering rate. Field tests have demonstrated that brines, i.e. calcium/sodium chloride solutions close to saturation, can be freed from copper, zinc, cadmium and lead at 10 mg/l each. For brines at 50 % concentration the removal efficiency is quantitative but is lowered in the concentrated ones. This can, however, be circumvented by the combination with another waste product.

The combination of slag and bark is suitable for the removal of cations, significantly lower the concentrations of anionic metal species and lower the concentrations of PFAS. However, a fully employed system needs more work on optimization. However, mixing of materials or layers of different filter materials is a challenge both from a construction and purification efficiency point of view. Fluoride ions can be removed from complex solutions by some slag varieties. It was discovered that one modification of Si-AOD had a high capacity, rapid response and high tolerance for matrix changes in the water to be treated.

The reactivity of minerals, which slags are composed of, with water has primarily been seen as something to prevent as it can result in unwanted leaching. However, being reactive in water is also connected to desirable properties. The reactivity of the slag minerals is connected to the ability of purifying water. The connection between the reactivity and purification would be interesting to determine further, if it applies to all minerals, as well as the mechanics behind the purification. Ageing of the slags has shown to negatively influence the removal of pollutant elements. It can also affect the leaching of chromium from the slag matrix. In order to overcome long ageing periods, a method by auto-clave treatment to fast-age slag, was successfully tested with low-alloy EAF.

The project found possibility to make changes in slag composition that only affects the properties of solidified slag and not the properties of slag in the furnace, for examples impurity removal and refractory wear. Most of the time, changes in composition are made to remove an unwanted property of the slag. However, it would be interesting to see if these kinds of changes can be used to improve the wanted qualities and result in slag that is custom-made for an intended application.

The pilot and full-scale water filtration systems tested in the field were successful and proved the tested slag materials´ capacities to clean water to required standards. We strived to implement the solutions in real facilities together with the companies, but unfortunately there were delays for various reasons. This caused the test period to be considerably shortened, which meant that it is difficult to deduce from the results how long the life of the various filter systems can be.

Slag that varies between being wet and dry conditions shows a tendency to sinter or burn like cement quite rapidly. In that case, the specific surface area will decrease and the porosity of the bulk will get lost and causing hydraulic failure. If the filter system is designed in such a way that the slag varies between being wet and dry conditions this might be problem, particularly if the slag has a particle size below 4 mm.

7 CONCLUSIONS

The conclusion of both the laboratory-scale and the full-scale trials is that brownmillerite is the main mineral responsible for chromium leaching from a low-alloy EAF slag that was included as one candidate for water filtration purposes. However, brownmillerite formation can be avoided by decreasing the basicity, CaO/SiO_2 ratio, to 2.2 or less. Moreover, basicity should be higher than 2.0 to avoid formation of merwinite. We concluded that basicity is not the only parameter affecting undesirable chromium leaching; a faster cooling rate, still resulting in a crystalline material, decreases chromium leaching, albeit not to the same extent as decreasing the basicity. It may not be possible to control the full-scale process to an exact basicity for each batch, but the resulting decrease in basicity may still result in an overall decrease in chromium leaching.

The dissolution rate of a mineral correlate to pH and elemental composition in the mineral. This confirmed result is important for the understanding of mechanisms for metal and phosphorus sorption (i.e. cationic and anionic species) to the different slags produced in Sweden.

In combination with limited hazardous metals leaching, the AOD-slag (Outokumpu, Avesta, Sweden) is appropriate for use as a filter material for treatment of contaminated water and it has been successfully applied as filter material for treatment of arsenate spiked natural water sample with average removal efficiency of 84 % (solid to liquid ratio of 200).

The practical functionality of slags showed pros and cons in the field experiments. The few cons can be overcome with minor changes such as control of the high water pH from slag filter effluent. The life of various types of slags produced in Sweden is still unclear after the water treatment systems applied in project MINRENT. However, the metallurgic slags used and developed in the project meet eminently program goals (see Appendix 4) and outcome targets. The remaining work is for the industry and water treatment companies to improve the opening of the value chain. The academic research entities have to follow-up pilot and full-scale plants for scientific validation of their long-term water purification efficiencies.

8 IMPLEMENTATION OF THE RESULTS AND FUTURE WORK

The participating companies from the steel industry have in several respects reached milestones concerning management, product development and marketing. At the end of the project, the companies have gained knowledge about e.g. process control to avoid undesirable mineral formation, which in slags implies chromium leaching. Moreover, how slags should be prepared to meet standard requirements in filtration systems as well as consent limits for purification. Wastewater treatment businesses involved in the project have learned how to use mineral slags in their present systems as well as in new applications. Problem owners such as municipalities and government agencies have contacted the companies, which indicates an incipient market uptake.

The future arena of research to reach full "payment" of the effect targets is within sustainable industrial recovery and recycling of limited resources. In the case of phosphorus, methods should be developed for recovery from municipal wastewater using steelmaking slag products as an adsorbent to selectively separate phosphorus from wastewater before its concentration by e.g. the forward osmosis (FO) process. Concerning metal recovery after filtration of metal-contaminated wastewater, leaching is the most widely used one as it can be a stand-alone process as well as a pre-treatment of slag application in construction. Thermal (heating) treatment was reported to be an effective method for recovery of selected metals which have volatile properties. Besides these possibilities, many other applications in environmental treatments can be mentioned, water treatment as adsorbent and filtration media, neutralizing agent, soil treatment, gas treatment and catalysts.

9 SUSTAINABILITY

Effect of the project	Reuse and possible recycling of by-product slag in water and wastewater treatment
Reference case	Phosphorus or metal removal from wastewater (Höganäs vicinity, Skåne; Vallentuna, Uppland; Norrtälje, Uppland

	1. Raw materials	2. Production	3. Use	4. Recycling	5. Residuals
A. Use of resources	0	0	+	+	0
B. Emission of greenhouse gases	0	0	-	0	0
C. Other emissions	0	0	0	+	0
D. Influence on the natural environment	0	0	0	0	0
E. Working environment and health	0	0	0	0	0
F. Human rights					
G. Equality and diversity					
H. Economic advantage for companies	0	+	+	+	+
J. Economic advantage for society	0	+	+	+	+

	Area (e.g. A-I, E-4)	Describe how the project affects this aspect of sustainability
Positive aspects (+)	A3	Use of slag instead of costly storage (landfilling)
	A4	Resource recycling for environmental applications
	C5	Capture of phosphorus and metals leaching to surface/ground water
	H2	More environmental-friendly slags produced
	H3	Economic benefit instead of costly landfilling
	H4, H5	Economic benefit and contribution to sustainable development
	J2, J3, J4, J5	Less environmental impact, clean lakes and seas
Negative aspects (-)	B3	Transport with heavy vehicles to designated water treatment sites

10 REFERENCES

Caspersen, S., & Hermansson, C. (2019). Fosfor–återföring från avlopp till åker med slagg. LTV-fakultetens faktablad. Fakta från SLU Partnerskap Alnarp 2019:7

Engström, F., Adolfsson, D., Samuelsson, C., Sandström, Å. & Björkman, B. (2013). A study of the solubility of pure slag minerals. *Minerals Engineering*, 41, 46-52.

Navarro, C., Diaz, M. & Villa-Garcia, M.A. (2010). Physico-chemical characterization of steel slag. Study of its behavior under simulated environmental conditions. *Environmental Science and Technology*, 44, 5383-5388.

Sjöberg, V. & Karlsson, S. (2015). Impact of organic carbon on the leachability of vanadium, manganese, iron and molybdenum from shale residues. *Minerals Engineering*, 75,100-109.

Strandkvist, I., Björkman, B. & Engström, F. (2015). Synthesis and dissolution of slag minerals - a study of β-dicalcium silicate, pseudowollastonite and monticellite. *Canadian Metallurgical Quarterly*, 54, 446-454.

Strandkvist, I. (2020). Minimisation of Chromium Leaching from Low-Alloy Electric Arc Furnace Slag by Mineral Modifications. (Doctoral dissertation). Luleå University of Technology

Sou, G., Wu, Y., Chen, X., Hou, W. & Wang, Q. (2014). Adsorption of heavy metal ions between EAF steel slag and common mineral adsorbents. *Desalination and Water Treatment*, 52, 7125-7132.

Zuo, M., Renman, G., Gustafsson, J. P. & Renman, A. (2015). Phosphorus removal performance and speciation in virgin and modified argon oxygen decarburisation slag designed for wastewater treatment. *Water Research*, *87*, 271-281.

Zuo, M., Renman, G., Gustafsson, J. P., 2016. Optimised phosphorus removal technology for small-scale wastewater treatment by combining metallurgical slags. Proceed. of 13th IWA Specialized Conference on Small Water and Wastewater Systems in Athens, 14-16 September 2016.

APPENDICES

Appendix 1 Project Organisation and participants

a) Participating researchers and industry representatives

Name	Organisation
Robert Eriksson	Jernkontoret
Agnieszka Renman	KTH Royal Institute of Technology
Gunno Renman	KTH Royal Institute of Technology
Fredrik Engström	Luleå University of Technology
Ida Strandkvist	Luleå University of Technology
Stefan Karlsson	Örebro University
Björn Haase	Höganäs Sweden AB
Gunnar Ruist	Outokumpu Stainless AB
Ingegerd Hemdal	Ovako Sweden AB
Kjell Pålsson	Ovako Sweden AB
Jeanette Stemne	SSAB
Anita Wedholm	SSAB
Staffan Rahmn	Vargön Alloys AB
Annelie Papadopoulos	Vargön Alloys AB
Magnus Jansson	Vargön Alloys AB
Olle Sundqvist	Sandvik Materials Technology, AB
Peder Eneroth	FlexiClean AB
Ragnar Sjöberg	Ramson AB
Kent Jansson	Swerock AB
Martin Tengsved	Swerock AB
Fredrik Wåhlin	Team Wåhlin Mark & Asfalt AB
Clara Hermansson	Alnarp Cleanwater Technology AB
Magnus Alfredsson	NCC AB

b) Description of the project organisation

The MINRENT project managed seven work packages of which WP 1 was solely project administration and management. The coordinating organization was KTH Royal Institute of Technology in cooperation with Jernkontoret. The total budget was 10 319 578 SEK of which 4 000 000 SEK was received from Vinnova.

Appendix 2 Publications

a) Refereed publications (published or accepted for publication in a scientific journal)

Nr	Title	Authors	Journal
A1	Phosphorus removal by slag depends on its mineralogical composition: A comparative study of AOD and EAF slags.	Zuo, M., Renman, G., Gustafsson, J.P. & Klysubun, W.	Journal of Water Process Engineering 25, 105-112. (2018)
A2	Effect of FeO/MgO Ratio on Dissolution and Leaching of Magnesiowüstite	Strandkvist. I., Sandström. Å., Engström, F.	Steel Research International, Vol. 88, 6, (2017)
A3	Dual slag filters for enhanced phosphorus removal from domestic waste water: performance and mechanisms.	Zuo, M., Renman, G., Gustafsson, J. P. & Klysubun, W.	Environmental Science & Pollut. Research, 25(8), 7391-7400. (2018)
A4	Removal mechanism of arsenic (V) by stainless steel slags obtained from scrap metal recycling.	Liem-Nguyen, V., Sjöberg, V., Dinh, N. P., Huy, D. H., & Karlsson, S.	Journal of Environmental Chemical Eng. 8(4) 103833. (2020)
A5	Removal mechanisms of cadmium and lead ions in contaminated water by stainless steel slag obtained from scrap metal recycling.	Huy, D. H., Seelen, E., & Liem-Nguyen, V.	Journal of Water Process Engineering, 36, 101369 (2020)
A6	Minimizing Chromium Leaching from Low-Alloy Electric Arc Furnace (EAF) Slag by Adjusting the Basicity and Cooling Rate to Control Brownmillerite Formation.	Strandkvist, I., Pålsson, K., Andersson, A., Olofsson, J., Lennartsson, A., Samuelsson, C., & Engström, F.	Applied Sciences, 10(1), 35. (2020)

b) Manuscripts submitted for refereed publication

Nr	Title	Authors	Journal
B1			

c) Manuscripts in preparation for refereed publication

Nr	Title	Authors
C1	Swedish steelmaking slags – properties and utilization in water pollution abatement	Renman, A., Engström, F., Renman, G.
C2	Treatment of road runoff by road shoulder filters	Renman, A., Renman, G.

d) Theses (published or in preparation)

Nr	Title	Author	Date
D1	Enhanced phosphorus removal from wastewater using virgin and modified slags: performance, speciation and mechanisms. PhD Thesis, Royal Institute of Technology	Minyu Zuo	2017-09-29
D2	Minimisation of chromium leaching from low-alloy electric arc furnace slag by mineral modifications. PhD Thesis, Luleå Technical University	Ida Strandqvist	2020-05-12

e) Internal reports

Nr	Title	Authors	Report number
E1			

f) Other dokumentation

Nr	Title	Authors	Description
F1	Adsorption of Zn, Cd, V, Ba, Cu, Mo, Ni, Cr, Li and Pb to silicon and aluminium reduced AOD-slag.	Elmroth, E.	Bachelor Thesis, Örebro University FULLTEXT01.pdf (diva-portal.org)
F2	Vattenrening vid biltvätt - Exemplet Arla Foods	Suokko, J.	MSc Thesis Royal Institute of Technology FULLTEXT01.pdf (diva-portal.org)

Appendix 3 Other dissemination

a) Non-refereed international conference papers

Nr	Title	Författare	Conference
H1	Optimised phosphorus removal technology for smallscale wastewater treatment by combining metallurgical slags.	Zuo, M., Renman, G., & Gustafsson, J. P.	In: 13th IWA Specialized Conf.on Small Water & Waste-water Systems.
H2	Effect of aging on phosphorus removal of metallurgical slag and heat reactivation of aged slag.	Zuo, M., Renman, G., & Gustafsson, J. P	In: 2016 IWA Water Congress & Exhibition
H3	Influence of basicity on chromium leaching of low alloy EAF slag	Strandkvist. I, Engström. F, Andersson. A.	3rd ESTAD 2017 : European Steel Technology and Applications Days, Vienna, Austria, 26-29 June 2017
H4	Water purification with slag (Poster)	Haase, B., Ruist, G., Engström, F., Renman, A., Renman, G.	10th European Slag Conference, 8-11 October 2019, Thessaloniki, Greece

b) Non-refereed national conference publications, miscellaneous

Nr	Title	Authors	Date - place
J1	Projekt MINRENT: Resurseffektiv vattenrening med biprodukter från svensk stål- och metallindustri. POSTER	Haase, B., Hermansson, C.	Havs- och vattenforum, Göteborg 16-17 May, 2017
J2	Projekt MINRENT - Järn- och stålindustrin i industriell symbios med Vattenreningsindustrin - Leaflet	Project	2018
J3	Fosfor – återföring från avlopp till åker med slagg	Caspersen, S. Hermansson, C.	LTV-fakultetens faktablad Fakta från SLU Partnerskap Alnarp 2019:7

c) Seminars etc.

Nr	Title	Authors	Date- place
K1	Användningsområden – som vattenrening och ballastmaterial	Renman, G. & Stjernholm, J.	Cirkulär ekonomi & industri. Seminarium på Jernkontoret 25 okt 2018

Appendix 4 Description of the programme

The MINRENT project is part of the strategic innovation program

Metallic materials

The strategic innovation program Metallic Materials is a collaboration program between Jernkontoret, Swedish Aluminum and the Swedish Foundry Association, which is part-financed by VINNOVA and runs during the years 2013–2019.

The program aims to realize the strategic innovation agenda **National Assemblage on Metallic Materials**, whose long-term vision is that the Swedish metal industry should be a central element in the world's efforts to shape a better future. This means that its offerings to customers must be at the absolute technical, economic and environmental forefront and developed by driven and committed people. At the same time, the manufacturing methods must have as small an environmental footprint as possible.

The program supports initiatives in seven focus areas for renewal, growth and increased competitiveness:

1. Develop the offer!
2. Open the value chain!
3. Increase the rate of material development!
4. Increase flexibility!
5. Increase resource efficiency!
6. Reduce environmental impact!
7. Increase competence and attractiveness!

In addition to R&D projects selected in open calls, the program's efforts also consist of strategic projects and activities.

The program office, with responsibility for the management and administration of the program, is Jernkontoret.

Jernkontoret

Den svenska stålindustrins branschorganisation

Jernkontoret grundades 1747 och ägs sedan dess av de svenska stålföretagen. Jernkontoret företräder stålindustrin i frågor som berör handelspolitik, forskning och utbildning, standardisering, energi och miljö samt transportfrågor. Jernkontoret leder den gemensamma nordiska stålforskningen. Dessutom utarbetar Jernkontoret branschstatistik och bedriver bergshistorisk forskning.

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