Research outputs:

**Characterization of sewage sludge ash and its effect on moisture physics of mortar**

A study was carried out to investigate the potential use of ash obtained as an incinerated by-product in sewage sludge treatment, as a possible supplementary cementitious material. Chemical parameters and granulometry of the sewage sludge ash and selected physical and hygroscopic properties of cement-ash-based mortar are presented and compared with results from previous studies. The effect of different ratios of cement substitution and two pre-treatment methods for ash, i.e. ash grinding and water washing, on the physical properties of mortar were investigated by using density, porosity and compressive strength as elemental indicators of the mortar quality. The hygroscopic sorption properties of the individual constituents alone and the resulting mortar samples were described by sorption isotherms for water vapour and by a capillary water absorption test. Results showed that the SSAs typically consisted of larger particles compared to the cement particles. Incorporation of ash resulted in more porous mortar structures compared to cement-based mortar, which affected the material's mechanical properties such as the compressive strength. 28-day compressive strength decreased with increasing ash content and porosity. Cement conveyed the greatest ability to adsorb and react with water and there were clear differences between the different ashes. Despite the differences in sorption properties between the different constituents, the effect of ash content on mortar sorption isotherms was negligible.
Electrodialytic remediation can be applied to remove heavy metals from contaminated particulate materials in suspension. The applied electric current is the cleaning agent and the heavy metals are removed by electromigration. In this study, a two-compartment cell was compared to a three-compartment cell, for several contaminated materials such as soils, sediments, mine tailings and ashes and totally 20 experiments were conducted. The pH decrease was faster in the two-compartment cell, but the metal removal was higher in the three-compartment cell since anionic metal species are removed from the material suspension in this cell set-up. For materials with relatively high chloride content, fly ash and harbour sediments, up to 38% of the metals were found in the filtrate in the two-compartment cell. Up to 9% of the current was used to transport heavy metal ions in the experiments and the current was mainly carried by H+ and Ca2+. Even with the lower pH in the two-compartment cell experiments, there was little difference in the percentage of the current carried by the metal ions between the two set-ups. Multivariate analysis showed that the choice of cell set-up depends on the metals targeted by remediation and the material characteristics.

General information
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Web of Science (2017): Impact factor 6.434
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Web of Science (2016): Impact factor 6.065
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BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 5.54 SJR 1.633 SNIP 1.931
Web of Science (2015): Impact factor 4.836
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 5.21 SJR 1.814 SNIP 2.258
Web of Science (2014): Impact factor 4.529
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 5.09 SJR 1.822 SNIP 2.43
Electrodialytic extraction of Cr from water-washed MSWI fly ash by changing pH and redox conditions

Electrodialytic process offers a range of possibilities to waste management by electrodialytic separation (EDS) of heavy metals, depending on how the process is designed. Using three EDS cell setups (two two-compartment and one three-compartment) and their combinations, the extraction of Cr from municipal solid waste incineration fly ash by changing pH and redox conditions was investigated in the present work. The experiments were designed into single, two and three steps, based on the number of setups (by changing EDS cells) or effective setups (by shifting working electrode pairs) used. Prior to EDS the ash studied went through pretreatments such as water-washing and dry-sieving with a 50 µm sieve. The results showed that Cr was strongly bound in the ash, and the major fraction remained bound after the different treatments. Two/three-step treatment, which obtained the maximum Cr extraction rate of 27.5%, is an improvement on the single-step that extracted maximum 3.1%. The highest extraction was obtained due to the combined extraction of Cr(III) under low pH (accompanied with high redox) conditions and Cr(VI) under high pH (low redox) conditions subsequently.
The Cr leaching from the treated ashes with acidic pH was lower than from those with alkaline pH; after the three-step treatment, Cr leaching was much lower from the coarse fraction (> 50 µm), as compared to the fine (≤ 50 µm) or the unsieved ash. As for the coarse fraction, two/three-step treatment reduced the leaching of Cr compared to the single-step in the same pH range (either acidic or alkaline).

**General information**

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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions  
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Web of Science (2018): Indexed yes  
BFI (2017): BFI-level 2  
Scopus rating (2017): CiteScore 4.94 SJR 1.456 SNIP 2.059  
Web of Science (2017): Impact factor 4.723  
Web of Science (2017): Indexed yes  
BFI (2016): BFI-level 2  
Scopus rating (2016): CiteScore 4 SJR 1.407 SNIP 2.159  
Web of Science (2016): Impact factor 4.03  
Web of Science (2016): Indexed yes  
BFI (2015): BFI-level 2  
Scopus rating (2015): CiteScore 4.33 SJR 1.732 SNIP 2.263  
Web of Science (2015): Impact factor 3.829  
Web of Science (2015): Indexed yes  
BFI (2014): BFI-level 2  
Scopus rating (2014): CiteScore 3.43 SJR 1.763 SNIP 2.49  
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Web of Science (2014): Indexed yes  
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Scopus rating (2013): CiteScore 3.39 SJR 1.815 SNIP 2.413  
Web of Science (2013): Impact factor 3.157  
ISI indexed (2013): ISI indexed yes  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 1  
Scopus rating (2012): CiteScore 2.91 SJR 1.59 SNIP 2.18  
Web of Science (2012): Impact factor 2.485  
ISI indexed (2012): ISI indexed yes  
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 1  
Scopus rating (2011): CiteScore 2.99 SJR 1.694 SNIP 2.071  
Web of Science (2011): Impact factor 2.428  
ISI indexed (2011): ISI indexed yes  
Web of Science (2011): Indexed yes  
BFI (2010): BFI-level 1  
Scopus rating (2010): SJR 1.553 SNIP 1.821  
Web of Science (2010): Impact factor 2.358  
Web of Science (2010): Indexed yes
Electrodialytic treatment of Greenlandic municipal solid waste incineration fly ash

In Greenland, fly ash could contribute as a local resource in construction as a substitute for cement in concrete or clay in bricks, if the toxicity of the ash is reduced. In this study, fly ash from three different Greenlandic waste incinerators were collected and subjected to electrodialytic treatment for removal of heavy metals with the aim of enabling reuse of the fly ashes. Seven electrodialytic experiments treating up to 2.5 kg of fly ash in a 10 L suspension were made. The heavy metal removal was mostly dependent on the initial concentration in the fly ash. Heavy metal leaching was examined before and after treatment and revealed overall a significant reduction in leaching of Cd, Cr, Cu, Pb and Zn; however, Cr and Pb leaching were above Danish guideline levels for reuse purposes. Hg leaching was also reduced to below Danish guideline levels, although only investigated for one fly ash. Hexavalent Cr was not the dominant speciation of Cr in the fly ashes. Ettringite formed during electrodialytic treatment in the fly ash suspensions at pH above 12. The total concentration of eligible components for reuse such as CaO, SiO2 and Al2O3, increased during the electrodialytic treatment.

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Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4.94 SJR 1.456 SNIP 2.059
| Year | Web of Science | Scopus rating | BFI (BFI-level | Indexed | Web of Science | Scopus rating | BFI (BFI-level | Indexed | Web of Science | Scopus rating | BFI (BFI-level | Indexed | Web of Science | Scopus rating | BFI (BFI-level | Indexed | Web of Science | Scopus rating | BFI (BFI-level | Indexed | Web of Science | Scopus rating | BFI (BFI-level | Indexed | Web of Science | Scopus rating | BFI (BFI-level | Indexed |
|------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|----------------|---------------|---------------|---------|
| 2017 | Impact factor 4.723 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2016 | Impact factor 4.03 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2015 | Impact factor 3.829 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2014 | Impact factor 3.22 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2013 | Impact factor 3.157 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2012 | Impact factor 2.485 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2011 | Impact factor 2.428 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2010 | Impact factor 2.358 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2009 | Impact factor 2.18  |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2008 | Impact factor 1.919 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2007 | Impact factor 1.785 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2006 | Impact factor 1.819 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2005 | Impact factor 1.653 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2004 | Impact factor 1.911 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2003 | Impact factor 1.234 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2002 | Impact factor 0.903 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2001 | Impact factor 0.731 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 2000 | Impact factor 0.444 |                |               |         | Indexed yes    |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
| 1999 | Impact factor 0.541 |                |               |         |                |                |               |         |                |               |               |         |                |               |               |         |                |               |               |         |                |               |               |         |
Electrokinetically-Based Remediation of Chlorinated Ethenes in Low Permeable Soils

General information
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Organisations: Department of Civil Engineering, Materials and Durability, Capital Region of Denmark, Orbicon
Publication date: 2018

Host publication information
Title of host publication: Proceedings of the Eleventh International Conference on Remediation of Chlorinated and Recalcitrant Compounds
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Chlor_no._444_Ottosen_Proceedings.pdf
Research output: Research - peer-review » Conference abstract in proceedings – Annual report year: 2018

Mining sewage sludge ash by electrodialytic separation

General information
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Organisations: Materials and Durability, Department of Civil Engineering
Contributors: Ottosen, L. M., Kirkelund, G. M., Jensen, P. E.
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Host publication information
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Publisher: Technical University of Denmark (DTU)
Editors: Melero, C., Mølhave, K.
Article number: A-6
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Pre-treatment of Greenlandic municipal solid waste incineration residues before use in mortar or bricks

General information
State: Published
Organisations: Materials and Durability, Department of Civil Engineering, Technical University of Denmark, Aristotle University of Thessaloniki
Contributors: Kirkelund, G. M., Florian, C., Skevi, L., Ebert, B. A. R.
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Host publication information
Title of host publication: Sustain Conference 2018 : Creating Technology for a Sustainable Society
Place of publication: Lyngby, Denmark
Publisher: Technical University of Denmark (DTU)
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Research output: Research - peer-review » Conference abstract in proceedings – Annual report year: 2018
Project families: How to improve learning in thesis work and increase impact on research

General information
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Size: 9 slides

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Source: PublicationPreSubmission
Source-ID: 159851580
Research output: Communication › Sound/Visual production (digital) – Annual report year: 2018

Project families: How to improve learning in thesis works and increase impact on research
This paper describes the development of a new concept for organizing thesis work and supervision with the purpose of improving civil engineer students learning within the general key competences and increase their contribution to research and development, by using the student, supervisor and technicians resources in a more efficient way.
This concept organizes the traditional thesis works with 1 or 2 students collaborating at a project and a report into project families. A project family consists of a number of project students focusing on a common problem, where the students works supplement each other, share the supervisor team, test facilities, data and project room, while still being independent.
The paper presents results for 104 students thesis works and documents significant improvements in learning and in contributions to research and thus a better and more efficient use of the students resources and of the university resources.

General information
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Organisations: Structures and Safety, Department of Civil Engineering, Materials and Durability
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Research output: Research › Report – Annual report year: 2018

Recycling Concrete Aggregates in New Concrete: Investigations of Quality and Origin of the Concrete Waste

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Organisations: Materials and Durability, Department of Civil Engineering
Contributors: Pedersen, L. G., Jensen, K. N., Herløv, M. E., Kirkelund, G. M., Ottosen, L. M.
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Editors: Melero, C., Mølhave, K.
Ultrafine particles in inhabited areas in the Arctic - From very low to high concentrations

The Arctic is considered a pristine environment, where pollution mainly originates from global sources. The present study examines particle number concentrations (PNCs) and the main sources of airborne ultrafine particles (UFPs, d < 100 nm) in the town Sisimiut and two nearby settlements, Sarfannguit and Itilleq, in West Greenland. Measurements were carried out during three weeks in April and May 2016. Air temperatures during the measurements ranged from −4.4 to +8.7 °C. A portable condensation particle counter (P-Trak) was used for the measurements. Results showed that the lowest concentrations were found during days with high wind speeds, with the lowest PNC average of 72 ± 11 cm−3 (n = 9) (12 m/s). Background concentrations were usually low compared to more densely populated countries, with a couple of exceptions, where there was no clear cause for elevated PNCs in a background area East of Sisimiut. Measured PNCs in the flue gas in the waste incineration plant in Sisimiut showed up to 334,976 cm−3 and are expected to be higher in the gas after it is released through the chimney. Average PNCs up to 77,009 ± 43,880 cm−3 (n = 26) were measured by a road located by the harbor in Sisimiut, while subsequent measurements at the same location showed much lower PNCs. The presence of heavy machinery elevated PNCs highly during two measurement events, giving PNCs up to 270,993 cm−3 but dropping to 1180 cm−3 10 min later, after the vehicle had passed by. A measurement event in Sisimiut Airport while an aircraft landed and departed showed an average PNC of 44,741 ± 85,094 cm−3 (n = 21). Two 24-h measurements resulted in average PNCs of 2960 ± 5704 cm−3 and 3935 ± 10,016 cm−3 respectively.
Using polycarbobetaines for Cu recovery from catholytes generated by electrodialytic treatment of sewage sludge ash

Electrodialytic remediation is a process that uses a low current density to remove heavy metals from different waste matrices, such as sewage sludge ash (SSA). The SSA is suspended in water and separated from the anolyte and catholyte compartments by ion exchange membranes. The heavy metal cations are separated from the ash and electromigrate into the catholyte, where they can electrodeposite on the cathode. Despite this electrodeposition, the catholyte contains heavy metals after the remediation process. Newly developed water-soluble polycarbobetaines (PCBets) have shown potential for selective removal of metal ions and especially Cu in synthetic solutions. In this study, it was investigated for the first time if the PCBets can remove Cu from the catholytes generated by electrodialytic remediation. Four electrodialytic separation experiments were made, treating SSA in slurries at liquid to solid ratios 3.5-21. The Cu removal from the SSA was between 6-30 %, resulting in catholyte concentrations between 0.18-4.34 mg Cu/l. The Cu selective PCBet, PCEAC was added to the four different catholytes for Cu extraction after a pH adjustment to around 5 of the catholytes. The removal of Cu was almost negligible by the PCEAC, regardless of the initial Cu concentration. Thus, the samples were spiked with Cu to concentrations between 77 – 319 mg/l and then the removal of Cu was tested by the addition of PCEAC or PCEAMC from the catholyte solution, resulting in Cu removals up to 70 % and 40 % respectively. However, a significant co-adsorption of Al, Ca and Zn was also seen. Based on the results, there is a potential in combining the use of PCBets to electrodialytic treatment, however the metal concentration in the catholyte should be increased and the PCBets should be further developed to avoid co-adsorption.

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Contributors: Kirkelund, G. M., Mouton, J.
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Utilisation of Electrodialytically Treated Sewage Sludge Ash in Mortar

Phosphorous is a scarce resource and there is a need to develop methods for recovery of this irreplaceable nutrient from secondary resources, e.g. from sewage sludge ash (SSA). Today SSA is most often disposed of and the resource is lost. In the present study, about 90% phosphorous was recovered from SSA by electrodialytic separation in a bench scale set-up, and the particulate residue after the extraction (SSA-ED) was evaluated for use as cement replacement in mortar. The SSA-ED and untreated SSA were grinded for 0, 30 s and 10 min in order to obtain fractions with different degrees of fineness. Each fraction was tested as cement replacement with 20% substitution in mortar. The technical and aesthetical properties of mortars containing the two SSAs were compared to the properties of ordinary mortar. The SSA-ED was acidic; however, this did not significantly influence the mortar properties on short term investigated here. For example, the compressive strength of the mortar with SSA-ED only decreased by 8% compared to ordinary mortar. The workability of mortars with SSA or SSA-ED was reduced compared to the reference. The colour of mortar with SSA-ED was warm reddish, and more intense than the colour of the mortar with SSA. The intense colour was due to the increased concentration of hematite during ED. This study showed potential for separating SSA to two resources by combining electrodialytic extraction of phosphorous and subsequent utilization of the residual mineral ash in mortar.

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Colour, compressive strength and workability of mortars with an iron rich sewage sludge ash

This paper reports a study of the colour, compressive strength and workability of mortar when cement is partly replaced by sewage sludge ash (SSA). In the study, an iron rich SSA was dry milled into six different fractions. The results showed that the colour, compressive strength and workability parallel to one another gradually changed when the particle sizes of the SSA decreased. The milling of the SSA altered the performance of mortars to the extent that the compressive strength and workability were comparable to the performance of ordinary mortar. At the same time, the colour also changed from grey to a reddish colour. As the change in colour may be of importance for application, it is suggested to include colour as experimental parameter in future work.

General information
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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions
Comparison of different MSWI fly ash treatment processes on the thermal behavior of As, Cr, Pb and Zn in the ash

To reduce heavy metal leaching and stabilize municipal solid waste incineration (MSWI) fly ash, different methods and combination of methods were tested: water washing, electrodialytic separation and thermal treatment at 1000°C. A comparison of heavy metal concentration and leaching levels of As, Cr, Pb and Zn for the different untreated and treated ashes was made. The results showed that minimizing leaching to meet the limiting values of the all the studied heavy metals can be obtained at the same time by combining water washing, electrodialytic separation and thermal treatment. The ash subjected to this combination had lower Cr than the ash solely subjected to thermal treatment or subjected to water washing prior to thermal treatment. The electrodialytic separation (EDS) of the washed ash lowered pH from alkaline to acidic, which resulted in elevated leaching of Cd and Zn, while the Cr leaching was reduced. Up to 58.6% of Zn and 5.5% of Pb were extracted by EDS compared to less than 0.6% extraction by water washing. During thermal treatment of the EDS treated ash, the ash was re-alkalized. Due to solidification and possibly evaporation, most heavy elements left in the thermally treated ash were stabilized and immobilized. However, leaching of As and/or Cr was still problematic and did not meet the limit value for the thermally treated ash being recycled in construction work. The removal of Ca and decomposition of Ca oxides and minerals during EDS was linked to the leaching patterns of As and Cr after thermal treatment.

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Web of Science (2017): Impact factor 4.723
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4 SJR 1.407 SNIP 2.159
Web of Science (2016): Impact factor 4.03
Web of Science (2016): Indexed yes
Development of a joint Nordic master in cold climate engineering within the Nordic five tech alliance

Developments in the Arctic regions are intensifying and the industry now demands engineers who have Arctic competencies. Working as an engineer in the Arctic requires special skills, but yet no full Master’s programme in cold climate engineering has been offered in Europe. A joint Nordic master programme in Cold Climate Engineering was therefore established in collaboration between three Nordic technical universities; Aalto University in Finland, Norwegian University of Science and Technology (NTNU) and the Technical University of Denmark (DTU). These universities are part of a strategic alliance, Nordic Five Tech, which was established in 2006 with the goal of utilizing the shared and complementary strengths of the universities and creating synergies, also within education in the form of joint master programmes.

The Cold Climate Engineering students study for one year at two of the universities, having to pass 60 ECTS at each university. The programme is structured in three overall tracks: Sea (Aalto/NTNU), Land (DTU/NTNU) and Space (Aalto/DTU) using already existing courses offered by different departments at the universities. In Year 1, the students follow general competence and technological specialisation courses at University 1 and in Year 2, the students take one semester of technological specialisation courses and write their final Master thesis, which is co-supervised by University 1. This construction allows the students to achieve a double master’s degree.

The three universities have their own unique teaching profiles, but individually offer a limited number of cold climate and Arctic related master courses. For the Sea and Land tracks, one or two semesters can be taken at the University Centre of Svalbard (UNIS) and for the Land track a semester at the DTU campus in Sisimiut, Greenland is compulsory. Thus, the significant strength of this programme is that the universities are joining the use of their cold climate courses, creating an MSc programme that stands out from the regular MSc programmes at the universities, as well as offering courses at Svalbard and in Greenland. The students have access to laboratory and testing facilities at the universities as well as they can conduct field work in the Baltic Sea, Svalbard and Greenland. By actually going to the Arctic and applying their skills, the students get valuable first-hand insight into working as an engineer in one of the most challenging areas of the world and being attractive candidates to companies and research institutions working in extreme climates and different cultures. The first students started in the autumn semester 2016, with students coming from the N5T universities, European and international universities. The students are highly motivated when starting in the MSc programme and are eager to develop their competences within Cold climate and Arctic Engineering.
Evaluating potentials for waste sorting in the Arctic: waste separation studies from Greenland

General information
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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, Department of Environmental Engineering, Residual Resource Engineering, Technical University of Denmark, Ramboll Group AS
Contributors: Kirkelund, G. M., Diez, L., Scheutz, C., Eisted, R.
Publication date: 2017
Peer-reviewed: Yes
Event: Abstract from 5th International Conference on Sustainable Solid Waste Management, Athens, Greece.
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Electronic versions: Untitled.pdf
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Source-ID: 139682634
Research output: Research - peer-review > Conference abstract for conference – Annual report year: 2017

Recycling of MSWI fly ash in clay bricks - effect of washing and electrodialytic treatment
Fly ash generated from municipal solid waste incineration (MSWI) is a hazardous waste due to presence and leachability of heavy metals and organic pollutants (e.g. dioxins and polycyclic aromatic hydrocarbons). In 2000, approximately 25 Mt/year of fly ash was generated in USA, Japan and EU (Reijnders 2005). Electrodialytic remediation (EDR) is one technique for MSWI fly ash treatment (Ferreira et al. 2005), where an electric DC field is applied to an ash-water suspension to extract and separate heavy metal by migration towards anode or cathode through ion exchange membranes. Ferreira et al. (2008) observed that in MSWI ash treated by water washing and EDR, metals were mainly in the strongly bonded and residual phases, indicating a reduction in the ash’s environmental risk. Belmonte et al. (2016) made Greenlandic bricks (∼2 g discs) containing 20% and 40% of EDR treated MSWI fly ash, and found that bricks had a low durability and high leaching of As and Cr. In the present study, fired fly ash-clay bricks with a larger size and with lower EDR-treated ash (water-washed before EDR) contents (5%, 10% and 20%) were made and characterized. These bricks were compared with 100% clay bricks and with bricks made from original MSWI fly ash at 20% substitution rate. The feasibility of incorporation of MSWI fly ash treated by combined washing and EDR in production of sintered clay bricks was investigated.

General information
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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, University of Aveiro, Technical University of Denmark
Contributors: Chen, W., Klupsch, E., Kirkelund, G. M., Jensen, P. E., Ottosen, L. M., Dias-Ferreira, C.
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Source-ID: 139682493
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Utilisation of electrodialytic treated sewage sludge ash in cement based materials

General information
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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions
Contributors: Kappel, A., Kirkelund, G. M., Ottosen, L. M.
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Peer-reviewed: Yes
Event: Abstract from 5th International Conference on Sustainable Solid Waste Management, Athens, Greece.
Keywords: Mortar, Phosphorous, Heavy metal, Electrokinetic, Fly ash
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Assessment of kitchen waste compost from Sisimiut for use as plant growth medium or landfill biocover

General information
State: Published
Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, Department of Environmental Engineering, Residual Resource Engineering, Technical University of Denmark
Contributors: Skadborg, M., Nielsen, M., Kirkelund, G. M., Scheutz, C.
Number of pages: 2
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Bibliographical note
Byg Report R-340
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Characterisation of source-separated organic waste for composting in Sisimiut, Greenland

General information
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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, Department of Environmental Engineering, Residual Resource Engineering, Technical University of Denmark
Contributors: Díez, L., Kirkelund, G. M., Scheutz, C.
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Bibliographical note
Byg Report R-340
Research output: Research - peer-review › Conference abstract in proceedings – Annual report year: 2016

Characterization of particulate residues from Greenlandic MSWI for use as secondary resources
In Greenland, waste incineration is used in the larger towns to treat the municipal solid waste. The incineration reduces the amount of waste, but produces particulate incineration residues such as fly and bottom ash that are disposed of. Most construction materials are imported to Arctic areas. The focus in this study is a characterisation of Greenlandic incineration residues to assess the potential as local secondary resources. In this study, fly ash samples from all the incinerators and bottom ash from two incinerators were collected and investigated for several physical-chemical properties. The fly ash samples consisted of very fine-grained particles, with different grading for each incinerator. High water solubility due to high salt concentrations was seen for all fly ash samples along with high concentrations of leachable heavy metals, thus pretreatment is recommended before use as secondary material. The bottom ashes consisted of coarser particles and exhibited lower heavy metal leaching than the fly ash. All residue samples were different and evaluation of reuse should be made individually, however the fly ash shows potential as cement replacement and bottom ash as sand replacement for construction purposes.

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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, University of Aveiro
Contributors: Kirkelund, G. M., Dias-Ferreira, C., Jensen, P. E.
Electrodialytic upgrading of MSWI APC residue from hazardous waste to secondary resource

The aim of this project was to contribute to the development of electrodialytic treatment technology of air pollution control residues (APC) from municipal solid waste incineration (MSWI) to obtain maximal leaching reduction by optimization of treatment time and current density for different types of MSWI APC residues. The concept idea was in a pilot scale unit to reduce the mobility of toxic elements and salts by electrodialytic treatment enough for the residual product to constitute an environmentally safe resource for substitution of virgin resources in construction material e.g. for substitution of cement or fillers in concrete.

In general leaching could not be reduced by optimizing current density and treatment time in the pilot scale stack treatment unit, as hypothesized, even though there was evidence of dependency on current density for e.g. zinc, this was not true for most elements, and it was clear that experimental conditions and pre-treatments affected different target elements differently. Statistical analysis of the results revealed that the final pH was the major parameter determining leachability.

The robustness of the stack setup proved to be very limited. At several occasions during the project, the diluate spacers clogged, and areas with high resistance and heat development evolved. Membranes burned and had to be changed. Because the results of the pilot scale stack experiments did not give the anticipated results and tools for optimized up-scaling, instead laboratory investigations were made on the influence of different membrane brands and influence of different experimental setups.
Greenlandic Waste Incineration Fly And Bottom Ash As Secondary Resource In Mortar

Today, 900 tons incineration fly ash is shipped abroad annually from Greenland for deposits, whereas the 6,000 tons incineration bottom ash is deposited locally. These incineration ashes could be valuable in concrete production, where the cement has to be shipped to Greenland. For this purpose, the effects on compressive strengths of mortars by substituting cement or sand by raw, washed and electrodialytically treated fly ash or bottom ash were investigated.

Parts of the experimental fly ash had been pre-treated by either washing with distilled water or electro-dialytically treated to remove salts and by the latter method, also heavy metals. Mortar samples were cast where cement (5%-20%) or sand (5%-10%) was replaced with fly ash or bottom ash, together with references without replacements. The compressive strengths were measured after 7, 14, 28 and 42 days. Replacing cement by fly ash resulted in lower compressive strength at 20% content of fly ash. At 5% replacement with raw fly ash a compressive strength similar to the reference was seen. However, using washed and electrodialytically treated ash lead to lower strengths. The lowest compressive strength was seen when replacing both sand with bottom ash and cement with fly ash.

Based on the compressive strength tests, it is found that using Greenlandic incineration ashes in mortar as 5% cement replacement could consume all ash instead of disposals, and could thus turn the ashes into a local resource and simultaneously reduce the import of cement.

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Contributors: Kirkelund, G. M., Ottosen, L. M., Jensen, P. E., Goltermann, P.
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Scopus rating (2015): CiteScore 0.24 SJR 0.157 SNIP 0.275
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BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 0.23 SJR 0.134 SNIP 0.412
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 0.22 SJR 0.199 SNIP 0.364
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 0.12 SJR 0.116 SNIP 0.205
Incorporation of Different Fly Ashes from MSWI as Substitute for Cement in Mortar: An Overview of the Suitability of Electrodialytic Pre-treatment

General information
State: Published
Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, NOVA University Lisbon
Contributors: Magro, C. C., Guedes, P. R., Kirkelund, G. M., Jensen, P. E., Ottosen, L. M., Ribeiro, A. B.
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DOIs: 10.1007/978-3-319-20179-5_12
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Incorporation of treated straw and wood fly ash into clay building brick
High Cd content in straw and wood fly ash, generated from biomass-fired power plants, prohibits its recycling as fertilizer spreading on the landfill. To improve and alter the current mainstream of fly ash treatment by landfilling, different approaches were tried for treatment of straw and wood fly ash, such as washing with water to quickly recover the highly soluble salts (mainly K and Cl), and treatment of the washed fly ash with elevated heavy metal content resulted from washing by electrodialytic remediation (EDR). The finding that SiO2 (quartz) accounted for a significant portion in the treated ash, suggests the possibility of the ash reuse in sintered clay bricks. In this study, the straw and wood fly ash treated by washing and EDR was incorporated into yellow clay bricks at different substitution rates. The properties of the clay-ash bricks were studied in terms of shrinkage, water absorption, porosity, density, compressive strength and leaching behavior, and compared with the 100% clay bricks. It’s promising to use the treated ash as a secondary building material.

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ISBN (Electronic): 978-2-35158-177-3
Mercury Levels In Fly Ash And APC Residue From Municipal Solid Waste Incineration Before And After Electrodialytic Remediation

Fly ash (FA) and Air Pollution Control (APC) residues collected from three municipal solid waste incinerators (MSWI) in Denmark and Greenland were treated by electrodialytic remediation at pilot scale for δ to 10 h. The original residues and the treated material were analysed for mercury (Hg) in order to assess the influence of the electrodialytic treatment on the concentrations of this element. Mercury levels varied with the MSWI residue, ranging from 0.41 mg kg\(^{-1}\) in FA sample from electrostatic precipitator (ESP) to 8.38 mg kg\(^{-1}\) in MSWI residues from a semi-dry system with lime and activated carbon. Two distinct behaviours were observed for mercury as a result of the electrodialytic treatment. This element became enriched in the MSWI residues from the semi-dry system with activated carbon, whereas it decreased in ESP’s and cyclone’s FA. This work presents for the first time information about the effect of electrodialytic treatment on mercury levels and discusses the valorisation options for these MSWI residues.

General information

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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, Instituto Politecnico de Coimbra
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BFI (2012): BFI-level 1
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BFI (2011): BFI-level 1
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Scopus rating (2009): SJR 0.139 SNIP 0.424
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Scopus rating (2008): SJR 0.145 SNIP 0.329
Scopus rating (2007): SJR 0.146 SNIP 0.759
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Phosphorous recovery from sewage sludge ash suspended in water in a two-compartment electrodialytic cell

Phosphorus (P) is indispensable for all forms of life on Earth and as P is a finite resource, it is highly important to increase recovery of P from secondary resources. This investigation is focused on P recovery from sewage sludge ash (SSA) by a two-compartment electrodialytic separation (EDS) technique. Two SSAs are included in the investigation and they contained slightly less P than phosphate rock used in commercial fertilizer production and more heavy metals. The two-compartment electrodialytic technique enabled simultaneous recovery of P and separation of heavy metals. During EDS the SSA was suspended in water in the anolyte, which was separated from the catholyte by a cation exchange membrane. Electrolysis at the anode acidified the SSA suspension, and thereby P, Cu, Pb, Cd and Zn were extracted. The heavy metal ions electromigrated into the catholyte and were thus separated from the filtrate with P. More than 95% P was extracted from both SSAs. The charge transfer to obtain this varied when treating the two SSAs, and for one ash it was about 30% higher than for the other as a result of a higher buffering capacity against acidification. The repeatability of EDS results between experiments with the same SSA and the same experimental conditions was good, which shows that the process is easy to control at the studied laboratory conditions. About 80% P and 10% of the heavy metals remained in the filtrate from the anolyte after treatment of both SSAs. The heavy metal content relative to P in the filtrate by far meet the limiting values for use of industrial wastes as fertilizers, thus the filtrate is ready for direct processing into P-fertilizer.

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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4 SJR 1.407 SNIP 2.159
Web of Science (2016): Impact factor 4.03
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.33 SJR 1.732 SNIP 2.263
Web of Science (2015): Impact factor 3.829
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.43 SJR 1.763 SNIP 2.49
Web of Science (2014): Impact factor 3.22
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Polluted sediments in arctic harbors and electrodialytic remediation

General information
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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, Akvaplan-niva AS
Contributors: Ottosen, L. M., Pedersen, K. B., Kirkelund, G. M., Jensen, P. E.
Pages: 71-72
Replacement of 5% of OPC by fly ash and APC residues from MSWI with electrodialytic pre-treatment
Fly ash (FA) and air pollution control (APC) residues are waste products from Municipal Solid Waste Incineration (MSWI). They are classified as hazardous waste due to the content of leachable heavy metals (HM), salts and/or dioxins. An electrodialytic (ED) process was applied to FA and APC residues as pre-treatment prior to incorporation in mortar, aiming to stabilize and remove HM and chlorides. Eight ED experiments were performed for 7 days with a L/S ratio of 3.5. The number of compartments (2 or 3) and current density (0.1 or 1.0 mA cm⁻²) varied. After ED treatment the heavy metals left in the ash were not leached to the same extent as in the original ash. In mortar 5% of Ordinary Portland Cement was replaced by FA and APC residues (raw and ED upgraded). The studied parameters: compressive strength, HM leachability, and Cl content. The ED pre-treatment resulted in a decrease in both leaching of HM and the Cl content. The compressive tests presented comparable values to the reference mortars. This study suggests that the characteristics of FA and APC residues from MSWI after pre-treatment allows them to be reused in building materials, giving a new edge to waste management.

Screening of heavy metal containing waste types for use as raw material in Arctic clay-based bricks
In the vulnerable Arctic environment, the impact of especially hazardous wastes can have severe consequences and the reduction and safe handling of these waste types are therefore an important issue. In this study, two groups of heavy metal containing particulate waste materials, municipal solid waste incineration (MSWI) fly and bottom ashes and mine tailings (i.e., residues from the mineral resource industry) from Greenland were screened in order to determine their suitability as secondary resources in clay-based brick production. Small clay discs, containing 20 or 40% of the different particulate waste materials, were fired and material properties and heavy metal leaching tests were conducted before and after firing. Remediation techniques (washing in distilled water and electrodialytical treatment) applied to the fly ash reduced leaching before firing. The mine tailings and bottom ash brick discs obtained satisfactory densities (1669-2007 kg/m³) and open porosities (27.9-39.9%). In contrast, the fly ash brick discs had low densities (1313-1578 kg/m³) and high open porosities (42.1-51. %). However, leaching tests on crushed brick discs revealed that heavy metals generally became more available after firing for all the investigated materials and that further optimisation is therefore necessary prior to incorporation in bricks.
Suspended electrodialytic extraction of toxic elements for detoxification of three different mine tailings

Environmental effects of mining activities partly origin from the production of tailings, and the exposure of these to ambient physical and chemical conditions. Removal of toxic elements from tailings prior to deposition could improve environmental performance and reduce risks. Experimental results have shown that electrokinetic treatment can remove Cd, Cu, Pb, and Zn from tailings soils; As from tailings; and Cu from tailings. Still, however, a major concern is the long treatment-time required for the element-transport through the tailings matrix. Therefore several enhancement methods have been investigated including pre-treatment of the tailings with acid; insertion of bipolar electrodes; and implementation of pulsed or sinusoidal electric fields. In line with these efforts, we investigated the efficiency when extracting toxic elements from a suspension of tailings, rather than from a solid matrix, which could well be implemented as a final treatment step prior to deposition of tailings. Six electrodialytic experiments in laboratory scale with three different mine tailings (Codelco, Zinkgruvan, and Nalunaq) show that it is possible to extract residual Cu from the all the three suspended mine tailings, although with some difference between the tailings. From the Zinkgruvan sediment, which had the lowest Cu removal, Pb could also be extracted, while Cd and Zn were less extractable.

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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, Universidad Tecnica Federico Santa Maria
Contributors: Jensen, P. E., Ottosen, L. M., Hansen, H., Bollwerk, S., Belmonte, L. J., Kirkelund, G. M.
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BFI (2015): BFI-level 1
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The influence of electrodialytic remediation on dioxin (PCDD/PCDF) levels in fly ash and air pollution control residues

Fly ash and Air Pollution Control (APC) residues collected from three municipal solid waste incinerators in Denmark and Greenland were treated by electrodialytic remediation at pilot scale for 8-10 h. This work presents for the first time the effect of electrodialytic treatment on polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), and how these levels impact on the valorization options for fly ash and APC residue. 

PCDD/PCDF levels in the original residues ranged between 4.85 and 197 ng g\textsuperscript{-1}, being higher for the electrostatic precipitator fly ash. The toxic equivalent (TEQ) varied ten fold, ranging 0.18-2.0 ng g\textsuperscript{-1} I-TEQ with penta and hexa-homologs being most significant for toxicity. After the electrodialytic treatment, PCDD/PCDF levels increased in the residues (between 1.4 and 2.0 times). This does not mean PCDD/PCDF were synthesized, but else that soluble materials dissolve, leaving behind the non-water soluble compounds, such as PCDD/PCDF. According to the Basel Convention, PCDD/PCDF levels in these materials is low (<15 mg WHO-TEQ kg\textsuperscript{-1}) and the fly ash and APC residue could eventually be valorized, for instance as construction material, provided end-of-waste criteria are set and that a risk assessment of individual options is carried out, including the end-of-life stage when the materials become waste again.

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Contributors: Dias-Ferreira, C., Kirkelund, G. M., Jensen, P. E.
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Web of Science (2018): Indexed yes
Valorisation of ferric sewage sludge ashes: Potential as a phosphorus source

Sewage sludge ashes (SSA), although a waste, contain elements with socio-economic and environmental potential that can be recovered. This is the case of phosphorus (P). SSA from two Danish incinerators were collected during two years and characterized. The sampling was done immediately after incineration (fresh SSA) or from an outdoor deposit (deposited SSA). Although morphology and mineral composition were similar, physico-chemical and metal concentration differences were found between incinerator plants and sampling periods. No differences were observed between deposited and fresh SSA, except for the parameters directly influenced by disposal conditions (e.g. moisture content). All the SSAs had high concentrations of P (up to 16 wt%), but they all exceeded Danish EPA Cd and Ni thresholds for direct application at agricultural soil. Fresh and deposited SSA were acid washed aiming P extraction, achieving 50 g P/kg (approx. 37% of total P), but metals were also co-extracted to the liquid phase. To avoid and/or minimize the metals pollution of the extracted P, selective P recovery from the SSA was tested, using the electro dialytic (ED) process. ED laboratory cells, with 3 compartments (3c) and 2 compartments (2c), and two acid concentrations (H₂SO₄, 0.08 M and 0.19 M) were used for 7 days. The most concentrated acid solution increased P solubilization. The 2c-cell combined with the higher acid concentration resulted in higher P recoveries, 125 g of P/kg of SSA in the anolyte. The obtained results showed that the ED process is a valuable tool for the SSA valorisation as it promotes simultaneous P recovery and metals extraction from the SSA. (C) 2016 Elsevier Ltd. All rights reserved.
Wood ash used as partly sand and/or cement replacement in mortar

Wood ash (WA) is the residue generated during incineration of wood and wood products. The WAs in focus of this work are from incineration of virgin wood. Physical and chemical properties of WA vary significantly depending on many factors related to the wood species and the incineration process, and the present work reports a characterization of three different WAs. Properties of mortar samples with the WAs used as partly cement and/or sand replacement are reported.

Compressive strength development and porosity are the mortar properties in focus. The overall aim of the work is to evaluate the influence from the differences in ash characteristics to the properties of the mortar samples. The characteristics of the ashes did vary considerably. For example, one ash had very high loss on ignition (LoI) of 14% compared to 3% for the other ashes. Ash solubility in water ranged from 18% to 28%. Two of the ashes were dry and sampled just after the incineration, whereas one ash had a water content of 15%, because the ash was sprayed with water to avoid dust during ash handling at the incineration plant. Regardless of replacing cement or sand with WAs, the compressive strength decreased compared to a reference without ash, however, the decrease was small for two of the ashes. Using the ash with the high LoI resulted in significantly lower compressive strength compared to the other two ashes. The mortar samples with two of the ashes (with low LoI) had qualities, which were very encouraging in order to use WA as partly cement replacement (<10%). At higher percentages the workability was so low that extra water needed to be added and the results depended on the water:cement ratio rather than the ash mass.

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Scopus rating (2016): CiteScore 0.4 SJR 0.166 SNIP 0.274
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Scopus rating (2015): CiteScore 0.24 SJR 0.157 SNIP 0.275
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 0.34 SJR 0.146 SNIP 0.631
BFI (2013): BFI-level 1
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BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 0.22 SJR 0.199 SNIP 0.364
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 0.12 SJR 0.116 SNIP 0.205
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.115 SNIP 0.235
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.139 SNIP 0.424
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.145 SNIP 0.329
Scopus rating (2007): SJR 0.146 SNIP 0.759
Original language: English
Ammonium citrate as enhancement for electrodialytic soil remediation and investigation of soil solution during the process

Seven electrodialytic experiments were conducted using ammonium citrate as enhancing agent to remediate copper and chromium-contaminated soil from a wood-preservation site. The purpose was to investigate the effect of current density (0.2, 1.0 and 1.5 mA cm\(^{-2}\)), concentration of enhancing agent (0.25, 0.5 and 1.0 M) and remediation times (21, 42 and 117 d) for the removal of Cu and Cr from a calcareous soil. To gain insight on metal behavior, soil solution was periodically collected using suction cups. It was seen that current densities higher than 1.0 mA cm\(^{-2}\) did not increase removal and thus using too high current densities can be a waste of energy. Desorption rate is important and both remediation time and ammonium citrate concentration are relevant parameters. It was possible to collect soil solution samples following an adaptation of the experimental set-up to ensure continuous supply of ammonium citrate to the soil in order to keep it saturated during the remediation. Monitoring soil solution gives valuable information on the evolution of remediation and helps deciding when the soil is remediated.

Final concentrations in the soil ranged from 220 to 360 mg Cu kg\(^{-1}\) (removals: 78–86%) and 440–590 mg Cr kg\(^{-1}\) (removals: 35–51%), being within the 500 mg kg\(^{-1}\) limit for a clean soil only for Cu. While further optimization is still required for Cr, the removal percentages are the highest achieved so far, for a real Cu and Cr-contaminated, calcareous soil. The results highlight EDR potential to remediate metal polluted soils at neutral to alkaline pH by choosing a good enhancement solution.
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.92 SJR 1.721 SNIP 1.751
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ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.5 SJR 1.794 SNIP 1.618
Web of Science (2012): Impact factor 3.137
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.61 SJR 1.962 SNIP 1.508
Web of Science (2011): Impact factor 3.206
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.879 SNIP 1.424
Web of Science (2010): Impact factor 3.155
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.842 SNIP 1.572
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.658 SNIP 1.58
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.5 SNIP 1.605
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.418 SNIP 1.673
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.479 SNIP 1.558
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 1.627 SNIP 1.479
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 1.321 SNIP 1.323
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 0.902 SNIP 1.06
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 0.924 SNIP 0.978
Web of Science (2001): Indexed yes
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Source: FindIt
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Chemical herding and in-situ burning of crude oil in a water basin in Sisimiut, Greenland

General information
Electrodialytic remediation of fly ash from co-combustion of wood and straw

The heavy metal content in fly ash from biomass combustion, such as straw, wood and sludge, often needs reducing before the ash can be used as fertilizer for agricultural land or as a component in the production of construction materials. In this study, fly ash from a boiler fueled with wood chips and straw was treated either by electrodialytic remediation (EDR) directly or by a combination of EDR and pre-wash with distilled water to investigate the possibilities of reducing the heavy metal content and reusing nutrients as fertilizer and bulk material in construction materials. Different experimental set-ups were tested for EDR treatment primarily of Cd and Pb as well as of Cu and Zn. Elemental contents such as K, P and Ni were compared in ash samples before and after treatment. The results showed that pre-washing caused an increase in total concentrations of most heavy metals because the highly soluble fraction, mainly KCl and K2SO4, was removed. After EDR treatment, the Cd concentration was reduced to below 2mgkg⁻¹ in all ash samples with high and stable average removal of above 95%, no matter how high the initial concentration was. The amount of Pb removed varied from 12% to 67%. Even though Pb was extracted from the ash samples, its concentrations in the treated ash samples were elevated due to the ash dissolution, except in the case of pre-washed ash treated in a two-compartment EDR cell, where the mass of Pb removed was the highest with a final concentration of about 100mgkg⁻¹. The two-compartment EDR cell probably performed better due to a fast acidification process. In addition, this process was less energy-consuming. However, the fast acidification did in turn affect the leaching property of the treated ash, such as As and Ni, exceeding the limiting concentrations. The EDR/pre-wash-EDR treated ash mainly contained quartz, and the X-ray diffraction (XRD) peaks of K salts had disappeared. This shows that the potassium fertilizer potential was lost in the treated ashes, but the quartz mineral is beneficial in construction materials, such as ceramics. The K fertilizer could be recovered from the water after pre-washing and also from the catholyte through chemical operations, including a separation step.

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Web of Science (2017): Impact factor 5.116
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.74 SJR 1.355 SNIP 1.177
Web of Science (2016): Impact factor 4.798
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Electrodialytic removal of heavy metals and chloride from municipal solid waste incineration fly ash and air pollution control residue in suspension - test of a new two compartment experimental cell

Municipal solid waste incineration (MSWI) residues such as fly ash and air pollution control (APC) residues are classified as hazardous waste and disposed of, although they contain potential resources. The most problematic elements in MSWI residues are leachable heavy metals and salts. For reuse of MSWI residues in for instance concrete, the aim of remediation should be reduction of the heavy metal leaching, while at the same time keeping the alkaline pH, so the residue can replace cement. In this study a MSWI residues were subjected to electrodialytic remediation under various experimental conditions. Also a newly developed 2 compartment experimental cell was tested. The results show that the pH development in the MSWI residue suspension depended on the type of MSWI residue and the experimental cell type. The acidification of the suspension occurred earlier when using the 2 compartment setup and the acidification of the fly ash occurred earlier than for the APC residue but the highest removal was seen with the 3 compartment cell. The lowest final pH for the fly ash and APC residue was 6.4 and 10.9, respectively. The results showed that the leaching of Cd, Cu, Pb and Zn was reduced compared to the initial heavy metal leaching except when the pH was reduced to a level below 8 for the fly ash. On the other hand, Cr leaching increased by the electrodialytic treatment. Cl leaching from the MSWI residues was less dependent on experimental conditions and was reduced in all experiments compared to the initial levels.

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Web of Science (2016): Indexed yes
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Scopus rating (2015): CiteScore 4.86 SJR 1.321 SNIP 1.324
Web of Science (2015): Impact factor 4.803
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.59 SJR 1.378 SNIP 1.456
Web of Science (2014): Impact factor 4.504
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.44 SJR 1.427 SNIP 1.587
Electrodialytic upgrading of three different municipal solid waste incineration residue types with focus on Cr, Pb, Zn, Mn, Mo, Sb, Se, V, Cl and SO₄

Handling of air pollution control (APC) residues from municipal solid waste incineration (MSWI) is a challenge due to its toxicity and high leaching of toxic elements and salts. Electrodialysis (ED) of the material has shown potential for reduction of leaching of toxic elements and salts to produce a material feasible for substitution of cement in mortar. In this work...
results of 23 pilot-scale experiments (5-8kg APC residue each) in electrodialysis stack designed to investigate the leaching properties as a function of time and current density for APC residue from semi-dry and wet flue-gas cleaning systems, as well as MSWI fly ash without flue-gas cleaning products are reported. Significant leaching reduction of the critical elements Pb, Zn and Cl was obtained. The final leaching, however, depended mostly on the initial leaching, thus as leaching from fly ash and residue of wet flue-gas cleaning was lower before treatment compared to residues from semidry flue-gas cleaning, both Pb and Zn leaching could be reduced to lower levels in those materials, and they therefore appear more suitable for use in construction materials. The leaching reduction of Zn and to some degree Pb decreased with longer retention times and higher current densities. Cr and SO₄ leaching increased during ED treatment, with lower increase at higher current. Washing or carbonation in combination with ED significantly reduced leaching of Pb and Zn from semidry residue. An indication of a similar effect to carbonation by simultaneous aeration with ED was observed and should be investigated further. While Mn and Mo leaching did not, Se, V and Sb leaching exceeded threshold values in semidry residue. The leaching of V seemed to increase while Se and Sb remained more or less constant during ED treatment.

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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions, UiT The Arctic University of Norway, Escola Superior Agrária de Coimbra
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Scopus rating (2015): CiteScore 4.86 SJR 1.321 SNIP 1.324
Web of Science (2015): Impact factor 4.803
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ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 3.99 SJR 1.644 SNIP 1.574
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Experiencing engineering field work in Greenland through summer courses in Arctic Technology

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Organisations: Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions
Contributors: Kirkelund, G. M., Jensen, P. E.
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Kirkelund_Jensen_2.pdf
Source: PublicationPreSubmission
Source-ID: 275179875
Research output: Research - peer-review » Conference abstract in proceedings – Annual report year: 2015
Multivariate methods for evaluating the efficiency of electrodialytic removal of heavy metals from polluted harbour sediments

Chemometrics was used to develop a multivariate model based on 46 previously reported electrodialytic remediation experiments (EDR) of five different harbour sediments. The model predicted final concentrations of Cd, Cu, Pb and Zn as a function of current density, remediation time, stirring rate, dry/wet sediment, cell set-up as well as sediment properties. Evaluation of the model showed that remediation time and current density had the highest comparative influence on the clean-up levels. Individual models for each heavy metal showed variance in the variable importance, indicating that the targeted heavy metals were bound to different sediment fractions. Based on the results, a PLS model was used to design five new EDR experiments of a sixth sediment to achieve specified clean-up levels of Cu and Pb. The removal efficiencies were up to 82% for Cu and 87% for Pb and the targeted clean-up levels were met in four out of five experiments. The clean-up levels were better than predicted by the model, which could hence be used for predicting an approximate remediation strategy; the modelling power will however improve with more data included. (C) 2014 Elsevier B.V. All rights reserved.

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BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 6.75 SJR 1.787 SNIP 1.96
Web of Science (2017): Impact factor 6.434
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 6.31 SJR 1.742 SNIP 2.061
Web of Science (2016): Impact factor 6.065
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 5.54 SJR 1.633 SNIP 1.931
Web of Science (2015): Impact factor 4.836
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 5.21 SJR 1.814 SNIP 2.258
Web of Science (2014): Impact factor 4.529
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 5.09 SJR 1.822 SNIP 2.43
Web of Science (2013): Impact factor 4.331
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 4.73 SJR 1.953 SNIP 2.443
Web of Science (2012): Impact factor 3.925
ISI indexed (2012): ISI indexed yes
The colour potentials of SSA-containing mortar

This paper reports an experimental study of aesthetical qualities of mortar containing sewage sludge ash (SSA). SSA is the residue produced at water treatment plants where incineration of the sludge is applied in order to decrease volume and to prevent pathogens from spreading. Today SSA is, with a few exceptions landfilled and thus wasted. The purpose of the experiments was to examine the influence of SSA and how it affected the colour of mortar samples. SSA was ground in 6 different intervals and added to mortar mixes by replacing 20% of the cement. An additional focus was to examine the possibilities to accentuate the colours of the hardened mortar by using paper cuttings in the production of the samples. The result of the experiments showed that a colour scale can be developed from ground SSA, and that paper may have the potential of providing divers textural qualities when it is used in combination with other form materials.

General information

State: Published
Organisations: Section for Building Design, Department of Civil Engineering, Section for Geotechnics and Geology, Section for Structural Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions
Contributors: Kappel, A., Ottosen, L. M., Kirkelund, G. M., Bache, A. M., Goltermann, P.
Number of pages: 2
Publication date: 2015
The colour potentials of SSA-containing mortar: the long version

This paper reports an experimental study of aesthetical qualities of mortar containing sewage sludge ash (SSA). SSA is the residue produced at water treatment plants where incineration of the sludge is applied in order to decrease volume and to prevent pathogens from spreading. Today SSA is with a few exceptions landfilled and thus, wasted. The purpose of the experiments was to examine the influence of SSA and how it affected the colour of mortar samples. SSA was ground in 6 different intervals and added to mortar mixes by replacing 20% of the cement. An additional focus was to examine the possibilities to accentuate the colours of the hardened mortar by using paper cuttings in the production of the samples. The result of the experiments showed that a colour scale can be developed from ground SSA, and that paper may have the potential of providing divers textural qualities when it is used in combination with other form materials.

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State: Published
Organisations: Section for Building Design, Department of Civil Engineering, Section for Geotechnics and Geology, Section for Structural Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions
Contributors: Kappel, A., Ottosen, L. M., Kirkelund, G. M., Bache, A. M., Goltermann, P.
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Use of Greenlandic resources for the production of bricks

The housing situation in Greenland is critical. In 2012, approximately 20% of the housing was dilapidated, and due to an increasing population in the larger towns, there is currently an urgent need for the construction of new homes. Today, materials used in the Greenlandic construction industry are mostly imported, and due to high import costs, it is therefore important to investigate the potential for local construction material production. The aim of this PhD-study was to identify and test suitable raw materials for such local production. Clay-based bricks were chosen due to several reasons:

• Bricks, in general, are durable and fire-resistant materials, which possess good thermal and acoustic properties. In the harsh Arctic to sub-arctic climate of Greenland, which places high demands on construction materials, especially the thermal properties and durability of bricks are desirable characteristics.
• Bricks are heterogeneous materials, which can accommodate materials of wide ranging compositions without losing their technical properties. For this reason, the ceramic industry has been identified as one of the major recipients for waste in
the future. Wastes of different types are becoming an increasing environmental and logistical problem worldwide, and their recycling has therefore received much attention. The protection of the vulnerable Arctic nature is a great concern and waste management by ceramic incorporation should therefore be investigated.

- Historically, masonry constructions (including bricks) were dismissed in Greenland in the early 1950's, due to low frost resistance of the mortar. Although this dismissal might have been technically warranted at the time, the ceramic industry has since experienced extensive development, and today clay-based brick constructions can therefore be designed to withstand the Arctic climate conditions.

- In 2006, the Arctic Technology Centre, DTU Civil Engineering in collaboration with the Danish brickworks Petersen Tegl conducted a large scale brick pilot-production from Greenlandic glaciogene marine clay from an occurrence near the town of Kangerlussuaq. The bricks were used for the construction of a house in Sisimiut, Greenland and it was established that the Kangerlussuaq occurrence was suitable as raw material for bricks.

Large occurrences of fine-grained glaciogene marine sediments are, however, found throughout Greenland and the knowledge gaps identified and covered by this study are therefore:

- to establish the characteristics, similarities and variations of Greenlandic marine sediment occurrences in general, in respect to potential use as brick clays.
- to describe how the variations in the sediments influence the properties of produced bricks.
- to investigate the link between raw material characteristics, processing details and resulting technical characteristics of bricks produced from a representative sediment occurrence.

Furthermore, in relation to the potential for incorporating waste in the produced bricks, the following knowledge gap was identified and covered:

- to identify and conduct initial testing on waste types, which could be of interest in Greenlandic brick production. The waste types investigated in this study were municipal solid waste incineration (MSWI) ashes and tailings from the mining industry.

The major conclusions obtained from this study were:

- The Greenlandic marine sediments have very similar grain size distributions, mineralogy and major element chemistry. Furthermore, these properties are comparable to those of North American and North Scandinavian marine clays.
- Bricks with acceptable properties of e.g. compression strength, open porosity and water absorption can be produced from the sediments. However, the properties largely depend on the processing of the sediment, e.g. firing procedure and initial treatments.
- Addition of waste materials, such as the investigated bottom ash and mine tailings, generally improve the technical properties of the bricks, e.g. lowers the open porosity and increases the density. However, increased leaching of heavy metals was observed after firing, which could pose an environmental concern and requires further investigation.
Achieving generic competences through a cross-disciplinary research based course in Arctic Technology
In a research based course in Arctic Technology, different teaching activities were used to support learning of both technical and generic competences. The active learning was based around a 3-weeks field work period in Greenland in combination with lectures, assignments, project and peer group work prior to and after the field work. The students represent a heterogeneous group of nationalities, previous experiences and scientific subjects. It was clearly seen by the learning outcome and assessment that students who used the offered feedback options during the course actively were more successful in achieving both the scientific and generic competences than the students who did not. The students evaluate the course as being highly motivating for further learning and they get confident by successfully having executed a research based project in a new context. The project and field work support the process of developing generic competences and are preparing the students to become professional engineers. For the future teaching of the course we have some suggestions for improvements: • Include peer-work as a learning objective and specify rubrics of how to give feedback to make it more worthwhile for the students • Include the hand-ins of draft articles in the review process as an required element to pass the course, to distribute the work load and secure that all students receive process feedback • Explicitly tell the students that in the course there is focus on developing generic engineering competences, so they are more aware of this, instead of just focussing on improving their scientific competences.

A comparative study on electrodialytically treated bio-ash and MSWI APC-residue for use in bricks

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Organisations: Section for Construction Materials, Department of Civil Engineering, Section for Building Design
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**A comparative study on electrodialytic treated bio-ash and MSWI-APC residue for use in bricks**

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**Comparison of two experimental set-ups for electrodialytic removal of heavy metals and Cl from MSW APC residues**

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**Electrodialytically treated MSWI APC residue as substitute for cement in mortar**

Air pollution control (APC) residues from municipal solid waste incineration (MSWI) are considered hazardous waste and need pretreatment prior to possible reuse. Here, two MSWI APC residues, from which the most mobile fraction of heavy metals and salts has been removed by carbonation and/or electrodialytic remediation, were used in Portland cement mortar. Mortar bars with 15 % weight replacement of cement by APC residues showed compressive strengths up to 40 MPa after 28/32 days. Heavy metal and salt leaching from both crushed and monolithic mortars with APC residues was generally similar and comparable to both the reference mortar and mortar with coal fly ash. These results indicate that electrodialytic remediation could be used a pre-treatment method for MSWI APC residues prior to reuse in mortar.

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Contributors: Kirkelund, G. M., Geiker, M. R., Jensen, P. E.
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Electrodialytic removal of heavy metals from fly ash from co-combustion of wood and straw – influence from prewash

Electrodialytic Separation of Phosphorus and Heavy Metals from Two Types of Sewage Sludge Ash

During sewage sludge incineration phosphorus (P) is retained in the ash in a form not directly available to plants. As P is a sparse resource, it is important to develop techniques for recovery of P from incinerated sewage sludge ashes (ISSA). Heavy metals are concentrated in ISSA and separation of P and heavy metals is required. The present work is an experimental screening of a new combination of acid extraction and electrodialysis-electrodialytic separation (EDS) for simultaneous P recovery and removal of heavy metals. Experiments were conducted with two different ashes; rich in Fe or Al. The separation method was best suited for the Fe-rich ash, where it was possible to separate P into one processing solution, heavy metals (Cu, Zn, Ni, Pb) into another, keeping the ash suspended in a third solution (which though still contained P after 1 week of EDS). For the Al rich ash, the separation was not similarly encouraging. The high release of Al
during the extraction influenced the speciation of P and negatively charged P complexes were not prevailing. On the contrary to Al, the Fe containing ash particles were insoluble so Fe did not interfere with P speciation and separation after extraction.

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BFI (2015): BFI-level 1
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ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 1.2 SJR 0.534 SNIP 0.674
Web of Science (2012): Impact factor 1.164
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BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 1.1 SJR 0.47 SNIP 0.625
Web of Science (2011): Impact factor 1.088
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Scopus rating (2010): SJR 0.468 SNIP 0.684
Web of Science (2010): Impact factor 1.015
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Non-conventional waste water treatment methods for Greenlandic communities

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Contributors: Jensen, P. E., Kirkelund, G. M., Andersen, H. R., Heiske, S.
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Pilot scale electrodialytic treatment of MSWI APC residue to decrease leaching of toxic metals and salts

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Screening of waste for use in clay-based bricks in the Arctic

Clay-based ceramics, such as bricks, are heterogeneous materials, which can incorporate raw materials of wide ranging compositions, without impairing their technical properties (Dondi et al., 1997a,b). Due to this ability, bricks have become a popular material in waste management research worldwide and several studies have demonstrated that clay-based bricks and tiles can successfully accommodate waste types, such as incineration ashes, mine tailings and dredged harbour sediments (Zhang et al., 2011; Roy et al., 2007; Mezencevova et al., 2012). In the vulnerable Arctic environment, the impact of especially hazardous wastes can have severe consequences (Lemly, 1994) and the reduction and safe handling of these waste types are therefore an important issue in the Arctic nations. In comparison to other parts of the world, the Arctic region imports most of its construction materials and does not have a strong tradition for masonry structures. In Greenland, for example, bricks are neither currently produced locally nor frequently applied for construction purposes. Recent studies have, however, established that deposits of marine glaciogene clay, which are found throughout the former glaciated areas of the northern hemisphere, are suitable for brick production (Belmonte et al., 2014, a; Belmonte et al., 2014, b). This provides an excellent opportunity to test whether bricks produced locally in the Arctic could also help to solve issues regarding waste handling and disposal. In this study, two types of hazardous waste, municipal solid waste incineration (MSWI) ashes and mine tailings from Greenland, were investigated in order to determine their potential suitability for incorporation in the production of clay-based bricks. Furthermore, the MSWI fly ash was subjected to two remediation techniques (electrodialytic treatment and washing) with the purpose of studying the effects of these treatments on the leaching behaviour.

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Testing of new shifting current electrodialytic treatment setup for efficient treatment of Cr-contaminated soil fines

General information
State: Published
Organisations: Section for Geotechnics and Geology, Department of Civil Engineering
Contributors: Jensen, P. E., Ottosen, L. M., Kirkelund, G. M.
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The Aesthetical quality of SSA-containing mortar and concrete

SSA (sewage sludge ash) is resulting ash from the combustion of sewage sludge, and is a method employed at some water treatment plants in order to decrease volume and hygenize the sludge. Today, SSA is with a few exceptions landfilled. As cement production is responsible for app. 5% of the total global CO2 emission, the advantage of replacing cement with a secondary resource as SSA is obvious. The focus of previous conducted research has mainly been on the chemical, mechanical properties and environmental consequences attached to the use of SSA in construction materials. (Cyr et al., 2007) Thus, this present study has focused on both the aethetical and technical aspects of using SSA as a supplementary cementitious material. The SSA, which was tested, was taken from the wastewater treatment plant Avedøre Spildevandscenter, Biofos site in the Copenhagen area. This ash had a high content of Fe that gives a characteristic red colour. The process of grinding SSA has shown to improve the compressive strength of SSA-containing mortar (Donatello et al. 2010). Thus, in this study SSA was grinded in 6 different intervals ranging from 0 – 10 min, and then added to the mortar mix replacing 20% of cement. The experiment revealed that the colour of the SSA-containing mortar intensified as the time interval of the grinding process increased. Each of the 6 steps within the time interval

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provided an additional colour tone and generated a colour scale consisting of mortar samples ranging from greyish to a more saturated red brown colour. SSA shows potential for colouring concrete, and if the aesthetical aspects such as colour are taken into account at an early

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Organisations: Department of Civil Engineering, Section for Building Design, Section for Structural Engineering
Contributors: Kappel, A., Kirkelund, G. M., Ottosen, L. M., Bache, A. M., Goltermann, P.
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Two step electrodialytic remediation of soil suspension for simultaneous removal of As and Cu

**General information**
State: Published
Organisations: Department of Civil Engineering
Contributors: Ottosen, L. M., Jensen, P. E., Kirkelund, G. M.
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ZeroWaste: Turning waste into a new, sustainable resource for concrete
The ZeroWaste research group at the Department of Civil Engineering at the Technical University of Denmark (DTU Byg) was established two years ago and covers the broad range of expertise, required for turning waste materials into attractive, new materials. Members of the group have, prior to that, developed methods for removal of heavy metals and phosphorous from waste incineration, sewage sludge and other bio ashes, providing the basis of to make these ash types an attractive, new material for the building sector. Initial results for upgrading and using different types of ashes are presented in the paper, including an approach for involving large number of project students in the work.

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ZeroWaste BYG: Redesigning construction materials towards zero waste society
The ZeroWaste research group (www.zerowaste.byg.dtu.dk) at the Department of Civil Engineering was established in 2012 and covers the broad range of expertise required for turning waste materials into attractive, new materials. Members
of the group have developed methods for removal of heavy metals and phosphorous from waste incineration, sewage sludge and other bio ashes [1], providing the basis to make these ash types an attractive, new material for the building sector. The amount of waste increases and it is both difficult and expensive to handle many waste types as e.g. different ashes. At the same time there are fewer natural resources and the general consumption increases. We wish to utilize alternative and new ash types as raw material in concrete, similarly to what was previously seen with fly ash from coal combustion and microsilica, which were both transformed from problematic waste to valuable raw material. The physical-chemical characteristics of fly ash, such as large uniformity coefficient, clay-sized particles and rich in some metal elements and salts, show the possibility of being a raw material also for bricks and lightweight aggregates. In the future we expect increasing political pressure to change the status of different ashes from waste to raw material and that export for disposal will be no longer be allowed. We wish to influence the consequences from this new situation. In principle some of the ashes can be used already, but the huge variation in ash characteristics and lack of knowledge in the construction industry on the qualities some of the ashes can give the concrete and clay materials means that they are not used today.

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**Effect of pulse current on acidification and removal of Cu, Cd, and As during suspended electrodialytic soil remediation**

The effect of pulse current on the acidification process and the removal of heavy metals during suspended electrodialytic soil remediation were investigated in this work. Eight experiments with constant and pulse current in two polluted soils were conducted using a 3-compartment membrane cell, predominately working under overlimiting current density conditions. Soil 1 was sampled from a pile of excavated soil at a site with mixed industrial pollution (Cu and Cd), and soil 2 was sampled from the top layer of a wood preservation site (Cu and As). Results showed that pulse current improved the acidification by supplying more reactive H+ ions (defined as the H+ ions causing release of heavy metals from soil particles). The molar ratio of reactive H+ ions to total produced H+ ions (R_H+/P_H+) was higher in every pulse current experiment than in the corresponding constant current experiment. In addition the removal efficiencies of heavy metals were also improved. The carbonate buffering system in a soil is the first mechanism reacting with the produced H+ ions and impeding the heavy metal mobilization. It was found that the effect of improvement on both the acidification process and the removal of heavy metals were more significant in the soil with highest buffering capacity than the soil with low. Energy distribution analysis demonstrated that most energy was consumed by the transport of ionic species through the soil suspension, and then followed by membranes and electrolytes. The pulse current decreased the energy consumption to different extent depending on the pulse frequency. The lowest energy consumption was obtained in the experiment with the highest pulse frequency (96 cycles per day) for both soils.

**General information**

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Web of Science (2016): Impact factor 4.798
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.86 SJR 1.321 SNIP 1.324
Web of Science (2015): Impact factor 4.803
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.59 SJR 1.378 SNIP 1.456
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Scopus rating (2012): CiteScore 3.99 SJR 1.644 SNIP 1.574
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Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.685 SNIP 1.715
Web of Science (2010): Impact factor 3.65
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.523 SNIP 1.615
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.524 SNIP 1.458
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.551 SNIP 1.568
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Web of Science (2005): Indexed yes
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Scopus rating (2003): SJR 1.637 SNIP 1.505
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 1.534 SNIP 1.441
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 1.312 SNIP 1.376
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 0.889 SNIP 1.161
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Electrodialytic extraction of heavy metals from Greenlandic MSWI fly ash as a function of remediation time and L/S ratio

The management of Greenlandic municipal solid waste incineration (MSWI) fly ash could be improved. Presently, the fly ash is disposed of in Norway as the fly ash is classified as hazardous waste. Fly ash contains high amounts of leachable heavy metals, but also resources that could be beneficial for reuse. In electrodialytic remediation a direct current is applied to a contaminated particulate material to remove heavy metals from the material. In this study, electrodialytic remediation was applied to a Greenlandic MSWI fly ash from a small waste incinerator in Ilulissat. The fly ash was characterized before and after the electrodialytic remediation experiments for heavy metals content, amount of soluble heavy metals and pH. Before the electrodialytic experiments the water solubility of Ba, Cr and Pb was high from the alkaline fly ash. Six electrodialytic remediation experiments were made, where the fly ash was suspended in distilled water in different liquid to solid (L/S) ratios. Remediation times of 7 and 14 days were tested and the current strength was 50 mA in all experiments. The highest removal was seen when an acidic pH in the fly ash suspension was obtained. In an experiment lasting 14 days with L/S 10, up to 60 % Cd, 45 % Zn, 20 % Ni and Ba was removed. Regardless of the remediation time and L/S ratio, the fraction of soluble Ba, Cr and Pb decreased due to the electrodialytic remediation. The electrodialytic remediation method showed potential as a treatment method for the Greenlandic fly ash.

Electrodialytic Remediation of Different Heavy Metal-Polluted Soils in Suspension

Electrokinetic remediation of heavy metal-polluted soil faces different challenges in relation to implementation. One challenge is to cope with the nonlinear and transient geochemical changes in the soil and another is to increase the remediation rate. Both these challenges are met when treating the soil in a suspension in an electrodialytic cell. The soil suspension is stirred and uniform during treatment. Previously, it has been shown that a faster remediation can be obtained when remediating a stirred soil suspension compared to a stationary water saturated soil (all other parameters the same). The present work shows that the method for treating stirred suspensions was robust in the sense that in 1–3 weeks, three of four soils were decontaminated from heavy metal concentrations, where the soils must be deposited to concentrations where the soil can be allowed used for some purposes in Denmark. From the fourth soil of the investigation, 92 % Pb was removed during 14 days, but as the initial concentration was very high (33.6 g Pb/kg), the final concentration was still high and the soil maintained classified where there are no reuse options in Denmark, so optimization of the treatment for this soil is necessary to meet the goal. The good results were obtained even without optimization of processing parameters, but the investigation underlined that the optimal parameters are highly soil and pollution specific.
Electrodialytic removal of Cd from biomass combustion fly ash suspensions

Due to relatively high concentrations of Cd, biomass combustion fly ashes often fail to meet Danish legislative requirements for recycling as fertilizer. In this study, the potential of using electrodialytic remediation for removal of Cd from four different biomass combustion fly ashes was investigated with the aim of enabling reuse of the ashes. The ashes originated from combustion of straw (two ashes), wood chips, and co-firing of wood pellets and fuel oil, respectively. A series of laboratory scale electrodialytic remediation experiments were conducted with each ash. The initial Cd concentration in the ashes varied between 8.8 mg Cd/kg (co-firing ash) and 64 mg Cd/kg (pre-washed straw ash), and pH varied from 3.7 (co-firing ash) to 13.3 (wood ash). In spite of such large variations between the ashes, the electrodialytic method showed to be sufficiently robust to treat the ashes so the final Cd concentration was below 2.0 mg Cd/kg DM in at least one experiment done with each ash. This was obtained within 2 weeks of remediation and at liquid to solid (L/S) ratios of L/S 16 for the pre-washed straw ash and L/S 8 for the straw, co-firing and wood ash. © 2013 Elsevier B.V.

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Scopus rating (2015): CiteScore 5.54 SJR 1.633 SNIP 1.931
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Web of Science (2015): Indexed yes
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Web of Science (2014): Impact factor 4.529
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Web of Science (2013): Impact factor 4.331
ISI indexed (2013): ISI indexed yes
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BFI (2012): BFI-level 1
Extracting phosphorous from incinerated sewage sludge ash rich in iron or aluminum

Ashes from mono-incineration of sewage sludge (ISSA) generally contain high concentrations of phosphorous (P) and can be regarded as secondary P resources. ISSA has no direct value as fertilizer as P is not plant available. The present paper experimentally compares P extraction in acid from two different ISSAs; one rich in Al (67g/kg) and the other in Fe (58g/kg). The difference related to P precipitation at the waste water treatment facilities. Another major difference between the ashes was that flue gas purification products were mixed into the first ash and it contained about 5% activated carbon. The Al rich ash had a significantly higher buffering capacity and required more acid for extraction of P. When acid extraction of P from ISSA is the method for recovery, it is thus beneficial to go back to the waste water treatment facility and e.g. choose Fe for P precipitation rather than Al. Formation of a high amount of gypsum crystals in both ashes after extraction in H2SO4 was seen by SEM-EDX. H2SO4 is the cheapest mineral ash, but the gypsum formation must be taken into account when either finding possibility for using the remaining ash in e.g. construction materials or if the choice is deposition, as the gypsum increases the volume significantly.
Characterisation of MSWI bottom ash for potential use as subbase in Greenlandic road construction

The waste management situation in Greenland needs to be improved. Most waste in towns is incinerated with only limited separation prior to incineration and the bottom ash residue is disposed of at uncontrolled disposal sites. The bottom ash could be a valuable resource within the expansion of infrastructure due to increased oil and mineral exploitation. Thus, in this study MSWI bottom ash from a Greenlandic incinerator was tested for possible reuse as subbase in road construction. The mechanical properties (grain size distribution, wear resistance and bearing capacity) showed that the bottom ash was acceptable for reuse after some small adjustments in the grain size distribution to prevent frost sensitivity. Results obtained from heavy metal content and heavy metal leaching complied with the Danish guideline values for reuse of waste materials in construction. Leaching of Cu and Cr was high from small grain sizes and could be reduced by removing some of these smaller grain sizes to obtain the stability requirement of the bottom ash. All in all, this study showed that the Greenlandic bottom ash has potential for being reused in road construction.
Electrodialytic remediation of heavy metal polluted soil: treatment of water saturated or suspended soil

Electrodialytic soil remediation is a method for removal of heavy metals. Good results have previously been obtained with both treatment of a stationary, water saturated soil matrix and with remediation of a stirred suspension of soil in water. The two different setups have different uses. The first as in-situ or on-site treatment when there is no requirement for fast remediation, as the removal rate of the heavy metals are dependent on the distance between the electrodes (everything else equal) and in such application the electrode spacing must have a certain distance (often meters). In the stirred setup it is possible to shorten the transport route to few mm and to have a faster and continuous process. The present paper for the first time reports a direct comparison of the two options. The remediation of the stirred suspension showed faster than remediation of the water saturated soil even without a short distance between the membranes. The acidification of the suspended soil was fastest and following the mobilization of heavy metals. This may indicate that water splitting at the anion exchange membrane is used more efficiently in the stirred setup.

Electrodialytic remediation of suspended soil – Comparison of two different soil fractions

Electrodialytic remediation (EDR) can be used for removal of heavy metals from suspended soil, which allows for the soil remediation to be a continuous process. The present paper focused on the processing parameters for remediation of a soil polluted with Cu and As from wood preservation. Six electrodialytic treatments lasting from 5 to 22 days with different liquid to solid ratio (L/S) and current intensity were conducted. Among treatments, the highest removal was obtained from the soil fines with 5mA current at L/S 3.5 after 22 days where 96% of Cu and 64% of As were removed. Comparing the removal from the original soil and the soil fines in experiments with identical charge transportation, higher removal efficiency was observed from the soil fines. Constant current with 5mA could be maintained at L/S 3.5 for the soil fines while not for the original soil. Doubling current to 10mA could not be maintained for the soil fines either, and doubling L/S to 7 at 5mA entailed a very fast acidification which impeded the removal. The results showed that a very delicate balancing of current density and L/S must be maintained to obtain the most efficient removal.
Electrodialytic treatment of sewage sludge ash for the recovery of phosphorous

General information
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Electrodialytic treatment of sewage sludge ash for the recovery of phosphorous and separation of heavy metals

Mobilization and extraction of both phosphorus (P) and heavy metals (HM) from sewage sludge ash through means of acidification has been studied extensively. However, separation of both P and HM after mobilization to provide reusable materials has proven to be challenging. This study presents a combination of acidification and electrodialytic separation (EDS) to mobilize and separate P and HM from sewage sludge ash (SSA). The EDS experimental setup consists of three compartments, separated by ion exchange membranes which are located at either side of the stirred ash suspension. Through application of a direct current to electrodes in the outer compartments, ionic complexes migrate and concentrate in the electrode compartments in accordance to their charge. Application of both EDS and acidification of the ash resulted in an increased release of phosphorus from the ash, but did not always result in separation from the ash suspension to the anode compartment. Although 96% of the recovered P was mobilized, only 55% was separated from the ash suspension. Less mobilization (m), but better separation (s), from the ash and ash suspension was observed for heavy metals, 78% (m) 69% (s) for Cd; 24% (m) 7% (s) for Cr; 76% (m) 72% (s) for Cu; 23% (m) 20% (s) for Ni; 12% (m) 10% (s) for Pb; and 59% (m) 56% (s) for Zn.

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State: Published
Organisations: Department of Civil Engineering, Section for Geotechnics and Geology, Section for Construction Materials
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Electrodialytic upgrading of municipal waste incineration fly ash for reuse: optimization of time and energy consumption
As incineration becomes a more widespread means of waste treatment, volumes of incineration residues increase and new means of handling become a demand. Municipal Solid Waste Incineration (MSWI) fly ash is hazardous material, which is presently disposed off as such; primarily due to its high content of water soluble, mobile salts and heavy metals. It was shown that the mobility of salts and toxic elements can be significantly reduced by extraction with electrodialysis in stack [1, 2]; and that treated MSWI fly ash may potentially be utilized as a substitute for cement in concrete [3].

In order to optimize the process and reach the lowest possible leachability of target constituents (As, Ba, Cd, Cr, Cu, Mn, Ni, Pb, Zn, Cl, Na and SO4) at minimum time and energy consumption, the present work gives results of 10 pilot scale (8 kg MSWI fly ash each) electrodialysis experiments at different current densities and with three different types of fly ashes (semi-dry, dry and wet fluegas cleaning). Continuous monitoring of voltage, pH and conductivity of the diluate (MSWI fly ash) solution and the concentrate is reported. Sampling of the treated fly ash was made during and after each experiment to investigate the leachability of salts and toxic elements as a function of treatment time and current density.

Results show that a delicate balance between pH and treatment-time exist and that continuous monitoring of pH and conductivity may be used for controlling of the process at an industrial scale.

References

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Testing the possibility for reusing mswi bottom ash in Greenlandic road construction
In Greenland waste has traditionally been dumped at open disposal sites combined with uncontrolled incineration. In the mid 1990’ies the first waste strategy was implemented in Greenland. As a result simple and small municipal solid waste incineration (MSWI) plants were implemented in towns and settlements primarily to minimize the amount of waste at the disposal sites. In Greenland the household waste is generally sorted into four fractions [1]: combustible, metal, hazardous waste and mixed waste and there are problems of sorting the metal and hazardous waste properly from the combustible waste, which can influence the quality of MWSI residues. About 15,000 tons MSWI bottom ash is produced annually in Greenland and is disposed of at the open disposal sites without leachate collection or encapsulation. The MSWI bottom ash could have value as a secondary resource in construction work in Greenland. This would contribute to solve the problem of disposal and possible related environmental problems in the vulnerable Greenlandic environment.

In this study, MSWI bottom ash was collected from the disposal site in the town of Sisimiut in Western Greenland and characterized and tested for technical requirements (a grain size distribution, wear resistance, visual fraction analysis and bearing capacity) for reuse as fill material in road construction [2]. Environmental classification based on heavy metal content and leachability was also investigated.

The tests showed that it will not be possible to use the bottom ash directly after the incineration as the bottom ash did not comply with all the requirements specified by the Danish Road Directorate. These technical requirements could be
improved by removing large fractions (> 45mm) and metal parts as well as changing the grain size distribution in the smaller fractions (< 0.5 mm). The bearing capacity showed a CBR-value of 21.4%, which is acceptable for the intended use. The heavy metal content and leachable amount of heavy metals in the bottom ash were under the Danish guideline levels for reuse of contaminated waste for geotechnical purposes as filler in roads [3]. Thus, pretreatment or better sorting of the waste before incineration is necessary to improve the quality of the bottom ash before reuse as road fill is possible.

References


Evaluating the potential for reusing biomass combustion fly ashes after removal of Cd by electrodialytic remediation

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Research output: Research - peer-review » Conference abstract in proceedings – Annual report year: 2012

Electrodialytic treatment for metal removal from sewage sludge ash from fluidized bed combustion

Sewage sludge contains several potentially hazardous compounds such as heavy metals, PCBs, PAHs, etc. However, elements with high agricultural value (P, K or Ca) are also present. During the last years, the fluidized bed sludge combustor (FBSC) is considered an effective and novel alternative to treat sewage sludge. By its use, the high amount of sludge is reduced to a small quantity of ash and thermal destruction of toxic organic constituents is obtained. Conversely, heavy metals are retained in the ash. In this work the possibility for electrodialytic metal removal for sewage sludge ash from FBSC was studied. A detailed characterization of the sewage sludge ash was done initially, determining that, with the exception of Cd, the other heavy metals (Cr, Cu, Pb, Ni and Zn) were under the limiting levels of Danish legislation for the use of sewage sludge as fertilizer. After 14 days of electrodialytic treatment, the Cd concentration was reduced to values below the limiting concentration. In all experiments the concentrations of other metals were under limiting values of the Danish legislation. It can be concluded that the electrodialytic treatment is an adequate alternative to reduce the Cd concentration in FBSC ash prior to use as fertilizer.

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering, Section for Construction Materials, Arctic Technology Centre, University of Vigo
Evidence of Quick-Clay Deposit at Kangerlussuaq, West Greenland

In 2007 a large ice dammed lake at the Russel Glacier, near Kangerlussuaq, West Greenland, drained in a catastrophic flood event – a jökulhlaup. The draining was made possible by a general retreat of the glacier due to climate amelioration. Under normal circumstances such jökulhlaups go relatively unnoticed in Greenland, but in this case the jökulhlaup propagated through a river basin which passes by the main international airport in Greenland. Due to the erosion of the riverbank during the jökulhlaup, several man-made structures were affected – roads disappeared and several storage facilities were eroded and destroyed by the river. In the wake of the catastrophic flood, a previously unknown permafrozen fingrained marine deposit was observed in the erosional bank of the river. Laboratory studies have proven this material to have extremely high sensitivity, with natural water content much higher than the liquid limit. The formation has been stabilized by the presence of permafrost in the area, but the combination of erosional energy supplied by the river and the sensitive properties of the material have resulted in quick thaw, destabilization and erosion of the formation. As an effect, the riverbank was eroded approximately 40 m inland over the course of the jökulhlaup, which lasted approximately one day. It is the first time such a quick clay formation has been observed very near surface in inhabited areas in Greenland. If such deposits are found to be more widespread, it could be very problematic for the future infrastructural development in the region. Here we present the results of recent research, including a study of mineralogy of the quick clay using SEM and XRD. We also discuss the effect of climate warming on permafrost thaw in the area.

General information
State: Published
Organisations: Section for Geotechnics and Geology, Department of Civil Engineering, Arctic Technology Centre
Contributors: Ingeman-Nielsen, T., Kirkelund, G. M., Jørgensen, A. S., Foged, N. N.
Number of pages: 276
Publication date: 2010

Feasability test of electrodialytically upgraded MSWI APC residue utilization in mortar

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering, Section for Construction Materials, Arctic Technology Centre
Contributors: Kirkelund, G. M., Geiker, M. R., Jensen, P. E.
Investigations of Cu, Pb and Zn partitioning by sequential extraction in harbour sediments after electrodialytic remediation

Electrodialytic remediation was used to remove Cu, Zn and Pb from three different contaminated harbour sediments. Electrodialytic experiments lasting 2 and 4 weeks were performed and 48-86% Cu, 74-90% Zn and 62-88% Pb were removed from the different sediments and the removal increased with longer remediation time. A three step sequential extraction scheme (BCR), with an extra residual step, was used to evaluate the heavy metal distribution in the sediments before and after electrodialytic remediation. Cu was mainly associated with the oxidisable phase of the sediment, both before and after remediation. Zn and Pb were found in the exchangeable and reducible phases before remediation. Zn was still found in the exchangeable and reducible phases after remediation, whereas most Pb was removed from these phases during electrodialytic remediation.
Opgradering af farligt røggasaffald

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering, Section for Construction Materials, CHEC Research Centre, Department of Chemical and Biochemical Engineering, Arctic Technology Centre
Contributors: Jensen, P. E., Kirkelund, G. M., Ottosen, L. M., Christensen, I. V., Pedersen, A. J.
Pages: 16-19
Publication date: 2010
Reuse of harbour sediments in the Greenlandic construction industry
The purpose of this study is to investigate possibilities of using harbour sediments from the Greenlandic harbours as substitutes in the Greenlandic construction industry, mainly for concrete production and road construction. Materials for use in the Greenlandic construction industry are shipped to Greenland from all over the world and reuse and use of resources already in Greenland would therefore make a huge contribution to the local community.

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering, Section for Construction Materials, Arctic Technology Centre
Contributors: Belmonte, L. J., Kirkelund, G. M., Ottosen, L. M., Villumsen, A.
Number of pages: 4
Publication date: 2010

Host publication information
Title of host publication: ISCORD 2010 : Materials of the IX International Symposium on Cold Regions Development, June 1-5, 2010

Bibliographical note
Full conference paper is published on the conference CD
Source: orbit
Source-ID: 264095
Research output: Research - peer-review › Article in proceedings – Annual report year: 2010

Test of electrodialytic upgrading of MSWI APC residue in pilot scale: focus on reduced metal and salt leaching
In this study a pilot plant for electrodialytic treatment of municipal solid waste incineration (MSWI) air pollution control (APC) residue was tested and proposed as a treatment method which can lead to reuse of this otherwise hazardous waste. The pilot plant was developed based on a design that is adapted from conventional electrodialysis, e.g. used in desalination of solutions. The APC residue was treated in a suspension (8 kg APC residue and 80 L tap water) and circulated through an electrodialytic (ED) stack consisting of 50 cell pairs separated by ion exchange membranes. A direct current was applied to the ED stack for removal of heavy metals (As, Ba, Cd, Cr, Cu, Mn, Ni, Pb, Zn) and salts (Cl, Na, SO4) from the APC residue suspension. Different tank designs for mixing the APC residue suspension were tested as well as changing experimental conditions. A part of the raw experimental APC residue was carbonated by reaction with CO2 under moist conditions prior to electrodialytic treatment. The carbonation alone reduced the leaching of some heavy metals. However, it was not sufficient to reduce the heavy metal or salt leaching to meet the Danish Category 3 guideline levels for waste material reuse and could not stand as a treatment method alone. Leaching of both heavy metals and salts were significantly reduced by the electrodialytic treatment for both the raw and carbonated APC residue. In the electrodialytically treated carbonated APC residue only Cr exceeded the Category 3 levels while in the electrodialytically treated raw APC residue both Pb and Zn leaching exceeded the Category 3. Optimization of the electrodialytic upgrading method is necessary to meet the Category 3 levels for all heavy metals. Removal of Na and SO4 to below the Category 3 leaching levels were obtained in all the experiments. Cl removal was not sufficient in all experiments even if up to 1 kg of Cl was removed, the optimal conditions for Cl removal was a constant current of 5 A over the ED stack. The results of this study suggest that, with some optimization, electrodialytic upgrading, possibly in combination with carbonation, could be used as a treatment method for MSWI APC residue.

General information
Use of clay from Kangerlussuaq in the Greenlandic construction industry

Clay material from Kangerlussuaq in West Greenland was characterised and its possible use for the production of bricks, expanded clay products and inert filler material was investigated. It was generally found that it was possible to use the clay in all of the above mentioned materials, although, further investigations will be needed before a final conclusion can be made. This paper is based on results and conclusions of student projects that were carried out at the Arctic Technology Centre, DTU.

Electrodialytic remediation of harbour sediment in suspension - Evaluation of effects induced by changes in stirring velocity and current density on heavy metal removal and pH

Electrodialytic remediation was used to remove heavy metals from a suspension of dredged harbour sediment. The studied metals Cu, Pb, Zn and Cd are normally strongly bound in anoxic sediment. Six electrodialytic laboratory remediation experiments were made, lasting 14 days and under oxic conditions. The influence on the metal removal was investigated by changing current densities and stirring velocity of the sediment suspension. Using a current density of 1.0 mA/cm² gave the highest metal removal. The sediment suspension was partly oxidised when mixed into a suspension for the electrodialytic remediation experiments and was further oxidised during the experiments. Even at low stirring velocities, oxic conditions were obtained. The metal removal was dependent on the achieved pH in the sediment and the highest metal removal and corresponding low pH was obtained by using a current density of 1.0 mA/cm² and a stirring velocity of the sediment suspension of 1000 rpm. The highest removal obtained was 98% Cd, 78% Zn, 65% Pb and 44% Cu after 14 days of remediation. The metal removal was more dependent on the stirring velocity than on the current density. When manually stirring the sediment suspension or using a stirring velocity of 60 rpm the sediment deposited, which led to a slightly higher pH in the sediment and keeping all the sediment in suspension is essential for a successful remediation.
Electrodialytic treatment of air pollution control residues in pilot scale

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering
Contributors: Kirkelund, G. M., Jensen, P. E., Villumsen, A.
Publication date: 2009
Peer-reviewed: Yes
Event: Abstract from 8th Symposium on electrokinetic remediation, .
Source: orbit
Source-ID: 251599
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2009

Electrodialytic treatment of sludge ash from fluidized bed combustor

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering, Section for Construction Materials
Contributors: Pazos, M., Barata, R., Jensen, P. E., Kirkelund, G. M., Ottosen, L. M.
Publication date: 2009
Peer-reviewed: Yes
Event: Abstract from Electrochemical Science and Technology, Roskilde University, Denmark.
Source: orbit
Source-ID: 251598
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2009

Electrodialytic upgrading of municipal solid waste incineration fly ash in pilot scale

General information
State: Published
Organisations: Section for Arctic Technology, Department of Civil Engineering, Arctic Technology Centre
Contributors: Jensen, P. E., Kirkelund, G. M., Villumsen, A.
Number of pages: 28
Publication date: 2009

Host publication information
Title of host publication: Electrochemical Science and Technology
Source: orbit
Source-ID: 256137
Research output: Research - peer-review › Conference abstract in proceedings – Annual report year: 2009
Electrokinetic remediation of heavy metal polluted soil: Recent developments towards a continous process

General information
State: Published
Organisations: Department of Civil Engineering, Section for Construction Materials, Section for Arctic Technology, Universidad Tecnica Federico Santa Maria
Number of pages: 316
Pages: 112-113
Publication date: 2009

Host publication information
Title of host publication: CRC Care 2009, 3rd International Contaminated Site Remediation Conference: Program and Proceedings
Place of publication: CRC Care Pty Ltd
Source: orbit
Source-ID: 251461
Research output: Research - peer-review › Article in proceedings – Annual report year: 2009

Electrodialytic treatment of fly ash
Heavy metals are removed from the fly ashes by an electrodialytic treatment with the aim of up-grading the ashes for reuse in stead of disposal in landfill. A great potential for upgrading of bio- and waste incineration ashes by electrodialytic treatment exists. In the future, the applicability of the treated products for reuse in construction or farming sectors should be explored further, as should the possibility of recycling of valuable, extracted elements in the metallurgical industry.

General information
State: Published
Organisations: Section for Geotechnics and Geology, Department of Civil Engineering, CHEC Research Centre, Department of Chemical and Biochemical Engineering, Section for Construction Materials, Arctic Technology Centre
Contributors: Jensen, P. E., Pedersen, A. J., Kerkelund, G. M., Ottosen, L. M.
Publication date: 2008
Peer-reviewed: No
Source: orbit
Source-ID: 231615
Research output: Research › Poster – Annual report year: 2008

Electrodialytic extraction of Cd and Cu from sediment from Sisimiut Harbour, Greenland
A previous study showed that the sediment of Sisimiut Harbour, Greenland is polluted with Cu and Cd to an extent where toxicological effects must be expected. This study was aimed at evaluating the possibility for removing Cu and Cd from this sediment by an electrodialytic method and also to evaluate the removal rate of the two heavy metals. The sediment was suspended in distilled water during application of current. Both heavy metals were removed successfully. The Cu concentration was reduced from 97 to 16 mg/kg and the Cd concentration was reduced from 0.55 to 0.03 mg/kg after 28 days with an applied current density of 1.2 mA/cm^2. However, it was seen that the removal rate decreased considerably after 3 days with an applied current density of 0.5 mA/cm^2 and the major part of the two heavy metals was removed during the first 3 days (the Cu concentration was reduced with 74% and the Cd concentration with 80%). Thus a large reduction in concentrations can be obtained relatively fast. During the process of electrodialytic treatment the sediment suspension is acidified and reaches pH 2 after about 3 days (with 0.5 mA cm^2), where it stabilizes. A comparison with chemical extraction in HNO3 at about the same pH showed that 50-70% more Cu and 11% more Cd was removed during the electrodialytic treatment.

General information
State: Published
Organisations: Section for Construction Materials, Department of Civil Engineering, Section for Geotechnics and Geology, Arctic Technology Centre
Pages: 271-279
Publication date: 2007
Peer-reviewed: Yes

Publication information
Journal: Journal of Hazardous Materials
Leaching properties of estuarine harbor sediment before and after electrodialytic remediation

Electrodialytic remediation (EDR) can be used to extract heavy metals from a variety of different media. In this work, contaminated harbor sediments from two locations in the United States and one in Norway were subjected to EDR, and were compared with batch extractions conducted with the sediment. pH-dependent leaching tests were used to evaluate changes in leaching properties of treated and control sediments. Significant fractions of total concentrations were removed during treatment (35-95% with an average of 75% for all sediments and elements investigated). The release of elements in pH-dependent leaching tests, however, demonstrated equal or greater leaching from treated sediments in the neutral pH range. Dissolved organic carbon appears to be a significant contributor to post-treatment increases in leaching, and dissolution of significant iron and aluminum sorption sites is hypothesized to also play a role. This research highlights the importance of understanding contaminant speciation and availability, as total metals concentrations, in this particular case, do not relate to estimates of the environmental availability of metals (total concentrations were typically two to three orders of magnitude greater than concentrations released during pH-dependent leaching).
Electrodialytic removal of Cd and Cu from sediment from Sisimiut Harbour

General information
State: Published
Organisations: Section for Construction Materials, Department of Civil Engineering, Section for Arctic Technology, Arctic Technology Centre
Contributors: Ottosen, L. M., Kirkelund, G. M., Villumsen, A.
Number of pages: 103
Pages: 71-77
Publication date: 2006

Host publication information
Title of host publication: The Greenlandic Environment : Pollution and Solutions
URLs:
http://www.arktiskcenter.gl
The use of desorbing agents in electrodialytic remediation of harbour sediment

Electrodialytic removal of Cu, Zn, Pb and Cd from contaminated harbour sediment was made with the emphasis of testing the effectiveness of different desorbing agents: HCl, NaCl, citric acid, lactic acid, ammonium citrate and distilled water. Extraction experiments with the desorbing agents were made prior to the electrodialytic experiments. The extractions showed that HCl was most efficient for metal desorption, probably due to the low pH and complexation with chloride. The metals were not extracted by distilled water. However, in the electrodialytic experiments, the removal was high when using distilled water and the desorbing agents did generally not enhance the heavy metal removal compared to distilled water. The only exception was with lactic acid, where the Cu removal was 20% higher compared to the other desorbing agents. The removal was 48% Cu, 80% Zn, 96% Pb and 98% Cd, when using distilled water. Metal speciation with the different desorbing agents was simulated with the geochemical model Visual MINTEQ version 2.15. Variations in the Cl concentration were found to be of crucial importance since it influences the formation of metal chlorocomplexes, especially uncharged species. All the acidic desorbing agents were predicted to form mostly cationic species, which was in agreement with the removal direction in the electrodialytic remediation experiments.

General information

State: Published
Organisations: Department of Civil Engineering, Section for Construction Materials, Section for Geotechnics and Geology
Pages: 25-37
Publication date: 2006
Peer-reviewed: Yes

Publication information
Journal: Science of the Total Environment
Volume: 357
Issue number: 1-3
ISSN (Print): 0048-9697
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4.98 SJR 1.546 SNIP 1.65
Web of Science (2017): Impact factor 4.61
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 5.09 SJR 1.652 SNIP 1.856
Web of Science (2016): Impact factor 4.9
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.33 SJR 1.653 SNIP 1.648
Web of Science (2015): Impact factor 3.976
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.2 SJR 1.635 SNIP 1.843
Web of Science (2014): Impact factor 4.099
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.73 SJR 1.527 SNIP 1.745
Web of Science (2013): Impact factor 3.163
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.7 SJR 1.749 SNIP 1.82
Acidification of Harbour sediment and removal of heavy metals induced by water splitting in electrodialytic remediation.

Harbor sediments are often contaminated with heavy metals, which can be removed by electrodialytic remediation. Water splitting at the anion exchange membrane in contact with the contaminated material in electrodialytic remediation is highly important for the removal of heavy metals. Here it was investigated how acidification caused by water splitting at the anion exchange membrane during electrodialytic remediation of contaminated harbor sediment and hence the metal removal, was influenced by different experimental conditions. Two different experimental cells were tested, where the number of compartments and ion exchange membranes differed. Totally, 14 electrodialytic experiments were made, with varying remediation time, current densities, and liquid to solid ratio (L/S). pH in the sediment decreased slightly after 1 day of remediation, even if the sediment had a high buffering capacity, suggesting that water splitting at the anion exchange membrane started early in the remediation process. An increase in the voltage over the cell and a decrease in the electrical conductivity in the sediment suspension also indicated that the water splitting started within 1 day of remediation. When the sediment was acidified, the voltage decreased and electrical conductivity increased. After 5 days of remediation the sediment was acidified at the chosen current density (1 mA/cm²) and the main metal removal was observed shortly after. Thus it was crucial for the metal removal that the sediment was fully acidified. Lower metal removal was seen in an experimental cell with three compartments compared to five compartments, due to increased sensitivity of pH changes in the cell.
Electrodialytic removal of Cu, Zn, Pb, and Cd from harbor sediment: Influence of changing experimental conditions

Electrodialytic remediation (EDR) was used to remove Cu, Zn, Pb, and Cd from contaminated harbor sediment. Extraction experiments were made prior to EDR, and the metal desorption was pH dependent but not liquid-to-solid ratio (L/S) dependent. The desorption order was Cd $GRT Zn $GRT Pb $GRT Cu. Electrodialytic experiments were made with HCl as desorbing agent in a sediment suspension, which was stirred during EDR. Effects of different current strengths and L/S ratios on the heavy metal removal were investigated on wet and air-dried sediment. The effects of drying the sediment were negligible for the removal of Cu, Zn, and Pb, probably due to oxidation of the sediments during stirring. Contrary, Cd removal was lower in the wet sediment as compared to the air-dried. The heavy metal removal was influenced by higher current strengths and varying L/S ratios. The highest removal obtained was in an experiment with dry sediment (L/S 8) and a 70 mA applied current that lasted 14 days. These experimental conditions were thereafter used to remediate more strongly contaminated sediments. Regardless of the initial heavy metal concentrations in the sediments, 67-87% Cu, 79-98% Cd, 90-97% Zn, and 91-96% Pb were removed. ©2005 American Chemical Society.

General information
State: Published
Organisations: Section for Building Materials and Geotechnics, Department of Civil Engineering
Contributors: Nystrøm, G. M., Ottosen, L. M., Villumsen, A.
Pages: 2906-2911
Publication date: 2005
Peer-reviewed: Yes

Publication information
Journal: Environmental Science & Technology (Washington)
Volume: 39
Issue number: 8
ISSN (Print): 0013-936X
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 6.58 SJR 2.535 SNIP 1.941
Web of Science (2017): Impact factor 6.653
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 6.26 SJR 2.559 SNIP 1.902
Web of Science (2016): Impact factor 6.198
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 5.61 SJR 2.546 SNIP 1.838
Web of Science (2015): Impact factor 5.393
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 5.5 SJR 2.777 SNIP 2.003
Web of Science (2014): Impact factor 5.33
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 5.52 SJR 2.952 SNIP 2.102
Web of Science (2013): Impact factor 5.481
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 5.17 SJR 3.115 SNIP 2.043
Web of Science (2012): Impact factor 5.257
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 5.16 SJR 3.18 SNIP 1.945
Web of Science (2011): Impact factor 5.228
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.979 SNIP 1.726
Web of Science (2010): Impact factor 4.827
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 2.86 SNIP 1.809
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 2.96 SNIP 1.935
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 2.774 SNIP 1.914
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 2.55 SNIP 1.893
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 2.608 SNIP 1.999
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 2.86 SNIP 2.046
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 2.54 SNIP 2.065
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 2.392 SNIP 1.949
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 2.387 SNIP 1.968
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 3.03 SNIP 2.315
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 3.367 SNIP 2.351
Original language: English
Source: orbit
Source-ID: 181833
Research output: Research - peer-review › Journal article – Annual report year: 2005
Test of experimental set-ups for electrodialytic removal of Cu, Zn, Pb and Cd from different contaminated harbour sediments

Electrodialytic removal of heavy metals from different harbour sediments was investigated. Electrodialytic remediation experiments in laboratory scale were made with calcareous and non-calcareous harbour sediments. Two different experimental set-ups were used for the study, one with stirring of the sediment slurry, the other without stirring. The removal of heavy metals was highest in the non-calcareous sediment, where 94% Cd, 91% Zn and 73% Cu were removed after 24 days. The highest removal obtained for the calcareous sediment was 81% Cd, 76% Zn, 75% Pb and 53% Cu after 21 days, with stirred sediment slurry. Electrodialytic experiments without stirring of calcareous sediment gave high removals (84% Zn, 58% Pb and 48% Cu), but there were problems with precipitations in the sediment, which limited the removal. The stirred experiments gave the highest removals of heavy metals and the voltage was the most stable in these experiments, and thus, the stirred set-up is the best choice for experimental set-up. The order in which the heavy metals were removed from the harbour sediments was Cd>Zn>Pb>Cu.
The use of sequential extraction to evaluate the remediation potential of heavy metals from contaminated harbour sediment

General information
State: Published
Organisations: Department of Civil Engineering, Section for Building Materials and Geotechnics, Section for Geotechnics and Geology, Arctic Technology Centre
Contributors: Nystrøm, G. M., Ottosen, L. M., Villumsen, A.
Pages: 975-978
Publication date: 2003
Peer-reviewed: Yes

Publication information
Journal: Journal de Physique IV
Volume: 107
ISSN (Print): 1155-4339
Ratings:
BFI (2008): BFI-level 1
Web of Science (2005): Indexed yes
Web of Science (2004): Indexed yes
Web of Science (2003): Indexed yes
Investigations of soil solution during enhanced electrodialytic soil remediation

General information
State: Published
Organisations: Department of Civil Engineering
Contributors: Nystrøm, G. M.
Publication date: 2001

Publication information
ISBN (Print): 87-7877-068-8
Original language: English
(ByG Rapport; No. R-009).
Electronic versions:
byg-r009.pdf
URLs:

Projects:

Valorization of MSWI Fly Ash for Use in Cement Based Materials
Ebert, B. A. R., PhD Student, Department of Civil Engineering
Kirkelund, G. M., Main Supervisor, Department of Civil Engineering
Geiker, M. R., Supervisor, Department of Structural Engineering and Materials
Steenari, B., Supervisor
Institut stipendie (DTU)
01/12/2017 → 30/11/2020
Award relations: Valorization of particulate waste materials in construction materials in cold climates
Project: PhD

Utilization of Wood Ash in Mortar and Concrete
Sigvardsen, N. M., PhD Student, Department of Civil Engineering
Ottosen, L. M., Main Supervisor, Department of Civil Engineering
Geiker, M. R., Supervisor, Department of Structural Engineering and Materials
Jensen, P. E., Supervisor, Department of Civil Engineering
Kirkelund, G. M., Supervisor, Department of Civil Engineering
Samfinansieret - Andet
01/07/2017 → 01/03/2021
Award relations: Utilization of Wood Ash in Mortar and Concrete
Project: PhD

Alternative Asker i Beton - Ny Æstetisk og Byggeteknisk Performance
Kappel, A., PhD Student, Department of Civil Engineering
Ottosen, L. M., Main Supervisor, Department of Civil Engineering
Goltermann, P., Supervisor, Department of Civil Engineering
Kirkelund, G. M., Supervisor, Department of Civil Engineering
Jensen, L. B., Examiner, Department of Civil Engineering
Jensen, L. B., Examiner, Department of Civil Engineering
Ferreira, C. M. D., Examiner
Brix, L. D., Examiner
Ferreira, C. M. D., Examiner
Circular Ocean
Bertelsen, I. M. G., PhD Student, Department of Civil Engineering
Ottosen, L. M., Main Supervisor, Department of Civil Engineering
Belmonte, L. J., Supervisor, Department of Civil Engineering
Schmidt, J. W., Supervisor, Department of Civil Engineering
Fischer, G., Supervisor, Department of Civil Engineering
Kirkelund, G. M., Supervisor, Department of Civil Engineering
Samfinansieret - Andet
01/10/2015 → 15/02/2019
Award relations: Circular Ocean
Project: PhD

In-Situ Burning of Crude Oils under arctic Conditions
van Gelderen, L., PhD Student, Department of Civil Engineering
Jomaas, G., Main Supervisor, Department of Civil Engineering
Fritt-Rasmussen, J., Supervisor, Department of Civil Engineering
Rangwala, A., Supervisor
Kirkelund, G. M., Examiner, Department of Civil Engineering
Brandvik, P. J., Examiner
Torero, J. L., Examiner
Institut stipendie (DTU)
01/01/2014 → 20/04/2017
Award relations: In-Situ Burning of Crude Oils under arctic Conditions
Project: PhD

Elektrodialytisk fjernelse af tungmetaller fra havneslam
Kirkelund, G. M., PhD Student, Department of Civil Engineering
Ottosen, L. M., Main Supervisor, Department of Civil Engineering
Villumsen, A., Supervisor, Department of Civil Engineering
Mortensen, J., Examiner
Calmano, W., Examiner
Ledin, A., Examiner, Department of Environmental Engineering
Centerfinansieret
01/10/2001 → 23/03/2005
Award relations: Elektrodialytisk fjernelse af tungmetaller fra havneslam
Project: PhD

Reuse of resources and materials in the Greenlandic construction industry
Belmonte, L. J., PhD Student, Department of Civil Engineering
Ottosen, L. M., Main Supervisor, Department of Civil Engineering
Jensen, P. E., Supervisor, Department of Civil Engineering
Kirkelund, G. M., Supervisor, Department of Civil Engineering
Villumsen, A., Supervisor, Department of Civil Engineering
Fabricius, I. L., Examiner, Department of Civil Engineering
Burns, S., Examiner
Hjorslev Hansen, M., Examiner, Department of Civil Engineering
Institut, samfinansiering
01/09/2009 → 24/04/2015
Award relations: Reuse of resources and materials in the Greenlandic construction industry
Project: PhD

Electrochemical upgrading of different fly ases for use in production of bricks and leightweight aggregates
Chen, W., PhD Student, Department of Civil Engineering
Ottosen, L. M., Main Supervisor, Department of Civil Engineering
Jensen, P. E., Supervisor, Department of Civil Engineering
Kirkelund, G. M., Supervisor, Department of Civil Engineering
Schmidt, J. W., Supervisor, Department of Civil Engineering
Elektrodialytisk opgradering af røggasaffald fra farligt affald til sekundær ressource


Jensen, P. E., Project Manager, Department of Civil Engineering
Ottosen, L. M., Project Participant, Department of Civil Engineering
Kirkeland, G. M., Project Participant, Department of Civil Engineering
Villumsen, A., Project Participant, Department of Civil Engineering

Project ID: 26141
Program. Andre statslige danske - Miljø: DKK1,875,097.00
01/01/2011 → 31/12/2013
Collaborators: I/S Refa, Jurag Separation A/S
Award relations: Elektrodialytisk opgradering af røggasaffald fra farligt affald til sekundær ressource
Project: Research

Elektrodialytisk opgradering af grænlandske flyveaske fra farligt affald til sekundær ressource

Kirkeland, G. M., Project Manager, Department of Civil Engineering, Arctic Technology Centre, ARTEK
Jensen, P. E., Project Participant, Department of Civil Engineering, Arctic Technology Centre, ARTEK
Ottosen, L. M., Project Participant, Department of Civil Engineering, Arctic Technology Centre, ARTEK
Villumsen, A., Project Participant, Department of Civil Engineering, Arctic Technology Centre, ARTEK

01/06/2010 → 31/12/2011
Project: PhD
metaller og dels for at ændre fosfors kemiske form til plantetilgængelig.

Ottosen, L. M., Project Manager, Department of Civil Engineering, Section for Construction Materials
Jensen, P. E., Project Participant, Department of Civil Engineering, Section for Construction Materials
Kirkelund, G. M., Project Participant, Department of Civil Engineering, Section for Construction Materials
Christensen, I. V., Project Participant, Department of Civil Engineering, Section for Construction Materials
Dame, A. J., Project Participant, Department of Civil Engineering, Section for Construction Materials

Project ID: 26132
Forskningsprojekter - Miljø- og Energiministeriet: DKK390,000.00
15/10/2010 → 15/10/2011
Award relations: Udvikling af ny teknik til fosfor-indvinding fra aske fra forbrænding af spildevandsslam
Project: Research

Oprensning af bundsediment fra forurenete sær og damme
Den mest effektive og langsigtede reetablering af eutrofierede sær og damme opnås ved fjernelse af bundsedimentet, som typisk indeholder store lagre af især fosfat. Denne løsning vil samtidig medføre en forbedring af de rekreative muligheder idet navigationsdybden øges. Ofte fravælges løsningen imidlertid, fordi det er vanskeligt at håndtere de store mængder sediment, der typisk også indeholder forhøjede koncentrationer af tungmetaller og især cadmium, og derfor skal deponeres i specialdepot. Projektet sigter imod at vise, at ED er en billig (konkurrencedygtig med deponering som eneste alternativ) og miljøvenlig måde at løse håndteringen af de store mængder sediment, som skal fjernes fra eutrofe sær og damme i forbindelse med systemets naturgenopretning.

Jensen, P. E., Project Manager, Department of Civil Engineering
Kirkelund, G. M., Project Participant, Department of Civil Engineering
Ottosen, L. M., Project Participant, Department of Civil Engineering
Villumsen, A., Project Participant, Department of Civil Engineering

Project ID: 26078
Forskningsprojekter - Miljø- og Energiministeriet: DKK499,960.00
01/12/2009 → 01/12/2010
Award relations: Oprensning af bundsediment fra forurenete sær og damme
Project: Research

Prizes:

Annual DTU Award for developing Teaching and Learning
Jens Henrik Nielsen (Recipient), Per Goltermann (Recipient), Lisbeth M. Ottosen (Recipient), Jacob Wittrup Schmidt (Recipient), Pernille Erland Jensen (Recipient), Gunvor Marie Kirkelund (Recipient) & John Forbes Olesen (Recipient)
Department of Civil Engineering, Section for Structural Engineering, Section for Building Design

Details
Awarded date: 2017
Granting Organisations: Technical University of Denmark
Prize: Prizes, scholarships, distinctions

DTU Award for Development of Teaching & Learning
Gunvor Marie Kirkelund (Recipient)
Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions

Description
Received for the case "Project families: How to improve learning in thesis works and increase impact on research" together with 6 colleagues at DTU Civil Engineering.

Details
Awarded date: 4 Dec 2017
Degree of recognition: Local
Prize: Prizes, scholarships, distinctions

DTU Internationalization Award
Gunvor Marie Kirkelund (Recipient)
Department of Civil Engineering, ARTEK, Section for Arctic Engineering and Sustainable Solutions

Description
Awarded for establishing and coordinating the Nordic Master in Cold Climate Engineering in the Nordic Five Tech-alliance.
Details
Awarded date: 28 Apr 2017
Degree of recognition: Local
Granting Organisations: Technical University of Denmark
Prize: Prizes, scholarships, distinctions