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Electrodialytically treated MSWI fly ash use in clay bricks

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Abstract

Fly ash from municipal solid waste incineration (MSWI) is classified as hazardous waste, due to high heavy metal and salt content. Thus, beneficial use is restricted, and the fly ash hazardousness should be reduced before testing reuse options. Electrodialytic treatment can remove heavy metals and soluble salts and be used to decontaminate MSWI fly ash. In Greenland, MSWI fly ash is stored at uncontrolled disposal sites, and a more sustainable solution for handling fly ash is needed. At the same time, most construction materials are imported from Europe to Greenland, and increased use of local materials would greatly benefit the circular economy in the area. In this study, it was investigated if local Greenlandic resources could have potential in brickmaking. Two different clays; a Danish clay (used commercially in brick production) and one Greenlandic (not used commercially) and raw and electrodialytically treated MSWI fly ash from Sisimiut, Greenland were used. Small clay discs with a 0, 10, 20 and 30 % substitution of clay by MSWI fly ash were fired at 1000°C for 24h. Substituting clay with fly ash generally resulted in lower technical properties of the clay discs. From this initial screening, the clay discs with electrodialytically treated fly ash and Greenlandic clay showed the lowest porosity and water absorption, which could be beneficial for use as construction material in cold climates.

Keywords: heavy metals, circular economy, secondary resources, ceramics, Arctic.

1. Introduction

Incorporation of waste residues in building materials has been gained increased focus in the past years as a waste management practice on the one hand and a way to upgrade construction materials' properties on the other. Industrial wastes, like fly ash from coal combustion, silica fume and blast furnace slag are fine-grained materials with a high content in CaO, SiO_2, Al_2O_3 and other relative minerals, and this composition is compatible with cement-based and clay-based materials. Therefore, several studies investigate the application for partly replacement of cement and clay with these waste materials as secondary raw materials for the production of mortar, concrete and bricks [1, 2]. Ceramic materials made of clay, like bricks, are considered particularly attractive for the incorporation of wastes due to the heterogeneous composition of clay that can incorporate and stabilize various wastes in the matrix even if the wastes contain toxic substances. Also, there is a need for preservation of natural clay resources, and thus research on replacing part of clay for more sustainable brick production has been encouraged. It has, also, been demonstrated that the use of wastes as clay supplements in bricks do not affect significantly key properties of the final product [3], while in some cases they can even contribute to the enhancement of several of its properties.

Municipal solid wastes (MSW) account for about 10% of the total waste production, but due to their complex composition, their treatment presents certain difficulties. A common practice for avoiding the landfill disposal of these solids wastes and thus for minimizing the environmental risk is incineration as it greatly reduces the mass and volume of the wastes. The miscellaneous composition of MSW depends on the sources of the wastes, which can vary for different countries according to waste management regulations and policies. Household and commercial wastes are the most common sources which may include different amounts of food waste, plastic and synthetic materials, even electrical devises and batteries when these are not recycled. As a result, MSW has a large content of organic and inorganic contaminants, such as heavy metals and alkaline salts. All these toxic compounds are finally highly concentrated in the residues of the incineration process. Handling of these residual materials, like fly ash, bottom ash and air pollution control residues (APC), can be very challenging. Disposal in landfills is a widely applied solution, but imposes a danger on the environment as a result of the leaching of the soluble elements which contaminate the soil and the water resources in the area. A more sustainable approach suggests the recycling and reusing of these materials. MSWI fly ash is an ultrafine material rich in calcium, silica and aluminium oxides and therefore it could be used as a cement and clay substitution for the production of sustainable building materials. However, because it also contains heavy metals, like Pb, Cd, Cr, Mo, Zn and alkali metal salts such as K and Na chlorides and sulphates it is classified as a hazardous waste. Thus, proper treatment for reducing the hazardousness of the material in acceptable limits is essential prior considering its possible beneficial uses.

Various techniques have been proposed for reducing the concentration of heavy metals and salts in MSWI fly ash [4]. Water washing is a simple method, often used as a pre-treatment before other techniques since it is more suitable for removing salts and very mobile fractions of heavy metals. Other techniques which stabilizes heavy metals include carbonation, chemical stabilization and thermal and hydrothermal treatment. The electrodialytic treatment has been proposed as an alternative method for the removal of heavy metals and soluble salts and has been applied for the decontamination of MSWI fly ash [5,6]. The method relies on the application of an electric current to the waste material and the subsequent removal of heavy metal ions in the electric field [5]. Untreated and treated MSWI fly ashes have been tested in building materials in laboratory stage [7-10]. In [11] untreated Greenlandic MSWI fly and bottom ash were added in mortars as cement replacement, and it was concluded that up to 5% of ashes could be stabilized successfully in the mortar. In [3] it was tested if 20 % or 40% MSWI fly ash could replace clay for brick production and especially 40 % replacement resulted in deteriorating the properties of the final product and leaching of several heavy metals, especially an increase of Cr leaching was seen. There is a need to find the optimum replacement percentage of MSWI fly ash in brick products, for this application to be feasible. Removal of heavy metals and salts from the MSWI fly ash is also needed, to reduce the toxicity of the fly ash.

MSWI fly ash in Greenland is so far stored at uncontrolled disposal sites, before being shipped for end disposal abroad. Thus there is a need for a more sustainable and economically feasible solution. At the same time, most construction materials are imported from Europe to Greenland, while increased use of local materials would greatly benefit the circular economy in the area. Therefore, there is an option of using MSWI fly ash as a substitution of clay in bricks, which should stabilise the heavy metals and conserve primary resources. This study investigates the potential of brick production from Danish and Greenlandic clay that is partly substituted with MSWI fly ash, by screening the production on small clay discs. The effect of electrodialytic treatment of the fly ash in the final product is evaluated in comparison with that of the untreated waste.

2. Methodology

2.1 Experimental materials

Two different clays were used for the clay discs; commercially available Teglværksler (denoted T) from Wienerberger, Denmark and a clay sediment sampled from Sisimiut, Greenland (denoted S). MSWI fly ash was collected from the incineration plant in Sisimiut, Greenland and was used raw (denoted R) or electrodialytically treated in the clay discs. The electrodialytic treatment was performed in both a two- and a three-compartment cell (denoted E and D respectively), to remove heavy metals from the fly ash as a treatment method. More specific information and details about the electrodialytic treatment experiments can be found in [6]. Particle size distribution and mineralogy were determined on the separate electrodialytically treated ashes, whereas heavy metal leaching and total content were measured on a mix of the two ashes (denoted ED). All notations of the experimental materials are shown in Table 1.

Table 1: Experimental materials

Clay	Symbol
Teglværksler (Danish clay)	T
Sisimiut ler (Greenlandic clay)	S
Fly ashes	
Treated fly ash (2 compartments)	E
Treated fly ash (3 compartments)	D
Mix E and D fly ashes	ED
Untreated (Raw) Sisimiut fly ash	R

2.2 Analytical methods

The Atterberg limits (liquid and plastic limits) were determined for the two clay samples to evaluate the plastic properties of the clays. The plastic limits (W_p) were determined by the rolling method (ISO/TS 17892-12), and liquid limits (W_L) were measured using the Casagrande method (DIN 18122-1). The particle size distribution was determined for all samples with a Malvern Mastersizer 2000 laser diffractometer on dry samples. Clay and ash mineralogy was studied by X-ray powder diffraction (XRD) for identification of major crystalline phases. The instrument was a PANalytical X'Pert Pro operating at 45 mA and 40 kV applying Cu Kα radiation with a 2ΘX'Celerator detector. The samples were scanned within 4–70 2Θ for 2.5 h. The diffractograms were interpreted using the ICDD PDF-4 database for minerals. Total heavy metal concentrations were measured by Inductive Coupled Plasma – Optical Emission Spectrometry (ICP-OES) after pre-treatment according to DS 259. Heavy metal leaching was performed in a modified version of DS/EN 12457-1 (L/S 2), where 15 g ash was mixed with 30 mL distilled water (instead of 2 kg and 40 L as described in the standard) and suspended for 24 hours, before pH was measured in the suspension, filtration of the suspension and measurement of heavy metals in the eluate by ICP-OES.

2.3 Production of the discs

Twelve different clay mixtures with ash were made and compared to clay without fly ash (Table 2).

Table 2: Composition of the clay mixtures with the amount of fly ash given in wt%. The sample name follows the denotation in Table 1, and the numbers in the names of the samples refer to the percentage by weight of replaced fly ash.

Sample name	T	S	E	D	R
T0	100				
TED10	90		5	5	
TED20	80		10	10	
TED30	70		15	15	
TR10	90				10
TR20	80				20
TR30	70				30
S0		100			
SED10		90	5	5	
SED20		80	10	10	
SED30		70	15	15	
TR10		90			10
TR20		80			20

TR30	70	30

For the study, small brick specimens in the form of discs were constructed following the method that was applied in a previous study [3]. According to this method, the materials were mixed with a total weight of 2.3 g material, and distilled water was added to the material to obtain a paste-like texture. The mixture then absorbed the moisture for 24h. Next, the clay mixture was pressed into discs mechanically (Instron 6022), under a maximum load of 10 KN. The produced discs weighted approximately 2 g while their diameter and thickness (height) were around 20 mm and 3 mm respectively. Five discs of each mixture were produced, and their exact dimensions and weight was immediately measured with a micrometre scale gauge and a precision balance. The discs were then dried at 105ºC for 24h and the dimensions and weight of the dried discs were again measured. Finally, the discs were fired at 1000ºC for 24h and their dimension characteristics were again measured. The loss of mass (ML) and the linear shrinkage (LS) was determined between the wet, dry and fired condition, the total mass loss (TML) and total linear shrinkage (TLS) from wet to fired condition as described in the following equations. X is the diameter when referring to linear shrinkage and the mass when referring to the loss of mass.

$$DLS\ (or\ DML) = \frac{x_{wet} - x_{dry}}{x_{wet}} \times 100\ \% \tag{1}$$

$$FLS\ (or\ FML) = \frac{x_{dry} - x_{fired}}{x_{dry}} \times 100\ \% \tag{2}$$

$$TLS\ (or\ TML) = \frac{x_{wet} - x_{fired}}{x_{wet}} \times 100\ \% \tag{3}$$

Where:

DLS – dry linear shrinkage

FLS – fired linear shrinkage

DML – dry mass loss

FML – fired mass loss

TLS- total linear shrinkage

TML- total mass loss

The open porosity, dry density and water absorption were determined according to the procedure Ti-B-25 by the Danish Technical Institute. The discs were dried at 105ºC, cooled to room temperature in a desiccator and weighed (m_{dry}). The discs were placed in a vacuum in the desiccator for 3 h, whereafter distilled water was added until the discs were submerged. The vacuum was again added for 1 h, whereafter the vacuum was released and the submerged discs were left at atmospheric pressure overnight. The water saturated discs were then weighed in water (m_{sw}) and air (m_{sa}) after being wiped for excess water. The open porosity, dry density and water absorption were then calculated as:

$$Open\ porosity = \frac{m_{sa} - m_{dry}}{m_{sa} - m_{sw}} \cdot 100\%$$

$$Dry\ density = \frac{m_{dry} \cdot \rho_w}{m_{sa} - m_{sw}} \cdot 100\%$$

$$Water\ absorption = \frac{m_{sa} - m_{dry}}{m_{dry}} \cdot 100\%$$

Where ρ_w is the water density at room temperature.

Mineralogy (XRD) and heavy metal leaching were also performed on crushed clay discs.

3. Results and discussion

3.1 Characteristics of experimental materials

Geotechnical properties of the clays are shown in Table 3 and the particle size distribution of the raw materials, clays and treated fly ashes is shown in Figure 1. The plasticity index (I_p) can be used to evaluate the span between the plastic and liquid limits. Both clays used in this study present low plasticity, especially Sisimiut clay, which has a very low plastic index (<10). This agrees with results found by [3]) and indicate that their moulding range is very limited. Belmonte et al. [3] found higher plasticity index for mixtures of clay with fly ash than the clay itself, and the moulding of the clay discs with fly ash was not more difficult in practice than the clay itself. The two treated fly ashes, E and D, have similar particle size distribution as it is shown in the graph above. Also, their particles' size presents similar distribution with the one of the Sisimiut clay, although this the Sisimiut clay to have a slightly higher fraction of finer particles. Teglværks clay (T), on the other hand, has a larger volume percentage of coarse particles than the fly ashes and the Sisimiut clay. According to the Unified Soil Classification System (USCS) (ASTM D2487-17) both clays are classified as fine-grained soils (silt and clay) as more than 50% of their volume contains particles with fraction d<75 μm. For both clays, the clay fraction (<2 μm) was about 10% of their total volume, while approximately 45% of the volume of Teglværks and 65% of Sisimiut clay consisted of silt. The rest of their volume consisted of sand, 45% and 25% for Teglværks and Sisimiut clay, respectively. Finally, the raw untreated fly ash (R) consisted of finer particles than the treated fly ashes (E and D) and the two clays (T and S).

Taking into consideration the liquid limit (W_L) and plasticity index (I_p) of the clays as well as their particle size distribution according to the Casagrande plasticity chart [12], Teglværks clay is characterized as sandy lean clay, while Sisimiut clay as lean clay with sand.

Table 3: Geotechnical properties of the clays. Plasticity Index $I_P= W_L - W_p$.

Clays	Plastic Limit	Liquid Limit	Plasticity Index
	W_p (%)	W_L (%)	I_P (%)
T	15.2	28.5	13.3
S	14.2	22.5	8.3

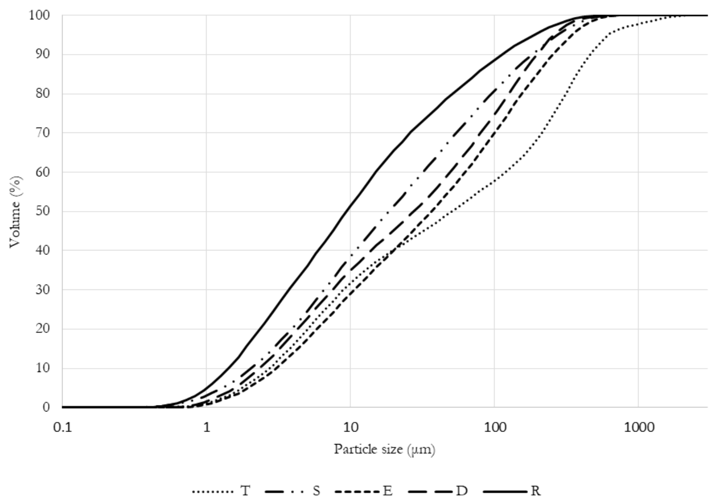

Figure 1: Particle Size Distribution of Teglværksler (T), Sisimiut clay (S), treated fly ashes (E&D)

and raw fly ash (R)

The XRD diffractograms of clays and fly ashes are shown in Figure 2.

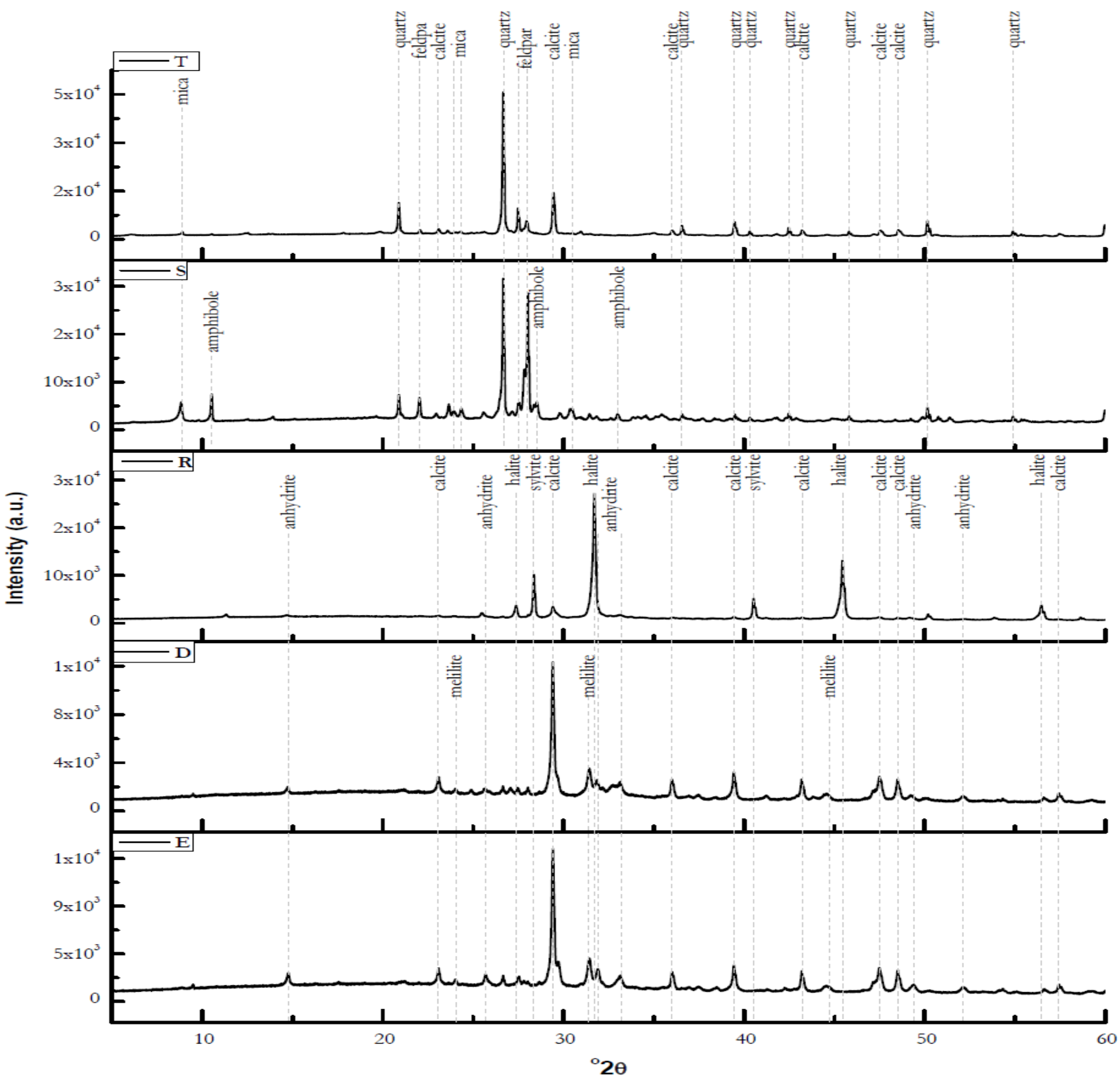

Figure 2: X-ray diffractograms of the experimental materials Teglværksler (T), Sisimiut clay (S), treated fly ashes (E&D) and raw fly ash (R)

As shown in the diffractogram, of Teglværks clay (T), this clay sample was dominated by quartz (SiO_2) and calcite ($CaCO_3$), and it also consisted of feldspars (albite ($NaAlSi_3O_8$) and microcline ($KAlSi_3O_8$) as well as micas (muscovite ($KAl_2(AlSi_3O_{10})$). Sisimiut clay (S), on the other hand, mainly consisted of quartz and did not contain calcite. Instead, the second most dominant mineral phase in the Sisimiut clay was feldspars (albite, microcline and anorthite ($CaAl_2Si_2O_8$)), followed by amphibole (magnesiohornblende) and Fe – rich mica (phlogopite). This explains the light grey colour of Danish clay due to calcite, in comparison with the dark grey of the Greenlandic clay (photos of clays not shown). As for the fly ashes, the untreated raw fly ash (R) was dominated by salts: halite (NaCl) and sylvite (KCl). It also contained calcite and anhydrite ($CaSO_4$) as minor mineral phases. The two electrodialytically treated fly ashes (D and E) present identical mineralogy. As shown from their diffractograms they were calcareous but, unlike the untreated fly ash, they did not contain salts. Also, the phase of anhydrite (basanite) intensified in the electrodialytically treated ashes compared to the raw fly ash and traces of melilite mineral phases (gehlenite) were identified. It shows that the electrodialytic treatment is responsible for the removal of the salts in fly ashes D and E. Based on the similar particle size distribution and mineralogy, it was determined to mix the two electrodialytically treated ashes in for the further experiments.

Total heavy metal concentration and leaching of heavy metals, chloride and sulphate were measured for raw fly ash (R) and the mixture of the two treated fly ashes (ED). The results are shown in Table 4, in which the pH of the fly ashes is also given. The values are compared to the limits given by the Danish Ministry of Environment for use in geotechnical applications [13], as no limits exist for the use of waste in construction materials. The total metal concentrations show a significant reduction in the total content of heavy metals due to the electrodialytic treatment, but the leaching of As, Cr, Ni and Zn increased, also to above the Category 3 limit. There was a significant reduction in the chloride and sulphate leaching, linked to the removal of chloride and sulphate containing mineral during the electrodialytic treatment.

Table 4: Total heavy metal concentration and leaching of the fly ashes.

	Raw ash	**ED ash**	**Category 3**
Total concentration (mg/kg)	Average	Average	
As	277	29	>20
Cd	162	132	>0.5
Cr	109	71	>500
Cu	1,350	667	>500
Ni	32	73	>30
Pb	8,770	2,170	>40
Zn	21,600	8,680	>500
Leaching (μg/l)			
As	91	600	8-50
Cd	1560	2	2-40
Cr	550	1190	10-500
Cu	120	33	45-2000
Ni	46	125	10-70
Pb	397	35	10-100
Zn	109	340	100-1500
Cl	$155 \cdot 10^6$	$1.7 \cdot 10^6$	$1.5 \cdot 10^6$ - $3.0 \cdot 10^6$
SO_4	$3.04 \cdot 10^6$	$0.75 \cdot 10^6$	$2.5 – 3.0 \cdot 10^6$
pH	10.3	9.8	

3.2 Characteristics of the clay discs

The produced discs are shown in Figure 3, in the left the Teglværks clay discs and in the right the Sisimiut clay discs, both containing different amounts of substitution with fly ashes, treated (ED) and raw (R). It is seen in Figure 3 that as the amount of the fly ashes increases the colour of the discs gets lighter, both for the Danish (Teglværksler) and the Greenlandic (Sisimiut) clay mixtures. The stronger red colour of the Sisimiut S0 disc is probably linked to the Fe-minerals that were identified in this clay. There was a difference in the colour of the discs with raw fly ash and electrodialytically treated fly ash. This was more dependent on the clay used than the ash since the disc with electrodialytically treated fly ash in Teglværksler were darker than with raw fly ash, but the discs with Sisimiut clay were darkerst with raw fly ash.

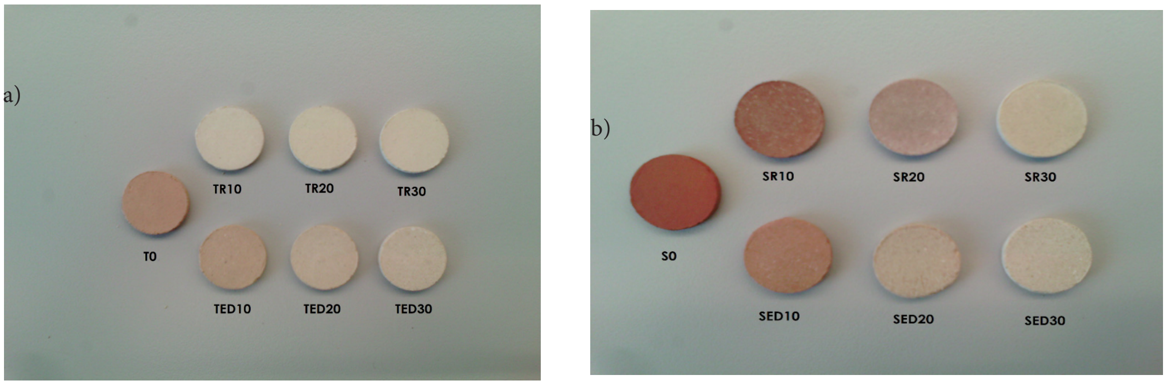

Figure 3: Colours of discs with substitution of clay with different amounts (0%, 10%, 20%, 30%) fly ash (R – raw, ED – treated. a) Teglværks (T) clay discs, b) Sisimiut (S) clay discs

The total loss of mass, total linear shrinkage, total volume change, porosity, dry density and water absorption of the produced discs are given in Figure 4. The total volume change of the discs containing raw fly ash (R) was negative for both types of clays, meaning that these discs expanded instead of shrinking as the other discs did, and their expansion was larger as the amount of fly ash increased. This can be attributed to a bloating effect due to gas from the decomposition of sulphates or carbonate [3]. On the contrary, the addition of more treated fly ash (ED) resulted in lower volume change for both clay discs, since sulphates are removed by electrodialytic treatment [5]. A lower mass loss but a higher linear shrinkage were seen for the Sisimiut clay discs compared to Teglværksler discs and increasing the amount of electrodialytically treated fly ash increased the volume change. This is clearly linked to the results of porosity, dry density and water absorption show in Figure 4. The porosity and water absorption increased by the addition of fly ash for both clay and fly ash types. Teglværks clay discs showed the highest porosity for substitution with raw fly ash, which is also linked to the higher mass loss for these clay discs compared to the Sisimiut clay discs. For the Sisimiut clays discs, the porosity was highest when treated fly ash was added, with corresponding lower densities of the discs and a higher water absorption, even if bloating occurred for the Sisimiut clay discs with raw ash. The water absorption was lower for all Sisimiut clay discs than for the Teglværksler clay discs, also linked to the porosity. In bricks used in the building industry, typical ranges are: dry densities 1610-2120 kg/m^3 [14, 15]; open porosities 18.8-39 % [15] and water absorption 22-37 % [16]. Only the water absorption is lower for some of the samples in this study, especially for the discs with Sisimiut clay and raw fly ash.

For the discs with electrodialytically treated fly ash, there was a difference when using Teglværksler or Sisimiut clay. The performance of the discs was lower with Teglværksler than the Sisimiut clay, which is also linked to the properties of the clays themselves. The low porosity, high density and low water absorption for the Sisimiut clay discs indicate good performance in cold climates. However, the pore size should be studied further to evaluate the possibility of resisting frost/thaw cycles.

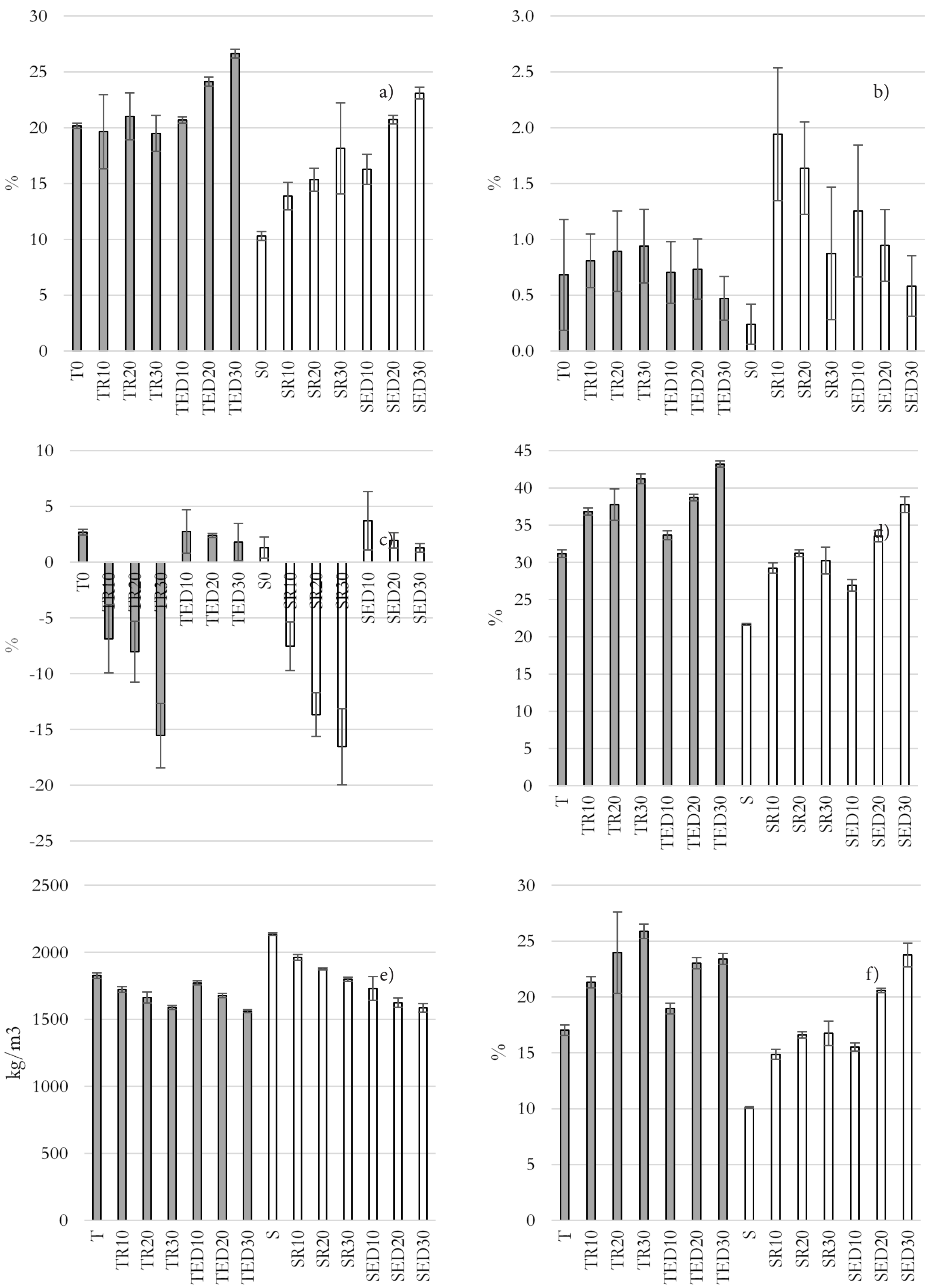

Figure 4: Physical properties of the clay discs: a) total mass loss, b) total linear shrinkage, c) total volume change, d) porosity, e) dry density, e) water absorption

The diffractograms of discs made of Teglværks (T) clay and treated fly ash (ED) in different proportions is shown in Figure 5 and for discs made of Sisimiut clay in Figure 6.

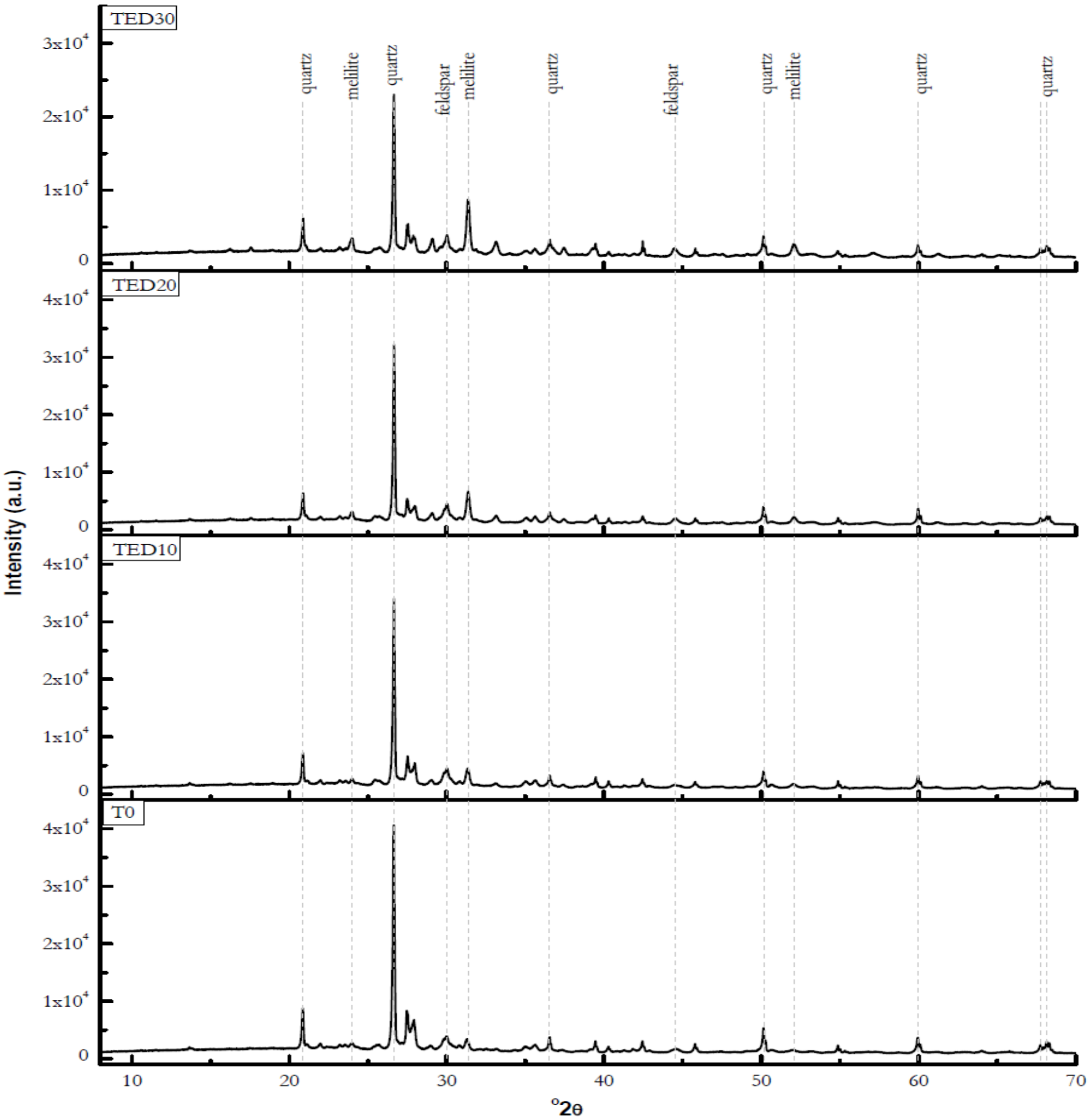

Figure 5: Diffractogram of Teglværks (T) clay discs with treated fly ash substitution of clay at 0%, 10%, 20% and 30%.

The reference discs with Teglværks clay, without the addition of fly ash, mainly contained quartz and feldspars (albite, microcline) as well as traces of melilite. As the amount of treated fly ash increases in the Teglværksler discs, the peak of quartz decreased significantly while that of melilite becomes more intense. In the discs with Sisimiut clay quartz was also the dominant mineral but feldspars (albite and microcline) were also abundant. Moreover, pyroxene was found in the control sample and increased by the addition of fly ash. On the other hand, hematite that appeared in the control sample showed decreased peaks as the amount of fly ash increased. The occurrence of hematite in the Sisimiut discs, especially the control sample, justifies the red colour of the Sisimiut clay discs, unlike the yellowish colour of the Teglværks clay discs where there was no presence of an iron-based mineral.

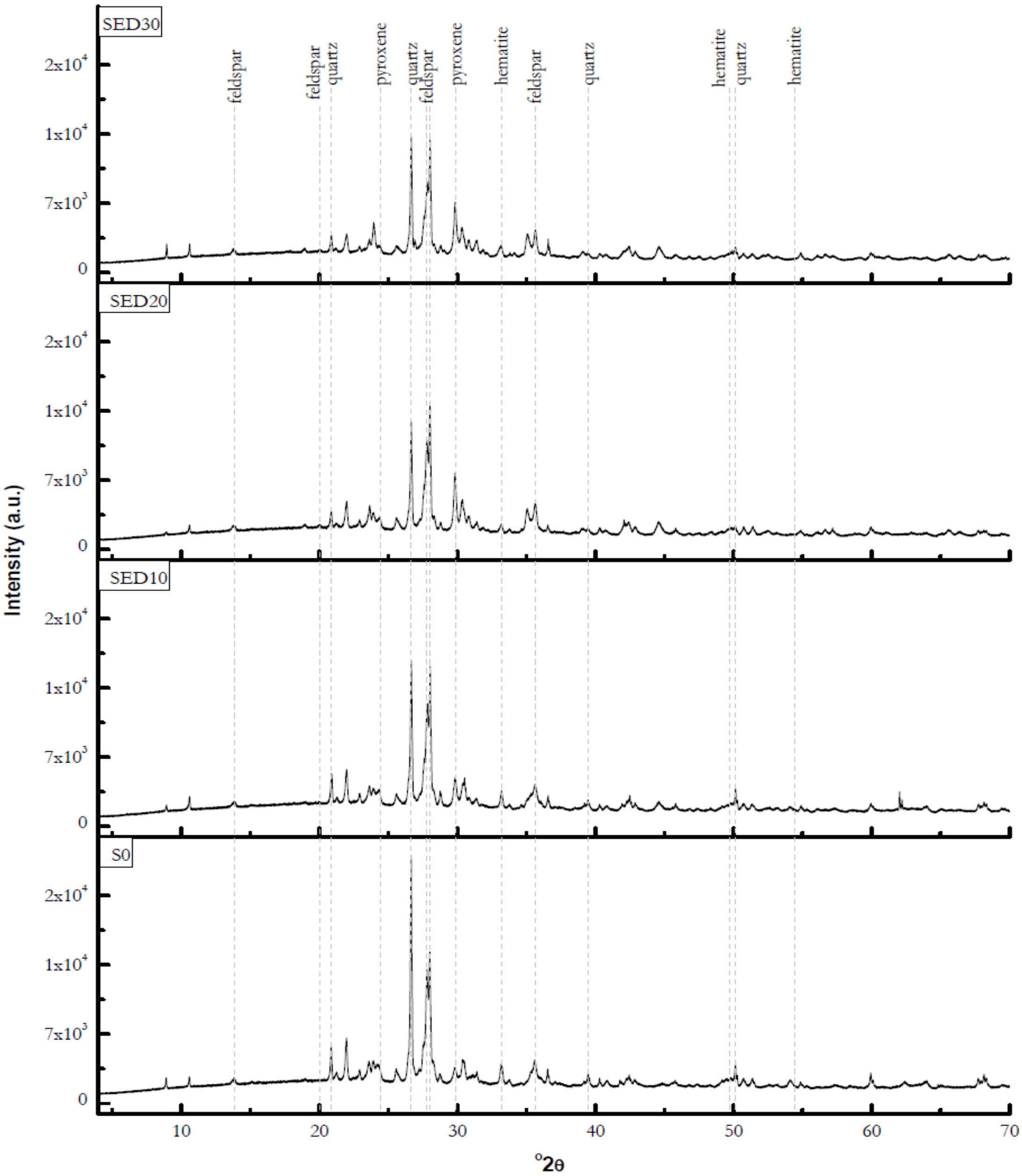

Figure 6: Diffractogram of Sisimiut (S) clay discs with treated fly ash substitution of clay at 0%, 10%, 20% and 30%.

Table 5 shows the leaching properties of the brick discs. There is no clear pattern in increased metal leaching with increasing addition of fly ash. However, these leaching results are from only one replicate, and there could be large uncertainties in the leaching values because of this. As leaching from most of the clay discs and Cr leaching from the TED10 sample was above the Category 3 guideline. The mobility of the metals was calculated, showing the extent of the immobilization of the metals when added in the bricks in comparison with the metals' leaching from the fly ashes. Belmonte et al. [3] observed increased mobility of As and Cr in clay discs containing 20 % and 40 % pre-treated MSWI fly ash by washing and electrodialytic treatment. The contrary was observed in this study, were all samples showed immobilization in the clay matrix, except for the sample TED10, where Cr leaching increased compared to the initial leaching of the ED fly ash. Wan et al. [10] studied the incorporation of MSWI fly ash in 5×5×5 cm^3 bricks and found that leaching of heavy metals both in batch leaching (determined by DS/EN 12457-1) and total leachability (determined by the Dutch leaching test at pH 4) was below the regulatory standards for these tests. This could indicate that producing such a small number of the specimen as in this study should be used with care for conclusive studies of leaching properties and also that the leaching properties should be investigated further.

Table 5: Leaching of Teglværks and Sisimiut clay discs

Sample	pH	As (µg/l)	Cd (µg/l)	Cr (µg/l)	Cu (µg/l)	Ni (µg/l)	Pb (µg/l)	Zn (µg/l)
T0		115	<20	354	51	<20	<20	53
TR10	10.1	<20	<20	53	<20	<20	<20	<20
TR20	9.9	<20	<20	46	<20	<20	<20	<20
TR30	9.8	47	<20	74	<20	<20	<20	<20
TED10	11.2	50	<20	3240	33	<20	<20	31
TED20	10.7	75	<20	102	23	<20	<20	40
TED30	9.9	80	<20	<20	<20	<20	<20	80
S0		64	<20	<20	<20	<20	<20	39
SR10	10.1	<20	<20	<20	<20	<20	<20	<20
SR20	9.7	279	<20	<20	<20	<20	<20	<20
SR30	9.4	52	<20	<20	<20	<20	<20	<20
SED10	9.9	100	<20	<20	<20	<20	<20	33
SED20	9.7	64	<20	<20	<20	<20	<20	36
SED30	9.6	94	<20	<20	<20	<20	<20	38

4. Conclusions

The commercial clay consisted mainly of the minerals quartz, calcite, feldspars and mica, whereas the Sisimiut clay consisted of quartz, feldspars, amphibole and mica. The MSWI fly ashes consisted mainly of calcite and anhydrite and the raw fly ash also of halite and sylvite. The clay discs with Sisimiut clay presented a reddish colour compared to commercial clay, which gave white/greyish colour. Hematite was detected in the clay discs with Sisimiut clay, although increasing the fly ash proportion resulted in lighter colours. Leaching of Cr of untreated and treated fly ash exceeded the limits of Danish regulation for wastes in construction but was lower than for disposal at non-hazardous waste disposal sites. Apart from this, treated fly ash presented much lower heavy metal concentration than the untreated fly ash. Most heavy metals were incorporated into the clay disc matrix, and the mobility of metals decreased after firing. Expansion of the discs occurred for the samples containing raw fly ash, caused by bloating due to gas formation from the decomposition of minerals during firing. The expansion increased with the increased amount of fly ash in the clay discs. The porosity and water absorption increased with the addition of more fly ash while dry density decreased. The clay discs with Sisimiut clay showed the lowest porosity and water absorption, which will be beneficial for use in the cold climates. As the electrodialytically treated MSWI fly ash showed better environmental performance than raw fly ash in the clay discs, there is a potential for using these Greenlandic raw materials in bricks, to support local production of construction materials.

5. Acknowledgement

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6. References

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