

Enabling safe dry cake disposal of bauxite residue by deliquoring and washing with a membrane filter press

Kinnarinen Teemu, Lubieniecki Boguslaw, Holliday Lloyd, Helsto Jaakko-Juhani,
Häkkinen Antti

This is a Final draft version of a publication

published by SAGE Publications

in Waste Management & Research

DOI: 10.1177/0734242X14567503

Copyright of the original publication: © SAGE Publications 2015

Please cite the publication as follows:

Kinnarinen, T., Lubieniecki, B., Helsto, J.-J., Häkkinen, A., Enabling safe dry cake disposal of bauxite residue by deliquoring and washing with a membrane filter press, Waste Management & Research, 2015, 33(3): 258-266. DOI: 10.1177/0734242X14567503

**This is a parallel published version of an original publication.
This version can differ from the original published article.**

Enabling safe dry cake disposal of bauxite residue by deliquoring and washing with a membrane filter press

Teemu Kinnarinen^{1*}, Boguslaw Lubieniecki², Lloyd Holliday³,
Jaakko-Juhani Helsto⁴, Antti Häkkinen¹

¹LUT Chemistry, Lappeenranta University of Technology, P.O. Box 20, FI-53851 Lappeenranta, Finland

²LBX Consulting, ul. Kukulek 61, Katowice, Poland

³Outotec (Filters) Oy, 8 Winchilsea Ave, Newark, United Kingdom

⁴Outotec (Filters) Oy, Riihitontuntie 7, FI-02200 Espoo, Finland

*Corresponding author Tel.: +358 40 5621398, E-mail: teemu.kinnarinen@lut.fi

Abstract

Dry cake disposal is the preferred technique for the disposal of bauxite residue, when considering environmental issues together with possible future utilisation of the solids. In order to perform dry cake disposal in an economical way, the deliquoring of the residue must be carried out efficiently, and it is also important to wash the obtained solids well to minimize the amount of soluble soda within the solids.

The study presented in this paper aims at detecting the most important variables influencing the deliquoring and washing of bauxite residue, performed with a horizontal membrane filter press and by determining the optimal washing conditions. The results obtained from pilot-scale experiments are evaluated by considering the properties of the solids, for instance, the residual alkali and aluminium content, as well as the consumption of wash liquid. Two different cake washing techniques, namely classic washing and channel washing, are also used and their performances compared. The results show that cake washing can be performed successfully in a horizontal membrane filter press, and significant improvements in the recovery of alkali and aluminium can be achieved compared to pressure filtration carried out without washing, or especially compared to the more traditionally used vacuum filtration.

Keywords

Bauxite residue, red mud, filtration, deliquoring, washing, dry cake disposal

Introduction

Bauxite residue, also referred to as red mud, is the biggest pollutant generated during the production of alumina from bauxite ores. About 90-120 Mt per annum of bauxite residue are generated globally (Wang et al., 2008; Gräfe and Klauber, 2011) and by 2011, approximately 2.7 Gt were stored (Gräfe et al., 2011). The aluminium bearing minerals present in bauxite ore are dissolved in caustic soda with the Bayer process, while the non-dissolved solids and the residual alkali form the waste fraction. Currently, 95 % of alumina worldwide is produced using this simple process (Klauber et al., 2011). Bauxite residue is separated from the aluminium-rich liquid phase by multi-stage countercurrent washing and thickening, and the final separation stage prior to disposal can be either filtration or thickening (Hind et al., 1999). Washing the residue requires large amounts of water, and minimization of the overall water consumption is an important issue when developing bauxite residue processing techniques.

The soluble aluminium minerals in bauxite ores include gibbsite, i.e. aluminium trihydroxide, boehmite, and diasporite (aluminium oxyhydroxides) (Hind et al., 1999; Whittington, 1996). However, a drawback of the Bayer process is that about 1 - 2.5 tonnes of bauxite residues are

discharged when producing one tonne of Al_2O_3 (Nguyen and Boger, 1998). The composition of the bauxite residue depends on the ore quality and the process conditions, but typically it contains iron oxide as crystalline hematite, alumina, silica, calcium oxide and sulfate, titania, and traces of other metals (Singh et al., 1996; Brunori et al., 2005). The slurry is highly alkaline, the pH is normally between 10 and 12.5 (Zhong et al., 2009), sometimes higher than 13 (Johnston et al., 2010). The bauxite residue is also characterised by a high salt content and electrical conductivity (Gräfe et al., 2011), fine solids (Johnston et al., 2010), as well as the presence of heavy metals (Ghosh et al., 2011).

The utilisation of bauxite residue at a large scale would be important in order to avoid problems related to the disposal. However, due to the composition of the residue, there are currently no feasible applications where it could be utilised at a large scale (Gräfe and Klauber, 2011). The use of bauxite residue for various purposes, such as the production of cements (Singh et al., 1996), paints and pigments (Pera et al., 1997), adsorbents and coagulants (Apak et al., 1998; Poulin et al., 2008; Altundogan et al., 2002), could be possible in a technical sense. The recovery of metals from bauxite residue has also been studied (Liu and Naidu, 2014; Hargreaves et al., 2013; Jayasankar et al., 2012; Li et al., 2009). The utilization of bauxite residues, either the solids or the caustic liquid, can be undoubtedly facilitated by appropriate solid-liquid separation, for instance, the treatment presented in this paper.

Because of the large size of aluminium plants and the small or no commercial value of bauxite residue, large areas are required for its final disposal. Dumping the residue in the sea is no longer a realistic option because of the environmental impacts, and there are also certain problems with wet disposal (Liu and Wu, 2012; Liu and Naidu, 2014; King, 2001). The possible risks of wet disposal include, for instance, seepage of the alkaline liquid, spillage from damaged pipelines and dams, and potential for groundwater contamination (Li, 2001; Cooling, 2007). Therefore, dry cake disposal could provide the most environmentally acceptable means for the final disposal. Dry disposal techniques are safer, improve the recovery of water and chemicals, decrease the volume of the tailings, and help to minimize the storage area required (Sofra and Boger, 2002). In 2007, 70 % of alumina producers used dry disposal methods (Power et al., 2011). The residue is typically pumped as thick slurry from the plant to the disposal area. Currently only 2 to 3 % of the alumina capacity in the world relies on marine disposal of the residue, and for instance Japan is committed to ceasing marine disposal by 2015 (Power et al., 2009).

In order to enable efficient dry cake disposal of the solids and to ensure high recovery of water, pressure filtration of bauxite residue may be the preferred technique over vacuum filtration or thickening. After pressure filtration, the residual moisture content in the solids is typically from 26 to 29 %. Currently, however, many plants still use thickeners in the final stage of separation (Power et al., 2009). Pressure filtration is a potential solution for difficulties observed in the separation of fine bauxite residues. One example of such case is separation of residues where goethite is the main iron mineral. Thickening of that kind of slurries is difficult due to the presence of small particles, special surface properties and, furthermore, the specific gravity, which is not as high as that of hematite (Hind et al., 1999; Li, 2001; Li and Rutherford, 1996). In general, the current technology applied in the industrial scale cannot provide satisfactory recovery of alkali and aluminium from bauxite residue. Taking economical and environmental aspects into consideration, there is an obvious need to find more effective methods for the filtration and washing of bauxite residue.

Vacuum drum filters have been commonly used for the final separation after the thickening and washing of bauxite residue (Borges et al., 2011; Sparks et al., 2010) and recently also hyperbaric steam filtration has been recognized as an emerging technique for bauxite residue filtration (Power et al., 2009). Automatic filter presses enable high capacity, low moisture content of the cake, and effective cake washing. Consequently, direct dry disposal of the cakes is possible, which is beneficial considering both environmental issues and future utilisation of the cakes.

This paper presents some examples of results obtained during an extensive study aiming at comparing the efficiencies of different deliquoring and washing techniques in a horizontal membrane filter press. Irrespective of the washing method applied, the effect of washing ratio on the residual alkali content of the filter cakes was studied. Additionally, the influence of temperature on the filtration rate was determined using a laboratory-scale pressure filter.

Materials and methods

In this study, over 60 filtration tests were performed either on site, in the filtration pilot plant of Outotec (Filters) Oy, Finland, or in the filtration laboratory at Lappeenranta University of Technology, Finland. This paper considers only the experimental results that were obtained from the pilot plant and laboratory tests.

Slurry preparation

The slurry used in the pilot plant and laboratory tests was obtained from a full-scale industrial process. The pH of the slurry was 13.2. Before starting the tests, the slurry was carefully homogenized in a jacketed 1.0 m³ mixing tank equipped with heating elements and a temperature control unit ($T \approx 65\text{ }^{\circ}\text{C}$). To make it possible to pump the slurry with a diaphragm pump, coarse sand and other large particles were first removed by wet sieving. The slurry was mixed for several hours before starting the experiments, in order to make certain that the properties of the slurry were stable and that the temperature in all parts of the feed tank was constant. The concentration of total solids in the slurry was approximately 42 w-% in the beginning of the experiments. The undersize particle size distribution of the solids, determined prior to the experiments, showed that the particles were relatively fine: $D_{10} = 0.9\text{ }\mu\text{m}$, $D_{50} = 2.8\text{ }\mu\text{m}$, $D_{90} = 37.1\text{ }\mu\text{m}$.

Tests with a laboratory scale Nutsche pressure filter

The tests were started by performing a series of experiments in the laboratory with a pressure Nutsche filter ($V = 0.3\text{ dm}^3$). The aim of these tests was to study the effect of filtration temperature (20 - 80 °C) on the filtration properties and the residual alkali content of the filter cakes. Possible loss of alkali by precipitation in the cake was studied by comparing the alkali contents in the filtrates obtained from the tests carried out at different temperatures. Cellulose discs (Pall Corporation) were used as filter media, and the filtration pressure and the slurry mass in each experiment were kept constant, 6 bar and 250 g, respectively. The total solids content of the slurry was also constant, 42 w-%.

Tests with a pilot scale horizontal membrane filter press

The horizontal membrane filter press used in the pilot plant tests was Outotec Larox[®] FFP 0.27 / 0.81 that consisted of either 1 or 3 filter chambers, one pressing diaphragm for each chamber, piping and valves, and a hydraulic closing mechanism. The effective filtration area in each chamber was 0.27 m². The filtrates obtained from different stages of operation (filtration, pressing, washing, air deliquoring) were collected in separate vessels, and the filtrate volumes were measured. The test unit is shown in Figure 1a and the operational stages of the filter are illustrated in Figure 1b.

The aim of the pilot plant tests was to carry out filtration and washing cycles by using different washing ratios and two different washing methods (Figure 1b) to reduce the residual alkali and aluminium content of the filter cakes. It was observed that the filling of the filter press and formation of the cake happened fairly quickly, in less than 90 seconds. Therefore, a pumping time of 60 s was used in most experiments. The pressures during pumping (6 bar), 1st and 2nd pressing (4 and 12 bar), washing (6 bar), and air drying (6 bar) were kept constant. The washing time was varied to achieve different washing ratios. The temperature of the wash water was 60 - 65 °C, and the quantity of water consumed during the washing was estimated according to the amount of wash filtrate collected during the washing process.

Two different cake washing methods were used, and the washing results were evaluated based on the residual alkali contents in the cakes. The first washing method, channel washing, means that the wash water is fed into the filter chamber through the slurry channel, without pressing the cake before washing. In the second, so called classical washing method, water is pumped via the filtrate channels and through the filter cloth and consequently through the cake that has been pressed at a low pressure in order to maintain sufficient permeability.

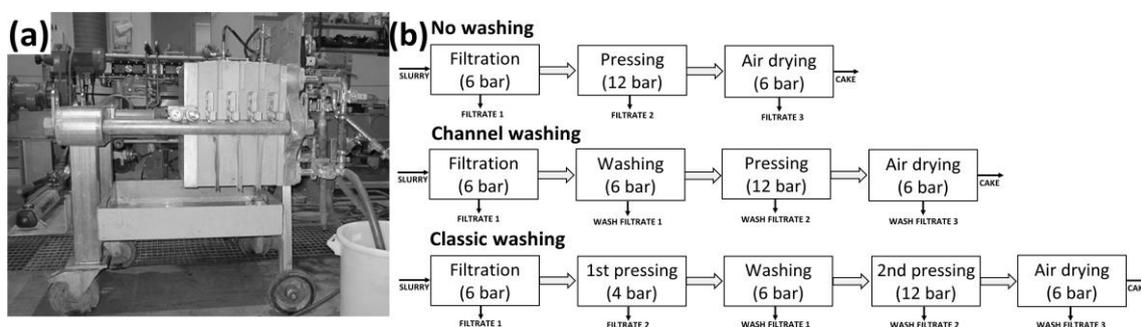


Figure 1. a) Membrane filter press with three filter chambers ($A = 0.81 \text{ m}^2$) and b) the applied operational sequences of the filter.

Sampling and analyses

The total number of the collected samples of cake, slurry, filtrates and wash filtrates during the whole study exceeded 200. Some details concerning the laboratory analyses are summarized in Table 1.

Table 1. Different kinds of samples collected and analytical techniques used in the study.

Characteristic	Instrument/equipment	Sample treatment
Total solids content (TS)	Heating chamber	-
Total suspended solids content (TSS)	Heating chamber	Filtration

Total dissolved solids content (TDS)	Heating chamber	Filtration
Soluble Na and Al contents in liquid phase	Inductively coupled plasma spectrometer (ICP) ¹	Filtration, dilution
Total Na content in slurry	Scanning electron microscope ²	Drying
Insoluble Na content in solid phase	Scanning electron microscope ²	Washing, filtration, drying
Other elements in solid phase	Scanning electron microscope ²	(Washing, filtration), drying
Particle size distribution of solids	Laser diffraction analyzer ³	-
Mineralogical composition of slurry	X-ray diffractometer ⁴	Drying

¹ Thermo Electron IRIS Interpid II XDL

² JEOL JSM-5800

² Beckman Coulter LS 13320

³ Bruker D8 Focus

The solids contents of the slurry and cake samples were measured by drying them in a heating chamber at 105 °C until a constant weight was obtained. The slurry was analyzed for total solids (TS), total suspended solids (TSS) and total dissolved solids (TDS), while the cakes were analyzed only for TS.

The mineralogical composition of the dry slurry sample was determined using X-ray diffraction (XRD). A Bruker D8 Focus diffractometer with the following specifications was applied: CuK α radiation, 40 kV voltage, 40 mA current, step size 0.05°, one step per second. The range of measurement for the diffraction pattern was 2 - 70°.

For measuring the concentrations of soluble Na and Al in the cake samples, roughly 10 g of the original cake was reslurried with roughly 90 g of water. The exact weights of the cake and dilution water were recorded. The bottles were then shaken with a VWR orbital shaker for one hour. After this, the samples were allowed to stabilize for at least 24 hours. The liquid was then separated from the reslurried cake sample by filtering it through a syringe filter with a 0.2 μ m pore size filter. This means that the values measured in the analyses describe the amount of water-soluble Na and Al in the samples. The samples from the filtrates were taken through a 0.2 μ m pore size filter and analysed without further treatment, except for dilution, typically 100-fold, to match the calibration range of the analyzer.

The efficiency and homogeneity of cake washing were carefully monitored by sampling of the cake from five different points of the filtration chamber.

Calculations

The weight-based wash ratio (w/w) was calculated from Eq. (1), based on the wash water consumption when washing a cake, which contains a certain mass of dry solids (D.S.).

$$\text{Wash ratio } (w/w) = \frac{m_{\text{wash water}}}{m_{\text{D.S., cake}}} \quad (1)$$

In this study, the weight-based wash ratios are discussed almost exclusively. Only an approximate range for the volumetric (V/V) wash ratios [Eq. (2)] is given. In Eq. (2), the void volume of the cake is calculated after measuring the dimensions of the cake, as well as the cake moisture and densities of the solid and liquid phases.

$$\text{Wash ratio } (V/V) = \frac{V_{\text{wash water}}}{V_{\text{void, cake}}} \quad (2)$$

In order to present the mass balance of each filtration and cake washing experiment, the mass of alkali (Na) in the cake and the filtrates, collected during different stages of the process, was calculated. The mass of Na in a filter cake was calculated as a product of the wet cake mass and the Na concentration in the wet cake [Eq. (3)]:

$$m_{Na,cake} = m_{cake} \cdot c_{Na,cake} \quad (3)$$

In the case of filtrates, several samples taken during the filtration and cake washing stages were needed for the calculation. As the mass and concentration of each filtrate fraction was determined, the total mass of Na removed within the filtrates is [Eq. (4)]:

$$m_{Na,filtrates} = \sum(m_{filtrate} c_{Na,filtrate}) \quad (4)$$

The alkali recovery [Eq. (5)] for a filtration experiment was calculated as a ratio of the mass of Na removed in the filtrates and the total mass of Na fed into the filter as follows:

$$Alkali\ recovery\ (\%) = \frac{m_{Na,filtrates}}{m_{Na,slurry}} \cdot 100\ \% \quad (5)$$

Results and discussion

Composition of slurry

In the examined case, the total concentration of alkali (as Na) in the dried bauxite residue slurry was about 11 w-%. The amount of alkali (Na) left in the solid phase after several washings with demineralized water was about 7 w-%, which shows the relation between the contents of water-soluble and insoluble alkali in the slurry. Therefore, about one third of the total sodium can be considered as soluble that can be removed by deliquoring and cake washing. Other metals, which were detected with SEM at concentrations worth mentioning, were Fe, Al, Ti, and Ca. Additionally, oxygen was one of the main elements in the bauxite residue slurry, while the relative amounts of Si and C were significantly lower. The main sources of oxygen were most probably various hydroxides and oxides, such as NaOH and Fe₂O₃.

X-ray diffraction was used in order to determine the most important minerals in a dried slurry sample. The diffractogram (Figure 3) shows the most abundant mineral phases identified. The JCPDS file numbers are also presented in Figure 3, and some minor peaks are not labeled for clarity. Regarding the elemental composition of the minerals, these results are in accordance with the elemental analysis performed with scanning electron microscopy.

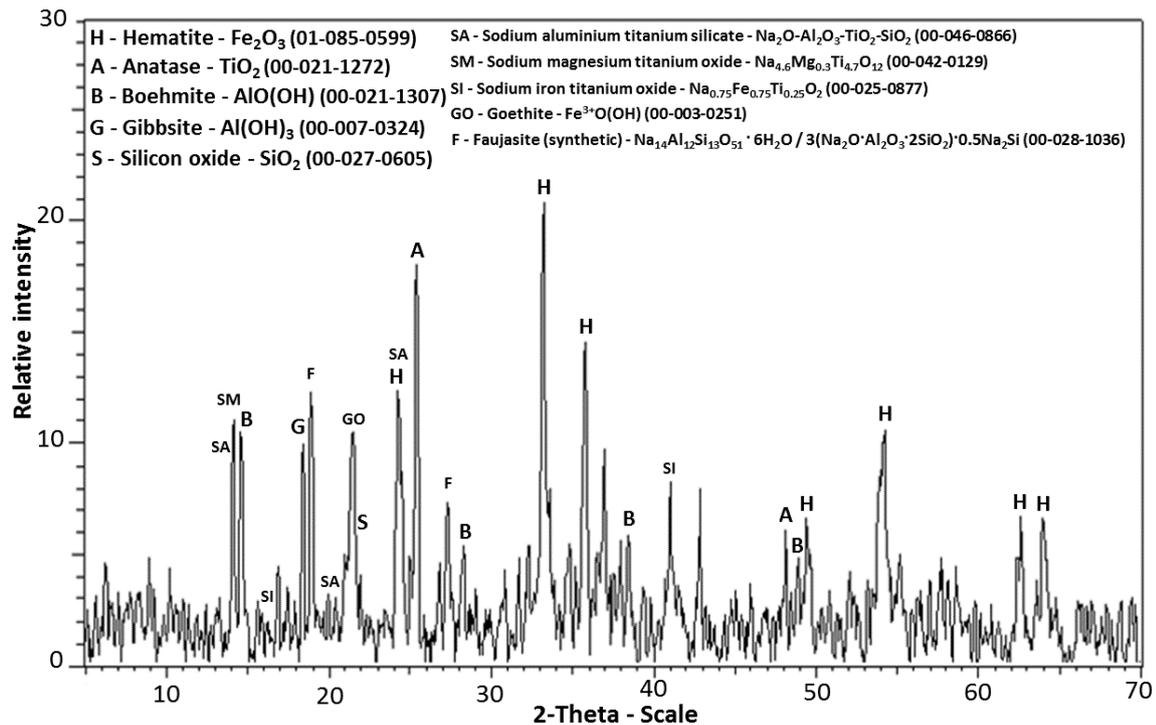


Figure 2. Mineral phases in the slurry identified with X-ray diffraction.

The particle size analyses of the slurry samples showed that the size distribution of the particles was multimodal. A majority of the particles were between 0.3 and 20 μm in size, but also some larger particles, between 30 and 100 μm , existed. The mean and median sizes were about 9 and 3 μm , respectively, and it was observed that the size distribution remained constant throughout the tests. The pH-values of the slurry and filtrate samples were fairly high, ranging from about 12.9 to 13.2. Some differences in the solid contents of the slurry were observed during the tests (from 42 to 49 w-%), and these differences also corresponded with the amount of soluble Na in the slurry samples. However, as a large number of laboratory analyses were performed, these variations could be taken into account when analyzing the results of the filtration and washing tests.

Laboratory-scale experiments

The results obtained with the small Nutsche pressure filter showed that the slurry temperature did not have a significant effect on the alkali recovery. The alkali concentrations in the filtrates, as Na, varied from 22 g L^{-1} to 23 g L^{-1} . The accumulation of filtrate at different filtration temperatures, at $\Delta p = 6$ bar, is shown in Figure 3a. The main conclusion from this is that the dissolved alkali in the slurry is not crystallized within this temperature range, but the temperature has a great influence on the filtration capacity. Moreover, the heat balance of the process has to be taken into account in industrial filtration processes.

The data collected during the Nutsche tests was used for determining the average specific resistances of the bauxite residue cakes. The experimental coefficients a needed for the calculations were equal to the slopes of the lines presented in Figure 3b, and the viscosities of the filtrates were approximated based on the known viscosities (Goncalves and Kestin, 1981) of aqueous Na_2CO_3 solutions. The resulting values of the cake resistances at a constant pressure

of 6.0 bar did not depend significantly on the temperature and they were all found to be approximately $6.0 \cdot 10^{11} \text{ m kg}^{-1}$. The moisture contents of the filter cakes obtained in the Nutsche filter tests ranged from 31 to 34 w-%.

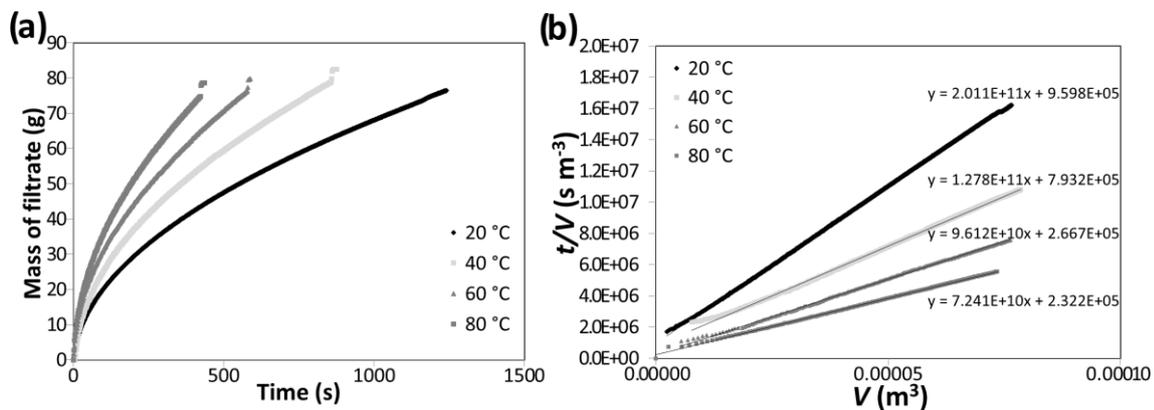


Figure 3. Results obtained with the laboratory scale Nutsche filter: a) Accumulation of filtrate during the experiments, b) t/V against V plot for the calculation of average specific cake resistances.

Deliquoring and cake washing with a horizontal membrane filter press

The primary aim of the study presented in this paper was to compare the efficiencies of different deliquoring and washing techniques in a horizontal membrane filter press in minimizing the loss of alkali and aluminium with the disposed bauxite residue slurry. Also the effect of the wash ratio on the residual alkali content of the filter cakes was studied. The applied weight-based and volumetric wash ratios in one-chamber tests ranged from 0.69 to 1.88 and from 0.58 to 1.57, respectively.

The results of the three different cases (Fig. 1b) are summarized here by using mass balance charts created by using the experimental values obtained during the tests. Mass balance charts were created separately for each test, and the charts presented here describe the typical results obtained. As mentioned above, the values presented in these charts for the properties of the slurries, filtrates, etc. are based on an extensive set of laboratory analyses performed for samples collected during the testing, and the weights of the different streams are ones measured during the tests.

The relationship between the alkali (sodium) and aluminium concentrations in the filtrates and wash filtrates is illustrated in Figure 4. It is apparent that the accuracy of the ICP analysis was very good. Another conclusion that can be drawn from Figure 4 is that neither Na nor Al precipitate during cake washing, even though the pH of the wash filtrate may be slightly reduced during it.

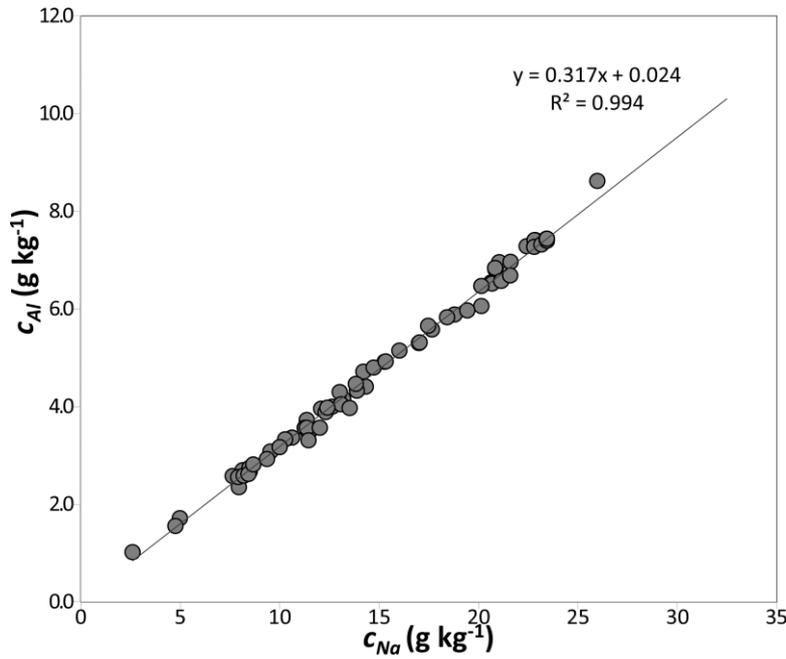


Figure 4. Respective concentrations of sodium and aluminium in the filtrate samples, determined by ICP.

The alkali recovery, perhaps the most important outcome of this study, is presented in Figure 5 as a function of the wash ratio. It is clearly shown in Figure 5 that an alkali recovery of approximately 80 % (see Eq. (5) for definition) is achievable at a wash ratio of 1.5, whereas a wash ratio higher than 2 is probably required for obtaining an alkali recovery of 90 % or higher. The variation in the results is likely due to the differences in the filtration cycles, slurry composition, as well as possible channelling of the wash liquid during the cake washing and post-treatment stages. It is important to note that in practice the alkali recovery can be over 100% if the wash ratio is high enough and the time of contact between the solids of bauxite residue and the wash liquid is long. The main reason for this is that sodium is slowly dissolved, or may migrate slowly, from the “insoluble” solid residue to the liquid phase. This phenomenon, observed earlier by Thornber and Binet (1999), deserves to be more accurately studied in the future. Calculation of the alkali recovery based on the alkali contents of the filtrates and cakes could eliminate the possibility of obtaining excessively high recoveries, but it was not done in this study due to the relatively high uncertainty related to cake analysis.

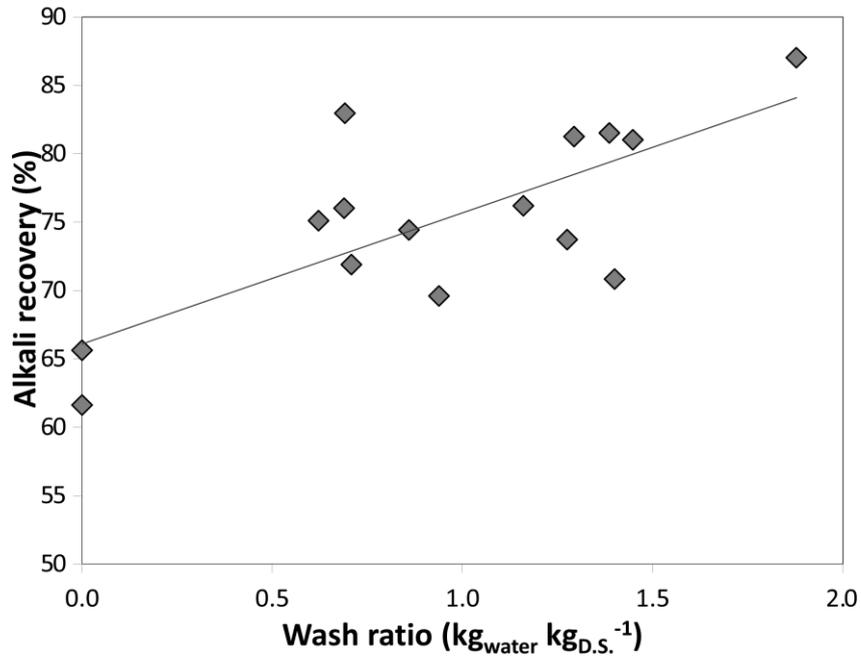


Figure 5. Alkali recovery curve created based on the results of the ‘channel wash’ tests.

In the industrial scale, the wash ratio should be as low as possible for economical reasons, and therefore the use of wash ratios higher than 1.0 in industrial pressure filters could be unlikely.

Comparison of washing methods using mass balances

The final moisture contents of the filter cakes obtained in all pressure filtration tests ranged from about 26 to 29 w-%. In order to investigate the alkali recovery in closer detail, mass balance charts for the three different separation cases (Figures 6a-c) were created. Figure 6a presents the mass balance chart for the case where cake washing was not applied and the filtration cycle consisted of filtration (i.e. pumping), pressing and air deliquoring stages.

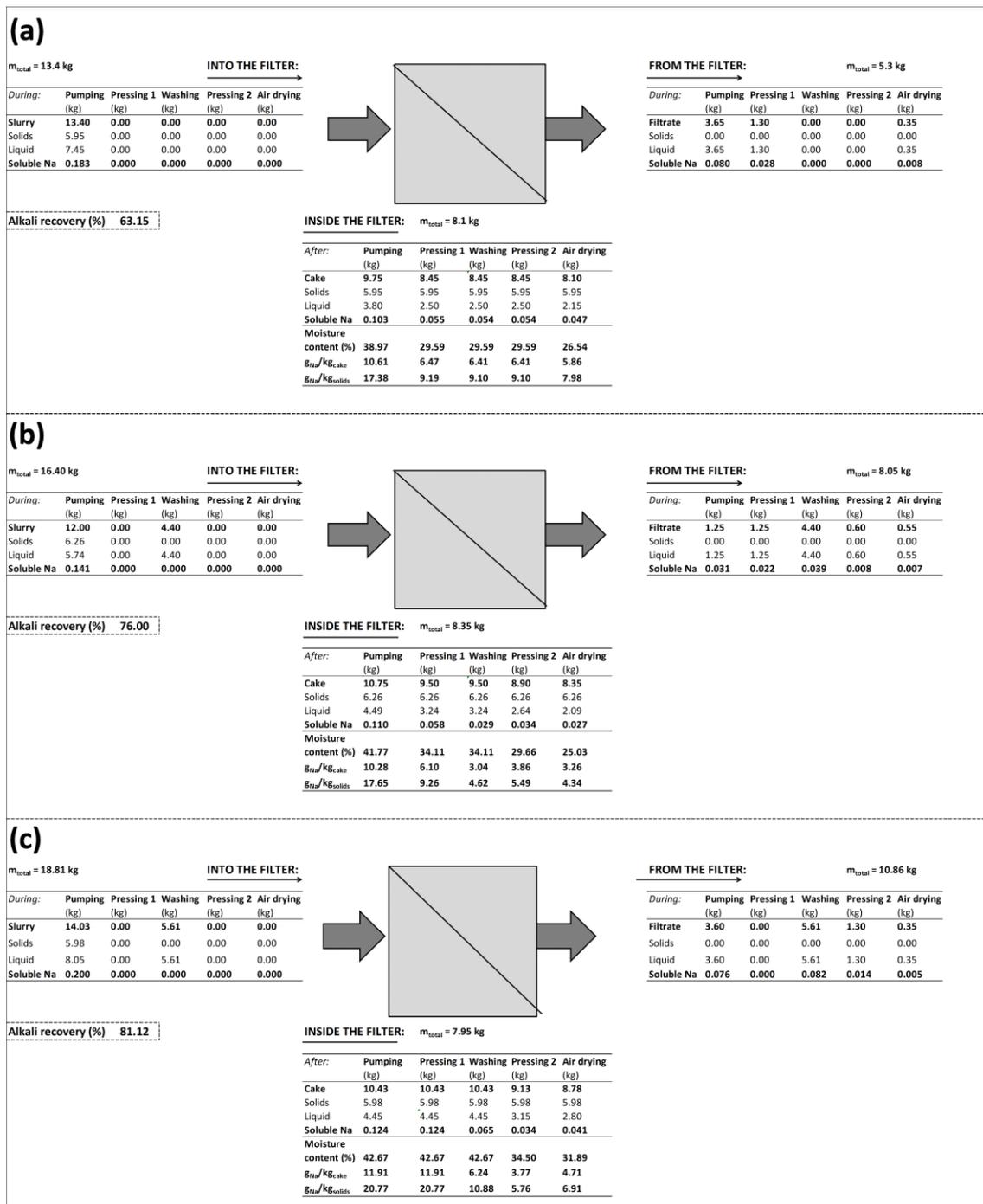


Figure 6. Mass balance charts for a test without cake washing (a), with ‘classic cake washing’ (b), and with ‘channel cake washing’ (c). The filtration and washing sequences are illustrated above in Figure 1b.

It can be observed in Figure 6a that the overall amount of soluble Na fed into the filter during the pumping stage was 0.183 kg, and 0.080 kg of this amount was recovered into the filtrate phase during this stage. Further application of mechanical pressing increased the recovery by 0.028 kg and air deliquoring by 0.008 kg. This means that 0.116 kg of the total soluble Na (out of 0.183 kg) could be recovered, which corresponds to an alkali recovery of 63.2 %. If the slurry used in these experiments were filtered with a conventional vacuum filter, the average cake

moisture content after filtration and typical vacuum dewatering stages would be significantly higher.

The recovery of alkali and aluminium can be further improved by washing the cake as a part of a pressure filtration cycle. Figure 6b shows a mass balance chart for the 'classic wash' case where the pumping and pressing stages were followed by washing and air deliquoring. The wash ratio in this test was about $0.90 \text{ kg}_{\text{Water}} \text{ kg}_{\text{Dry Solids}}^{-1}$ and as can be noticed, the alkali recovery in this case was 76.0 %. In other words, the recovery of alkali and aluminium was further increased from 63.2 % to 76.0 % with conventional cake washing.

One objective of this study was to find out if the cake washing process could be improved by performing the washing in a different way. The description of the so-called 'channel washing' technique was presented above, and the mass balance chart for a typical channel washing test is shown in Figure 6c. The results presented in Figure 6c reveal that it is possible to improve the recovery of soluble alkali and aluminium even further by using 'channel washing' instead of 'classic washing'.

It can be noticed that the amount of soluble Na recovered in the filtrates at the end of the cycle (0.178 kg) corresponds to about 81.1 % of the total amount of Na fed into the filter (0.200 kg). This means that the recovery of alkali and aluminium can be increased from 76.0 % up to 81.1 % by using 'channel washing'. The wash ratio in this case was about $0.94 \text{ kg}_{\text{Water}} \text{ kg}_{\text{Dry Solids}}^{-1}$, which means that it can be rather reliably compared with the 'classic cake washing' test illustrated in Figure 6b. The maximum alkali recovery, 87 %, was obtained using a wash ratio of $1.9 \text{ kg}_{\text{Water}} \text{ kg}_{\text{Dry Solids}}^{-1}$. Even though the obtained alkali recovery was high, it was lower than it has usually been in similar tests, according to the experience of the authors. It is important to remember that all bauxite residue slurries are different, and in this this case the slurry was exceptionally difficult to filter and wash.

Effect of wash ratio on production capacity

Generally, an increase in the wash ratio can be implemented in two practically reasonable ways: 1) using a short pumping time, which results in the formation of a thin cake, and 2) increasing the washing time. In both cases, the effect on the dry solids (D.S.) production capacity is negative (Figure 7). There is great variation in the results presented in Figure 7, because the other operational parameters than the wash ratio were varied.

Regarding the operational parameters of the filter, the obtained capacity also depends on the required moisture content of the cakes. When low moisture is targeted, the post-treatment (pressing and air deliquoring) times are usually long, which in turn reduces the capacity. The main consequence of reduced production capacity is an increase in the filter area requirement, which is a significant cost factor in the dewatering and washing process.

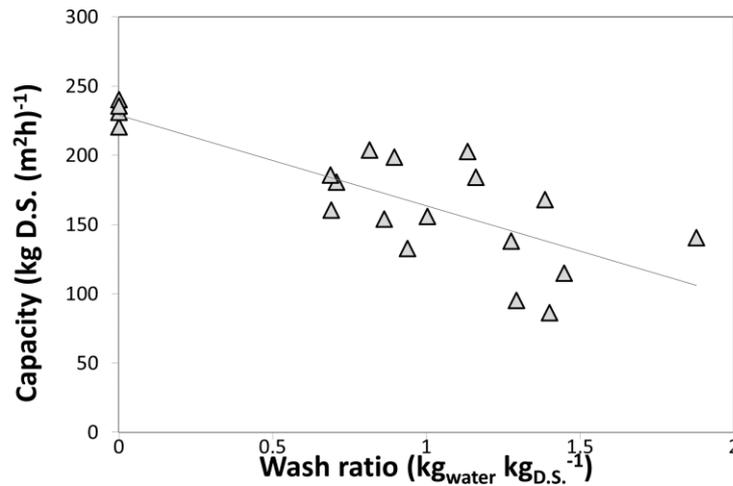


Figure 7. Dependence of the dry solids (D.S.) capacity of the membrane filter press on the applied wash ratio.

Conclusions

The aim of the study presented in this paper was to compare the efficiencies of different deliquoring and washing techniques in a horizontal membrane filter press to minimize the loss of alkali and aluminium in disposed bauxite residue slurry. It was found that the recovery of alkali and aluminium from bauxite residue can be significantly improved by using membrane filter presses for filtration and cake washing. The main conclusions are presented below.

1. It was shown that an alkali recovery level of over 80 % could be obtained using the channel washing technique with a relatively low wash ratio. Additionally, the low moisture content of the washed and deliquored bauxite residue cakes enables safe and economical dry cake disposal.
2. Depending on the operational sequence of the filter, the filtration capacities ranged from approximately 150 to 200 kg D.S. (m²h)⁻¹. High wash ratios increased the alkali recovery, but reduced the production capacity.
3. The assembly of the plate pack in horizontal membrane filter presses is vertical, which can limit the efficiency of cake washing and can cause deviations when compared with the efficiencies that could be expected according to the theories of displacement cake washing. It is probable that the washing results obtained in this study can be further improved by optimizing the parameters of the filtration cycle as well as the design of the filter plate pack for this application.

Acknowledgements

The authors would like to acknowledge Outotec Research Center (Pori, Finland) for performing the XRD analysis.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

- Altundogan HS, Altundogan S, Tümen F, Bildik M (2002) Arsenic adsorption from aqueous solutions by activated red mud. *Waste Manage*, 22, 357-363.
- Apak R, Tütem E, Hügül M, Hizal J (1998) Heavy metal Cation retention by unconventional sorbents (red muds and fly ashes). *Water Res*, 32(2), 430-440.
- Borges AJP, Hauser-Davis RA, de Oliveira TF (2011) Cleaner red mud residue production at an alumina plant by applying experimental design techniques in the filtration stage. *J Clean Prod* 19, 1763-1769.
- Brunori C, Cremisini C, Massanisso P, Pinto V, Torricelli L (2005) Reuse of a treated red mud bauxite waste, studies on environmental compatibility. *J Hazard Mater B* 117, 55-63.
- Cooling DJ (2007) Improving sustainability of residue management practices – Alcoa World Alumina Australia. *Paste 2007 – A. Fourie and R.J. Jewell (eds). Australian centre for geomechanics, Perth, Australia.*
- Ghosh I, Guha S, Balasubramaniam R, Kumar AVR (2011) Leaching of metals from fresh and sintered red mud. *J Hazard Mater* 185, 662-668.
- Goncalves FA, Kestin J (1981) The viscosity of Na₂CO₃ and K₂CO₃ aqueous solutions in the range 20-60°C. *Int J Thermophys* 2(4), 315-322.
- Gräfe M, Klauber C (2011) Bauxite residue issues: IV. Old obstacles and new pathways for *in situ* residue bioremediation. *Hydrometallurgy* 108, 46-59.
- Gräfe M, Power G, Klauber C (2011) Bauxite residue issues: III. Alkalinity and associated chemistry. *Hydrometallurgy* 108, 60-79.
- Hargreaves JSJ, Pulford ID, Balakrishnan M, Batra VS, (Eds.) (2013). *Conversion of large scale wastes into value-added products*, CRC Press, ISBN 9781466512610.
- Hind AR, Bhargava SK, Grocott SC (1999) The surface chemistry of Bayer process solids: a review. *Colloid Surface A* 146, 359-374.
- Jayasankar K, Ray PK, Chaubey AK, Padhi A, Satapathy BK, Mukherjee PS (2012) Production of pig iron from red mud waste fines using thermal plasma technology. *Int J Miner Metall Mater* 19(8), 679-684.
- Johnston M, Clark MW, McMahon P, Ward N (2010) Alkalinity conversion of bauxite refinery residues by neutralization. *J Hazard Mater* 182, 710-715.
- King JR (2001). *The aluminium industry*, Woodhead Publishing Ltd, ISBN 978-1-85573-151-6.
- Klauber C, Gräfe M, Power G (2011) Bauxite residue issues: II. options for residue utilisation. *Hydrometallurgy* 108, 11-32.
- Li LY (2001) A study of iron mineral transformation to reduce red mud tailings. *Waste manage* 21, 525-534.
- Li X, Xiao W, Liu W, Liu G, Peng Z, Zhou Q, Qi T (2009) Recovery of alumina and ferric oxide from Bayer red mud rich in iron by reduction sintering. *T Nonferr Metal Soc* 19, 1342-1347
- Li LY, Rutherford GK (1996) Effect of bauxite properties on the settling of red mud. *Int J Miner Process* 48, 169-182.
- Liu D-Y, Wu C-S (2012) Stockpiling and comprehensive utilization of red mud research progress. *Materials* 5, 1232-1246.

- Liu Y, Naidu R (2014) Hidden values in bauxite residue (red mud): Recovery of metals. *Waste Manage* 34, 2662-2673.
- Nguyen QD, Boger DV (1998) Application of rheology to solving tailings disposal problems. *Int J Miner Process* 54, 217-233.
- Pera J, Boumaza R, Ambroise J (1997) Development of a pozzolanic pigment from red mud. *Cement Concrete Res* 27(10), 1513-1522.
- Poulin E, Blais J, Mercier G (2008) Transformation of red mud from aluminium industry into a coagulant for wastewater treatment. *Hydrometallurgy* 92, 16-25.
- Power G, Gräfe M, Klauber C (2011) Bauxite residue issues: I. Current management, disposal and storage practices. *Hydrometallurgy* 108, 33-45.
- Power G, Gräfe M, Klauber C (2009) Review of current bauxite residue management, disposal and storage, practices, engineering and science. *Csiro Document DMR-3608*, May 2009, Australian Government
- Singh M, Upadhyay SN, Prasaa PM (1996) Preparation of special cements from red mud. *Waste Manage* 16(8), 665-670.
- Sofra F, Boger DV (2002) Environmental rheology for waste minimisation in the minerals industry. *Chem Eng J* 86, 319-330.
- Sparks T, Huhtanen M, Kinnarinen T, Salmimies R, Häkkinen A (2010) The challenge of red-mud filtration. 13th Nordic Filtration Symposium, June 10-11, 2010, Lappeenranta, Finland.
- Thornber MR, Binet D (1999) Caustic soda adsorption on Bayer residues. In: *Alumina*, Worsley (Ed.), 5th International Alumina Quality Workshop. Bunbury, AQW Inc., pp. 498-507.
- Wang S, Ang HM, Tadé MO (2008) Novel applications of red mud as coagulant, adsorbent and catalyst for environmentally benign processes. *Chemosphere* 72, 1621-1635.
- Whittington BI (1996) The chemistry of CaO and Ca(OH)₂ relating to the Bayer process. *Hydrometallurgy* 43, 13-35.
- Zhong L, Zhang Y, Zhang Y (2009) Extraction of alumina and sodium oxide from red mud by a mild hydro-chemical process. *J Hazard Mater* 172, 1629-1634.