

CAPACITY OF CLAY SEALS TO RETAIN RESIDUE LEACHATE

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Abstract

Historically, tailings and process residues have been placed in impoundments either constructed with engineered clay liners or excavated from clay basement materials, collectively considered here as 'clay seals'. The capacity of these clay seals to retain the leachates is an important consideration in the design of such impoundments. This is especially important when considering the potential environmental impacts that would result from any ensuing contamination of the underlying groundwater system.

Over the last several years, Alcoa World Alumina Australia has carried out a number of investigations on clay seals in such impoundments (residue areas). The investigative work has focussed on its Kwinana refinery where permeable sandy soils increase the dependence on engineered clay liners to contain residue leachate well beyond the operating life of the residue areas. These investigations included detailed examination of cores of clay liners and clay-leachate reactivity experiments.

These investigations reveal that clay seals, designed to have low permeability to residue leachate, can experience enhanced permeability from alteration of clay minerals and the formation of new compounds due to clay-leachate interactions. These investigations indicate that the principal mechanisms involved in clay-leachate interactions are dissolution, precipitation and ion-exchange reactions. It has also been found that the residue leachate can move through the clay seal more in response to its structural features than to alteration of clay minerals as a result of clay-leachate interactions.

These findings have implications in terms of the long-term management of impacts on groundwater quality resulting from enhanced seepage of alkaline leachate from residue areas, which rely solely on clay materials as a base seal. Alcoa has responded to these implications through a number of measures to both minimise and ensure effective management of any groundwater contamination.

1. Introduction

Impoundments either constructed with engineered clay liners or excavated from clay basement materials have historically been used in the minerals processing industry, including alumina refining, as repositories for tailings or process residues. The security of such impoundments, and more specifically the effectiveness of their 'clay seals' to retain the leachates, is an important design consideration. This is especially important when considering the potential environmental impacts that would result from any ensuing contamination of the underlying groundwater system. Accordingly, considerable emphasis has been placed on the physical aspects of placement or preparation of these clay seals, including selection of appropriate clay materials, quality control and testing during construction, and protection of the clay seal to avoid damage during the operation of the residue areas.

However, there is evidence that clay seals will not retain their sealing attributes when in contact for prolonged period with certain chemicals [4, 5, 6]. From thermodynamic considerations, clay minerals may become unstable with changes in the geochemical conditions of their environment [1]. But these findings also need to consider the kinetics of the clay-leachate interactions in order to confidently predict the likely time scale for such reactions to occur. Information about clay instability under changing geochemical conditions has been obtained through laboratory studies. For

example, under highly alkaline conditions and at high sodium concentrations, the sodium zeolite analcime is stable with respect to other clay minerals [1]. In particular, analcime has been shown to form at the expense of montmorillonite [1]. It has also been shown through experimental work that the rate of dissolution of kaolinite in alkaline solutions increases with increasing pH [2].

There is also evidence from high pH (9–11.5) natural soil and lacustrine environments that a wide variety of materials, including clay minerals such as smectite and kaolinite, are transformed into zeolites [3].

In relation to the clay mineralogy of clay seals in bauxite residue areas and their long-term exposure to a highly alkaline environment, there is evidence as described above that these clays may be altered over time thereby adversely affecting their effectiveness as seals. Even so, there are no published detailed case studies that have investigated the effect of alkaline solutions, in particular Bayer process fluids, on the integrity of clay seals.

Mindful of the above matters, Alcoa carried out a number of investigations on clay seals in residue areas at its West Australian Kwinana alumina refinery, in the mid to the late 1990s, to assess the capacity of these clay seals to retain residue leachate well beyond the operating life of the residue areas. The principal findings of these investigations are presented here with reference to the engineered smectitic clay seals for Residue Areas A and F at the Kwinana site.

2. Kwinana site

Figure 1 shows a schematic cross-section of the construction of an early residue area and the near-surface strata at the Kwinana site. The engineered smectitic clay seal of 40 cm nominal thickness was positioned several metres above the water table in sandy strata. A sand blanket (obtained from local sources) of similar thickness was installed over the clay seal to protect it from erosion and desiccation.

However, operational practices in the 1960s and 1970s involving deposition of bauxite residue into the residue area, and erosion and desiccation cracking of the clay seals resulted in defects developing in the clay seals at Residue Areas A, C and F. This resulted in higher rates of leachate escape and the development of groundwater contaminant plumes.

The discovery of groundwater contamination in 1974 resulted in a number of improvements including: the adoption of higher security composite clay-geomembrane seals; base drainage systems to minimise hydrostatic heads; dewatering systems to recover leachate from within residue deposits; and ultimately conversion to 'dry stacking' techniques.

Investigations to detect and grout up defects in the clay seals were carried out from 1980 to 1998 and a large proportion of the defects was sealed. However, there still remained the uncertainty of the capacity of the clay seals to retain residue leachate in the long term. As a start to address this uncertainty, the Area F clay liner was sampled from 1994 to 1997 as part of investigations of liner defects.

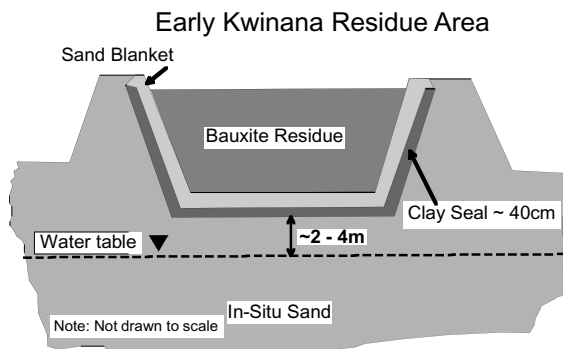


Figure 1 — Schematic cross-section of the construction of an early residue area and the near-surface strata at the Kwinana site.

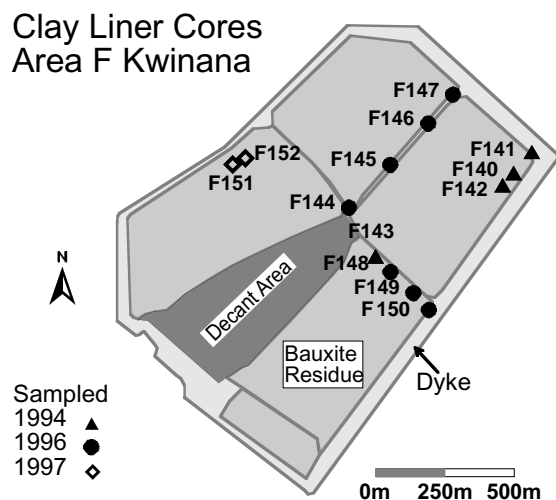


Figure 2 — Locations of clay liner cores sampled from Residue Area F Kwinana from 1994 to 1997.

Residue Area F

The locations of the clay liner cores sampled from Area F are shown in Figure 2. A composite photograph of the longitudinal section of clay liner core F146, which was sampled well away from any known leaks, is shown in Figure 3; and its sampling log is contained in Table 1. Note in core F146 that its upper part is brittle, grey and crumbly in appearance, which is distinctly different to the lower part comprising well compacted, plastic grey-green clay. The clay material in the upper part has been 'altered' from the original clay material, which is represented in the lower part.

Table 1 — Sampling log for clay liner core F146

ID	Depth from toc (cm)	Description
	0-5	Bauxite residue and sand blanket material
1-2	5-12	Brittle, light grey sandy clay, crumbly
3	12-15	Gravel-sized brittle, grey lumps
4	15-18	Transition zone
5-10	18-39	Well compacted, plastic grey-green clay, occasional sand patches

toc: top of core

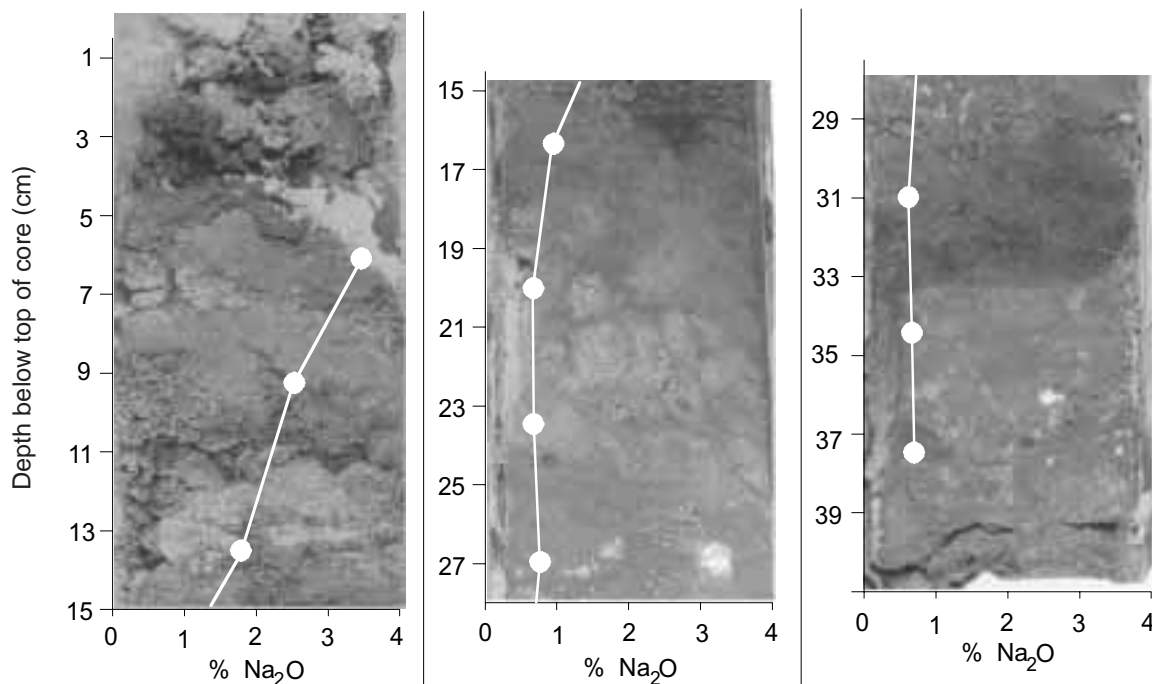
Similar observations on the other Area F clay liner cores have been made. Figure 4 displays the observed depth of 'altered' compared to 'unaltered' clay for clay liner cores F140 to F150 sampled in 1994 and 1996. This figure shows that the extent of clay alteration is quite variable as is the thickness of the clay seal recovered when compared to the design thickness of 40 cm.

In Figure 3, there is also evidence of a strong correlation between the depth of altered clay in core F146 and its percentage Na₂O content, as determined from X-ray fluorescence spectrometry (XRF) measurements on clay core samples (Table 2). The percentage Na₂O profile also indicates the extent of penetration of residue leachate into core F146 because of the high Na concentration in the residue leachate. Furthermore, the information on depth of altered clay and percentage Na₂O profile for this and the other clay liner cores suggests that reactions between the clay material and residue leachate are responsible for the observed alteration of the clay material.

In order to determine the cause of the alteration of the clay materials in the cores, several of these cores, including core F146, were subjected to detailed chemical and mineralogical examination. This detailed analytical work was preceded by a reassessment of analytical methods associated with strongly alkaline clay materials. A significant outcome was the use of a clay:water ratio of 1:3 in the extraction procedure. This had the advantages of:

- Minimising the disruption of the clay: solution equilibria.
- Providing sufficient solution to allow the analysis of the selected suite of analytes.
- Allowing division of the core into relatively narrow segments, so that systematic changes through the profile of the clay liner could be detected.

From here on, discussion of the detailed analytical work on clay liner cores from Area F will be restricted to core F146, which is considered to be representative of the cores recovered from Area F's clay liner. The analytical data for the 1:3 clay:water extracts of samples from core F146 are contained in Tables 3 and 4. The depth sampling intervals for the ten segments of core F146, on which all analyses have been performed, are listed in Table 2. Table 4 also contains analytical data for oxalate extractable iron, aluminium and silicon.

F146 Clay Liner Core & Na₂O contentFigure 3 — Longitudinal section of clay liner core F146 and its percentage Na₂O content.

Observations on clay liner cores at Area F

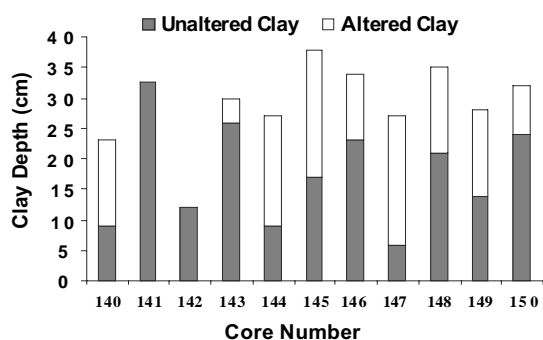


Figure 4 — Observations on clay liner cores from Residue Area F Kwinana

The concentrations of exchangeable cations extracted by 1 M ammonium chloride solutions and the Cation Exchange Capacities at pH 7 and with 60% ethanol at pH 8.5 for samples from core F146 are listed in Table 5. The latter method was used for soils above pH 8, as the former method is not appropriate for alkaline soils containing calcium carbonate. Table 5 also contains the concentrations of sodium and magnesium dissolved by the ethanol-glycol wash solution prior to the ammonium chloride extraction. The difference between the sum of the exchangeable cations and the CEC, the cation excess, is an indication of the amount of soluble (mostly sodium) bicarbonates, carbonates and sulphates that are not captured by the ethanol-glycol wash. The cation excess also includes the truly exchangeable sodium that is associated with the variable charge component of the CEC when the pH of the clay is increased from 8.5 under the conditions of the CEC procedure to the natural pH of the altered clay material, which may be as high as 11.

The analytical data show that:

- The sodium profile determined for total sodium throughout the clay liner is similar to that for the water soluble and exchangeable forms of sodium.

- Higher sodium concentrations in the altered part of the core are also associated with elevated pH and total alkalinity and increased concentrations of fluoride, oxalate, phosphate, arsenic, uranium and vanadium, all of which are characteristic of bauxite residue leachate. In contrast, the concentrations of chloride, sulphate and manganese are lower in the altered clay section of the core, which are also likely to be characteristic of residue leachate relative to the chemical composition of the pore fluid in the unaltered (natural) clay liner material.
- Exchangeable and soluble calcium and magnesium are not present in significant concentrations in the altered clay material. Geochemical modeling of the chemical composition of the water extracts indicates that calcium and magnesium occur as sparingly soluble minerals, such as calcite, in the altered clay section of the core. These observations indicate that, to the depth that residue leachate has penetrated the clay liner core, sodium ions from the leachate have largely replaced the calcium and magnesium on the clay by ion exchange reactions.
- Penetration of residue leachate appears to be limited by the low calcium content of the clay material. This accords with the observation that calcitic soils are more permeable than sodic soils.
- The altered clay material contains high concentrations of oxalate extractable aluminium and silicon. This indicates that there has been significant alteration of the clay minerals by dissolution and precipitation reactions to form amorphous aluminosilicate compounds. The presence of these amorphous compounds coincides with a significant increase in the Cation Exchange Capacity (CEC) and the presence of zeolite minerals in the altered clay section of the core. The presence of the zeolite minerals partly explains the increase in the CEC of the altered clay material.

Table 2 — Elemental composition (as oxides) for samples of clay liner material from core F146

ID	Depth from toc (cm)	CaO	MgO	Na ₂ O	K ₂ O	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	TiO ₂	P ₂ O ₅	SO ₃
1	5–7	0.92	1.62	3.54	0.27	11.24	4.10	49.16	0.51	0.05	0.14
2	7–12	0.78	1.40	2.42	0.28	8.70	3.45	56.87	0.55	0.01	0.13
3	12–15	0.76	1.26	1.88	0.29	8.05	2.99	64.14	0.57	0.01	0.16
4	15–18	0.07	0.47	1.05	0.33	9.15	4.46	61.86	0.65	0.02	0.32
5	18–22	0.08	0.35	0.73	0.38	6.88	2.94	71.78	0.64	0.01	0.16
6	22–25	0.13	0.46	0.75	0.39	7.88	3.08	68.13	0.72	0.01	0.07
7	25–29	0.17	0.64	0.86	0.33	9.63	4.39	58.06	0.64	0.01	0.21
8	29–33	0.24	0.59	0.75	0.29	9.13	4.16	58.68	0.66	0.01	0.27
9	33–36	0.87	0.84	0.72	0.27	10.26	4.98	53.53	0.57	0.01	1.27
10	36–39	0.52	0.70	0.79	0.30	9.68	5.72	55.05	0.58	0.01	0.64

Units are % (g/100g); toc: top of core.

Table 3 — Chemical analyses for 1:3 clay:water extracts of samples from core F146

ID	pH	Alk	Ca	Mg	Na	K	Br	Cl	F	NO ₃	Ox	PO ₄	SO ₄
1	10.2	3400	<10	<10	1800	<10	1	70	2	<1	45	9	360
2	10.3	3900	<10	<10	2100	<10	<1	62	4	<1	36	14	380
3	10.2	2200	<10	<10	1200	<10	<1	29	3	<1	16	12	240
4	8.1	240	<10	<10	460	<10	1	76	4	<1	<1	<1	490
5	7.5	86	34	93	570	<10	<1	52	4	<1	<1	<1	260
6	7.6	98	21	130	340	6	<1	55	3	<1	<1	<1	200
7	7.6	75	<10	<10	340	<10	1	97	1	<1	<1	<1	460
8	7.7	92	9	9	430	<5	1	79	<1	<1	<1	<1	600
9	7.4	43	29	18	720	<5	1	87	1	<1	<1	<1	1600
10	7.2	23	420	120	1200	<10	1	84	<1	<1	<1	<1	4500

Units are mg/L except for pH, which is dimensionless. Alk: Alkalinity as mg CaCO₃/L. Ox: oxalate.

Table 3 (Continued)

ID	As	B	Cr	Cu	Ga	Mn	Ni	Pb	Sr	U	V	Zn
1	0.90	<0.2	0.011	0.04	0.07	<0.01	0.01	<0.01	<0.01	0.20	6.8	0.01
2	1.40	<0.2	0.012	0.06	<0.01	0.01	0.01	0.01	0.02	0.17	3.0	0.02
3	2.00	<0.2	0.170	0.14	0.01	0.04	0.09	0.10	0.08	0.06	3.5	0.23
4	0.29	<0.2	<0.005	0.05	<0.01	0.03	0.03	0.03	0.01	0.09	0.43	0.04
5	0.02	<0.2	<0.005	0.12	<0.01	0.87	0.04	0.13	0.49	0.27	0.49	1.2
6	0.04	0.5	0.012	0.08	0.01	0.61	0.05	0.09	0.27	0.10	0.42	1.2
7	0.05	<0.2	<0.005	0.04	<0.01	0.03	0.01	0.01	0.02	<0.01	0.15	0.02
8	0.01	<0.1	0.005	0.03	<0.01	0.12	0.01	0.02	0.04	0.01	0.12	0.03
9	<0.01	<0.1	<0.002	0.01	<0.01	0.05	0.01	0.02	0.08	<0.01	0.02	0.02
10	0.01	<0.2	<0.002	0.01	<0.01	0.40	0.02	<0.01	1.0	<0.01	<0.01	0.02

Units are mg/L.

Table 4 — Concentrations of total Fe, Al & Si and soluble Si in 1:3 clay:water extracts (mg/L) and total Fe, Al & Si in 0.3 M ammonium oxalate extracts (mg/kg) of samples from core F146

ID	Fe mg/L	Al mg/L	Si _{tot} mg/L	Si _{sol} mg/L	Fe mg/kg	Al mg/kg	Si mg/kg
1	1.1	2.8	17	11	2500	10400	8400
2	3.4	3.2	220	260	1400	3900	1900
3	6.5	13	620	620	3100	1200	580
4	9.7	11	62	23	2400	490	560
5	93	34	9500	54	670	260	240
6	82	62	4900	63	750	380	370
7	2.6	2.1	34	20	1200	550	400
8	8.2	3.7	460	32	1900	560	440
9	<0.5	<0.5	22	25	1000	520	350
10	<0.5	<0.5	25	28	870	460	340

Si_{tot}: total Si as mg SiO₂/L; Si_{sol}: soluble Si as mg SiO₂/L.

Table 5 — Exchangeable and soluble cations extracted by 1 M NH₄Cl and Cation Exchange Capacities at pH 7 and with 60% ethanol at pH 8.5 (*italics*) for samples from core F146

ID	CEC ₇	Ca _e	Mg _e	Na _e	K _e	Ex	Mg _s	Na _s	Ca _e	Mg _e	Na _e	K _e	Ex	CEC _{8.5}
1									<i>0.4</i>	<i>0.3</i>	<i>74.3</i>	<i>0.2</i>	<i>20</i>	<i>55</i>
2									<i>0.1</i>	<i><0.1</i>	<i>77.7</i>	<i>0.3</i>	<i>29</i>	<i>49</i>
3									<i>0.6</i>	<i><0.1</i>	<i>50.6</i>	<i>0.1</i>	<i>13</i>	<i>38</i>
4									<i>2.1</i>	<i>2.3</i>	<i>34.4</i>	<i>0.1</i>	<i>3</i>	<i>36</i>
5	19	2.3	4.2	14.8	0.2	2	0.1	0.7						
6	26	3.6	7.8	20.9	0.2	6	0.1	0.9						
7	39	10.1	12.2	28.0	0.2	11	0.2	1.0						
8	32	9.0	12.4	17.8	0.2	7	0.1	0.7						
9	36	14.5	14.4	23.2	0.2	16	0.2	0.9						
10	36	25.5	14.2	24.0	0.2	28	0.2	1.0						

Units are milliequivalents/100g

CEC₇: Cation Exchange Capacity at pH 7; CEC_{8.5}: Cation Exchange Capacity at pH 8.5

e: exchangeable and soluble in 1 M NH₄Cl at pH 7, and at pH 8.5 (*italics*) for only samples 1–4

s: soluble in ethanol-glycol

Ex: cation excess defined as difference between the sum of the four cations (Ca, Mg, Na and K) and CEC

Ca_s and K_s were below the detection limit (0.1 milliequivalents/100g) for all samples

Clay-leachate reactivity

In order to further investigate the nature of the reactions between residue leachate and the clay liner materials that became evident from the detailed examinations of the clay liner cores from Area F, the following clay-leachate reactivity work was performed.

Representative clay materials were obtained as used in the clay liners for the residue areas at Kwinana. Four different leachates were used of similar sodium concentrations but with pH ranging from 7 to 13 (Table 6). Individual clay-leachate reactivity experiments were allowed to proceed for periods ranging from 14 to 222 days.

This clay-leachate reactivity work confirmed and further clarified the findings from the examinations of the clay liner cores from Area F in that:

- Ion exchange is the primary reaction that occurs. Sodium ions from the leachates were exchanged for other cations (calcium, magnesium, potassium and hydrogen) on the clay minerals.
- In the alkaline solutions, the primary ion-exchange reaction was sodium for hydrogen ions, which resulted in an appreciable decrease in the alkalinity of the respective solutions.
- Calcium and magnesium were not detected in the alkaline solutions, as was evident from the significant decrease in the concentrations of exchangeable calcium and magnesium in the clay residues, and were considered to have precipitated as sparingly soluble carbonates.
- In the alkaline solutions, some alkalinity was consumed in the dissolution of some of the clay minerals. This dissolution reaction produced soluble silica and aluminium, which subsequently reacted to form amorphous aluminosilicate compounds. The presence of these amorphous materials was indicated by an increase in the CEC and the amounts of silica and aluminium that were extractable with ammonium oxalate solution.
- The increase in the CEC is also partly attributed to zeolite minerals that were identified in the clay residues though they were not as prominent as in the altered clay sections of the clay liner cores from Area F. The lesser presence of zeolite minerals in this experimental work is attributed to the much shorter time available for zeolites to form from the amorphous aluminosilicate compounds.

- A significantly larger amount of aluminosilicate material was formed when residue leachate was used in the experimental work. This was attributed to the presence of appreciable quantities of aluminium in the residue leachate.
- The relatively high reactivity of the Kwinana clay material is attributed to its smectitic nature and its high level of reactive silica. It should be noted, however, that a lower reactivity does not necessarily imply improved performance of the clay material as a seal. The capacity of a clay material to retain alkaline solutions in a residue area depends not only on what structural changes are undergone by the clay minerals but also on what structural defects exist within the clay liner.

Table 6 — Leachates used in the clay-leachate reactivity experiments

Composition	pH	Purpose
NaCl	7	Extent of ion-exchange reactions
Na ₂ CO ₃	11	Extent of clay-leachate reactions at moderately alkaline pH
Na ₂ CO ₃ /NaOH	13	Extent of clay-leachate reactions at pH of residue leachate
Residue leachate	13	Extent of clay-leachate reactions using residue leachate

Overall, the findings from the examination of the Area F clay liner cores and the clay-leachate reactivity experiments indicated that alteration of the clay material would occur, which may result in increased permeability of the clay seal. However, no direct measurements of the permeability of the clay seals at Kwinana had been obtained.

Residue Area A

In 1997, eleven clay liner cores were obtained from Residue Area A, within the Residue Area ABC complex, with the main purpose to obtain measurements of the permeability of the clay liner. In addition, physical and chemical examination of the cores was carried out but on a much lesser scale compared to that performed on the Area F clay liner cores. Nonetheless, this examination was sufficient to assess the texture of the clay liner materials and the extent of penetration of residue leachate into the clay seal.

Similarities observed between the clay liner cores sampled from Areas A and F were the variability in their physical appearance and texture and the thickness of clay liner sampled, though for Area A the thickness varied over a greater range from 20 to 95 cm. In contrast to Area F, all clay liner cores from Area A had full penetration of residue leachate (Figure 5). It should be noted, however, that at the time of sampling of the respective clay liners, Area A had been in operation 34 years compared to ~20 years for Area F. Figure 5 also shows that residue leachate has penetrated the Area A clay liner to varying degrees, with most cores having significant gradients in concentrations of chemical species indicative of residue leachate. This indicates that, in most cases, the clay material has retained a certain capacity to neutralize the alkalinity of the leachate.

Permeability measurements were made for a number of clay liner segments, with pH values of their 1:3 clay:water extracts ranging from <9 to 12 (Figure 6). For each permeability measurement, the pH values of the 1:3 clay:water extracts are presented for the clay liner material both above and below the core segment used for the measurement. Residue leachate or a 1:4 dilution with water was used as the permeant for the permeability measurements.

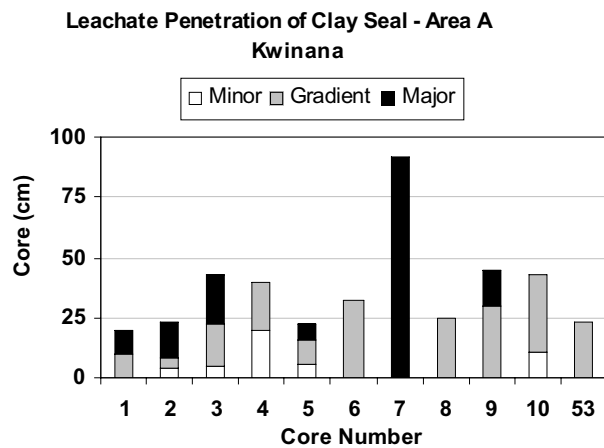


Figure 5 — Extent of residue leachate penetration of the clay seal at Residue Area A Kwinana

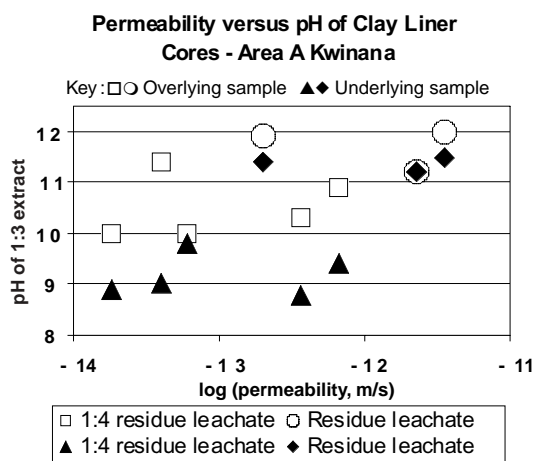


Figure 6 — Permeability versus pH of clay liner cores from Residue Area A Kwinana

Note that the permeability measurements for samples of the altered clay liner materials from Area A (Figure 6) are very low compared when to the design and expected permeability of the clay liner but are not consistent with the observed extent of leachate penetration in the Area A cores. However, it is important to note that the core samples

selected for permeability measurements were generally free of physical defects and may not reflect the overall permeability of the clay liner. Higher rates of permeation of residue leachate can be expected from clay liner material that had undergone alteration to the extent, as observed in several cores, where the clay material was crumbly and could not be sampled for permeability measurements. The presence of cracks, sand lenses and extraneous material, including pieces of limestone and wood, which were observed in segments of the clay liner cores from Area A would also contribute to higher rates of leachate penetration than expected. It is generally recognised that most clay liners contain macropores, or preferred pathways, which transmit greater amounts of flow than micropores, which are minimised during the engineering of the clay liner [7].

Even with the lower than expected permeability measurements for the Area A clay material, the data in Figure 6 indicate that with increasing pH of pore fluids in the clay material, hence increased alteration of the clay material, its permeability increases. This result concurs with all other examinations of the clay liner cores from both Areas A and F, which suggested that alteration of the clay material may result in increased permeability of the clay seal, primarily due to the formation of new compounds, such as zeolites.

3. Conclusions

Investigations of the capacity of clay seals to retain residue leachate for the clay liners in Kwinana’s Residue Areas A and F have concluded that:

- Clay minerals can be altered through reactions with residue leachate.
- The principal mechanisms of these clay-leachate interactions are:
 - Ion exchange. Sodium from the residue leachate is exchanged for other cations (calcium, magnesium, potassium and hydrogen) on the clay minerals.
 - Dissolution of clay minerals and formation of new compounds. This dissolution reaction produces soluble silica and aluminium, which subsequently react to form amorphous aluminosilicate compounds, and eventually zeolite minerals.
- Precipitation of sparingly soluble (calcium and magnesium) carbonates. Calcium and magnesium become available from ion-exchange reactions involving the clay minerals.
- Alteration mechanisms are likely to result in higher permeabilities of clay seals.
- Structural features in constructed clay seals are also likely to contribute to the penetration of residue leachate.

A number of implications follow from the above conclusions, and the ways in which Alcoa has responded are also mentioned:

- The design of seals for bauxite residue areas or other facilities designed to contain highly alkaline materials needs to consider the risk of long term changes in performance that could result in increased seepage losses to the environment. These clay seals possess a finite capacity to chemically attenuate the alkalinity of residue leachate through ion-exchange, dissolution and precipitation reactions. However, these reactions lead to alteration of clay minerals, which may result in increased permeability of clay seals over the long term. More secure seal designs, such as composite clay-geomembrane seals should be considered.

Following the discovery of groundwater contamination in 1974, all residue and process water storage areas associated with the Kwinana refinery have been

constructed with composite clay-geomembrane seals thereby limiting the exposure of clay to alkaline leachate. Subsequent to the findings of the studies reported herein, composite clay-geomembrane seals have been adopted as a standard for all of Alcoa's residue areas at its three alumina refineries in Western Australia.

In addition, defects in the liners of the clay-only-seals for Kwinana's older residue areas have been sealed through an extensive grouting program. Seepage from these residue areas has also been reduced through dewatering systems, which have recovered leachate from within the residue deposit, and base drainage systems together with 'dry stacking' techniques, which minimise hydrostatic heads within the residue deposit.

- The risk of increased groundwater contamination resulting from a gradual increase of clay seal permeability associated with older generation residue areas needs to be assessed through an adequate understanding of the site hydrogeology, and a review of data from an appropriate water quality monitoring program of the underlying groundwater system and any nearby surface waters.

The results from the clay seal investigations reported herein have been used in a quantitative risk assessment of groundwater contamination at Kwinana

which has formed the basis of its future groundwater management strategy. This detailed risk assessment of groundwater contamination affirmed that the current strategy of contaminant recovery and containment by a system of recovery bores was the most appropriate. Associated with this strategy was a plan to implement a range of capital works, such as more effective and efficient recovery systems, and hydrogeological investigations to improve the management of groundwater contamination. This strategy and plan is updated and reviewed in response to annual reviews of groundwater quality and abstraction at the Kwinana site and bimonthly scrutiny by a groundwater management team to ensure that management targets are met.

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