

Bauxite Residue CO₂ Mineral Sequestration Assessment

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<https://doi.org/10.71659/icsoba2025-br001>

Abstract

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Since the start of the century, bauxite residue has received re-occurring attention as a potential material for carbon capture and storage. While several studies have explored this possibility, a comprehensive evaluation of the underlying chemistry, technical implications and economic viability for the alumina industry has been lacking. This paper, commissioned by the International Aluminium Institute, addresses these aspects, particularly in the context of securing carbon credits to offset emissions penalties. A typical bauxite residue mineralises approximately 12 kg CO₂ per tonne of dry bauxite residue solids (BR), equating to about 1.5 % of an alumina refinery's carbon footprint. A review of the chemistry of CO₂ capture and CO₂ mineral sequestration shows that typically two-thirds of the CO₂ initially absorbed is not mineralised and cannot be mineralised economically, creating a two-fold problem for alumina refiners. Firstly, two-thirds of the flue gas compression energy is wasted and secondly, the heavily carbonated residue liquor cannot be returned to the Bayer process untreated. The Scope 2 CO₂ emissions associated with compression energy consume a substantial fraction of the amount of CO₂ mineralised. Even without considering Scope 2 emissions, both the operating cost and the capital cost would be prohibitive on their own at the commonly used carbon credit projections at or around 100 USD/t CO₂. A carbon credit value of at least 700 USD/t CO₂ is required for the economics to break even. More viable opportunities exist in carbonating lime waste products separate from the residue. The paper discusses important aspects of the chemistry, such as pH rebound, chemical soda loss recovery potential, release of fluoride from tri-calcium aluminate, and operating preferably under reduced carbonation reactor operating pressure and reduced liquor/solids ratio.

Keywords: Bauxite residue, Carbonation, CO₂ storage, Carbon credits, Economics.

1. Introduction

Contacting bauxite residue with CO₂ has been the subject of various studies over the past few decades. In some cases, and in two PhD studies, the primary objective was assessing the potential contribution to the effort of reducing global warming [1–3]. In other studies, this was a secondary objective with the main focus being e.g. residue neutralisation [4], more efficient revegetation [5], chemical soda loss recovery [6] or metals recovery [7]. Alcoa had operated a bauxite residue carbonation unit on an industrial scale at Kwinana from 2008 for a few years using CO₂ rich waste gas from a nearby ammonia plant [8]. This was done to improve residue disposal management, while recognising the benefit of reducing the carbon impact of the operation on the climate.

It is widely recognised that bauxite residue can capture and mineralise CO₂. However, the studies published so far present only a fragmented picture. No conclusions have been drawn yet if bauxite residue carbonation is a viable proposition. The alumina industry has embarked on a program of

decarbonisation initiatives. It is of interest to the industry to know the impact of bauxite residue carbonation within the overall scheme of initiatives and if indeed bauxite residue carbonation is economically feasible in the first place. The International Aluminium Institute (IAI) commissioned a study to provide answers to these questions; this paper summarises the main conclusions from this study.

Understanding the carbonation chemistry is of crucial importance, as it is the basis for establishing (a) the quantity of CO₂ being captured, (b) the quantity of CO₂ being mineralised, (c) the key carbonation process design criteria and (d) any potential effects there may be on the Bayer process. These factors ultimately determine the cost incurred per net tonne of CO₂ mineralised, being the difference between the amount of CO₂ permanently stored in the residue and the amount of CO₂ emitted to the atmosphere due to the effort to accomplish this. The potential economic rewards are the carbon credits obtained.

2. Carbon Credits

Carbon credits can only be claimed when certain conditions are met according to the certification requirements in the applicable country. Carbon credits trading has been established in many economies around the globe, although structure and implementation is not uniform. Schemes vary between being voluntary and being compliance-based. The schemes in the EU and in Australia are compliance-based and are amongst the most developed schemes in the world. Furthermore, with the EU and Australia having well established alumina production facilities, the focus on certification requirements has been directed to those regions in the present study.

In the EU, legislation exists for geological storage of CO₂ but this concerns underground storage [11]. Legislation is under development for ground level storage, but the proposals so far are focused on agricultural and forestry projects and do not include storage in mine waste [12]. Australia is one step further since new legislation appears to apply also to ground level storage in mine waste streams [13]. The legislation distinguishes between 100-year and 25-year permanence projects. In the present study, the projected value of these carbon credits is assumed to be 100 USD/t CO₂.

Common to the EU and Australian regulations are some strict criteria for carbon storage certification. In the EU, these criteria are known as the “QU.A.L.ITY” criteria [14]:

1. QU: QUanitification
Carbon removal activities need to deliver unambiguous benefits for the climate and be measured, monitored and reported accurately. Note that monitoring means monitoring for leakage and that this also needs to continue for a long time after storage closure.
2. A: Additionality
Carbon removal activities need to go beyond existing practices and what is required by law. Note that this implies that any naturally occurring carbonation is excluded and needs be deducted from actively achieved carbonation.
3. L: Long-term Storage
Certificates are linked to the duration of carbon storage and should ensure long-term storage.
4. ITY: Sustainability
Carbon removal activities must contribute to sustainability objectives such as climate change adaption, circular economy, water and marine resources and biodiversity.

These criteria imply that certification requires ongoing monitoring and registration of the quantities of CO₂ being mineralised and being maintained in storage. This requires periodic borehole sampling and analysis of the residue deposit area for establishing a baseline and for quantifying any losses over time.

make more sense to carbonate the waste lime streams that contain TCA rather than the entire bauxite residue stream to which these lime streams are added. Even better is to reduce the formation of TCA in the Bayer process all together since this will reduce the plant lime consumption and therewith the CO₂ emissions of burning CaCO₃ in lime kilns (chemically bound CO₂ as well as fuel combustion CO₂).

From a process technical perspective as well as an economic perspective it appears best to design an alkaline waste CO₂ mineral sequestration unit for the lowest practical pressure and lowest practical (e.g. with respect to agitation) L/S ratio. Dilution should always be avoided.

6. References

1. Cuong P. Tran, Red Mud Minimisation and Management for the Alumina Industry by the Carbonation Method, *Thesis University of Adelaide*, (2016).
2. Cuong P. Tran et al., An Evaluation of Carbon Dioxide Capture by Carbonation of Red Mud under Different Operating Conditions, *Chemeca – Adelaide*, (2016), 547–558.
3. Maria José Moreno Correia, Séquestration des Émissions de CO₂ dans le Secteur de Production de l'Aluminium à partir des Résidus de Bauxite issus du Procédé Bayer, *Thesis Université du Québec*, (2022).
4. D.J. Cooling, P.S. Hay, L.M. Guilfoyle, Carbonation of Bauxite Residue, *6th International Alumina Quality Workshop*, (2002), 185–190.
5. Sameer Khaitan et al., Field Evaluation of Bauxite Residue Neutralization by Carbon Dioxide, Vegetation, and Organic Amendments, *Journal of Environmental Engineering, ASCE*, (October 2010), 1045–1053.
6. C.M. Cardile, Process for the Treatment of Red Mud, *WO Patent 16003*, (1993).
7. Rudolfo Rivera et al., Neutralisation of Bauxite Residue by Carbon Dioxide prior to Acidic Leaching for Metal Recovery, *Minerals Engineering*, (2017), 112, 92–102.
8. IAI report: Bauxite Residue Management: Best Practice, International Aluminium Institute, (2013), 16.
9. T.D. Rushendra Revathy, A. Ramachandran, K. Palanivelu, Sequestration of CO₂ by Red Mud with Flue Gas using Response Surface Methodology, *Carbon Management* (2021), 12:2, 139–151.
10. Shu-Yuan Pan, E.E. Chang, Pen-Chi Chiang, CO₂ Capture by Accelerated Carbonation of Alkaline Wastes: A Review of Its Principles and Applications, *Aerosol and Air Quality Research*, (2012), 12, 770–791.
11. EU Directive 2009/31/EC on the geological storage of carbon dioxide (23 April 2009), *Official Journal of the European Union*, 5.6.2009.
12. EU 2022/0394 (COD) Proposal for establishing a EU certification framework for permanent carbon removals, carbon farming and carbon storage in products, (2022).
13. Australia Carbon Credits (Carbon Farming Initiative) Act 2011, Compilation No. 23, (March 2024).
14. European Commission – Press release, European Green Deal: Commission proposes certification of carbon removals to help reach net zero emissions, Brussels, (30 November 2022).
15. L.N. Plummer, E. Busenberg, The solubilities of calcite, aragonite and vaterite in CO₂-H₂O solutions between 0 and 90 °C, and an evaluation of the aqueous model for the system CaCO₃-CO₂-H₂O, *Geochimica et Cosmochimica Acta*, (1982), Vol. 46, 1011–1040.
16. C.W. Davies, The extent of dissociation of electrolytes in aqueous solution and Debye-Hückel theory, *Journal of the Chemical Society*, (1938), 2093–2098.
17. Young-Soo Han et al., Bauxite residue neutralization with simultaneous mineral carbonation using atmospheric CO₂, *Journal of Hazardous Materials*, 326, (2017), 87–93.
18. Luke J. Kirwan et al, Chemistry of Bauxite Residue Neutralisation and Aspects to Implementation, *International Journal of Mineral Processing*, (2013), 119, 40–50.

19. S.B. Rai et al., Sequestration of Carbon Dioxide in Red Mud, *Desalination and Water Treatment*, (2013), 51:10–12, 2185–2192.
20. L.C.A. Venancio et al., Pilot Test of Bauxite Residue Carbonation with Flue Gas, *TMS Light Metals*, (2013), 113–118.
21. Geoff Riley et al., Plant Impurity Balances and Impurity Inclusion in DSP, *5th International Alumina Quality Workshop*, (1999), 404–414.
22. Peter Smith, C. Wingate, L. De Silva, Mobility of included soda in sodalite, *8th International Alumina Quality Workshop*, (2008), 27–30.
23. M. Gräfe, G. Power, C. Klauber, Bauxite residue issues: III. Alkalinity and associated chemistry, *Hydrometallurgy*, (2011), 108, 60–79.
24. J.H.N. Butterly et al. Thermodynamics of hydrocalumite formation in causticisation, *TMS Light Metals*, (2002), 185–190.
25. Sameer Khaitan, David A. Dzombak, Gregory V. Lowry, Chemistry of the Acid Neutralisation Capacity of Bauxite Residue, *Environmental Engineering Science*, (2009), 5, 873–881.
26. D.J. Wilson et al., Fluoride chemistry in the Bayer Process, *6th International Alumina Quality Workshop*, (2002), 281–287.
27. A. Suss et al., Production of Sodium Carbonate and Alumina from Dawsonites, *12th International Alumina Quality Workshop*, (2002)
28. M.L. Roberson et al., Bayer Process Production of Alumina, *US Patent 4,036,931* (1977).
29. J. Qin et al., Insights into active and passive carbon sequestration and causticity reduction in hazardous red mud slurry, *Carbon Research*, (2023), 2:40, 1–16.
30. Danai Marinos et al., Carbonation of Sodium Aluminate/Sodium Carbonate Solutions for Precipitation of Alumina Hydrates – Avoiding Dawsonite Formation, *Crystals*, (2021), 11, 836, 1–14.
31. R. Dilmore et al., Sequestration of CO₂ in Mixtures of Bauxite Residue and Saline Wastewater, *Energy & Fuels*, (2008), 22, 343–353.
32. P. Bénézeth et al., Dawsonite synthesis and reevaluation of its thermodynamic properties from solubility measurements: Implications for mineral trapping of CO₂, *Geochimica et Cosmochimica Acta*, (2007), 71, 4438–4455.
33. John P. Kaszuba, Hari S. Viswanathan, J. William Carey, Relative stability and significance of dawsonite and aluminum minerals in geologic carbon sequestration, *Geophysical Research Letters*, (2011), 38, L08404, 1–5.
34. G. Winkhaus, Background and Development of the Bayer Process in Europe, *TMS Light Metals*, (1969), 1007–1011.
35. J. Regnier, Bauxite - Its Technical and Economical History during the last Hundred Years, *TMS Light Metals*, (1988), 13–30.
36. L.K. Hudson, C. Misra, K. Wefers, Aluminum Oxide, *Ullmann's Encyclopedia of Industrial Chemistry*, (1985), Volume A1.
37. S.P. Rosenberg, E.A.J.M. Boom, Sequestration of carbon dioxide using tricalcium aluminate, *WO Patent 137480*, (2011).
38. G. Jones et al., Carbon Capture and the Aluminium Industry: Preliminary Studies, *Environmental Chemistry*, (2006), 3, 297–303.
39. Paulo Braga et al., Use of Bauxite Residue (Red Mud) as CO₂ Absorbent, *5th International Seminar on Tailings Management*, (2018), 1–10.
40. Vishwajeet S. Yadav et al., Sequestration of carbon dioxide (CO₂) using red mud, *Journal of Hazardous Materials*, (2010), 176, 1044–1050.
41. Li Liang, Wu Min, An overview of utilizing CO₂ for accelerated carbonation treatment in the concrete industry, *Journal of CO₂ Utilization*, (2022), 60, 102000, 1–17.
42. Sabrina Francey, Hongli Tran, Niklas Berglin, Global survey on lime operation, energy consumption, and alternative fuel usage, *Tappi Journal*, (August 2011), 19–26.
43. A. Laveglia et al., Hydrated lime life-cycle assessment: Current and future scenarios in four EU countries, *Journal of Cleaner Production*, (October 2022), 369, 133224.

44. E. Medina-Martos et al., Environmental and economic performance of carbon capture with sodium hydroxide, *Journal of CO₂ Utilization*, (2022), 60, 1-1991, 1–13.
45. Amit Kumar, Fengmin Du, John H. Lienhard, Caustic Production, Energy Efficiency, and Electrolyzers, *ACS Energy Letters*, (2021), 6 (10), 1–13.
46. Halina Marczak, Energy Inputs on the Production of Plastic Products, *Journal of Ecological Engineering*, (2022), 23(9), 146–156.
47. D.J. Cooling, P.S. Hay, L.M. Guilfoyle, Treatment of Alkaline Bayer Process Residues, *WO patent 077830*, (2005).
48. G. Montes-Hernandez et al., In situ kinetic measurements of gas-solid carbonation of Ca(OH)₂ by using an infrared microscope coupled to a reaction cell, *Chemical Engineering Journal*, (2010), 161(1/2), 250–256.
49. Shu-Yuan Pan et al., An Overview: Reaction Mechanisms and Modelling of CO₂ Utilization via Mineralization, *Aerosol and Air Quality Research*, (2018), 18, 829–848.
50. Wouter J.J. Huijgen, Carbon dioxide sequestration by mineral carbonation, *Thesis Energy Research Centre of The Netherlands*, (2007).
51. Dutch Association of Cost Engineers (DACE), *DACE price booklet (DACE prijzenboekje, in Dutch)*, ed. 24, Elsevier, The Netherlands, (2005).
52. M.S. Peters, K.D. Timmerhaus, Plant design and economics for chemical engineers, *McGraw-Hill*, New York, USA, (1991).
53. R.K. Sinnott, Chemical Engineering Design, *Coulson & Richardson's Chemical Engineering*, Volume 6, ed. 2, Butterworth-Heinemann Ltd., (1997).