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Review of the Valorization of Normalized Red Mud as Environmentally Sustainable Waste Management

Siba Prasad Mishra[1*], Madhurima Das[2] and Saswat Mishra[3]

[1]Department of Civil Engineering, Centurion University of Technology and Management, Odisha, India.
[2]Department of Civil Engineering, Sophitorium Engineering College, Baniatangi, Khordha, Odisha, India.
[3]Department of Civil Engineering, Kalinga Institute of Technology and Management, Odisha, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The Red Mud has focused through major industrial and scientific research in industrial waste valorization. Red mud is the discarded produce of alumina extraction processes from its parent the bauxite ore. Its high alkalinity causes it to be kept in large quantities, resulting in increased deforestation. Annually, it is estimated that 64.2 MMT of red mud wastes are formed around the world, and India produces about 9MMT with less hope of being reused, posing a serious threat of pollution and contamination of both soil, ground water and the environment. Large numbers of research have shown that this bauxite solid waste can be refurbished to make construction bricks, pavement tiles, ceramic materials, but no full large-scale benign re-utilization have been made. The intent of the research is to probe in to the applications of red mud in the construction and various sectors, giving emphasis on Indian context. Other researchers' observations were considered and analyzed in terms of environmental, economic, and technical feasibility to fulfill zero waste demand due to red mud.

**Corresponding author: E-mail: 2sibamishra@gmail.com;*

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1. INTRODUCTION

Red mud (RM) evolved from the alumina industries as residue at 2.5 to 3MT/ 1MT extraction of Alumina by the Bayer's Calcination Process. Later by the Hall–Héroult process (electrolyzing aluminum oxide to aluminum) is employed to extract pure Aluminum from the Alumina. Aluminum is the 2^{nd} human used metal in the globe [1,2]. The red or brick colour solid waste has been projected to be consumed in the globe during the year 2021, global to about 64.2 MMT which shall produce more than minimum 65MMT of RM and estimated to raise 78.4MMT by 2029. Presently the method of disposal of RM is the pump & dump method is used in RM slurry ponds, backfilling of ore extracted ditches. This highly alkaline non-toxic and non-Newtonian fluid with high density has erratic behaviour in the pond, so that the earthen embankments rarely maintain lateral pressure (shear failure) to the embankment which is made of earth or masonry (Kelly [3]). Not only the RM pond failure occur, but the other tailing dams also that has breached are of Tin, Copper, iron and even gold and many others whose wastes need immediate refurbishing for human use, Wei et al. [4]. Application of Nano technology with high molar ratio of Na_2O to Al_2O_3 that improves the strength but decrease in Na_2O to Al_2O_3 molar ratio tries to develop workability of fresh and the green concrete. Hence an optimized mix of Na_2O to Al_2O_3 ratio is to fix to maintain the optimized strength and workability (Ahmed et al. [5]). The grinded Bauxite ore passing through Bayer's process evolve semiliquid RM and finally normalized for reuse (Fig-1).

Many Alumina tailing failures have been reported around the world. The disposal of the red mud was come to lime light when a settling pond breached in Hungary. The noted failure of red mud ponds in the world are summarized in Table 1.

Fig. 1. From powdered bauxite ore to normalized Red Mud for reuse

Table 1. The failure of RM ponds of Alumina plants in the globe

Place of failure	Date of failure	The name of the factory	Losses	Source
Muri, (Lat 23. 364E , long. 85.871N	9^{th} April 2019	Hindalco works Ltd	Gabion failure; checked by rail-track; noloss	Kelly, 2019[3] Samal 2021 [6]
Red Mud Over Spill At Alunorte Barcarena, Brazil	Feb. 16th and 17th 2018	Alunorte-Alumina do Norte do Brasil S.A (Para river)	Heavy rainfall, tripping of pumps, quality of water supply affected, plant become idle	CPCB, 2021 [7]
Hennan state China	8^{th} Aug., 2016	Henan Xiang jiang Wanji Aluminum Co., Ltd	2MCum of RM of 1.5 km, 2 village sunken, length. With RM	Dave Petley 15th Aug 2016 [8]
Ajka (Hungary)	4th Oct., 2010	Alumina Refinery of MAL Zrt	10dead, 286 suffered, 120 in hospital, inun-dated 1017ha crop land,367 houses buildings affected	Turi et al, 2013 [9] George Bánvölgyi, 2020 [10].

2. CHEMICAL COMPOSITION OF RED MUD

The expensive transportation, conveyance and surged pollution are grave teething troubles for Alumina Industries for disposal of the Red mud. The waste comprises of about 30% to50% of Fe2O3, balances are Al2O3, and SiO2 depending upon the variety of the ore. Metallic elements like Vanadium (V), chromium (Cr), magnesium (Mg) and zirconium (Zr) along with haematite, goethite, anatase, rutile, quartz and sodalitare are also existent in trace amount which tells RM is a potential source many metals (Pyasi [11]).

The major crystalline constituents in RM like Fe2O3, SiO2, (rutile, and anatase) are inert. But the alumino-silicates, is hardly crystalline whether crystalline or amorphous phases are pozzolanic (Reddy et al. [12]) whereas RM blended with lime can develop cementous properties that special cement can be obtained for materials for construction, (Singh et. al., [13], Kumar et. al. [14], Ojha et. al. [15]).

2.1 RM as Waste Management

RM since highly alkaline and have high pH value (pH range 10.5 to 13), its judicious disposal to environment can be done after normalization. The procedures of disposal employed in various alumina industries are (i) direct disposal to sea, (ii) clay lined land filling in RM lagoons, (iii) dewatered and landfill in layers as dry sacking, (iv) initially washed, treated and dried for further use in sister industries). The feasibility to neutralize through bioremediation of bauxite trailing to achieve neutrality was tested by Hamid et al., [16], Jain et al. [17]. The major Alumina factories in India presently functioning are Hindlaco Industries Ltd, Jharkhand, Renukoot, UP, and Belgaon, Hindalco (Belgaon), and in Odisha are Vedanta (Lanjigarh), NALCO (Damanjodi), and Utkal Alumina (Rayagada). Each plant has its own red mud reservoir and the quantity of RM created annually in average in India is 1723.34th MT that must be disposed or reused affecting the geo-bio-hydro environment. (Table-2). RM generated depending upon raw material administered, and at 1–2.5MT/ 1MT generation of alumina in India. In average Indian Alumina industries produce about 8.5 to 9MMT annually (data from 2015 to 2019) which is about 6-7% of the total generation of red mud in the globe (Reddy et al. [18], Patel et al. [19]).

Some of the Alumina industries have been closed in India after Sept, 2009 like Korba, BALCO company “Bharat Aluminum Company Ltd”,Chhattisgarh, It was obtaining bauxite from the Amarkantak (Shandol Dist. of MP) and electricity from the Korba Thermal Power Plant from 1965. The BALCO was closed due to steep fall in the prices of the metal besides dumping from China and falling margins (The Hindu; APRIL 02, 2016 11:17 IST). Vedanta Group has taken over the old plant for major expansion. MALCO “Madras Aluminum Company Ltd”, Mettur Dam, TN. bauxite from the Shevaroy Hills and electricity from the Mettur Hydel Project. The industry started its commercial production in the year 1965 and operations were closed in 2008 but it had stopped production on environmental legal issues and focused into sale of power in commercial market.

Table 2. Major Alumina industries and their red mud produce for the period 2015-2019

Red Mud discarded (Th MT) in the year	Hindalco Ind. Ltd, Muri, Jharkhand	Hindalco Industries Ltd, Renu koot, UP	Hindalco Ind. Ltd, Belgaum, Karnataka	Vedanta Limited. Lanjigarh, Odisha	NALCO Ltd Damanjodi, Odisha	Utkal Alumina Rayagada, Odisha
Launch Year	1948	1962	1969	2007	1981	1993
2015-16	525.33	828.52	356.88	1497.73	2789.16	1914
2016-17	590.96	972.32	434.36	1626.19	3137.85	1974
2017-18	610.02	968.03	443.91	1694.69	3096.64	2049
2018-19	542.86	946.21	468.4	1758.46	3057.51	2082
2019-20	143.37	933.6	412.02	Poor RM yield strikes/COVID-19		

Amount of RM produced in the major alumina factories (Bayer's process) ≈ 8.9Th MT

2.2 Normalization of Red Mud

The waste RM can be hardly reused if it is not normalized to reduce its pH value from 12-13 to 8-10. The processes of normalization can be done by adding sea water, molasses wastewater (reduction acidity), and bagasse (pore-enlarging agent) and even tried with biomaterials like cow dung and cow urine, low-cost Fenton-like catalyst (ACRMbp). The highly alkaline red mud is said to neutralize when its pH value comes down to <9 and alkalinity is < 200mg/l ($CaCO_3$ equivalent). It is done to reduce sodicity (Na ion) at pH (pH 8.5 to 9) and neutralizes alkaline buffer minerals and the toxic elements become in soluble. Red mud neutralization is done through three methods such as (i) acid neutralization), (2) Sea water neutralization, (3) biological remediation (Jain et al. [17]).

2.3 Reuses of RM-Waste

Considering the above properties, researchers have thought of refurbish and reuse the noxious material for human utility after a procedural chemical treatment. Literature studies reveal that the RM can be effectively reused in the segments like (i) Ceramics, (ii) construction, and (iii) manufacture (cementous materials). The popular practices of reusing the RM in various sectors are (i) metallurgical (in iron, and steel manufacture, recovery of alumina, alkali, titanium, and some minor constituents), (ii) construction materials (building bricks, LW (light weight) blocks, roofs and floor tiles, cements *etc.*), (iii) catalytic agent, ceramics (sanitary ware, pottery, Specific tiles, glasses, glazes, and ferrites), and (iv) diversified direct uses like waste treatment, filler, and fertilizer and many other uses *etc.*, Rathod et al. [20], Rana et al. [21], Raheem et al. [22].

3. ENVIRONMENT CONCERNS

The ecosystems are deteriorated; vegetation and crop failure occur around the less toxic but very fine particle red mud in its reservoirs. It is due to its high alkalinity (pH value 10.5-13) and high sodicity (alkalinity 5-20 g/lit, Na_2CO_3 (caustic Soda) should escort every ton of RM solids. (Taneez et al., [23]). The underground aquifers gets adulterated due to seepage of alkali and other environmental casualties are instability during storage (Semi liquid containing 10-30% solid), Alkaline dust in affecting flora and fauna, consume problems with storage and disposal land etc. Cement production need enough heat energy (3.1–3.8 GJ/ MT of cement and source wise 5% CO2) and huge raw materials that pollute the environment (Singh et al., [24], Jaskulski et al., [25]). Part substitute of red mud against cement can reduce global environmental issues and efficient waste disposal. Not only RM trailing dam failure, the highly alkaline semifluid infiltrate to the ground water (GW) table, contaminates the GW and added to run off pollute the drains and the rivers. The polluted water kills its portability and, deteriorates the flora and aqua-fauna.

The red mud with a porous matrix consists of fine particles, least toxic, large surface area acting as a good sorbent. The porous particles can capture organic pollutants and encourages sulfidation (treating with H_2S, Na_2S, K_2S, $(NH_4)_2S$, and CaS_x) which can easily absorb mainly toxic heavy metals like cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg). This property of sulfidizing red can be an efficient procedure for water purification and make the discolored water clean and drinkable as per Joe Iannicelli, (Habashi, [26],Ritter et al., [27]).

3.1 Red Mud as Ceramics

RM, the secondary bauxite ore resources can be turned to ceramics, glass, vitreous tiles and house hold utilities to impact glaze and aesthetics by providing different colours (terracotta red, purple, or black) by calcination at various temperatures like table wares, silos, Chimneys, hardware pipes, and decorative.

Fig. 2. The ceramics produced from red mud and clay minerals

Architectural designers like Designers G. Whittembury, J. O. Rikkert, K. Rouff, and L. P. Bockelmann had contributed in in designing blend of red-mud and clay minerals heating at 850°C, 950°C, and 1050°C (Babisk et al., [28]). Processes involved are drying, palletization (storing and carrying goods on a pallet).

3.2 Red Mud as Construction Materials

The huge waste of RM can be efficiently recycled and refurbished as raw materials in various components of construction. They are voluminous of utilization building materials; moderate environmental deterioration; waste disposal, and maintain the soil and water quality of the red pond reservoir area (Yang et al., [29]). However before use of RM for construction materials it must be normalized before use (reduction of pH value, which can be done either by bio-remediation or salinization *etc.*) (Jain S., [17]). The available uses of RM after moderation (by drying, pressing and sintering) can be used to manufacture or make bricks, roof tiles, paving blocks and slabs, pipes, bollards, benches, litter bins, sea defenses, floor dividers, Kerbs of roads, colorants or driveway bases. The RM can also be hugely used as fine aggregates or filler material for cement concrete after drying and granulation by normalizing.

As a common architectural material by blending RM with cement (20-40%) can be employed like manufacture of bricks, back filling, interlocking blocks, paver's blocks, hollow bricks, and back filling of foundation trenches as main building materials (Das Mohapatra et al., [30]). Coloured flooring, lipping mud built houses and plastering can be undertaken by adding red mud with cement, to add to the aesthetics. The building materials become light weight, earthquake resistant and reduce the energy use, (Garg et al., [31), Carrie Carlson, from FEECO, RM concrete can be prepared and utilized with 15% RM, 80% OPC, and 5% hydrated lime and the compressive strength results are well compatible with the normal same grade OPC concrete (Raheem et al., [22]). The raw bricks with 50-90 wt % of RM and rest with clay minerals when dried with heated gases <70°C, and later fired to a temperature between 900°C to 1100°C, construction bricks can be manufactured (US Patent 3886244, (Ghatak K., [32]).

3.3 Pavement Construction

RM can also be utilized as packing materials in bituminous mixtures or in pavement foundation strata when employed in motorways and roads as of high average density (3.26 g/cm^3 for sintered RM), and 2.70 g/cm^3 for Bayer RM) (Feng et al., [33]). This novel alternative is promising, cost saving process.

The Ca $(OH)_2$ in lime have reaction with silica (SiO_2), and aluminum oxide (Al_2O_3) in the same manner that it does in ceramic and cement materials, causing hydration (pozzolanic) reactions that increase material resilience. The red mud could also be used as a filer in bituminous mixtures in road construction, railway track formations, Paver blocks, and fill materials in embankments, filling low lands (Fotini, [34]), Fig. 3.

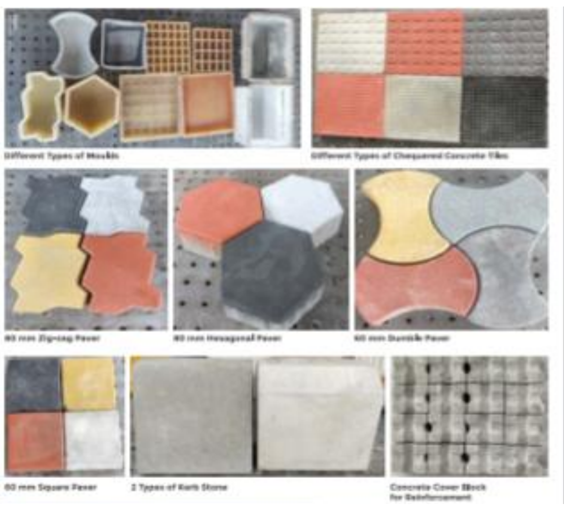

Fig. 3. The paver blocks & hollow bricks from CC and RM (Source: Centurion Univ. products)

3.4 Metallurgical Industry

The major constituents that the RM possesses are iron oxide, Alumina, quartz (SiO_2: 3-50Wt %). The minor contents are titanium dioxide (TiO_2: 8.5 Wt %), calcium oxide (CaO: 2-8 wt %), vanadium pentoxide (V_2O_5: 730 mg/kg), and manganese oxide (MnO: 85 mg/kg) are commonly found in red mud. The leading phases of RM are katoite (Ca_3Al_2 (SiO_4) $(OH)_8$), andradite ($Ca_3(Fe0_{.87}Al0_{.13})2$ $(SiO_4)_{1.65}$ $(OH)_{5.4}$), calcite ($CaCO_3$), hematite (Fe_2O_3), muscovite ($KAl_2Si_3AlO_{10}(OH)_2$), diaspore (AlO(OH)) (Pengfei et al, [35], CPCB data [7], Samal, [6]).

Iron is the major constituent material which can also be recovered from RM (Thakur et al., [36], Pengfei et al [35]). The process of recovery is in the laboratory but not commercially. Other minor metals like Aluminum and REEs (Ti, Z) can be extracted from RM by aluminum alkaline leaching and carbonate leaching, (Boyarintsev et al., [37]).

3.5 Red Mud as Cement Raw Material

The most common SCPM (supplementary cementous pozzolanic material) is the fly ash received as waste from coal based thermal power plants. As the globe has opted for solar or hydrogen based green and nonrenewable energy sources, the numbers of captive power plants (CPP'S) are reducing from beginning of 21st century. Paucity of fly ash has forced for another supplementary construction materials (SCM) alternative as RM. This waste product possesses cementous properties as that of OPC as it possess siliceous and aluminous materials, less cementous value but finely divided on contact with moisture, and react with Ca(OH)2 at room temperature as per ASTM C125 (Jaskulski et al., [25]). The iron rich Portland cement can be manufactured when mixed red mud lime, gypsum, and bauxite. After drying, sintering to manufacture iron opulent cements can have higher strengths than OPC when heated up to 1250°C for 1.5hours. Ordinary pozzolanic RM cement can be produced by sintering mixture of lime, RM, bauxite; gypsum and fly ash have the same mechanical properties as that of Ordinary Portland cement (OPC).

3.6 RM in Chemical Domain

RM is used in some chemical manufacturing to produce adsorbents, resin containing materials, coloring pigments, and fillers for plastics after few reprocessing activities like drying and treating chemically for removal of contaminants from waste water, paper, dye, and many industries being used as an adsorbent, catalyst, and coagulant material (CPCB, [7]).

3.7 Other Utilizations

Appraisals on this RM utilisation have been suggested, and also published for further extraction and other applications like:

(i) Recovery of parent constituents like iron (Fe), vanadium (V), chromium (Cr), and aluminum oxide (Al2O3) (Kumar et al., [38])
(ii) Metallurgical processes can be negotiated with production of steel, titanium, alumina, and alkalis (Prasad et al., [39])
(iii) Commercial absorbents for the effective removal of phosphate from biogas slurry (Xue et al, [40])
(iv) Mixed with RM (55%), fly ash (30%), cement (7.5%) etc can be used as back filling materials to fill the sink holes/ interstices in UG mines (Xue et al., 2018[40]).
(v) Preparation of Porous Ceramics at Low Temperature using foaming Technology, (Yang et al., [41])
(vi) Paver's blocks layered with RM and fly ash geo-polymer paste develops aesthetics, eliminates plastering, and develops the structural durability (Singh et al., [24]).
(vii) RM can be used as a corrosion inhibiter Steel immersed in NaOH and RM, showed lower corrosion potential (Rahim et al., [22]).
(viii) To improve soil quality, neutralized RM spread over the agricultural field to reduce the leaching of phosphorus by water (Ghatak et al, [32]).

Alcoa, an Aluminum factory converts carbonate red mud using CO2 from industrial gas streams to get red sand is employed to manufacture cement used in pavement making. Attempts are made to recuperate iron and rare-earth metals from red mud (Ritter [27]).

4. DISCUSSION

4.1 Large-scale Valorization of RM

The biggest worry about using RM in structure is the greater alkalinity, and of high pH value of about 10-13 which is almost equal to the fresh concrete. Because it can encourage heavy metal leaching into subsurface water, it is crucial to understand how these qualities can influence and bias the environment before using them in road layers. Despite these difficulties, recent research suggests that employing the RM to normalize/ stabilize, and achieves the improvised quality.

In agriculture, RM can promote phosphate preservation in sandy earth and rise to a high pH value. Past research reveal that the RM with high vales of Fe, Al, and silica can arrest toxic metals from the polluted soils, and remove them from wastewaters, and prevent soil nutrient leaching. According to Kehagia, [42] the usage of RM is safe as it leaches metals and toxic elements. They claim that RM possesses squat permeability when compacted, and can be better alternative for the road. In 2010, the embankment of the RM reservoir in Hungria collapsed, flooding the environment with more than 800000 m^3 of toxic (alkaline with pH ≈ 13), the RM slurry, stratified over 1017 acres of agricultural land with low rainfall rates.

Lima et al., [43], and Das Mohapatra et al., [30] have studied the performance of mixtures of RM with bituminous mixtures, and matched the findings of efficacy of the mixtures made with conventional materials like RM bricks, Paver blocks *etc.* [Fig 4].

Both investigations reveal that RM can increase the resilience of bituminous layers. Lima had experimented with different red dirt ratios to see how this would affect performance. The quantity of filer, on the other hand, is a crucial component in determining bitumen use. In general, more bitumen is requested by larger percentages of filer. Lima's plan was to investigate the impact of red mud.

4.2 Environmental Viability

There are two techniques to achieve environmental viability for red mud application: neutralization and inertness. However, because only the alkalinity is solved, even neutralization is insufficient to provide a safe application. The best choice is to employ the residue in inert applications that prevent leaching into the milieu. Researches reveal that applying RM to building materials made of ceramics like bricks, slabs and, tiles can improve the performance, and strength properties. However, being cost effective, such applications are considered environmental deteriorative because the residue is not inert and red mud leaching is a possibility. Without a doubt, the construction sector is the finest place to employ red mud because it allows for easy blending of the remains with cement, ceramics, and many polymers.

Fig. 4. The red mud clay bricks and biscuits manufactured from red mud

Furthermore, the choice to use old stacked wastes of RM can be an alternative material with cheap prices, allowing for a reduction in the consumption of mineral aggregates. As materials for road construction, RM can be used as filler in bituminous mixtures. It is preferable because the residue is chemically similar to other types of filler already in use. Larger amounts of this residue can be utilized with bituminous combinations, and the bitumen covers the RM granules that render them inert, and prevent leaching. The incorporation of RM to bitumen mixtures is cost-effective because it does not require any particular management or processing.

Environmental adversities of red mud on human health are burning on dust inhalation & skin and eye irritation/ corrosion, death of zoo planktons, aqua flora/fauna, habitats, and soil biota are due to alkaline effect, limited nutrient ingestion, and deposition in fish gills (CPCB [7]).

The RM when used for filling interstices, in small amounts for making bituminous mixes for any road construction one should ensure environmental and financial feasibility. The disproportion of silica and alumina in RM varies based on the bauxite source and Bayer method employed, that affects pozzolanic activity and the group of hydrated calcium silicates and aluminates. Consequent upon the resistance deliberated by hydrated chemicals is not durable. The hydration reaction induced by red dirt and $Ca(OH)_2$ source occurs in the same manner as cement does when exposed to water. The calcium hydroxide ($Ca(OH)_2$) reacts with silica, and aluminum oxides (Al_2O_3) to form calcium silicates and aluminates, which increase the mechanical properties.

4.3 Beneficial Uses of Red Mud

On view point of the potential negative effects of RM on the environment, as well as the need to save and conserve exquisite natural resources, it is critical to investigate the effective application**.** Exploring innovative applications, the reuse of RM has imposed global priority. The continuous upsurge in the RM generation demands sophistication in the Bayer process technology and evolution of new methodology for dry mud stacking, which should be extensively cost-effective. Numerous prior studies have demonstrated that the RM waste materials can be successfully utilized in infrastructural and various other projects (Rai et al, [44]).

4.4 Leachability of Potentially Toxic Elements

Environmental acceptability to normalized RM is one among the most serious industrial waste management issues. The scientists and engineers are raising voice about the reuse of RM due to the potential release of potential toxic elements (PTEs), like Ba, As, Zn, Ni, Cu, Pb, Cr, , Zr, V, Hg, and others. The chemical configurations of the various bauxite ore, refinery extraction procedures, and the analysis methodologies used can all affect the concentrations of these components (Sun et. al., 2019[45], CPCB [7], Li et al., [46], Samal S., [2]).

4.5 Dispersion Behavior

The dispersion behaviour of a material is not captured by traditional geotechnical testing. Wastes satisfy the suitability chucks for given applications in most cases. However they frequently fail to meet the dispersivity requirement.

As a result, independent testing is required to determine the of wastes or byproducts dispersivity, particularly when utilized as a standby for natural geo-materials or use in embankment of a dike, and as alternatives in geotechnical structures frequently prone to flooding. They demand to be suitably stabilized or treated with chemical additive materials having a dispersive character are rarely used to build earthen structures.

Dispersion-induced erosion can be mitigated by stabilizing the RM with appropriate additives like as cement, lime, and gypsum after neutralization by HNO_3. The presence of these substances raises the electrolyte concentration and substitutes (Na+ + Ca2+), resulting in a flocculation effect that eliminates dispersivity (Kang et al., [47], Marvila et al., [48]). Also fewer studies are done on stabilization of soil by using Nano particles, Karakouzian et al., [49].

The final reuse of red mud can be reused as steel making, metal recovery, slag additive, some major metals, minor metal and rare earth element recovery, construction industries, cement industries, building sectors, ceramic, paper, paint and polymer industries, waste water treatment, soil stabilization and mining drainage purposes. The Table-3 depicts the different reuses of red mud after various treatment technologies.

Table 3. Remediation and Rehabilitation of Red mud evolved Aluminum plants

Area of Reuse	Pretreatment procedures	Rehabilitation approaches	Sources of Uses
Construction Sector			
High Alumina cement production	Neutralization, drying and sintering	Cement Binders & Portland cement clinker	Cement, special cement, cement additive, mortars, sewer set-up and marine erection
Burnt clay bricks Part substitute RM (CBRI) or Light weight bricks adding foaming agent	Neutralization, drying and pressing	red mud + fly ash + foaming agent	Light weight bricks, Walls, roads, bricks, blocks, lightweight aggregates
Filling & backing materials and Pozzolanic properties	Drying	ditches/ shallow & fallow land as impermeable materials	Dam , backfilling, Dock & Harbour, thermal insulation mat., sink holes etc.
Coarse Aggt.; (Olivera et al., [50])	Neutrilzation, drying & granulation	With Metakaolene & active Silica	Substitute for Hard Granite materials
Metallurgical Sector			
Major element extraction & REE's (Ions); Borra et al., 2016 [51]	De-alkalination, Magnetic separation, leaching, ionic separation	Leaching direct, by minerals, organic acids, Alkali (H2) Carbonates, Ionic, Bioleaching	Extraction of Elements like Mg, V, Mn, Cr, K and REE's like Ce, La, Sc, Nd, Sm etc.
Minor Metals (recovery)	Neutrilzation, drying & reduction or Thermal Plasma Technology	Magnetic separation (Fe), Leaching (Al) sintering, acid or bio leaching , Coating or mixing Technology)	(Fe, Ti, Mn, Na, K) Production of steel or other metals
Glass & Ceramic Industry	Neutrlisation, puddeling, baling, drying & firing	Pallets are sintered in graphite crucible	House hold gadgets, sanitary fittings
Chemical Industries	Chemical treatment (like:RM+ Fe Catalysts for Hydrogen yield by Catalytic Methane Decomposition)	As catalyst; Situ Catalytic Pyrolysis of Biomass; catalytic-active metals such as Ni,Fe, V etc., used direct as catalyst	Paint (Colouring pigment), Paper and polymer Industry; H_2 Production from Ammonia
Corrosion resistant coating materials	Drying and Chemical treatment	Adsorption of methylene blue by sintering RM. Thermal plasma spray technology	adsorbents, clouring pigments, resin, polymer products, paper, fillers for plastics in industries
Removal waste water contaminants	Reduction, adsorption, oxidation, membrane filtration and ion exchange (Activation of RM)	remove contaminants like H2S, copper, Arsenic, Zinc & Phosphate ion	Removal of moisture; undesirable elements, liquid waste treatment
Geotechnical properties	Adding 2% of lime, 20% red mud in soil (Kehagia 2008[42] Aswasthi et al., 2019 [52])]	Improves strength by 15% and make soil impermeable	Expansive or clayey soil stabilization mixing with lime or EKO soil enzymes (Roads, dykes, levees)
Agriculture soil	neutralization, and	Added to saline/acid/	remediation of soil,

Area of Reuse	Pretreatment procedures	Rehabilitation approaches	Sources of Uses
improvement	adsorption (after testing PTE's and Radio activity)	silicate soils, organic rich material, at suitable pH	promote vegetation and yield
Remediation of AMD and Other uses	Drying , Chemical treatment & adsoption	Neutralization, adsorption, ion exchange, membrane technology, biological mediation, and electrochemical for reducing AMD	As filters, neutralization of Acids, Acid Mine Drainage (AMD)

5. CONCLUSION

RM can be used as an adsorbent, an immobilizing agent, a building material, a reactive element, and so on. The performance of RM in synergy with other additives can have use for both short-term and long-term resilience. It is rarely investigated. That RM can be a full or part substitute of OPC up to 20%, for strength enhancement and so also fine aggregate up to 30% (Rahim et al., [22]). There are almost no studies in the literature that look at the impact of phase composition on the geotechnical and geo-environmental behaviour of the RM. Future interdependence-related researches are essential to identify to recycle and refurbish the RM more efficiently. In terms of pollution or usage, RM's high pH and Na+ level pose significant hurdles. More researches are needed to probe into fundamental understanding about the stabilization of Red Mud with other compounds or pozzolanic resources, and as well as the creation of an environmental friendly cost-effective approach. New and creative extensive engineering uses for RM must be investigated, and the long-term viability should be examined using triple bottom line (environmental, economic, and social) sustainability criteria.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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