Indian Journal of Engineering & Materials Sciences
Vol. 29, August 2022, pp. 401-410
DOI: 10.56042/ijems.v29i4.52349

Review Article

Recycling and potential utilization of red mud (Bauxite Residue) for construction industry applications

Ashutosh Singh Raghubanshi[a,b], Manish Mudgal[a,b*], R K Chouhan[b], Anil Kumar[b], & Avanish Kumar Srivastava[a,b]

[a]Academy of Scientific and Innovative Research, Ghaziabad 201 002, India

[b]Centre for Advanced Radiation Shielding & Geopolymeric Materials, CSIR-Advanced Materials and Processes Research Institute, Bhopal462 026, India

Received: 12 July 2021; Accepted: 21 September 2021

Red mud (RM, a Bauxite Residue) is the huge waste materials generated during the alumina production followed by the Bayer Process, which processed about 1.25 – 1.5 ton from per tons of alumina production. The disposal of this waste materials is a serious issue as increasing the demand for aluminium with time. Whereas extensive research and developmental activities have been done approximately last two decades and further going on around the world to find an effective route to bulk utilization of bauxite residue (Red mud).Which, include in form of various products, processes, and technologies development with directly & indirectly consumption of red mud. Present researches worked on have been a number of potential uses to the utilization of this industrial waste. Hence the present article attempts to review the quantity, characteristics, recycling, and potential utilization of red mud (bauxite residue) especially for construction industry applications with specific reference to the product, processes, and technologies developed in India.

Keywords: Bauxite residue (red mud), Generation, Recycling, Utilization, Construction materials

1 Introduction

India which really isrich in mineral resources, mining and holds the position of top 10 mineral generating countries around the world. Indian economy also depends on the value of mineral processing, which shows the major portions of the mining raw materials are used for industrial activities such as iron ore used for steel and cast iron production, bauxite used for aluminium production, etc. Moreover, worldwide aluminium is the most usable metal after steel due to its excellent properties such as lightweight, high strength, etc. So, the demand for aluminum has been continuously increasing day by day because of its various applications in many sectors like infrastructural, electronics, automobile, aerospace, and defence, etc., which contributed social and economic progress of the nation. The major aluminium is being produced through bauxite ore, which contains high quality alumina and also some aluminium, obtained by recycling. However, in bauxite processing the two process steps are involved: In I[st], step alumina is refined through the Bayer process (developed by Carl Josef Bayer) and II[nd] step the aluminum is produced by dissolving alumina using Hall-Heroult process[1]. Moreover, In the I[st] step the bauxite ore is chemically dissolved with caustic soda in presence of lime at elevated temperature. The un-dissolved product is washed and filtered, which is called bauxite residue or red mud. However ~55 to 65% of residue were generated during bauxite processed i.e 1 ton of alumina produces around 1.25 to 1.5 ton of red mud and also depends on the qualityof bauxite processed[2]. However, the globally metallurgical alumina genation was~136 million tonnes in 2020, which generate around ~191 million tonnes of red mud[3-4]. While in India ~ 6.5 million tonnes of alumina was produced in 2018-19, which also produced ~9.1 million tonnes of red mud[5]. Moreover, the red mud generation is continuously increasing every year with the worldwide production rate of 0.18 billion tonnes per year, which also increases the worldwide reserve of red mud and it was forecasted to reach about 4 billion tonnes in 2019[6], However, the generation of red mud are also involved highly alkaline reactions, which make strong alkaline nature of red mud (pH 11 to 13)[7]. Due to its high alkalinity and high production rate, a significant impact on the environment and has consumed a vast area of land. It is harmful to

*Corresponding Author
(E-mail: manishmudgal@ampri.res.in)

groundwater, fertile land, and the surrounding atmosphere of disposal area. So, the safe disposal and treatment of this residue are necessary around the location of alumina refinery plants either in dry disposal on land or slurry disposal in sea/pond, but it's involved high cost and huge area land[8]. Worldwide, the recycling and potential utilizations of this residue have been a major issue in the 21st century for alumina/aluminium producing industries, especially for environmental pollution and harmful for human health. However, many researchers have been working on recycling, potential utilization, and treatment of this insoluble residue red mud for the last two decades. According to a Web of Science search result for the keyword "red mud," there were 997 publications altogether from 2001 to 2018[9]. The Indian researchers are also more concerned about this serious environmental issue and paying larger attention to the recycling, bulk utilization, and treatment of red mud. Moreover various achievements on red mud applications such as building and construction industry, valuable metal element recovery, soil stabilization, catalyst, paints and pigments, pollution control, and development of new materials. The chemical and mineralogical properties of red mud show huge potential applications of red mud in the construction industry like cement, brick, blocks, aggregate, and concrete[10], this industry also possible to utilize the red mud in bulk quantity. This paper focused on worldwide effort of researcher' store cycle and potential utilization of red mud in the construction industry is being highlighted. Alumina and red mud generation along with chemical compositions worldwide and in India have been stated in this paper. Also, sub-applications of red mud in the construction industry, cement, brick, synthetic aggregate, geopolymers, and road construction with fillers have been elaborated with mentioning pilot plant studies conducted in these application areas. Some issues regarding its potential utilization in the construction industry have been also discussed.

2 Materials and Methods

2.1 Red Mud generation

Worldwide, Alumina generation is around 136 million tonnes in which India contribute around 6.7 million tonnes in the year 2020[4, 11]. China leading alumina producer with a share of 55-56% followed by Australia 16%, Brazil 7%, and India 5%. Whereas, the four major producers National Aluminium co. Ltd (NALCO), Hindalco Ind. Ltd., Bharat Aluminum Co. Ltd., and Vedanta Aluminum Ltd. are at the forefront in alumina/aluminum generation in India. However, around the World, bauxite is the primary raw material for producing alumina through two different processes knows as sintering and Bayer Process[12]. The Bayer process has been widely used in industry for filtering bauxite as well as alumina production because this process is economical for producing alumina using bauxite. The line diagram of this process is shown in Fig. 1, whereas pre-desilication step is completed by combining pure bauxite and caustic soda in the presence of lime. (~100°C, ATM Pressure). Further hot NaOH solution was used for processed the pre-desilication stage mixture, hence alumina present in bauxite is converted to aluminium hydroxide $Al(OH)_3$. The aluminium hydroxide $Al(OH)_3$ decomposes the alumina. A large amount of alumina is dissolved to produce aluminium using the smelting Hall-Heroult process. The other element present in bauxite is not dissolved in hot sodium hydroxide solution (NaOH), then this undissolved solution is washed and filtrated for obtaining the bauxite residue[13]. This residue is called red mud, which is strong solid waste, high alkaline in nature, very fine grained material, and red in colour due to being rich in iron (III). Approximately 1.25 – 1.5 tons of residue (red mud) is discharged during per ton of alumina production, depending upon the bauxite source and alumina generation process efficiencies[14].

The worldwide reserve of red mud was forecasted to reach about 4 billion tons in 2019, with a generation rate of 0.18 billion tons/year[15]. The amount

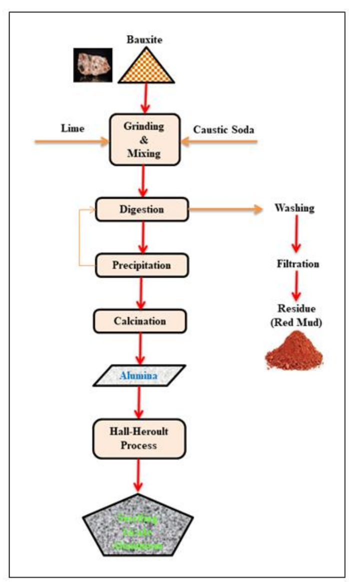

Fig. 1 — Line diagram of Bayer Process.

of red mud generation can be calculated by using an average ratio of 1.4 to production data for alumina. Hence ~191 million tonnes of red mud generated globally in 2020[4]. The generation of red mud is anticipated to expand in the future because of the extraction of the best quality bauxite sources, which has resulted in a decrease in the class of bauxite ore and an increase in production of red mud compared to bauxite[16]. In India, ~9 million tonnes of red mud has been produced in 2020, which is around 5% of the worldwide generation. However, the generation is also continuously increased because of the increasing per capita consumption of alumina/aluminium. The last seven year of alumina production and red mud generation of red mud in India are represented in Fig. 2 (a and b).

2.2 Properties and Characterization of red mud

The chemical compositions and, physical properties including characterizations of red mud depend on the mines location, bauxite type, and parameters (various)of production process. The main chemical constituents present in red mud are Fe_2O_3,Al_2O_3,SiO_2, TiO_2, CaO, Na_2O as well as minor elements like V, Mn, Cr, K, Pb, Ba, Cu, P, Zn, etc. The worldwide variation of chemical constituents of red mud is high[17-19]. The red mud generated from the Bayer process has much higher contents of Fe_2O_3 and Al_2O_3 compare to the sintering process. However, the sintering process has contents higher CaO and SiO_2 as compare to the Bayer process. The major valuable chemical constituents present in red mud, basis on worldwide various countries are given in Table 1[20-28]. The typical chemicals compositionin red mud produced from Indian alumina/aluminium plants are given in Table 2[29-32].

The red mud is generated during the alumina extraction process, so it's a fine grained material. The dispersion of particle sizes in Indian red mud is usually finer than 75µm for 90-95% of total particles[33]. The red mud is alkaline, thixotropic, and a large specific surface area between 10 to 30 m^2/g, with specific gravity in the range of 2.85 to 3.34 depending on the degree of bauxite grinding. A zeta potential value of red mud is - 45mV[34].

The mineralogy present in red mud has been comprised of more compounds because the

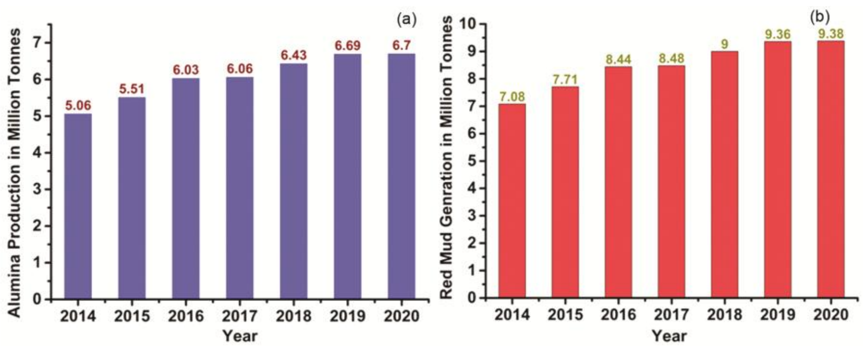

Fig. 2 — (a) Alumina production in India and, (b) Red Mud generation in India.

Table 1 — Main Chemicals Constituent of red mud in different Nations

Country	Plant	Chemical Constituents (Wt %)					
		Fe_2O_3	Al_2O_3	TiO_2	SiO_2	Na_2O	CaO
Italy[20]	Eurallumina	35.2	20	9.2	11.6	7.5	6.7
Turkey[21]	Seydisehir	36.94	20.39	4.98	15.74	10.10	2.23
China[22]	Guizhou	26.41	18.94	7.40	8.52	4.75	21.84
Australia[23]	Kwinana	28.5	24.0	3.11	18.8	3.4	5.26
Brazil[23]	Alunorte	45.6	15.1	4.29	15.6	7.5	1.16
Germany[23]	AOSG	44.8	16.2	12.33	5.4	4.0	5.22
USA[23]	RMC	35.5	18.4	6.31	8.5	6.1	7.73
UK[24]	ALCAN	46.0	20.0	6.0	5.0	8.0	1.0
France[24]	Gardanne	26.62	15.0	15.76	4.98	1.02	22.21
Vietnam[25]	Tanrai	30.8	15.6	2.58	31.7	3.14	3.51
Russia[26]	Uralsky	36.9	11.8	3.54	8.71	0.27	23.8
Greece[27]	Boeotia	42.34	16.26	4.27	6.97	3.83	11.64
Spain[28]	Alcoa	47.85	20.20	9.91	7.50	8.40	6.22

Table 2 — Chemical constituent of red mud generated from Indian Alumina/Aluminium Plant

Company	Chemical Compositions in Wt%						
	Fe_2O_3	Al_2O_3	TiO_2	SiO_2	Na_2O	CaO	LOI
NALCO, Damanjodi[29]	51-57	16-18	3-5	8-12	4-6	1-2.5	11-13
HINDALCO, Renukoot[30]	34 -40	17-19	15 -16	7 - 8	5 - 6	1 - 5	8 - 10
HINDALCO, Muri[31]	44-46	19-21	17-19	5-7	3-4	1 - 2	12-14
HINDALCO, Belgaum[32]	44 -47	17-20	8-11	7-9	3-5	1 - 3	10-14
MALCO, Metturdam[32]	40-26	18-22	2-4	12-16	4-5	1-3	11-15
BALCO, Korba[32]	35-37	18-21	17-19	6-7	5-6	1-2	11-14

composition is not uniform. The majority are iron oxides, mainly Hematite (Fe_2O_3) and Goethite (FeOOH), together with boehmite (AlOOH), Gibbsite ($Al(OH)_3$), Rutile (TiO_2), Calcite ($CaCO_3$), Sodium aluminum silicate ($Na(AlSiO_4)$), dicalcium silicate (Ca_2SiO_4) and Quartz (SiO_2). The detailed characterizations of red mud has been analyzed by using XRD, FE-SEM & EDX, FT-IR, TGA, DTG, TEM, UV–Vis, and NMR sectroscopy[35-37].

2.3 Disposal and Environmental impacts of Red Mud

Worldwide, due to million tons of red mud generation, most of alumina/aluminium industry have been facing a significant problem to reducing, recycling, and utilizing this alkali waste to convert in wealth. Due to high alkalinity (pH 11-13), the growth of the plant is not possible in red mud[38], alkali seepage into groundwater, the large acre of land needed for disposal, dried and dusty in nature has another serious cause of environmental pollution, harmful for human health[39] and containing traces of toxic heavy metals (Chromium, Arsenic, Cadmium etc) and radionuclides[40].Moreover, some soluble constituents present in red mud e.g. Na_2CO_3, NaOH, and $NaHCO_3$ can disperse in rainwater caused pollution in land and rivers accordingly. However, hazardous rules in several nations have divided red mud into various categories, such as hazardous waste, by product, non-hazardous industrial waste, etc. The HOWM rules 2016 (Hazardous and Other Wastes Management), notified by Indian government under the Environment (Protection) 28 Act, 1986, exempts red mud from the hazardous waste schedule and instead classifies it as a "High Volume Low Effect Waste." Moreover, the adverse effects of red mud mishandling and weak management affect not only human life but also aquatic life, soil quality, plant growth, etc. These adverse effects are listed in Table 3[41].

The dumping space requirements and dispose of this waste have another environmental issue associated with red mud. The safe disposal of red mud is primary focus of all alumina/aluminium producing industry. Worldwide, red mud can be dispose via dry disposal, slurry disposal, and solar/sun disposal methods. The schematic diagram of disposal methods of red mud is shown in Fig. 3. The currently most commonly used disposal method for red mud is dry stacking method. This technique is capable to dilute the leakage of caustic liquid in the nearby environment, reducing large acre of land requirements, and also increase the efficiency of soda and alumina recoveries. In the dry stacking method, the thixotropic like paste of red mud with huge amount of solids constituent (~46-55%) slurry has been pumped by pipeline to depot area. Where, this

Table 3 — Adverse effects related to the environmental release of Red Mud[41]

Impacts	Probable effects
Human's	Burning, dusty, and toxic chemicals inhalation; skin irritation and corrosion; eye irritation and corrosion
Fish's	Alkalinity, suspended solids, and deaths: effects on the body as a whole and the gill
Freshwater Zoobenthos	Whole-body effects of alkalinity include habitat destruction.
Aquatic Biota	Effect of harmful compounds: deaths, habitat loss
Soil Biota	Effect of alkalinity - body, deaths, habitat loss
Plants	Minimum uptake of nutrient.
Soil	Toxic compounds - total soil and their nutrition's

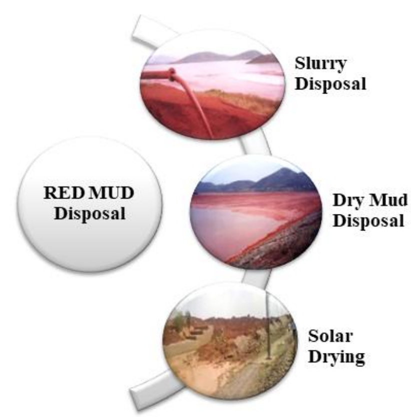

Fig. 3 — Disposal methods of Red Mud.

slurry has been spread in layers and allow it de-water using mixing of drainage with evaporative drying[42].

W. M. Gerald[43] has been granted patent on the safe disposal of red mud. However, due to the lack of available land, just 7 of the 84 aluminium refineries across the world still use planned sea disposal[44]. Table 4 shows the disposal methods adopted by the Indian alumina/aluminium industry[45, 46] and the benefits, and drawbacks of these disposal methods are given in Table 5[46]. Moreover, the moisture present in red mud is decreased via using the pressure filters because they

Table 4 — Disposal Methods adopted in India[45, 46]

Alumina Plants	Disposal Methods employed
NALCO, Damanjodi	TTD (Thickened Tailings Disposal) system at 2001, which disposed bauxite residue (red mud) as 55 – 57 % solid content by weight
HINDALCO (Utkal, Muri, Renukoot, Belgavi)	Red Mud is transported by dumpers to own red mud pond by a process called DMS (Dry Mud Stacking) Company has installed a second pressure filter to increase percentage solids.
Vedanta Ltd. Lanjigarh	Utilizing a particular method, the moisture content is reduced to 25% for dry disposal using the progressive rise and step deposition method, which is typically employed in hilly or heavily sloped areas.
BALCO Korba	After settling, residue is currently filtered and washed four times. The filter cake is repelled with water that the pond has returned, and thrown into the pond. Use a modified CCD disposal system. The current pond's dykes are made of stone masonry, a clay liner, and a polythene liner that is well protected.

Table 5 — Benefits and Drawbacks of the disposal systems[46]

Disposal Methods	Benefits	Drawbacks
Slurry disposal	Caustic solution return to the plant Economical transportation mode	Large space requirement, Higher storage cost Huge investments for construction of ponds, Possible pollution hazards risk, The continuous requirements for theenhanced the ponds or making of Area reclamation is involved high cost and lot of time consuming process
Dry disposal	Environmentally friendly Less space required Consolidate rapidly	Huge investment involved in machinery cost and earthmoving equipment Huge investment in pump the slurry generally trucks are used to transport the cake. Require high energy
Lake disposal	Investment not involved in ponds the natural surface used as bank of residue pond Reasonable investment in machinery for transportations Lower energy requirements	No return water; therefore, less recovery of caustic solution Pipeline requirements which add to cost
Solar drying	less space is needed than slurry disposal, more space is needed for dry disposal method reduced losses from soluble soda Economical because drying is done naturally with the help of the sun	Effectiveness is low during the rainy season Huge requirements of surfaces for pumping out rainwater

Converting slurry of red mud into a dry cake, then it's disposed by dry mud stacking method.

3 Result and Discussion

3.1 Possible utilizations

In the last two decades, many more attempt has been applied worldwide for finding a suitable utilization, recycling, and treatment of red mud, because of its unique physical and chemical properties. The main objective application areas of bauxite residue (red mud) should be aimed toward utilization in bulk. So the alumina/aluminium industry doesn't need to be concerned about this residue at all. However, alumina (10–20%) and SiO_2 (6-7%) are present in bauxite waste (red mud), indicating that it is used in construction and building applications[47]. Moreover, researchers are looking at ways to recover the iron contents from bauxite waste because of the significant amount of iron oxide present (35–60 percent). Additionally, it contains TiO_2 (5–15%)[48], which is one of the interesting research topics that can be extracted through acid leaching. The potential applications of red mud have been mentioned in the sections below.

3.1.1 Production of Cement

Red mud is used as a source material for production of cement in cement producing industry. In various studies, production of Portland cement, the red mud were utilized as a source material[49-50]. These, studies noted that the major obstacle for red mud utilization(as a raw material)in cement generation with contents of high water (400 g/L). Present work, the researcher utilized upto 5%wt. mixing of ferro-alumina for filter and to red mud for de-water. The mixtures of cement were ready via a mix of limestone, red mud, and sandstone[51].

In other study, iron rich cement was produces via lime, red mud, gypsum, and, bauxite ore. The observation indicated that of compressive strength this cement is depends upon proportions of above raw materials. Accordingly, cement specimen made using (i) Red mud, lime, and bauxite, and (ii) Lime, red mud, gypsum, and bauxite, shows greater strengths compare to OPC cement, when they heated upto 1250℃ for 1.5 hours[52].

A next study, the properties of cement produced utilizing various compositions of lime, red mud, gypsum, fly ash, and, bauxite. The analysis shows that the compositions of (i) red mud, bauxite and, lime and, (ii) gypsum, bauxite, lime, and red mud shows that the compressive strengths approximately equivalent to OPC cement. However, cement composition prepare via fly ash was not get comparable result because that composition cement was poor in quality.

Tsakiridis et al.[53] produces cement via a mixture of schist, limestone, red mud, and bauxite. The reference batch of cement mix was produced from bauxite, schist, limestone, and, milos sand. The characterization shows that the red mud addition was not affected in the mineralogical compositions of the clinker of cement. The red mud including reference of clinkers of cement both showed the similar mineralogical phases. However, the mechanical properties (Setting time, Consistency, Compressive Strength, and Soundeness) of both developed cements were closer to reference cement clinker.

3.1.2 Production of Bricks

Red mud, a waste material of the alumina/aluminum industry, has been effectively utilized by Indian industry to make bricks with the minimal possible of compositional modifications. These modifications in composition will give orange, pale brown and golden yellow colour in bricks, which also depend upon the firing temperature. However, BMTPC (Building Materials Technology Promotion Council) has been synthesis RFPC Red mud jute fiber polymer composite, for replacement of wood, that wood is used to manufacture wood based panel for building industry. Moreover, the raw materials uses in product are zero energy aided and also in room temperature processing it conserves energy. This composite is constituted of 82.5 percent cellulose and 11.3 percent lignin via jute fiber, and the ferric oxide, alumina, and titanium oxide via red mud. Additionally, this may be used to flooring, panelling, and furniture.

Red mud may be used to produce superior tiles, exposable bricks, corrugated roofing sheets, as well as a variety of other items such composite doors and panels. CBRI, Roorkee, India[54] has also developed clay burnt bricks via partly replacement of clay using red mud, and fly ash. This process red mud was anticipated to be used extensively in the building and construction industries. The attempt has also been made to addition of little percent of lime in the red mud. The moisture contents, strength, and stability against erosive effect of water were tested on produced bricks. Maximum wet compressive strength with 5% of lime and 8% of lime was found to be 3.75 MPa and 4.22 MPa respectively. The brick's suitability for usage as a walling material for inexpensive shelters was determined after it was tested for accelerated weathering[55].

The main advantages for producing red mud bricks are:

Brick production is the biggest demand in the construction sector, the brick can consume the red mud waste to fulfil this demand and also solve the pollution and disposal problems associated with this waste.

The utilization of red mud waste for brick production can save the clay partly. Red mud also enhances the bricks' quality made via inferior clays.

As face bricks, they have high architectural significance. Red mud contains alkali, which has an excellent fluxing effect, excellent plasticity, and enhances bonding in the bricks.

3.1.3 Production of Synthetic Aggregates

Red mud (bauxite residue) has been also used as raw materials for production of the synthetic aggregate because of its chemical compositions. Some researchers might use red mud for developing synthetic aggregate for construction industry applications by using a sintering process at high temperatures. In this process of synthetic aggregate development, red mud is used in bulk quantity and replaces naturally available aggregate. The red mud contains Fe_2O_3, Al_2O_3, and TiO_2 these compounds are sintered at high temperature and form bonds between them, so red mud based synthetic aggregate is also used as high temperature resistance concrete. Some of the researchers also used these synthetic aggregates for radiation shielding concrete. Recently Tian et. al.[56] fabricated artificial aggregate using red mud, and fly ash having strong strength and low density, they also proposed the developed aggregate are replaced natural aggregate. The more key developments in the area of synthetic/artificial aggregates production using red mud, methods, and their properties over few decades are summarized in Table 6[57-69].

3.1.4 Production of Geopolymers

Geopolymers is analumino silicate material that has various possible applications. Geopolymers are a an excellent choice to substitute the use of Portland cement[70]. Aluminium plants generated red mud, and many of them also produced fly ash. Therefore, the use of fly ash and red mud create aluminum industry much profitable due to lower transportation cost of residues with supports better management strategies in the long run for these industries. The red mud has been mix with fly ash to produce geopolymers. The aim of using red mud, and fly ash mixture is generally depends on factors for an additive of geopolymerization using fly ash, like AlO_4 and SiO_2, which are present in the red mud[71]. In this procedure, the red mud and an alkaline activator solution undergo a chemical reaction. Giannopoulou et al.[72] studied red mud and ferronickel slag based geopolymer with included objective of developing the advanced inorganic polymer materials having high mechanical and physical properties. The authors developed red mud based geopolymer with compressive strength of ~ 21Mpa, and Water absorption < 3%. Therefore, red mud may be used in construction and building materials applications.

The geopolymers development and their possible application are challenging work because of the industrial partners and technical shortcomings, which includes durability and lack of standards of geopolymers[73]. A detailed study requires to be clarifying the properties of geopolymers concrete, and demonstrating the issues related with the production of Geopolymeric products, like shrinkage and efflorescence. The geopolymer are constituted a lot of high soluble alkali with respect to conventional cement, and these have unlike pore structure compare to hydrate Portland cement. The white salt deposition towards the concrete surface is called efflorescence. The impact of efflorescence may be seen when the geopolymer is exposed to moist air or water[74], which is generally harm-less for physical presence in case of OPC cement concrete. In geopolymer foam concrete the pore size has been large and final porosity is high, then it shows the high efflorescence. However, red mud play important role in the producing of geopolymeric concrete, and may be used as the main source of concrete in construction and infrastructure application. However the geopolymer making technologies using red mud is one of the main obstacles. To optimize concrete for regional and local needs, the cutting-edge geopolymer research and development, as well as their manufacturing techniques, are needed .Other significant factors such as, analysis of cost and benefit, various resources, and demand of geopolymers in the public and private sectors needs to be considered.

3.1.5 Road Construction

Red mud can be main useful filler material for road construction in mixtures of bituminous or layers of pavement base. The Red mud used in road construction is also ingenious approach with superior prospects. Kehagia[75]analysized the behaviour of unpaved roads after 3 years, constructed using 97 percent red mud and 3percent fly ash. They have been constructed the layer of bauxite residue with the inclusion of bauxite aggregates. The author points out that a given red mud application should utilize a lot of volume and be aggressive in regards of quality, cost, and risk. Therefore, red mud also can be used in highway projects is particularly effective, when needs of large volume for earthwork in dry compacting, and mixing of appropriate binder, produce an excellent road material.

Jitsangian and Nikraz[76] studied red mud can be used as a road base materials. The mixture of Pozzolanic stability was produced via lime, fly ash, and water for improving the properties of residue. An optimum composition was to determine for a mixture should achieves 0.6 to 1.0 Mpa of compressive strength which required in Australian standard. The outcomes demonstrated that the effectiveness of stabilized residues was excellent in comparison of conventional material and also gives higher performance when applied

Table 6 — Key developments in the area of synthetic/artificial aggregates production using red mud

Year	Materials	Procedure description	Property observed
1976	Red mud and various chemical additives	Mixture were molded into spherical balls and heated in muffle furnace at 1260 to 1316°C for producing heavy and light weight aggregates[57].	Specific gravity
2010	Red mud, waste glass & bentonite	Raw materials pulverizing at 70:15:15 ratio than mixture was converted into pallets (3-6 mm dia) than sintered in muffle furnace at 1120°C for 40 min for obtaining synthetic aggregates[58].	density (1.08 g/cc), water absorption (10.45 %) cylindercompressive strength (8.22 Mpa)
2012	Red mud, Metakaolin and Active silica	Raw materials milled in 70:30 ratio than converted into pallets after that sintered in special oven at 1200°C for 3hr for producing synthetic aggregates after that produce concrete using those aggregates[59].	Density (2.6 g/cc) Water Absorption (3.5 %)
2014	Red mud and clay mineral	Red mud and clay mineral were blended 80:20 ratio than powder was converted into pallets using disk pelletizing after that heat treated in electric kiln at 1150, 1170, and 1190°C for 90 min[60].	water absorption (1-2%), density (2.5-2.6 g/cc)
2015	Red mud & pond ash	Artificial aggregate (AA) primarily made with red mud was also used as the partial replacement of pond ash[61].	The specific gravity (1.89), water absorption (16.92 %)
2016	Red mud and pulverized fuel ash	25, 31, 38, 44 and 50% Red mud replaced with pulverized fuel ash and mixtures were converted into pallets than sintered in rotary kiln at 1200°C for producing light weight aggregate[62].	pH (8), Density (1.04-1.71 g/cc), Crushing Strength (6-8 Mpa), Water Absorption (6.26%)
2016	Red mud, gold tailings & limestone	Raw materials mixing, pelletizing and sintered at 1200°C for obtaining aggregates[63].	Characterization
2018	Red mud & chemical Additives	Raw materials mixed with varying percentage than converted into small balls after that those balls was fired at 1300°C for 120 min for obtaining heavy density synthetic aggregates[64].	Density (3.7 - 4.16 g/cc), Impact Value (10-14%), Crushing Value (14 and 16 %), abrasion value (14 and 16 %)
2019	Red mud	Alkali activated concrete using red mud as an active aggregate[65].	Durability and radiological properties
2019	Gold mine tailings, Red mud, and limestone	Raw materials mixed and sintered at 1150°C[66].	Abrasion resistance (abrasion loss value 290mg) and Toxic Characteristic Leaching Procedure (TCLP)
2020	Acid-leaching tailings and Red mud	Raw materials mix in certain mass ratio using planetary ball mil, 5-6 mm pallet were sintered in electrically heated furnace with 1000-1085°C for 30 min[67].	Water absorption (1.46%), Bulk density (728.76 Kg/m^3) and Compressive strength (10.77 MPa)
2021	Red mud and fly ash	Red mud and fly ash blended with alumino silicate precursors[56].	mechanical properties, densities, and internal structures using X-ray computed tomography (XCT) images
2021	Red Mud and MSW bottom ash	Raw materials mixing, pelletizing by disc pelletizer and then high-temperature sintering to transformed lightweight aggregate ceramsites[68].	Bulk density (1046.73 Kg/m^3), apparent density (1783.44 Kg/m^3), particle strength (27.11 MPa), 1-hour water absorption (0.8%), and pH (8.9)
2021	Red mud, FGD gypsum, Aluminum dust and Carbide slag	Raw materials mixing, cold bonded granulation using disc granulator to obtained sintering-free lightweight aggregates[69].	Bulk density (900–1000 kg/m^3), 28 day cylinder compressive strength (9.2–11.3 MPa), and water absorption <10%)

in road base material. The hydration process (pozzolanic reaction), which enhances the material's resistance, is facilitated via $Ca(OH_2)$ (calcium hydroxide) in lime reacted with silica and aluminium oxides (Al_2O_3) in ceramic and cement materials.

4 Conclusion

Several approaches for recycling and potential utilizations of industrial waste red mud have been focused here. It is quite difficult to produce a recycled product that is both economical and beneficial for the environment. Whereas an industrial waste red mud the recycling approaches for bulk utilization has been examined in various research papers. These uses, which include making cement, bricks, and ceramics, are concentrated on applying a large amount of red mud. However, the construction sector may be an excellent option to utilize red mud, when the residue can be blended with cement, polymers or ceramics. The Red mud has been used in road building, which has been thought of as one of the most practical uses in many countries over the years.

Many studies indicate that red mud may be utilized as materials for building works such as, ceramic tiles, bricks, etc. with improvements in durability, and compressive strength. Moreover, this may be assumed that alkali leaching is another inheritance for the environment.

Assuredly, the best usage for red mud (bauxite residue) is in the construction industry, which once permission is granted allows for the residue to be mixed with cement, ceramics, polymers, and geopolymer. This is great option for use of these residues which, already stocked without specifying its objectives and a substitute material with minimum costs which, allows reducing the mineral/naturally aggregates consuming in construction industry.

Among all applications studied in last year’s worldwide, the most desirable is road construction. However, the construction sector is a promising area to utilize the industrial residue. In road construction, it is much pointed used as filler in mixtures of bituminous. Bituminous mixtures permit the use of this residue in high volume and can cover red mud to make it inert, avoiding leaching, meanwhile it is assumed that road construction using red mud should be more research and development to be confirm about environmental with budgetary feasibility.

Acknowledgements

The authors are grateful to the Director, CSIR-AMPRI, Bhopal, for providing necessary institutional facilities, guidance, and encouragement.

References

1 Habashi F, *Essential Readings in Light Metals*(Springer, Editon edn), 2016
2 Zhang R, Zheng S, Ma S, &Zhang Y, *J Hazard Mater*, 189 (2011) 827
3 Mineral commodity summaries (US geological survey), 2018
4 Mineral commodity summaries, (US geological survey), 2021
5 Indian Minerals Yearbook(Government of India), 2019
6 Khalifa A, Bazhin V, Kuskova Y, Abdelrahim A, & Ahmed Y, *J Ecol Eng*, 22(2021) 191
7 Liu Y, Lin C, & Wu Y, *J Hazard Mater*, 146 (2007) 255
8 Mahadevan H, Chandwani H, & Prasad P, *Proc of Nat Sem on Bauxites and Alumina*, edited by Banerjee G(Allied Publishers,India), 1996, 337
9 Alam M, Zanganeh J, & Moghtaderi B, *Resour Conserv Recycl*, 141 (2018) 483
10 Reddy P, Reddy N, Serjun V, Mohanty B, Das S, Reddy K, & Rao B H, *Waste and Biomass Valorization*, 12 (2021) 1185
11 Kopas J, York E, Jin X, Harish S, Kennedy R, Shen S V, & Urpelainen J, *Ecological Economics*, 176 (2020)106711
12 Barbosa F, Bergerman M, & Horta D, *Tecnologia em Metalurgia*,13 (2016) 106
13 Klauber C, Grafe M, & Power G, *Hydrometallurgy*, 108 (2011) 11
14 Paramguru R, Rath P, & Misra V N, *Miner Process Extr Metall Rev*, 26 (2004) 1
15 Wang L, Hu G, Lyu F, Yue T, Tang H, Han H, Yang Y, Liu R, & Sun W, *Minerals*,9 (2019) 281
16 Hua Y, Heal K V, & Friesl-Hanl W, *J Hazard Mater*, 325 (2017) 17
17 Sutar H, Mishra S, Sahoo S, & Maharana H, *Chem SciInt J*, (2014) 255
18 Khairul M, Zanganeh J, & Moghtaderi B, *Resour ConservRecycl*, 141 (2019) 483
19 Sglavo V, Campostrini R, Maurina S, Carturan G, Monagheddu M, Budroni G, &,Cocco G, *J Eur Ceram*, 20 (2000) 235
20 Altundogan H, Altundogan S, Tümen F, & Bildik M, *Waste Manag*, 22 (2002) 357
21 Wang P, & Liu D, *Materials*, 5 (2012) 1800
22 Snars K,,& Gilkes R, *Appl Clay Sci*, 46 (2009) 13
23 Srikanth S, Ray A K, Bandopadhyay A, Ravikumar B, & Jha A, *J Am Ceram Soc*, 88 (2005) 2396
24 Pera J, Boumaza R, & Ambroise J, *Cem Concr Res*, 27 (1997) 1513
25 Hai L, Khai N, Quy T, & Huan N, *Int J Res Earth Environ Sci*, 1 (2014) 6
26 Valeev D, Zinoveev D, Kondratiev A, Lubyanoi D, & Pankratov D, *Metals*, 10 (2020) 32
27 Alkan G, Schier C, Gronen L, Stopic S, & Friedrich B, *Metals*, 7 (2017) 458

28 Pascual J, Corpas F, López J, Benítez M, & Artiaga R, *J Therm Anal Calorim*, 96 (2009) 407
29 Meher S, *Int J Chem Stud*, 1 (2014) 1
30 Verma S, Amritphale S, & Das S, *Mater SciAppl*, 7 (2016) 192
31 Rai S, Wasewar K, Mukhopadhyay J, Yoo C, & Uslu H, A*rchEnvironSci*, 6 (2012) 13
32 Reddy N, & Rao B, *Indian Geotech J*, 48 (2018) 405
33 Sundaram R, & Gupta S, *Constructing Foundations on Red Mud*, paper presented at 6th International Congress on environmental Geotechnics, New Delhi, India, 2010
34 Rao B, & Reddy N, *Geoenvironmental Practices and Sustainability*, (Springer, Editon edn), 2017
35 Nath H, & Sahoo A, *Int J Biol Biomed Eng*, 8 (2014) 1
36 Antunes M, Couperthwaite S, Conceicao F, Costa C, Kiyohara P, Coelho A, & Frost R, *Ind Eng Chem Res*, 51 (2012) 775
37 Palmer S, Reddy B, & Frost R, *Spectrochim Acta A Mol Biomol*, 71 (2009) 1814
38 Xenidis A, Harokopou A, Mylona E, & Brofas G, *JOM*, 57 (2005) 42
39 Li L, *J Environ Eng*, 124 (1998) 254
40 Grafe M, & Davies I, *Chemistry of trace and heavy metals in bauxite residues (red mud) from Western Australia*, paper presented at 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane, Australia,2010
41 Mayes W, Burke I, Gomes H, Anton A, Molnar M, Feigl V, & Ujaczki É, *J Sustain Metall*, 2 (2016) 332
42 Liu W, Chen X, Li W, Yu Y, &Yan K, *J Clean Prod*, 84 (2014) 606
43 Williams G, *J Clean Prod*, 3 (1997) 242
44 Agrawal A, Sahu K, & Pandey B, *Resour Conserv Recycl* , 42 (2004) 99
45 Rai S, Bahadure S, Chaddha M, & Agnihotri A, *J Sustain Metall*, 6 (2020) 1
46 Mohapatra B, Rao M, Rao R, & Paul A, *Characteristics of red mud generated at NALCO refinery, Damanjodi, India,* (Light Metals: Proceedings of Sessions), 2000
47 Siverio M, Thives L, Haritonovs V, & Bajars K, *Materials Science and Engineering* (IOP Conference Series), 2017
48 Shoppert A, &Loginova I, *KnE mater sci*, 2 (2017) 150
49 Liu X, &Zhang N, *Waste Manag Res*, 29 (2011) 1053
50 Shih PH, Chang JE, Lu HC, & Chiang LC, *Cem Concr Res*, 35 (2005) 2110
51 Vangelatos I, Angelopoulos G, & Boufounos D, *J Hazard Mater*, 168 (2009) 473
52 Singh M, Upadhayay S, & Prasad P, *Waste Manage*, 16 (1996) 665
53 Tsakiridis P, Leonardou S, & Oustadakis P, *J Hazard Mater*, 116 (2004) 103
54 Singh M, Upadhayay S, & Prasad P, *Cem Concr Res*,27 (1997) 1037
55 Das S, Kumar S, & Ramachandrarao P, *Waste Manage*,20 (2000) 725
56 Tian K, Wang Y, Hong S, Zhang J, Hou D, Dong B, & Xing F, *Constr Build Mater*,281 (2021) 122552
57 Blank H, J Test Eval, 4 (1976) 355
58 Huifen Y, Chunge D, Wentao L, & Wen M, *Utilization of Red Mud for the Preparation of Lightweight Aggregates*, paper presented at International Conference on Digital Manufacturing & Automation, Changcha, China, 2010
59 Oliveira D, & Rossi C, *Mater Res*, 15 (2012) 333
60 Isaias L, Furlan L, Pelisser F, Peterson M, Montedo O,& Noni A, *Mater Sci Forum*, 798 (2014) 492
61 Do T, Kim Y,& Ryu B, *Int J Geo-Eng*, 6 (2015) 8
62 Molineux C, Newport D, Ayati B, Wang C, Connop S P, & Green J, *J Clean Prod*,112 (2016) 401
63 Park H, Kim S, Shin D, & Sohn J, *REWAS* (Springer, Editon edn), 2016
64 Mudgal M, Chouhan R, Verma S, Amritphale S, Das S, &Shrivastva A, *Radiochimica Acta*, 106 (2018) 59
65 Boiko O, Zozulynets V, Ivanychko V, & Kovalchuk O, *Technol auditprod reserves*, 5 (2019) 15
66 Sas Z, Sha W, Soutsos M, Doherty R, Bondar D, Gijbels K, & Schroeyers W, *Sci Total Environ*, 659 (2019) 1496
67 Song C, Zhang H, Dong Y, Pei L, Liu H, Jiang J, & Xu H, *Chin J Chem Eng*,32 (2021) 353
68 Sun Y, Li J, Chen Z, Xue Q, Sun Q, Zhou Y, Chen X, Liu L, & Poon C S, *Constr Build Mater*, 287 (2021) 122993
69 Wang G, Zhang C, Wang W, Wu S, Li J, Wang X, &,Wu C, *Materials*, 14 (2021) 218
70 Promentilla M, Thang N, Kien P, Hinode H, Bacani F T &Gallardo S, *Waste and biomass valorization*, 7 (2016) 929
71 Kumar A, & Kumar S, *Constr Build Mater*, 38 (2013) 865
72 Giannopoulou I, Dimas D, Maragkos I, & Panias D, *Glob Nest J*, 11 (2009) 127
73 Deventer J, Provis J, & Duxson P,*Miner Eng*, 29 (2012) 89
74 Skvara F, KopeckyL, MyskovaL, Smilauer V, Alberovska L, & VinsovaL, *CeramSilik*, 53 (2009) 276
75 Kehagia F, *WSEAS Trans Environ Dev*, 10 (2014), 2224
76 Jitsangiam P, & Nikraz H, *Aust J Civ Eng*, 11 (2013) 1