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REVIEW

Properties and Assessment of Applications of Red Mud (Bauxite Residue): Current Status and Research Needs

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Abstract

In order to conserve natural resources and prevent waste generation, effective utilization of industrial wastes and/or by-products for beneficial engineering applications becomes inevitable. In order to accomplish this, extensive research studies, exploring properties and new applications of waste materials in a sustainable and environmentally friendly manner, have been initiated worldwide. Red mud (RM, also known as bauxite residue) is one of the wastes generated by the aluminium industry and its disposal and utilization have been traditionally hindered due to the extreme alkalinity (pH about 10.5–13.5). To date, no comprehensive review on various properties of RM of different origin and associated challenges in using it as a beneficial engineering material has been performed. The objective of this study is first to critically appraise the current understanding of properties of RM through a comprehensive literature review and detailed laboratory investigations conducted on Indian RM by the authors, to assess and identify the potential engineering applications, and to finally discuss associated challenges in using it in practical applications. Physical, chemical, mineralogical and geotechnical properties of RMs of different origin and production processes are reviewed. Mechanisms behind the pozzolanic reaction of RM under different chemical and mineralogical compositional conditions are discussed. Environmental concerns associated with the use of RM are also raised. Studies relevant to leachability characteristics reveal that most of the measured chemical concentrations are within the permissible regulatory limits. Overall, the review shows that RM disposal and reuse is complicated by its extreme alkalinity, which is also noticed to be influencing multiple engineering properties. But with selected pH amendments, the treated RM is found to have significant potential to be used as an effective and sustainable geomaterial. The assessment is majorly based on the characteristics of Indian RMs; hence the adaptation of the findings to other RMs should be assessed on a case-by-case basis. Moreover, field studies demonstrating the performance of RM in various engineering applications are warranted.

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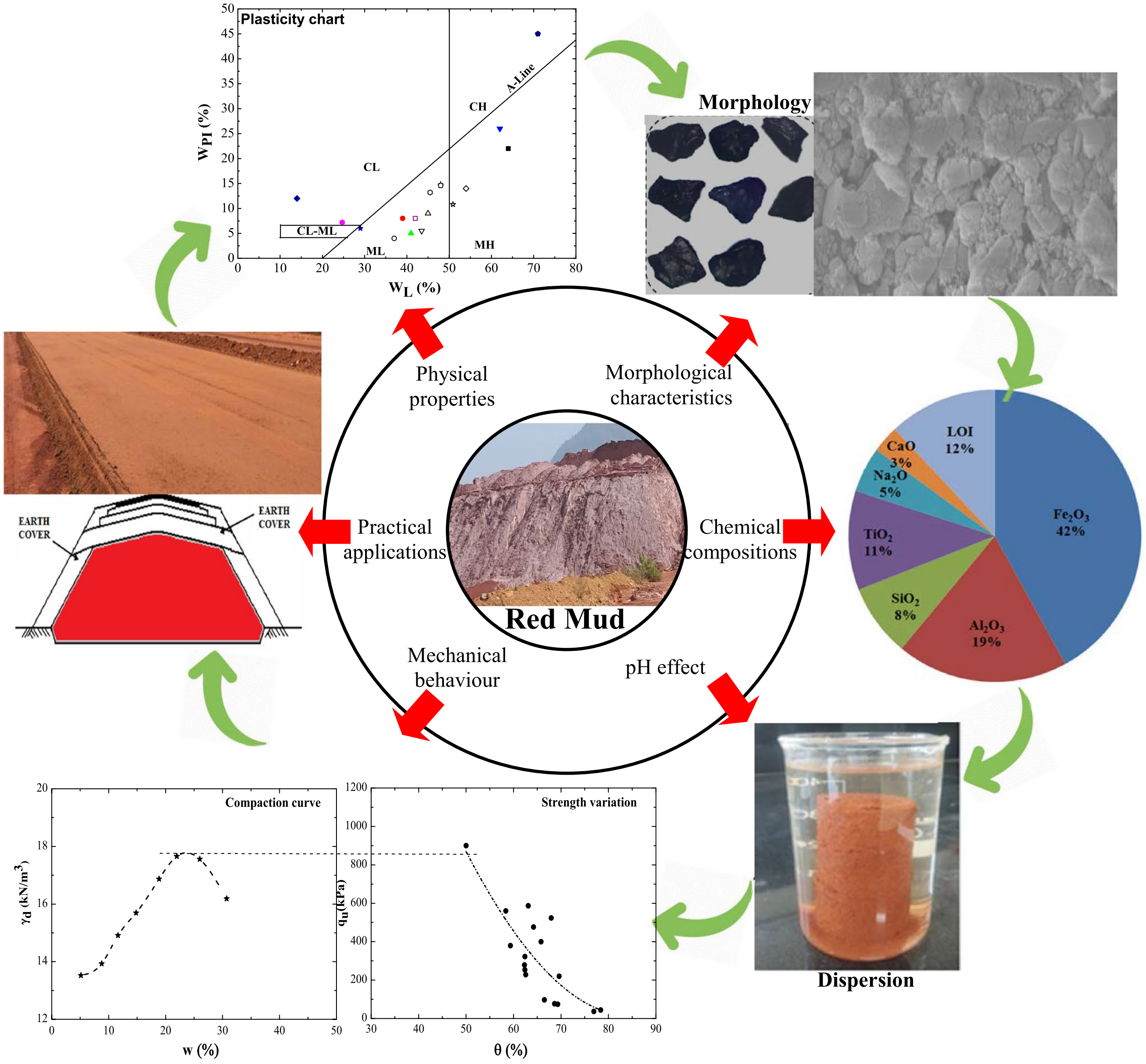
Graphic Abstract



Keywords Alkalinity · Red mud · Characterization · Geomaterial · Sustainability · Waste management · Waste utilization

Notations

c	Cohesion (kPa)
CBR	California bearing ratio
c_c	Compression index
CH	Clay of high plasticity
CL	Clay of low plasticity
C_p	Collapse potential
$CVPD$	Commercial vehicles per day
d	Diameter of a particle (mm)
e	Void ratio
G_s	Specific gravity
$GGBS$	Ground granulated blast furnace slag
HRS	Hindalco red sand
k:	Hydraulic conductivity
MH	Silt of high plasticity
ML	Silt of low plasticity
MP	Modified Proctor compaction test
NRS	Nalco red sand
OPC	Ordinary Portland cement
p	Applied pressure (kPa)

PTE	Potentially toxic elements
q_u	Unconfined compressive strength (kPa)
SEM/EDS	Scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy
SS1	Standard sand-1
SS2	Standard sand-2
SP	Standard Proctor compaction test
TCA	Tricalcium
TCLP	Toxicity characteristic leaching procedure
UCS	Unconfined compressive strength (kPa)
w	Water content (%)
w_L	Liquid limit (%)
w_{opt}	Optimum water content (%)
w_P	Plastic limit (%)
w_{PI}	Plasticity index (%)
γ_d	Dry unit weight (kN/m^3)
γ_{dmax}:	Maximum dry unit weight (kN/m^3)
ϕ	Angle of internal friction
θ	Volumetric water content (%)

Statement of Novelty

Published research studies on characterization and utilization of red mud (RM) are very disjointed, and characterization of RM for valorization is considered inadequate. To date, compilation and detail discussion on physical, chemical, mineralogical and geotechnical characteristics of RMs of different origin in a comprehensive way have not been reported in the literature. The present review is a first step addressing the potentiality of RM as a geomaterial based on critical assessment of each engineering property and engineering challenges to be encountered correlating with perspective practical applications. The microbial, biopolymer and geopolymer treatments are found beneficial for converting highly alkaline RM into an environmentally benign geomaterial. Field studies are needed to demonstrate performance and address practical considerations of RM for field applications.

Introduction

Among environmental hot spots all over the world are the tailings of RM, generated during the digestion of bauxite ore with sodium hydroxide by Bayer process for the extraction of alumina. The term ‘red mud’ is used as a synonym for ‘bauxite residue’. The residue generated is usually highly alkaline with pH about 10.5–13 [1, 2]. Bauxite ore primarily contains aluminium hydroxides (gibbsite) and oxy hydroxides (boehmite and diaspore) in the range from 35 to 65% (by weight) based on location and nature of its formation [2, 3]. Nearly, 85 manufacturing plants are in operational worldwide, of which 95% of the plants are adopting Bayer’s process and the remaining 5% plants are using either sintering process or combination of both for the digestion of bauxite ore [4, 5]. For every ton of produced alumina, approximately 0.4–2 tons [6] of RM is generated and roughly 2–3 tons of bauxite is consumed. The global average of RM is 1.35 t/t alumina [7]. It is estimated that a production rate of 0.15 billion tons of RM is generated annually across the world [7, 8]. The global inventory of RM was forecasted by Power et al. [9] to reach 4 billion tons by 2015. Prior to 1980, most of the inventory of RM was stored in lagoon-type impoundments. Over the decades, management and methods of storage of RM have evolved. At some places, thickened RM with 50% solids content or cake of vacuum drum filters with 65% solids content are disposed of. Over the last 10–15 years, more and more alumina refineries are resorting to plate and frame press filters and the resultant cake produced is disposed of [6, 7]. Filter press technology to remove high water content, which would address the environmental concerns and meets the stricter pollution regulations, followed by dry stacking method is the current best practice method adopted by the most aluminium refineries [10, 11]. Typical disposal practices adopted by different aluminum refineries, especially in India, are shown in Fig. 1.

The European Union (EU) waste legislation policy [12] introduced a five-step waste hierarchy, with a specific emphasis that waste is a resource. Moreover, the Construction Products Regulation No. 305/2011 includes the additional Basic Requirement No. 7, where the use of environmentally compatible raw materials in construction works, as well as secondary materials, is required. Numerous different types of industrial residues have been routinely recycled, in large quantities, in the construction sector. But in the case of RM, such practices are impracticable. Only limited technical knowledge is available about RM, which illustrates low recycling potential due to its innate chemical and physical properties. However, considerable efforts are in progress to find the potential applications of the RM [7]. Utilization of residues, such as RM, produced during the alumina production into valuable secondary raw materials can help the waste minimization and resource efficiency of both industrial and end-consumers (industry producing RM and construction sector). This also stimulates re-thinking of the current linear economic model to circular approach where the end-of-life product (RM) is considered as a resource for another cycle [13, 14].

Objectives of this Review

The objective of this review is to present in detail different problems with disposal of RM unified with the case studies, underline the need for beneficial utilization, and then

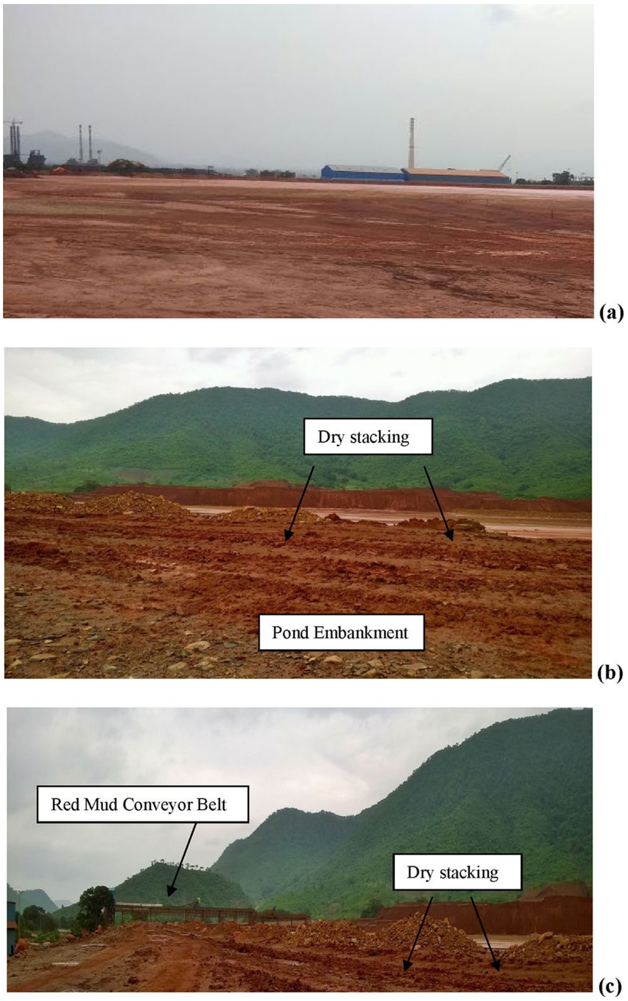


Fig. 1 Disposal of RM **a** slurry form with settled particles, **b** dry stacking, and **c** dry disposal by conveyor belt

critically review the physical, chemical, and mineralogical characteristics and elucidate their influence on different geotechnical properties. Additionally, various potential beneficial engineering applications based on the geotechnical properties of RM are assessed and discussed. High alkalinity is the prime limiting factor, hence a detailed discussion on how pH affects various engineering properties is provided. Various ways to control pH of RM and resulting changes in the important engineering properties of RM are highlighted. Comparisons of properties between pre-treated and post-treated RM samples concurrently identifying its potential applications in accordance with the standards or specifications are also made in the study. A detailed assessment of each property with pros and cons linking with utilization perspective is delineated and associated challenges are discussed. Finally, based on the current state-of-the-knowledge, future research needs that would maximize the constructive use of RM are highlighted. Overall, this study provides comprehensive fundamental and practical information that is useful for the researchers, policy makers, and potential end-users of RM for employing it in various civil and infrastructure engineering projects.

Problems with Red Mud Disposal

The physical presence of wastes or by-products in any form is a serious threat to land, water, and atmosphere; as they have potential to pollute these precious resources. In 2010, a tragic industrial accident occurred at the Ajka Alumina Plant in Hungary, where the northwestern corner of the bauxite residue disposal area No. 10 was collapsed, releasing approximately one million cubic meters of RM waste in its slurry form [15]. The pH of the released liquid phase was 13 [16]. On 9th April 2019, HINDALCO Plant at Muri, Jharkhand, India, experienced a failure of one of the dikes of bauxite residue disposal area, leading to spillage of RM slurry spreading across more than 35 acres of land. The environmental impact assessment shows no damage to the surrounding environment. Another such dike failure incident occurred at Xiangjiang Wanji Aluminium Plant in Luoyang, Henan Province of China (August 2016). Approximately, 2 million m^3 of slurry tailings was released, which has traveled over 1.5 km length causing evacuation of an entire village with over 300 people and killing many domestic and farm animals in the en route.

Several major issues were raised aftermath of the aforementioned tragic incidents including contamination of plant environment, increase in caustic nature of native soils with deposition of fine particles, release of potentially toxic elements (PTEs, viz., As, Ba, Ni, Zn, Cu, Zr, Pb, Cr, V, Hg etc.), and arouse of fine dust upon drying up of surface [17, 18]. In connection with these problems, Mayes et al. [17] reported the superior levels, beyond the permissible levels stipulated by regulatory bodies, of trace metals (As and V) in water bodies up to a distance of 2 km from the spillage area of bauxite residue disposal area at Ajka. In similar lines, Ruyters et al. [15] have reported based on their extensive field studies at Ajka Site, in particular, on plants affected by spillage that the toxicity induced in plants was below the toxic levels with no considerable effect on plant growth, which was, however, noticed to be harshly affected by excessive presence of Na retention in the soil. Gelencsér et al. [19] investigated the risk of dusting on post spillage of RM at Ajka Site on human health and confirmed that the effect is less on human health in comparison to the urban dusting problem. Apart from the above mentioned problems, arise of issues related to contamination of water bodies by rising the turbidity levels [20, 21], alkalinity of groundwater [22], overflow of materials during the rainy season and costly maintenance of large bauxite residue disposal areas due to the physical presence of RM cannot be undermined. The aforementioned incidents and problems emphasize the need for proper management of RM disposal facility, especially, if it is in slurry state to prevent failures that can cause catastrophic impacts on surrounding public and the environment.

Beneficial Uses of Red Mud

In the context of potentially serious consequences of RM on the environment and also on the necessity for saving and conserving precious natural resources, it becomes indispensable to explore its efficient utilization. With a continuous increase in the generation of RM, augmented by sophistication in the Bayer process technology and evolution of dry mud stacking, exploring newer application schemes became a global priority; as it requires extensive cost-intensive research, demonstration tasks and promotional schemes to use RM as a sustainable material. Numerous previous studies emphasize that waste materials can successfully be employed for beneficial utilization in infrastructure projects [23–25].

It is prudent to mention here the pilot project from Greece, the results of which are published by Kehagia [4], who successfully built road embankment (composed of three sections, section I: natural soil; section II: natural soil (60%) and RM (40%); and section III: mixture of RM and 4% fly ash) using RM and illustrated its geotechnical performance. The study demonstrated no signs of disintegration of the surface and no excessive settlements with time (a mere 10 mm after a period of 5 years) on section II, indicating practical viability of RM for constructing the embankments. In situ penetration tests on the embankment further confirmed increase in strength and California bearing ratio (CBR) parameters within the section II. In another field study performed by Qi [26] at Shandong Province of China, it is reported that RM is a suitable material for subgrade course in a highway (15 m wide and 4 km long). The study concludes that RM could be a potential resource material for pavement construction.

Based on the in situ standard penetration test (SPT) values, which measured in the range from 1 to 5 directly over the bauxite residue disposal area, Sundaram and Gupta [27] demonstrated that RM behaves similar to soft soils. Authors attributed this phenomenon to high water retention capacity and low permeability [28–30]. Additionally, efforts are also devoted to evaluate the feasibility of RM to be employed for constructing earthen structures (viz., embankments, levees, fills, etc.) and roads [1, 31–33]. Trails carried out of using RM for capping municipal landfills are reported, where RM was found to have advantages over natural clay. Further, neutralized RM (its coarse sandy fraction) was also successfully used for sub-grade and top dressing in the construction of roads [7]. Other potential uses of RM include: acid land reclamation, balancing the fertility of agricultural land, scrubbing of flue gas [34], adsorbent to remove H_2S from industrial sludge, raw material in buildings, catalyst for eliminating toxic elements from wastewater, amendment for remediation of contaminated soil [35] and preparation of anti-corrosive material [36].

The above field case studies, prima facie, demonstrate that it is necessary to stabilize or neutralize or perform both, in tandem, on RM using suitable amendments in order to foster its effective utilization. Study by Sundaram and Gupta [27] accentuate an inherent influence of high alkalinity on in situ tests and thus, on the strength and other engineering properties. While numerous laboratory studies heighten a gap in linking physical, chemical and mineralogical properties with the geotechnical properties, understanding of which are critical for evolving potential newer practical applications. More importantly, all the studies highlight that RM exhibits good geotechnical properties, which ascertain that it is practicable to use it in geotechnical engineering applications. But, the high caustic nature poorly endorses RM as a recyclable material or renders it not a substitute to natural resource materials. The aforementioned issues ardently lay emphasis on the necessity to develop holistic approaches and sustainable technologies that would encourage large scale utilization of RM, which in turn echoes in the prevention of growing adversities associated with disposal practices and consumption of valuable natural resources [2].

Review of Red Mud Characterization Methods

Physical, chemical, and mineralogical characteristics of RMs are mainly dependent on the nature of bauxite ore used in the process. Further, they are also strongly influenced by ore treatment process (e.g.: beneficiation), alumina extraction method, treatment of the RM, disposal and storage methods, depth and representative sampling, and age of the bauxite residue disposal area [37]. Various sample collection and testing methods are reported for characterization of RM.

The authors have performed extensive laboratory investigations on RM continuously for several years. The RM tested in these investigations was collected from the bauxite residue disposal area of National Aluminium Company Limited (NALCO), Damanjodi, Koraput, Odisha, which is located in the eastern part of India. Large quantity of RM samples were collected from different locations within the disposal area in accordance with ASTM D 6907 [38]. As such, the samples collected can be considered disturbed in nature. The wet collected samples were oven-dried at a temperature of 105 ± 5 °C for a period of 24 h. The samples were pulverized for separation of agglomerated particles prior to testing for physical, chemical and mineralogical properties. The detailed testing procedures and the results are presented and discussed by Reddy and Rao [28, 39–42], Reddy et al. [2, 43], Rao and Reddy [44] and Mishra et al. [45]. The reader should consult these publications for the detailed testing procedures. The results obtained from these studies are combined with the results from various other published studies by different investigators worldwide and then assessed to ascertain the range and variability of the RM properties.

Review of Physical, Chemical, Mineralogical and Morphological Characteristics

Specific Gravity

Table 1 summarizes the specific gravity (G_s) value of RMs of different origin across the world reported by various researchers. It is seen that G_s of RMs are consistently high, varying in the range from 2.7 to 3.7, reflecting the different origin of the investigated RMs. For natural soils, G_s commonly fall in the range from 2.65 to 2.75 [46, 47]. In comparison to the G_s of natural soils, it is obvious that G_s of RMs are relatively greater. RM predominantly comprises of metallic, in particular, iron rich phases, which may be a reason for higher values of G_s [20, 29, 48].

Particle Size Distribution

Particle size distribution is one of the key properties of any material since they intrinsically govern the overall behavior of each material [46]. The properties are quite useful to infer information regarding the percentage fraction of particle sizes along with the dominance of a specific size fraction. The median particle size of RM is reported to be in the range of 5–10 µm; however, the size and range of particles are broad, ranging from coarse sandy grains down to submicron particles varying from different alumina plants and different bauxites. The amount of sandy fraction can range from less than 1% to more than 50%. Some alumina refineries separate the sandy fractions during the processing while others do not [6, 7].

The grain size distribution curves of RMs (including RM sand) belonging to diverse origin across the globe are shown in Fig. 2. While, typical percent fraction range derived from the same figure are listed in Table 1. It can be seen that majority of particle fractions are silt to clay size with 90% of fractions passing 75 µm and an average particle size diameter of 10 µm [2, 20, 34, 48–51]. On the other hand, some of the studies reported that the RM contains clay size fractions in the quantity greater than 50% [6, 52, 53]. The prevalence of finer fractions may be linked to the dissolution of minerals and grinding process [54, 55]. However, grinding in Bayer plant is not extensive enough to produce very fine fraction of particles smaller than 10 µm. Dissolution of one mineral can liberate fine particles of other with a size smaller than 10 µm. The overwhelming majority of fines fraction is largely associated with the intimate mineral associations in the parent bauxite. As such, the statement related to dissolution process well corroborates with the results of Newson et al. [29], who have reported reduction in particles size resulting from the dissolution of fine particles when washed in acidic media. Pradhan et al. [56] reported variations in particle fractions in the range from 0.01 to 200 µm and attributed the reason for variance to the quality of ore and the separation technique employed by the refinery. Wang and Liu [57] reported that the grain sizes of RM produced by Bayer process are smaller in comparison to that produced by sintering process, wherein the grain sizes range from 0.8 to 50 µm with an average grain size of 14.8 µm. The presence of greater quantity of fine particles in a material may not be favorable, as the fine fractions show susceptibility to dispersion under extreme pH conditions [20]. Conversely, Newson et al. [29] pointed out that the presence of sizable amount of fine fractions in RM did not accelerate the consolidation settlement, rather caused long-term environmental degradation with possible contamination of surrounding environment [29].

On the other hand, the presence of fine fraction fetches an advantage of rendering the material suitable for constructing compacted clay liner systems as a hydraulic barrier material. The design of barrier accords prime importance to the hydraulic conductivity (k) [58, 59]. In this context, Benson and Othman [60] highlighted that the presence of finer fraction can reduce the permeability characteristics by blocking the pores and filling the voids concurrently. This effect goes well along with the study performed by Rubinos et al. [49], who explored the potential of RM as a liner material and reported that it shows significantly lesser hydraulic conductivity on account of its constituent finer fractions, which is similar to the CH soil.

Grinding of the RM also affects other physical properties such as angularity and frictional resistance, where the former property can further affect the shear modulus [61] and compression behavior of granular materials [62]. The results of Alam et al. [54] validate this observation. The study showed that the quantity of angular shaped particles in RM varies from 71.65 to 91.23%. A larger fraction of angular particles seems to be favorable, as it can contribute for considerable frictional resistance with simultaneous providence of counteract to the applied loads. The presence of angular particles further enhances the angle of internal friction [54], resulting in better shear strength. Angularity is the characteristics of the particles with sharp edges and corners (as shown in Fig. 3), and is much sought when the RM is meant to be used as a resource material for various geotechnical applications

Table 1 Physical and geotechnical properties of RMs originated in India and other than India

Property	Indian red mud			UK red mud[b]	Guinea red mud[d]	Spain red mud[e]	China[f]	Jamaica red mud[g]
	Nalco red mud[a]	Hindalco, Renukoot[c]	Hindalco Muri[c]					
Locations of the refinery								
Location	Damanjodi, Odisha, India	Renukoot, Uttar Pradesh, India	Muri, Jharkhand, India	Not defined (site in the United Kingdom)	Not defined (refinery in the USA)	Lugo, northwest Spain	Henan China, Guangxi, China Liulin, Shanxi, China	Various alumina industries in Jamaica (Alcan, Alpart, Aloca, Revere) Kirkvine, Arvida
Physical property								
Specific gravity, G_s	2.85 – 3.45	2.85 – 2.97	3.27	3.05	3.2 – 3.7	3.44	2.77	2.7 – 3.7
pH	10.7 – 11.5	10.2 – 11.0	11.53	11.6	13.1 – 13.5	10.2	–	11.25 – 12.5
Surface area (m^2/g)	20.4 – 47.2	–	–	–	–	23.7	–	–
Consistency limits								
W_l	21 – 45	40 – 45	39.89	54	44–66	39 ± 2	64	45
W_p	16 – 36	30 – 35	36.08	40	33–36	31 ± 2	42	36
W_{PI}	5 – 7	5 – 14	3.81	14	11–26	8	22	9
% Fraction								
Gravel	0	0	0	0	0	0	0	0
Sand	5 – 15	10 – 14	17	0	36	12	5	20–30
Silt	43 – 76	43 – 57	51	80	44	50	75	50
Clay	22 – 35	29 – 39	32	20	20	38	20	20–30
USCS	ML	MI	MI	MH	MI–CI	MI	MH	MI
Compaction characteristics								
γ_{dmax} (kN/m^3)	12.5 – 17.0	14.5 – 16.4	15.2 – 15.9	17.5	15.5	16.9	17.0	–
w_{opt} (%)	22 – 34	33	–	–	30	7–35	50.15	–
Consolidation properties								
c_v (cm^2/s)	$3 - 50 \times 10^{-3}$	–	–	–	–	–	–	7.5×10^{-4} to 3×10^{-2}
c_c	0.0933	–	–	0.41	0.28 – 0.38	–	–	0.268
Shear strength								
ϕ (°)	34 – 42	26 – 28	–	38 – 42	30–35	–	28 – 33	37 – 45
Cohesion (kPa)	7 – 28	10 – 20	–	10 – 20	–	–	11 – 35	–
q_u (kPa)	102 – 136	143	–	130	–	–	–	20 – 175
Hydraulic conductivity								
k (cm/s)	5.832×10^{-4} to $.13 \times 10^{-8}$	$2 - 30 \times 10^{-6}$	5.3×10^{-4} to 8.7×10^{-5}	$2–10 \times 10^{-7}$	$1.4 - 6.7 \times 10^{-6}$	–	4.5×10^{-6}	10^{-5} to 10^{-7}
Swelling property								

Table 1 (continued)

Property	Indian red mud			UK red mud[b]	Guinea red mud[d]	Spain red mud[e]	China[f]	Jamaica red mud[g]
	Nalco red mud[a]	Hindalco, Renukoot[c]	Hindalco Muri[c]					
Free swell index (%)	No swell	No swell	No swell	No swell	No swell	Very low	–	–

[a] References [1, 28, 54, 141]

[b] Reference [29]

[c] References [27, 54, 103]

[d] Reference [104]

[e] Reference [49]

[f] Reference [130]

[g] References [52, 66, 136]

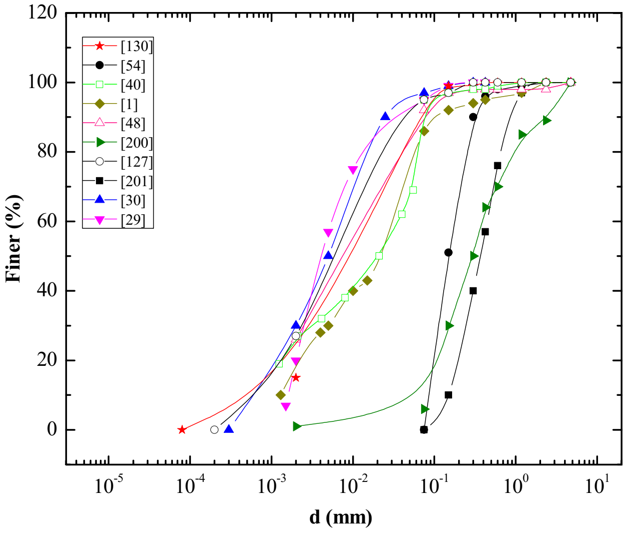


Fig. 2 Particle size distribution curves of red muds of different origin

[63]. As a result of RMs finer composition, its specific surface area is measured significantly high from 15 to 58 m^2/g, which is almost comparable with many clay soils such as kaolin [64–66].

The role of gradational properties in enhancing the settling characteristics of particles under different aqueous environmental conditions is highlighted by several researchers [41, 67]. Whereas in the case of RM, the presence of finer fraction, possibly mainly composed of goethite and sodalite mineral phases (with high specific surface area and lower density), seems influencing the settling characteristics [41, 68]. This is why various synthetic flocculants are used to make flocs with much higher sizes than the individual particles. When the RM is disposed, particle segregation occurs soon after discharging the slurry [37]. Especially from disposal perspective, it is important to know the characteristics of the particle size distribution as it immensely contribute to understanding the settling behavior of a material, which would aid in storing enhanced quantity of RM in a given volume [41, 67].

Mineralogical and Chemical Compositions

A brief insight into the conventional Bayer bauxite digestion process demonstrates that during the low temperature digestion, gibbsite and clay minerals of bauxite gets dissolved, with formation of sodalite as one of the end reaction product. While the high temperature digestion results in boehmite and diaspore solubilisation that starts forming cancrinite preferably with sodium–aluminium-hydrosilicate (DSP). Lime is added to the digestion for different purposes: facilitates the dissolution of diaspore, enhances transformation of aluminogoethite to hematite, forms hydrogarnet, etc. [69]. Although, mineralogical compositions of RM produced at different refineries primarily reflect the composition of parental bauxite ore and at the same time, it is defined also by the processing technology such as digestion technology and compounds formed and/or introduced during the Bayer process [29, 70].

Detailed knowledge of mineralogical and chemical compositions of RM is crucial in order to define their distinct influence on various engineering properties, which in turn can aid in devising the newer application schemes of the RM. The further acquaintance on these properties gives a concept for identification of the most suitable additive, which would not only be chemically compatible but also environmental friendly, for stabilization and/or solidification of the RM. The detail knowledge of the mineralogical composition enables determination of the buffering capacity during the dissolution of mineral phases in acidic media as well [66].

Different accompanying constituents of RM are defined to be: brookite (anatase), ilmenite, carnegieite, dolomite, hydrogarnet, various hydroxycancrinite, katoite-Si,

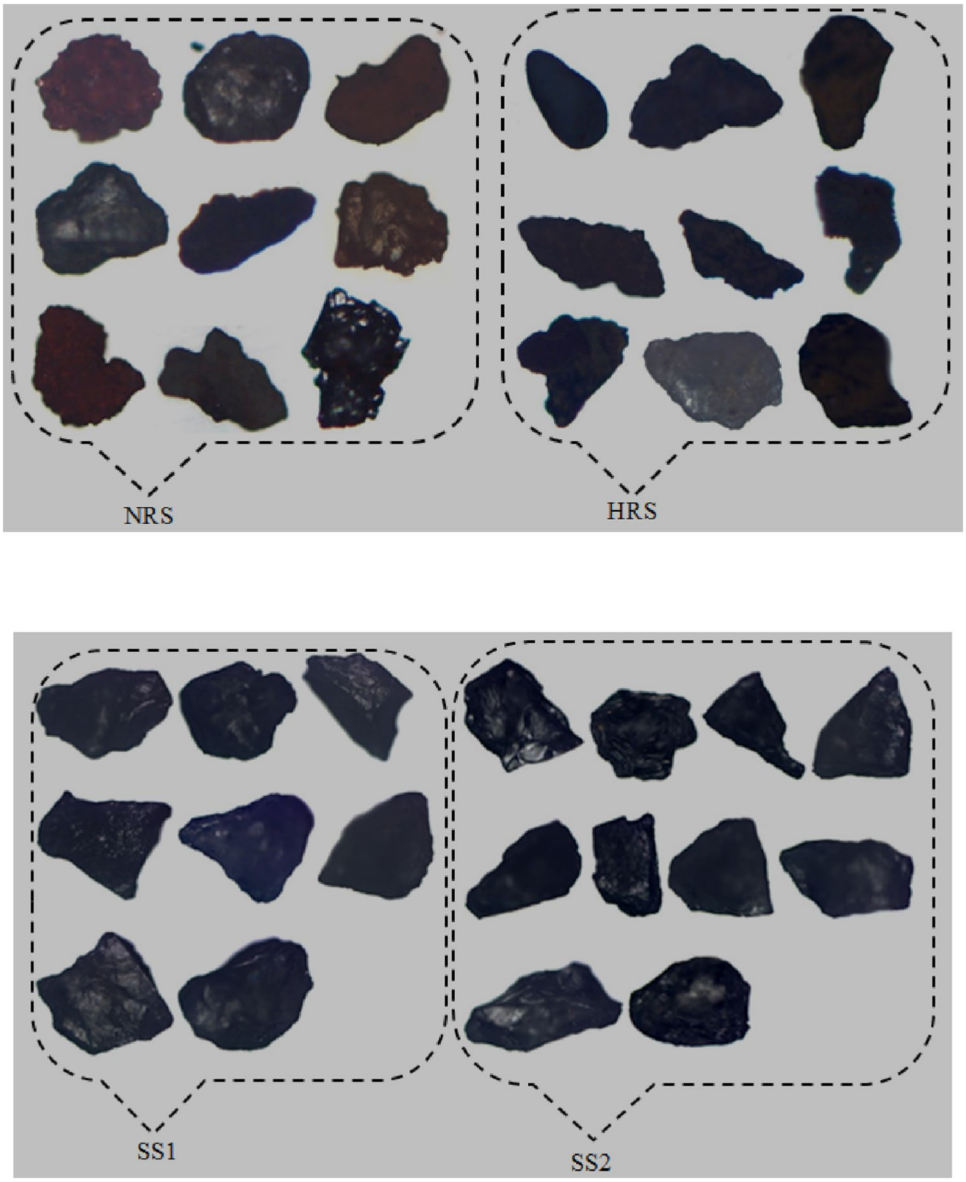


Fig. 3 Optical microscopic image of NRS, HRS, SS1 and SS2 samples

lawsonite, nepheline, nosean, portlandite, schaeferite, sodium titanate, zircon and also whewellite [50, 54, 71], hydrocalumite, dawsonite, hydrohematite, aluminogoethite, ferrihydrite, natrodavyne, plazolite, sodium carbonate hydrate, chantalite, imogolite, sodalite, boehmite, perovskite, rutile, magnetite [7, 28, 72–75]. The sandy fraction of RM may contain much of quartz, but not necessarily [6]. Evans [7] reported typical phase composition of RMs as: Al-goethite (1–55 wt%), cancrinite (0–50 wt%), sodalite (4–40 wt%), hematite (10–30 wt%) followed by crystalline and amorphous silica (3–20 wt%), calcium aluminate (2–20 wt%), calcite (2–20 wt%), boehmite (0–20 wt%), anatase with rutile (2–15 wt%), muscovite (0–15 wt%), perovskite (0–12 wt%) and, in lesser quantities also magnetite (0–8 wt%), kaolinite (0–5 wt%), gibbsite (0–5 wt%) and diaspore (0–5 wt%). Goethite, hematite and boehmite are the most abundant minerals present in RM in quantities up to 24%, 29%, and 10% respectively in RM from Australia [76]. In some cases gibbsite, quartz and sodalite are also reported as the major phases in RM [76]. Perovskite and calcite mineral formation occurs in RM as a result of the addition of lime during the extraction process [77]. CSIRO [78] reported that the RM generated from Eurallumina Plant (Sardinia, Italy), which used Weipa bauxite from Australia, contains 16–24% of sodalite [79] and up to 29–51% of cancrinite [79, 80]. Sodalite and cancrinite are members of feldspathoid mineral groups whose structure consists of an alumino-silicate framework of cavities. They have a cage-like structure reflected in many of the properties, such as high ion-exchange capacity and water retention capabilities, which are characteristic of zeolite minerals [29]. Further, the sodalite under alkaline environment may react with available anions (viz., Cl^-, OH^-, etc.) to form hydroxy sodalite [81]. The hydroxy sodalite phase of the RM is important because it is the primary component accountable for the aggregation of particle and as hydroxy sodalite bonds are so strong they offer considerable resistance during compressive loading due to particle rearrangement [29]. The shape, size and electric charge characteristics of hydroxy sodalite, with features consistent with clay and sand reported to be causing mechanical behavior to the RM [29]. However, the bonding becomes weak or gets dissociated (i.e. dissolves) when RM is admixed with acidic solutions [29].

The major bulk chemical compositions of RM commonly reported by Evans [7] are: Fe_2O_3 (5–60 wt%), SiO_2 (3–50 wt%), Al_2O_3 (5–30 wt%), followed by TiO_2 ($\leq$ 15 wt%), CaO ($\leq$ 14 wt%) and Na_2O ($\leq$ 10 wt%) [7]. Trace elements such as V, K, Pb, Ga, Zn, Cr, P, Mn, Cu, F, Cd, As, Ni, U, Th etc., were also identified [82]. Chemical compositions of RMs produced by different alumina refineries across India and globally are summarized and presented in Tables 2 and 3, and also shown in Fig. 4. Literature review (Fig. 4; Tables 2, 3) show that RMs produced by different aluminum industries are primarily constitute of Fe oxide. Besides Fe_2O_3, other major components are Al_2O_3, SiO_2, and CaO. Additionally, oxide components such as Na_2O, TiO_2, CaO etc., are also present in various amounts. It is obvious from Tables 2 and 3 that there is a significant variation in the oxides composition when RMs generated in India are compared to those generated elsewhere. Evidently, there is a close match in the proportions of different oxides composition among different Indian RMs can be noticed, even though their sources within India are distinct. On the contrary, a clear disparity in the chemical compositions can be witnessed when the RMs from different countries are compared. Gräfe et al. [66] reported that the RM generated by Bayer process is rich in iron oxide, accounting for more than 30% with a maximum of 60%. When CaO is dominant in the residue, it is obtained by the sintering process or the combined Bayer-sintering process, while these residues are sometime called brown mud. The major mineral in the residue from the sintering or combined Bayer-sintering is β-dicalcium-silicate. The dominance of Ca in the sintering process is assigned to the excessive addition of lime. Depending upon the refining process adopted by the refinery, Al_2O_3 found to vary from 10 to 20%.

In contrast to conventional soils which usually compose predominantly of aluminum-silicate (i.e., Al_2O_3 and SiO_2), RM constitutes with Fe_2O_3 as the dominant chemical oxide component. Furthermore, it is obvious to note from mineralogical compositions that minerals which belong to iron oxides/hydroxides family are rich in RM. Thus, it would be prudent to make a logical conclusion that the behavior of RM might largely be influenced by quantity of iron oxides/hydroxides [37, 83, 84]. To the best of authors' knowledge, no cases of investigation of the influence of oxides quantity

Table 2 Oxides composition of different red muds produced across the globe

Reference	% Composition (by dry weight)										
	Fe_2O_3	Al_2O_3	TiO_2	CaO	SiO_2	Na_2O	MgO	P_2O_5	MnO	K_2O	LOI
Jamaica (Pinnock et al. [145])	49.5	16.5	7	5.5	3	2.3	–	–	–	–	11.6
Hungary (Kolencsik-Tóth et al. [127])	31.63	10.5	5.9	11.66	12.2	6.09	0.53	0.55	0.34	0.05	–
ALCOA, Brazil (Ribeiro et al. [97])	19.85	19.87	2.66	4.61	14.34	7.35	–	–	–	–	27.20
ALCOA, Spain (Rubinos et al. [49])	37.22 ± 0.33	12.40 ± 1.07	20.10 ± 0.59	6.30 ± 0.20	3.81 ± 0.16	4.64 ± 0.41	0.14	0.51	0.06	0.05	11.34
China (Zhu et al. [178])	10.63	22.31	6.64	20.46	18.92	5.72	–	–	–	–	–
Aluminium of Greece (Rivera et al. [179])	46.7	18.1	5.8	8.5	7.3	2.8	–	–	–	–	8.5
China (Li et al. [180])	29.79	22.96	1.83	2.03	21.24	8.93	–	–	–	0.03	12.19
Iran (Deihimi et al. [181])	22.17	13.98	7.17	24.25	13	4.2	2.01	0.16	0.06	0.42	9.55
China (Chen et al. [182])	11.60	7.34	5.36	44.69	27.99	0.58	2.01	–	–	0.43	–
Spain (Lopez et al. [183])	31.80	20.10	22.60	4.78	6.10	4.70	0.20	–	–	0.03	–
Seydisehir Plant, Turkey, (Nadaroglu et al. [184])	35.04	20.20	4	5.30	17.29	9.40	0.33	–	–	–	8.44

Table 3 Major oxides composition of some Indian red muds [40, 54, 74, 129, 185–187]

Company	% Composition (by dry weight)						
	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	Na_2O	CaO	LOI
BALCO, Korba	18.10–21.0	35.0–37.0	6.0–6.84	17.0–22.50	5.2–5.5	1.7–2.2	11.8–14.0
HINDALCO, Renukoot	17.5–20.10	35.5–36.2	7.0–8.50	16.3–14.5	5.0–6.0	3.2–4.5	10.7–12.0
HINDALCO, Muri	16.80–20.5	35.34–46.0	5.5–15.63	17.0–18.9	3.3–13.56	1.24–2.0	12.0–14.0
HINDALCO, Belgaum	17.8–20.1	44.0–47.0	7.5–8.5	8.2–10.4	3.5–4.6	1.0–3.0	10.8–14.0
MALCO, Metturdam	18.0–27.0	40.0–45.17	5.70–16.0	2.5–5.15	3.64–4.5	1.5–2.5	11.0–15.0
NALCO, Damanjodi	3.38–30	33.80–60	1.21–20	1.20–3.30	1.35–10	0.03–8	10.8–13.5

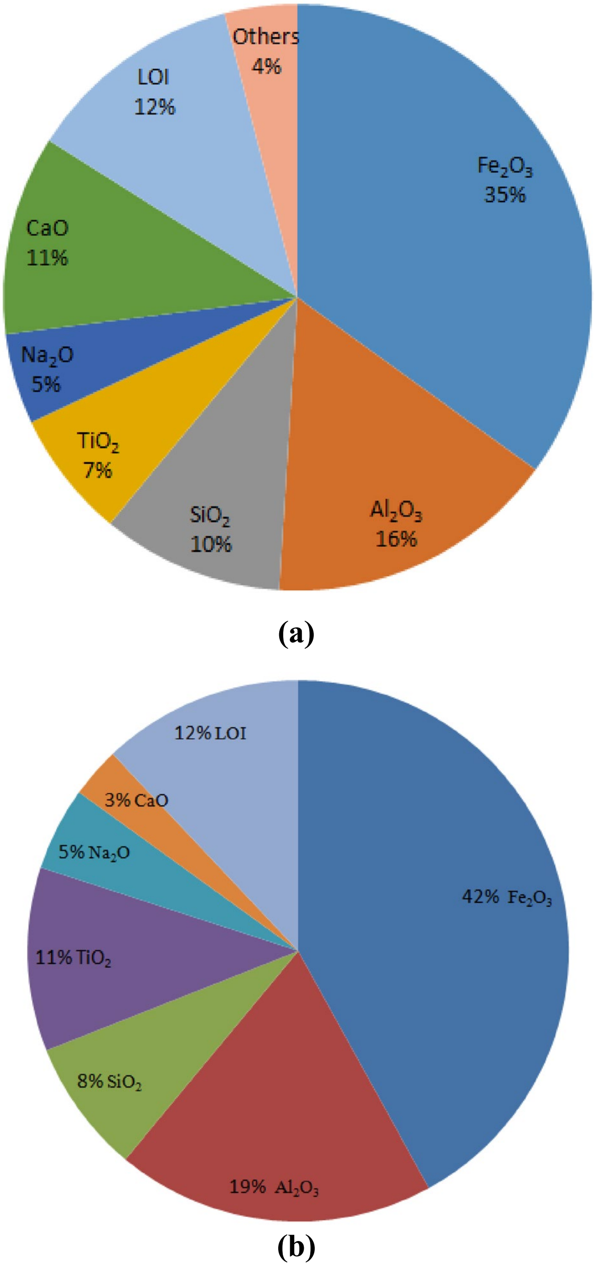


Fig. 4 Average chemical compositions of red mud generated by aluminium industries **a** across the globe and **b** across India

or bulk chemical composition or major oxides composition on the engineering behavior of the RM are attempted in the literature. In the future works, this interdependence will need to be defined in order to recycle the RM more efficiently.

The high content of iron and aluminium in RM, was reported to be beneficial for utilizing it as a raw material in cement production. It is suggested to be used as raw meal in the ordinary Portland cement (OPC) making (participating in the production of cement aluminium hydraulic crystal phases and in accelerating the clinkering process) and also as a substitute to slag as a source of Fe_2O_3 in cement industry. As such, Pontikes and Angelopoulos [85] suggested an optimum content of 30 kg of RM addition per ton of OPC cement clinker.

Pozzolanic Properties

The characteristic of hydraulic (cementitious) materials is that they harden upon hydration due to the formation of reaction products, typically similar to cement hydration. In contrast to hydraulic material, pozzolans commonly itself possesses little or no cementitious property. But, in their finely divided form and in the presence of moisture, they chemically react with calcium hydroxide to form cementitious compounds, resembling that of cement hydration (pozzolanic activity) [86]. For any waste to be utilized in practical applications, the presence of pozzolanic active phase(s) introduces a positive perspective [87].

Most of the crystalline phases (hematite, quartz, rutile and anatase) in RMs are reported to be inert, while the poorly crystalline (aluminosilicates such as sodalite or cancrinite) and/or amorphous phases are reported to be pozzolanically active. In the Bayer process, the amorphous phase is formed during the so called desilication process, before the formation/crystallization of sodalite and cancrinite [88, 89]. Contradictory data regarding the presence of amorphous phase in the RMs can be noticed in the literature. Some researchers have reported that amorphous phase does not present a constituent component of RM, while others stated that RM composes of almost 48 wt% of amorphous phase [66, 90, 91]. Pascual et al. [73] identified the amorphous phase as an important constituent of Spanish RM. The quantity of 20 mass% was reported for the RM from Italy [79], 22 mass% for the RM from China [77, 92], while RM from UK documented to contain 38 mass% of amorphous phase and the highest quantity 48 mass% was reported for Australian RM [66]. Newson et al. [29] has reported the amorphous phase also as component of the sandy fraction of RM in the quantity of 34 mass% [29]. On the contrary, fully crystalline nature was reported for RM samples from Monte Negro, Italy and Ireland [35, 93, 94].

Kumar and Prasad [82] have reported the gain in strength of RM–lime mix, on account of formation of hydration products such as cementitious gel like phase. Pera et al. [95] have investigated heat treated (calcinated) RM, to which pozzolanic properties were assigned on account to reactions between alumina phase from RM and the addition of an activator—lime. Hydration products calcium-silicate–hydrate (C-S–H) and mono-carboaluminate phases are generally formed as a result of pozzolanic reaction. Liu and Zhang [96] and Pera et al. [95] have defined the pozzolanic activity of calcinated RM on the basis of lime/portlandite consumption. The reactivity of RM was attributed to the conversion of goethite and boehmite into the pozzolanic active phases, during the calcination process [95, 96]. Ribeiro et al. [97] investigated the pozzolanic activity index of RM in cementitious composites. The results showed that RM cannot be considered as a purely pozzolanic material since some of the requirements were not satisfied. But the study concludes that the amount of cementitious composites in RM are very close to the limit of standards, and thus, can be considered satisfactorily for the partial replacement of cement in secondary construction applications.

Findings discussed herein bear very practical significance in the perspective of RM utilization, as it possesses partial pozzolanic characteristics and, thereby, induces the desired strength to the matrix with which RM is admixed. On the other hand, the presence of pozzolanically active phases can fetch an advantage as RM can react with the admixing agents during the stabilization or solidification. More importantly, defining the extent of pozzolanic activity of RM helps in identifying the appropriate stabilizer(s) and calculating its optimum dosage.

Morphology

Morphological characteristics, which reveal features such as surface topography, particle size, shape and their variations, agglomeration of particles, and discrimination/identification of phases can be derived from scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) analysis [98]. It is well known that the flocculated structure offers good compressive strength characteristics on account of its interlocking capability of the particles.

For the alkaline waste like RM, stabilization and/or solidification is essential in order to improve its engineering properties. Morphological characteristics are an effective tool to assess the efficiency and ascertain the compatibility of a stabilizing agent. Furthermore, aggregation of particles by pozzolanic reaction or particles interlocking or bonding before and after stabilization or solidification can be visualized only from the morphological studies [98]. Shear strength is another important property of constructional materials and it highly depends on the internal friction, which in turn is greatly affected by the shape and size of granules [99, 100]. In this context, Jerves et al. [101] investigated the effect of morphology on the critical internal friction angle of RM particles and reported that it decreases with an increase in particle angularity.

Figure 5 depicts SEM images at different magnification factors to disclose morphological features of RM of NALCO, Damanjodi, Koraput. It is seen from the images that the RM composes of particles with different shape (roundness and sphericity)—from well-rounded to very angular and from highly spherical to highly elongated. It is known fact that shapes of the particles have a definite influence on strength properties. In line with the above statements, Das et al. [48] reported that particles in the RM (NALCO, Damanjodi, Koraput) are irregular in shape with different sizes, and Jitsangiam and Nikraz [63] reported that the red sand isolated (separated sandy fraction) from RM originating from Alcoa, Perth, Australia, composes of sharp edged particles. Perth RM was reported to have very high contents of quartz, which gives rise to angularity to particles. Larger quantity of sharper edged particles with rough surface can be related to the mineralogical composition (quartz presence in the sample). Figure 5 reveals a fact that RM particles have mixed morphology, with no prevailing particular shape form. Contrarily, the majority of natural sand particles will usually be prevalent with sharp edged form [54].

pH

pH of material is a principal parameter which drives the reaction forward or backward [66]. The incomplete washing of residue after digestion with caustic soda (NaOH) leads to the retention of Na_2CO_3 and $NaAl(OH_4)$ in the liquid phase or on the surface of the RM before its disposal, resulting in high alkalinity [102]. Different studies report that pH ranges from 10 to 13.5 regardless of the origin of RM [1, 27, 29, 41, 49, 54, 96, 103, 104] (Table 1). It is to be noted that pH of RM is substantially greater than any other waste materials like fly ash (pH 5.5), but comparable to steel slag (pH 10.6–12.9) [105] or other wastes [106].

In the context of neutralization of alkaline wastes, it is indispensable to take into consideration the buffering capacity and thus, reduce the alkalinity levels to such an extent

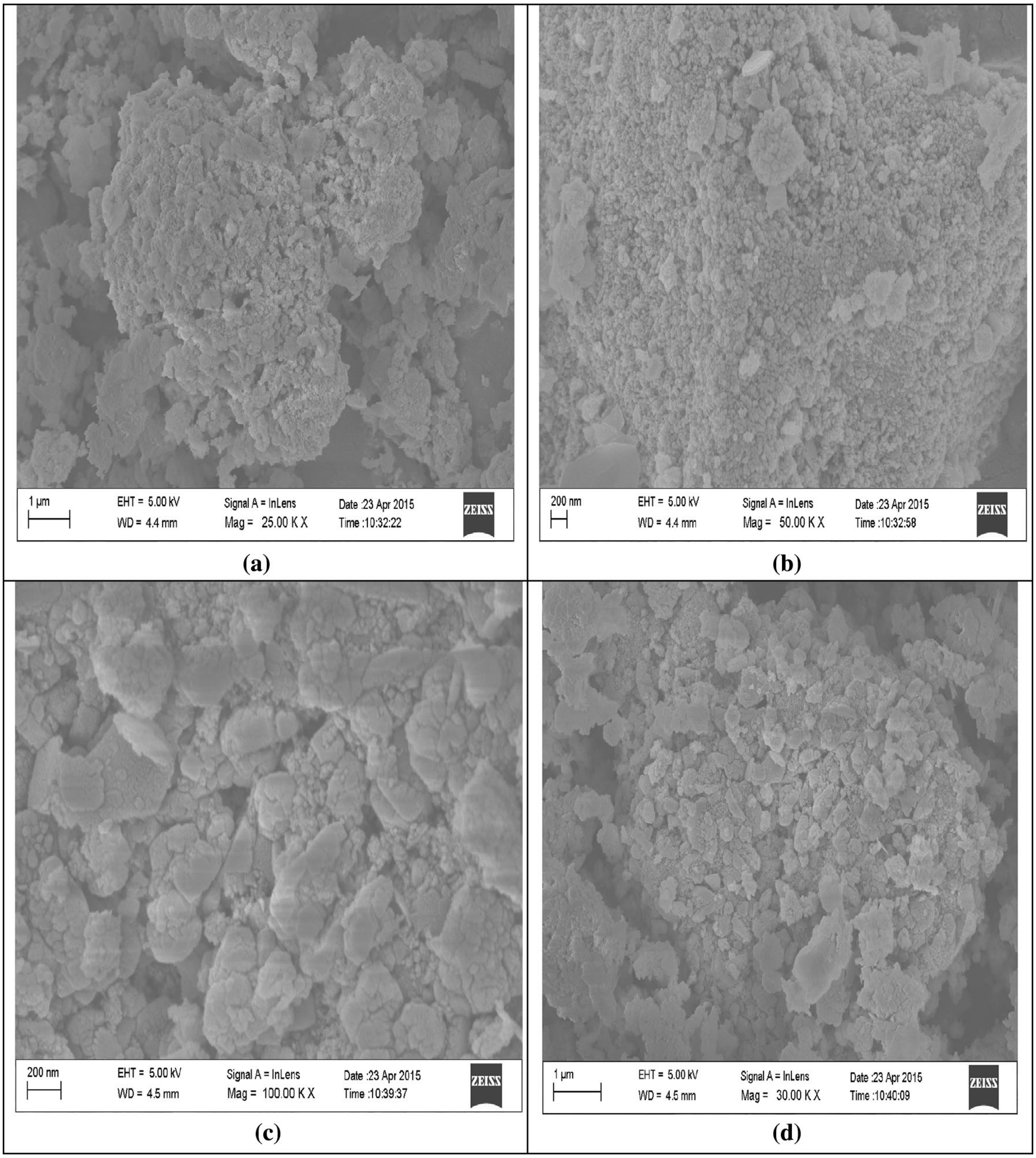


Fig. 5 SEM micrographs obtained at different magnification factors of untreated RM depicting different morphology [54]

to comply with different standards [107, 108]. It is mandatory to lower the alkalinity levels of the RM because it can affect the mobility of elements or conversely, it may impede the chemical reaction of RM particles when amended with stabilizers. Babu [109] emphasized that pH should be maintained at about 8 to obtain the elemental equilibrium as well as to eliminate the negative environmental impact. A study by Kutle et al. [110] showed that in the RM from Obrovac, a former alumina refinery in Croatia, negligible amount of mobile Cr at pH of 7 was identified, but its quantity rose by 48.4% when the pH was lowered to 3.5 due to the speciation mechanism of Cr. Similar results were obtained by Bartha [111] with the RM of the Ajka Alumina Refinery [112]. Hua et al. [113], who have admixed RM with natural soil, showed that the risk of elemental mobilization has been reduced in comparison to the RM alone. Further, Alam et al. [54] pointed out the threat of leaching of metal ions with a change in pH, in particular when the RM is used for the preparation of cement mortar. As such, the above studies clearly demonstrate variability in the mobilization of PTEs with a change in pH of the RM. Rubinos and Barral [84] has conducted leaching tests at different pH. They have concluded that a significant fraction of the metals was mobilised from RM only under very strong acid conditions, whereas Al is released in considerable amounts at pH below 5.3 [84]. However, studies pertaining to establishment of the relationship between pH and leaching of PTEs from RMs are relatively scarce.

Literature data reveal that the pH of RM can successfully be mitigated by amending with sea water [114–116], CO_2 [117], gypsum [118–120], fly ash [116], cow dung [74], etc. Treatment of RM with Ca^{2+} or Mg^{2+} brine solutions, which reduces the active Al and, thereby, inhibits the dissolution of tricalcium (TCA) in a soluble alkali, can also regulate its pH [121]. The soluble alkali present in the RM may lead to an increase in pH of the leached solution [2].

Studies also illustrate that pH is an important parameter that has a direct effect on the settling behavior of waste, as the particle surfaces commonly carry different electrical charge. In general, pH variation either retards or accelerates the settling phenomenon depending upon the concentration and chemistry of the suspension. The acidic treatment of RM leads to an increase in fines content and dispersion, which in turn increases the duration of settling. This observation confirms the study by Reddy and Rao [41], who investigated the settling characteristics of RM with different aqueous solutions (i.e. HCl and NaCl). The study reported that the settling duration of particles increased in HCl solution due to dissolution/dissipation and decreased in NaCl solution due to aggregation of particles. From these results, it can be inferred that the settling behaviour of particle in RM is influenced by the type of aqueous solution and its pH. Further, high pH causes negatively charged particles to repel from each other, resulting in dispersion of the RM particles [122, 123].

Leachability of Potentially Toxic Elements

One of the most important concerns raised regarding the use of RM is the environmental acceptability due to the possible release of PTEs (viz., As, Ba, Ni, Zn, Cu, Zr, Pb, Cr, V, Hg etc.). Concentrations of these elements can vary with the chemical compositions of the bauxite ore, extraction method adopted by the refinery and type of method employed for analysis (refer to Table 4). The leaching of different PTEs may be dictated by different environmental and climatic conditions. Studies pertaining to leaching of PTEs from RM with change of pH in the literature are scarce [84]. With this in mind, an effort is made to compile the data on PTEs reported by different researchers on RMs of diverse origin, as listed in Table 4. Further, the maximum permissible concentration of species given by USEPA guidelines [124–126] is also superimposed in order to check the hazardous nature of the RM as well as to compare the measured values with legislative limits. It can be noted that the results shown in Table 4 are pertinent to elements determined by resorting to toxicity characteristic leaching procedure (TCLP) only.

Though, most of the PTEs concentrations (Table 4) are found to be within the acceptable limits as per USEPA, concentration of a few of them are exceeded the prescribed limits: As [57], Ni [57, 127], Ba [128, 129], Zr [128–130] and V [128]. This observation obligates the requirement of stabilizing the RM for immobilizing the release of PTEs. On similar lines, Chandra and Krishnaiah [131], Urík et al. [132], Ghosh et al. [133], Zhang et al. [134], and Kim et al. [135] report leaching of PTEs at lower concentrations and stated that RM can be used as a nonhazardous material without impacting the surrounding environment.

Review of Geotechnical Properties

The ideal sector for practical and fruitful use of RM is the construction industry, especially geotechnical engineering. In such applications, synergetic benefits such as consumption of bulk quantity of industrial waste materials (residues and/or by-products) can be achieved. However, variability in geotechnical properties, from marginal to significant extent, is a big impeding factor for any waste, although it might have been picked up from the same source/location (i.e. disposal area). An important fact about the RM is that many of its mechanical and physical properties resemble that of clay and sandy soils, and also maintain similarities with clayey tailings [136]. In this context, it is crucial to establish detailed knowledge about the geotechnical properties of RM in order to recognise avenues for newer application schemes. A detail summary on various properties of RMs produced in India and by other countries is given in Tables 1 and 5. A detailed discussion on the geotechnical properties of the RM is presented in the subsequent sections.

Consistency Limits

A very general understanding about consistency limits is that soils which constitute with clay minerals can exhibit plasticity behavior, while degree of consistency depends on the type and amount of clay minerals present in it. For example, soils rich in montmorillonite type mineral phase commonly exhibit considerably high consistency indices such as liquid limit (w_L), plastic limit (w_P), and plasticity index (w_{PI}). Consistency indices, prima facie, provide basic information about the likely behavior of a soil with change in water content [137]. The plasticity index, in particular, reflects water holding capacity of a soil. Data presented in Table 1 shows the marked variability in consistency indices of RMs belong to different provinces.

It should be highlighted that the presence of clay minerals such as kaolinite, illite, and montmorillonite (that are commonly found and abundantly available minerals in

Table 4 Assessment of toxicity of red mud based on measured heavy metal concentrations in bulk and leachate of red muds of different origin

Literature	Units	Method	Pb	Zn	As	Cu	Ni	Ba	Cr	Zr	V	Hg
Urik et al. [132]	mg/kg	–	129.2	131.3	48.9	60.3	219.2	–	401.4	–	–	–
Kolencsik-Tóth et al. [127]	ppm	Multi stage acidic leaching, $KClO_3$	128	55	85	39	122	–	506	–	–	–
Qu et al. [128]	ppm	Bioleaching (spent medium)	0.61 ± 0.02	15.00 ± 0.85	8.60 ± 0.22	ND	3.43 ± 0.10	4.83 ± 0.17	5.19 ± 0.09	0.96 ± 0.07	4220	–
Wang and Liu [57]	ppm	–	56.6	103.2	267.3	78.2	984.9	212	537.8	–	–	–
Mohapatra et al. [129]	ppm	–	8.51	19.62	–	12.34	5.41	23.52	84.75	46.36	–	–
Ghosh et al. [133]	mg/kg	Microwave digestion	20.224 ± 1.167	ND	–	41.3 ± 5.01	ND	–	395.14 ± 30.20	–	–	–
Cusack et al. [118]	mg/kg	Untreated	32.22 ± 1.785	68.7 ± 1.205	21.9 ± 1.73	ND	11.07 ± 0.58	28.85 ± 1.1	1289 ± 20.5	–	–	–
Li et al. [138]	ppm	Untreated	120	16.2	13.6	39.2	68.5	83.4	322.6	1159.1	366.8	–
Misik et al. [188]	mg/kg	Untreated	22.2–143	42–123.4	17.8–22.3	26–112.1	12.5–283.1	120.4–417.5	40–703.3	180.2–920.5	57.9–898.8	–
Burke et al. [189]	µg L^{-1}	Leachate	405	–	6325	429	35	–	65	–	8977	–
Di Carlo et al. [190]	mg/kg dm	Unamended residue	–	13–26	0.4–0.65	4.6–5.4	2.3	–	2–2.5	–	1.5–5	0.08
Gruiz et al. [191]	mg/kg	Untreated	84.8	105	36.5	38.5	182	80.1	419	–	–	0.50
Higgins et al. [192]	µg L^{-1}	Leachate	–	–	3125	–	35	–	148	–	13.500	–

USEPA [154]: As-75 ppm, Cr-0.1 ppm, Cu-4300 ppm, Pb-420 ppm, Hg-840 ppm, Ni-75 ppm, Zn-7500 ppm, USEPA [126]: Ba-2 ppm, NSF [193]: Zr-0.7 ppm, USEPA [125]: V-0.05 ppm

Table 5 Summary on properties of red muds belonging different parts of the world

Reference	Materials	Property	Remark
Kalkan [30]	Red mud, clay, cemented red mud	UCS, hydraulic conductivity and swell percentage	Decreases in hydraulic conductivity, swelling percentage and increases in compressive strength. plasticity of soil reduced from high (CH) to low (MH)
Parekh and Goldberger [194]	Red mud	Basic characterization	Chemical, particle size, and mineralogy of red mud changes with origin of bauxite ore
Somogyi and Gray [156]	Red mud	Consolidation, physical properties	Reported that RM waste shows geotechnical properties similar to clayey tailings
Newson et al. [29]	Red mud	Physical, chemical and geotechnical properties	Reported no clay or quartz minerals in RM, the mechanical behaviour of red mud is similar to clay and sand due to electrically charged properties of the hematite, goethite and hydroxysodalite
Nikraz et al. [157]	Red mud, bitterns	Properties of red mud after neutralization	Studied the strength and compaction properties of raw and treated RM with carbonation and bitterns (NaCl) Found decrease in bulk density and increase in void ratio of treated waste and marginal changes in -value
Khaitan et al. [116]	Red mud (RM)	Red mud (RM) neutralized by carbon dioxide (CO_2)	Red mud pH reduced to 7.7
Rai et al. [2]	Red mud, sea water	Neutralization of red mud by sea water	pH value of slurry reached to 8.0 (disposable limits)

clayey soils) in the RM was not documented, as clay minerals (especially kaolinite) react with the Bayer liquor and DSPs (mainly sodalite and cancrinite form) even at the low temperature digestion circumstances. Usually sands are non-plastic materials, whereas clayey soils exhibit plastic behavior due to the presence of clay minerals as aforementioned. Even though, clay mineral phases are not constituents of RMs, it still exhibits plasticity characteristics (Table 1). Studies attribute it to the constituent particle sizes, which range from clay to silt size, along with electrical charge particles of hydroxy sodalite, cancrinite, goethite, and hematite minerals [29, 68].

It is seen from Table 1 that almost all the studies available in the literature document that the RM can exhibit plasticity behavior. Figure 6 shows the review of RM classification by different authors. By most of the studies, RM is classified as 'inorganic silts of low to high plasticity type material (i.e. ML or MH)', as shown in Fig. 6. From Table 1, it can be observed that the values of liquid limit (w_L) and plasticity index (w_{PI}) fall in the range of 38 – 64%, and 5 – 22% respectively. Depending upon the location and origin of the RM, a distinct variability in the values of w_L and w_{PI} is clearly visible. The variability may be attributed to grade of bauxite ore, its chemical and mineralogical compositions, the process technology and dissimilarity in proportions of electrically charged particles. Moreover, variability in w_L and w_{PI} may also be linked to the proportions of oxides composition. As such, RMs belong to China and Jamaican showed higher consistency limits, while those originated from India and USA manifested moderate to low consistency limits [138, 139]. These findings are in good agreement with the results of Villar et al. [37], who reported how the extraction process and grade of bauxite ore influence the consistency limits of RM originated from Brazilian rain forest. On the other hand, Rubinos et al. [49] showed that there is no influence of temperature on the consistency limits of RM (ALCOA-San Cibrao Bauxite Refinery, Lugo, Northwest Spain). However,

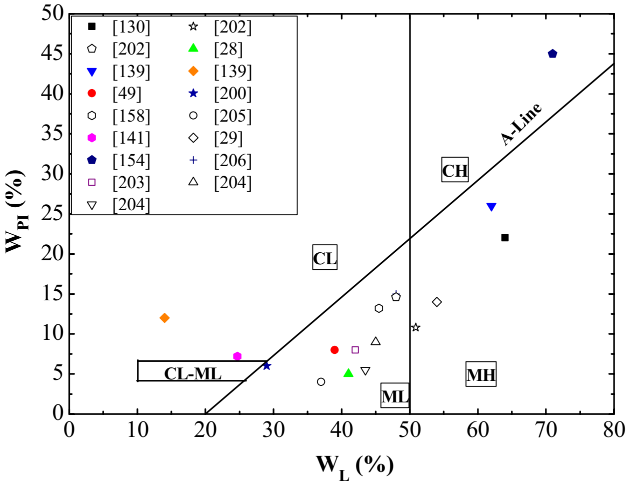


Fig. 6 Plasticity index of different red mud's around the world

it is not clear which oxide(s)/mineral phase(s) induce such greater plasticity behavior to the RMs.

Linear and Volumetric Shrinkage

Linear shrinkage is an indicative of expansion by a clay soil under varying moisture conditions. Plasticity is directly proportional to the shrinkage, as the plasticity is high so does the linear shrinkage [140]. Parameters like percent fraction, mineralogy, and type of exchangeable cations present also can have an influence on shrinkage characteristics. A material tends to undergo significant shrinkage if it contains lower concentration of Na^+ ions, finer particles, and minerals of low crystalline degree [49]. On the contrary, researchers have reported low values of linear ($<6\%$) and volumetric shrinkage ($<2\%$) for the case of RM, although it constituted with a substantial amount of Na^+ ions and that the quantity of finer particles was more than 90% [49, 54, 141, 142]. The reason for RM exhibiting lower linear and volumetric shrinkage may be due to the low plasticity characteristics, in addition to comprising of low degree of crystalline minerals such as goethite [76, 141]. It also depends whether the Na is bound in DSPs or is in the porewater. If a given soil exhibits the shrinkage limit of below 10 and the linear shrinkage of above 8, it is defined to be a critical degree of expansion [143]. The linear and volumetric shrinkage values of RM are significantly low and thus, it falls into the category of non-critical (low degree of expansiveness) [144]. The properties of linear and volumetric shrinkage stem their importance on the compressive strength of RM blocks and also in the formation of surface cracks upon drying [145, 146].

Compaction or Moisture–Dry Unit Weight Relationship

Establishment of dry unit weight versus water content relationship for a given material is vital in construction projects as it influences the mechanical behavior [147, 148]. Determination of compaction parameters gains more attention in the case of RM in light of alkali content (Table 1) and dominance of iron oxide, in particular, (refer to Tables 2, 3) [28]. Therefore, the effect of these parameters on compaction parameters (dry unit weight, γ_{dmax}, and optimum water content, w_{opt}) need to be understood critically. Studies related to evaluating the influence of iron oxide, specifically when its content exceeds that in natural soils, on the compaction characteristics are not reported. On the other hand, several studies Panda et al. [1], Reddy and Rao [28, 39] postulated variability in the values of γ_{dmax} and w_{opt} for the investigated RMs of similar origin. For the sake of clarity, compaction curves established for different compaction energy [standard Proctor (SP) and modified Proctor (MP) tests] are reproduced and presented in Fig. 7. The curves clearly demonstrate that RM is sensitive to moisture content and the same is reflected in greater compaction energy requirement to obtain reproducible results. For clarification, dry unit weight versus water content relationship established on RMs of diverse origin are compiled and reproduced in Fig. 8. Additionally, typical compaction characteristics of a variety of wastes and by-products were also assimilated and reproduced, as shown in Fig. 9.

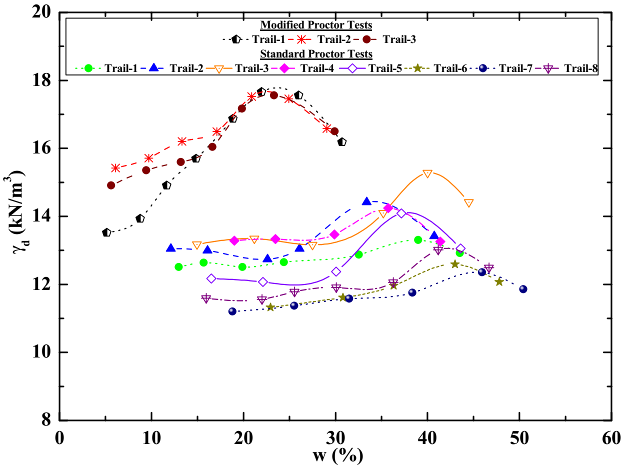


Fig. 7 Dry unit weight versus water content relationship on identical samples of untreated RMs [16]

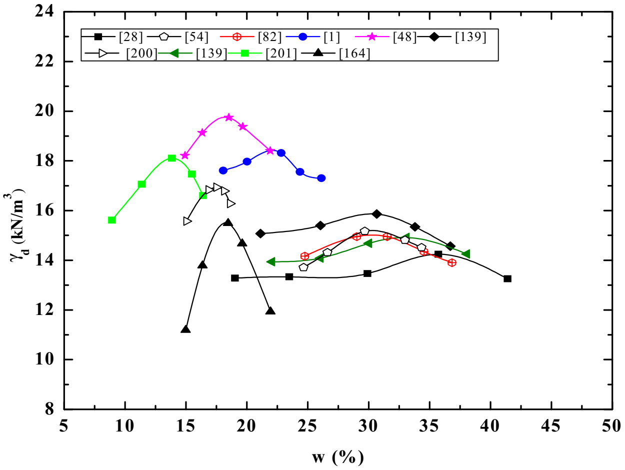


Fig. 8 Dry unit versus water content relationships of the RMs of different origin

As depicted in Fig. 8, an inherent variability in nature of compaction curve is clearly distinguishable. A disparity in peaks of the curves varying from very broad to sharp, resembling that of clay to silt to fine sandy soils [46], with variability in the values of γ_{dmax} and w_{opt} can be noticed. Further, it is seen from Fig. 9 that compaction characteristics of RM resemble to other waste types, except that of

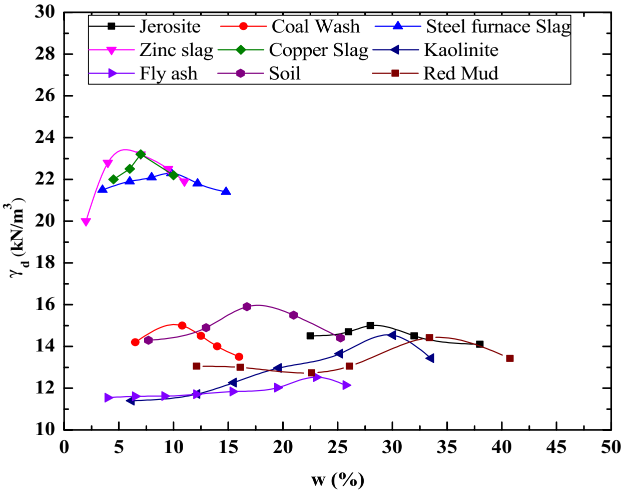


Fig. 9 Comparison of compaction characteristics of RM with other waste materials (modified after Reddy and Rao [16])

non-ferrous slags, whose dry unit weights are extremely high with significantly low water contents.

RM comprises of various mineral phases in different proportions, which in turn can bear significance on its compaction characteristics. Moreover, the proportions might vary with the type of bauxite ore, place of origin, and process technology, including method of extraction. Therefore, it is expected that RMs of different origin will exhibit their unique compaction characteristics. Evidently, the same is reflected from the compaction curves presented in Fig. 8, wherein, it is seen that the nature of compaction curves differ from source to source with diverse γ_{dmax} and w_{opt} values. Furthermore, Fig. 8 also substantiates a fact that RMs of same origin also produce dissimilar nature of compaction curves. As such, it can be inferred from the results presented in Figs. 7, 8 and 9 that the influences of alkali content and oxides composition on the compaction characteristics are impending.

In order to avoid the necessity of applying higher compaction energy needed for obtaining maximum dry unit weight and optimum water content, Reddy and Rao [28] have suggested treating of the RM by chemical solutions (e.g. HCl and NaCl) or waste materials (e.g. fly ash and GGBS).

Shear Strength

For proposing any soil or waste or by-product as a geomaterial for practical applications, it must exhibit adequate shear strength, complying to guidelines of standards [108, 149]. Many studies highlight that the RM has a capability of yielding reasonably good compressive strength, in spite of extreme alkalinity [48, 57, 150], and the strength behavior is quite similar to clayey or sandy soils [29]. As discussed in the context of gradational characteristics, the RM comprises of significant fines fraction, which has a tendency to adsorb large amount of water, which in turn causes poor contacts between the grains leading to reduction of resistance against applied stresses.

Jain [151] and Panda et al. [1] measured the unconfined compressive strength (UCS) of untreated RM in the range of 150–250 kPa, which is appreciably low matching with clayey soil of low to high plasticity (i.e. CL/CH). Sundaram and Gupta [27] based on in situ penetration tests categorized that RM behaves similar to soft soils. The dry RM seems to yield reasonably high shear strength due to the change in particle morphology [49]. Vogt [152] reported that the undrained shear strength of RM is higher than the uncemented clay. Authors attribute this to high frictional resistance offered by the particle fraction and particle morphology. In this context, it is worth to mention here that very high quartz content was found in the bauxite ore from Darling Range, Perth (Australia) and resulting RM. The quartz in these materials exists as angular particles, which is advantageous for RM to exhibiting greater shear strength properties [63]. Morphological characteristics shown in Fig. 5 confirm these observations. Additionally, shear strength parameters such as cohesion and friction angle of RMs of different origin were compiled and listed in Table 1. Apparently, very high frictional angle in the range of 26° − 45° can be noticed. Although, RMs are categorized as material exhibiting low to high plasticity characteristics (Table 1), yet they exhibit significantly high friction angle, matching with that of fine to coarse sand (27°−45°) [153]. On the other hand, the cohesion, as reported by many researchers, appears to be less in the range of 7−20 kPa (Table 1). Based on the results presented in Table 1 and Fig. 3, dependency of the high friction angle on the larger particles replicating that of sand size and their morphology can be inferred. These findings further validate the studies performed by Alam et al. [54], who evaluated the sphericity of RM particles (coarse sandy fraction of RM) and postulated that the frictional resistance increases with decrease in sphericity, and Srivastava [154], who measured cohesion and shear strength of the RM in the range from 1.77−7.7 kPa and 29−131 kPa respectively. Nikraz et al. [29] determined the drying characteristics and strength properties of untreated, carbonated and bittern RMs and compared the properties with seasonal variations (summer and winter). The carbonated RM showed low strength of 20 kPa after 37 days of stacking, whereas the strength of untreated RM measured during the summer season was even lower. Studies also show that the loss of shear strength can occur when the RM is exposed to an acidic environment [28, 29, 39].

The observations made herein have been further validated by a series of UCS and unconsolidated undrained (UU) tests performed on RM samples of Indian origin. A set of samples were prepared at different compaction states: dry unit weight from 13.6 to 14.8 kN/m^3 and optimum water content from 32 to 37%. Results obtained are presented in Figs. 10, 11, 12 and 13. From Fig. 11, it can be observed that with an increase in water content, strength decreased drastically from 270 to 80 kPa, almost to one third of the original value. Further, the increase in density led to increase in strength of the RM. The maximum and minimum strength values measured are as: 900 kPa and 80 kPa, respectively. Variability in the stress–strain response is evident from the graphs. This

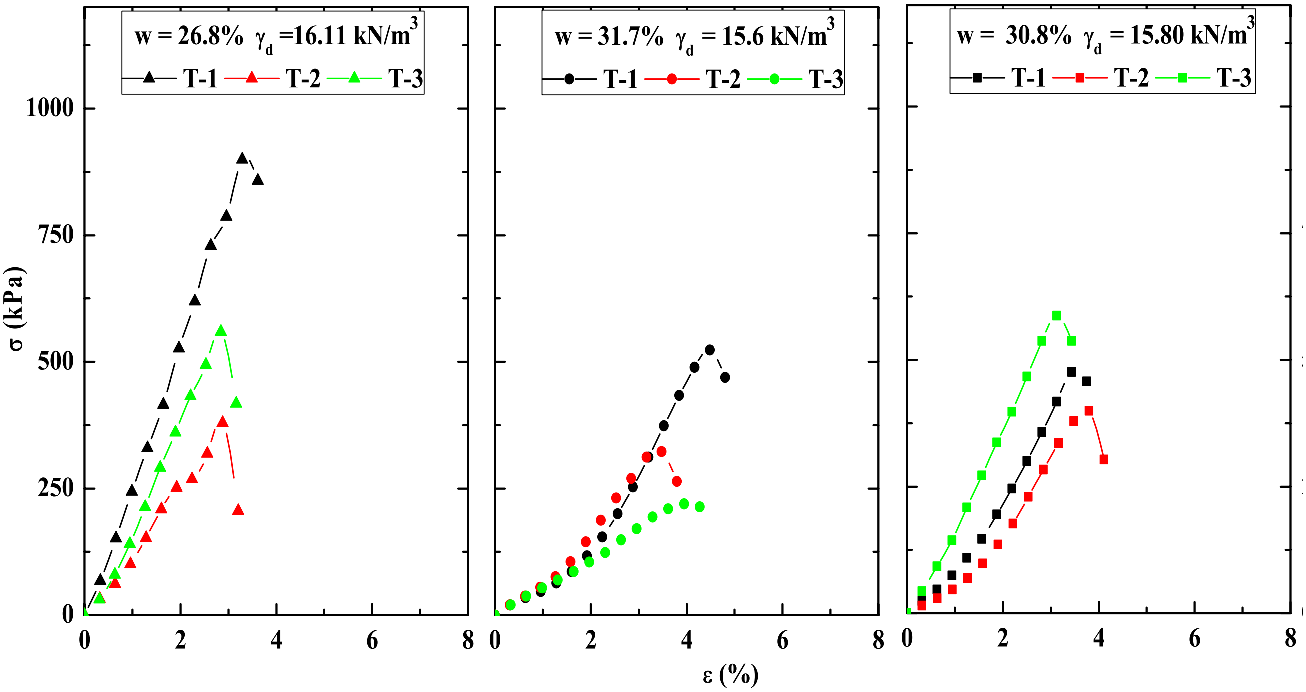


Fig. 10 Influence of compaction state on stress–strain response of RM obtained from UCS tests

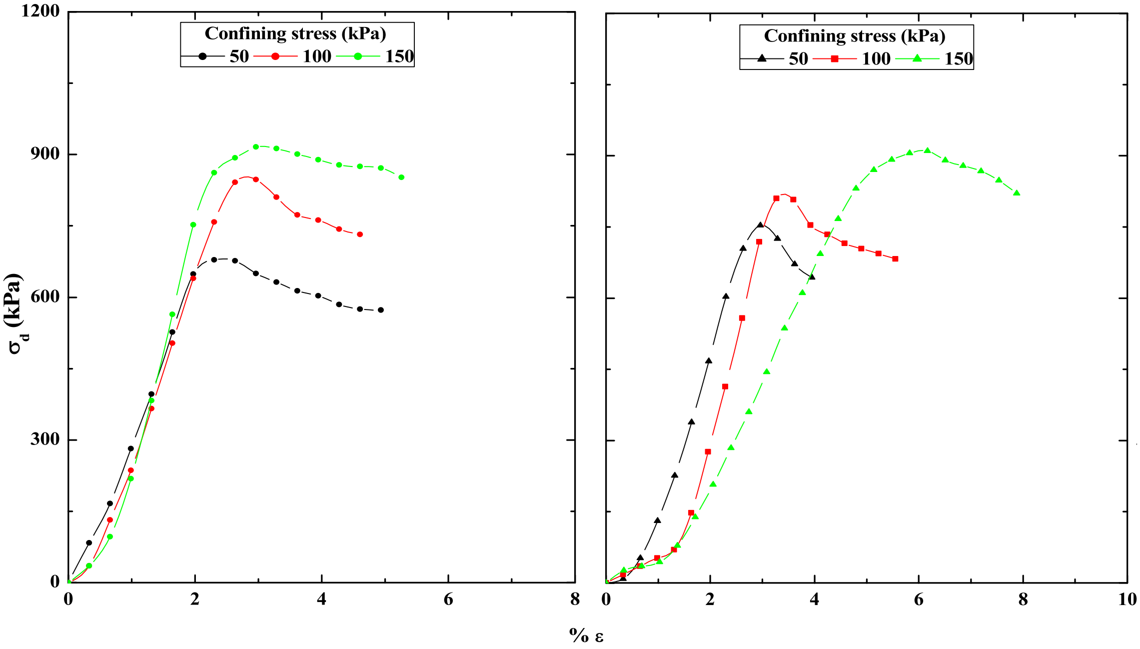


Fig. 11 Stress versus strain response obtained on untreated RM at different confining pressures by conducting (UU) tests

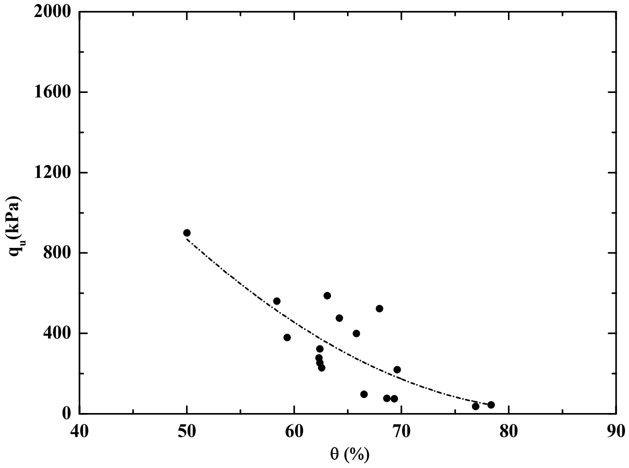


Fig. 12 Variation of compressive strength (q_u) with volumetric water content (θ)

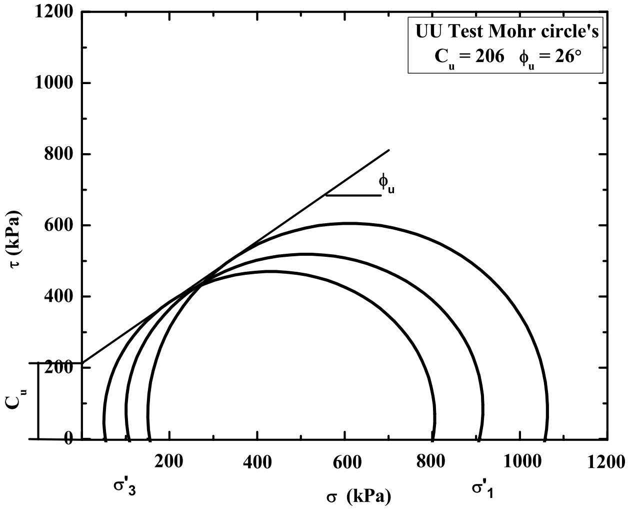


Fig. 13 Mohr–Coulomb failure envelopes from triaxial unconsolidated undrained (UU) test results

variability is pronounced with change in density rather than water content. To have a better understanding on the strength properties, the compressive strength is plotted against volumetric water content, which is a product of water content and dry unit weight, as depicted in Fig. 12. It is obvious from the results that the relationship between compressive strength and volumetric water content is non-linear, while compressive strength became constant when volumetric water content (θ) exceeded 50%. It can be concluded that desired high compressive strength can be attained, only if RM is compacted to a relatively denser state.

In Fig. 11, the results of UU tests conducted on samples compacted at w_{opt} (31%) and γ_{dmax} (15.4 kN/m^3) at a confining pressure of 50, 100, and 150 kPa are shown. It can be observed that as confining pressure increases so does the ultimate stress. Using the data of Fig. 11, Mohr–Coulomb failure envelop was developed to determine shear strength parameters such as cohesion and friction angle, as depicted in Fig. 13. The failure envelopes distinctly demonstrate a very high friction angle of 26°. Conversely, the results show reasonably high undrained cohesion of about 206 kPa, which is substantially greater than that reported by several researchers (refer to Table 1). Interestingly, the friction angle is comparable with normally compacted clays (20°–26°) and fine sands. Higher friction angle (37–45° and 38°) has been reported by Newson et al. [29] and Rubinos et al. [49] based on triaxial and direct shear test results. The high friction angle was also reported by Alam et al. [54] based on the tests on coarse sand fraction of RM.

Hydraulic Conductivity and Compressibility

Permeability is one of the important properties for the selection of a geomaterial for waste containment liner or cover systems [49], whose performance has a strong interrelation with it. Generally, the compaction and hydraulic conductivity, *k*, are interrelated. The low hydraulic conductivity can be obtained by compacting the soil to a greater dry unit weight [146] or alternatively by filling the pores with fine materials [30, 49]. The void ratio is the major parameter which influences the hydraulic conductivity. RM has more than 90% of particles in the form of fine fraction (<0.075 mm). These fine particles can drastically decrease the hydraulic conductivity of the RM by acting as filler in the pore spaces. Gore et al. [104] determined *k* value of the RM by rigid and flexible wall permeameter methods with and without back pressure and reported it as 10^{-6} cm/s. The RM practically allows low flow rates to be suitable it as a resource material for a levee application. Similarly, Kalkan [30] has demonstrated based on the permeability studies that the RM can be used for the modification of clay liner system, which in turn reduces the cost of stabilization as the RM is a freely and abundantly available waste material. The RM *k* value is comparable to natural clay samples (10^{-9} to 10^{-6} cm/s) [153], and it can further be reduced by resorting to stabilization in order to comply the required value (i.e. less than 10^{-7} cm/s) defined by the guidelines of USEPA to be used as clay liner material [155].

The compressibility of RM is an important property to classify it as ML (silt of low plasticity), even though the behavior resembles that of CH (clay of high plasticity) soils [104]. The consolidation characteristics of RM have not been widely researched [28, 156, 157]. Studies pertaining to RM specifically highlight that its compression behavior is quite similar to the clayey soil. Studies report the compression index for RM in the range of 0.202–0.56 [28, 49, 104, 136]. It is also important to note that the plasticity behavior of the RM is low to medium, but its compressibility values are yet low. In fact, for the same value of plasticity index (w_{PI}) between natural clay and RM, the latter material exhibited low compression index than the former one. The coefficient of consolidation, which represents the capability of a material to undergo consolidation with an increase in pressure, for RM is measured in the range from 3.64×10^{-2} to 4.75×10^{-2} cm^2/s [49]. The low compressibility is advantageous in terms of selecting RM as a substitute to natural soils, which can solve disposal and storage problems associated with it, perpetually.

California Bearing Ratio

CBR is widely used parameter for determining the thickness of a subgrade, an important integral part of the pavement structure. The presence of weak soil in the subgrade leads to poor performance of pavement with possible cracking, rutting, and pothole formation. Therefore, it is essential to ensure the subgrade material possesses high enough CBR value in accordance with the respective standards. Jitsangiam and Nikraz [63] have highlighted that the soaked CBR of stabilized RM is greater than that of unsoaked one. Based on the CBR value, RM after stabilizing with fly ash was used successfully to build 200–300 mm thick subbase layer for a road in Western Australia.

In view of data scarcity on Indian RMs, CBR of Indian RM before and after amending with granulated blast furnace slag (GBS) in varying percentages and curing periods is measured and the results are presented in Fig. 14. The results show a considerable increase in CBR value with the addition of GBS. The increase is continued up to 20% of GBS addition and thereafter, it stagnated under both soaked and unsoaked conditions. Apparently, the CBR under unsoaked condition is superior to the soaked condition, and there is a significant improvement in the values from 0 to 7th day curing period. The increment in CBR value accounts for the arrangement of particles and its close packing. Generally, CBR test is referred to as a penetration test and therefore, bonding is not the main criterion in this test. The addition of coarser material to RM enhances the resistance to penetration and, thereby, improves the CBR value. The results presented in Fig. 14 correlates excellent with the findings reported by Deelwal et al. [158], who observed an increase in CBR with the addition of 8 wt% hydrated lime and 1% gypsum. Similarly, Mukiza et al. [159] have observed that RM can be used as a stabilizer for strengthening the weak subgrade soils. It has been found from other studies that the enhancement in CBR can also occur due to the pozzolanic reaction [103, 160]. As such, utilization of RM in road and pavements can consume huge quantity, possibly aiding in mitigating disposal and environmental issues [28, 159].

Dispersion Behavior

The conventional geotechnical tests fail to portray the dispersion behavior of a material. In most practical scenarios, wastes or by-products may well satisfy all the suitability requirements for a particular application, but often not meet the dispersivity aspect. Hence, separate experimentation becomes necessary to assess dispersivity of wastes or by-products, especially when they have to be used as a substitute for natural geomaterial or in the construction of dikes, embankments, and other geotechnical structures, which are frequently exposed to flooding [161].

The absence of clay minerals and the presence of significant sodium content apparently found to exacerbate dispersion behavior in the RM [20, 41, 43]. Many studies based on results of crumb, sodium absorption ratio, cylindrical dispersion, and pinhole tests confirm the dispersion behavior of RM from high to very high [20, 31, 40, 48, 67]. The presence of highly exchangeable sodium ions, which commonly

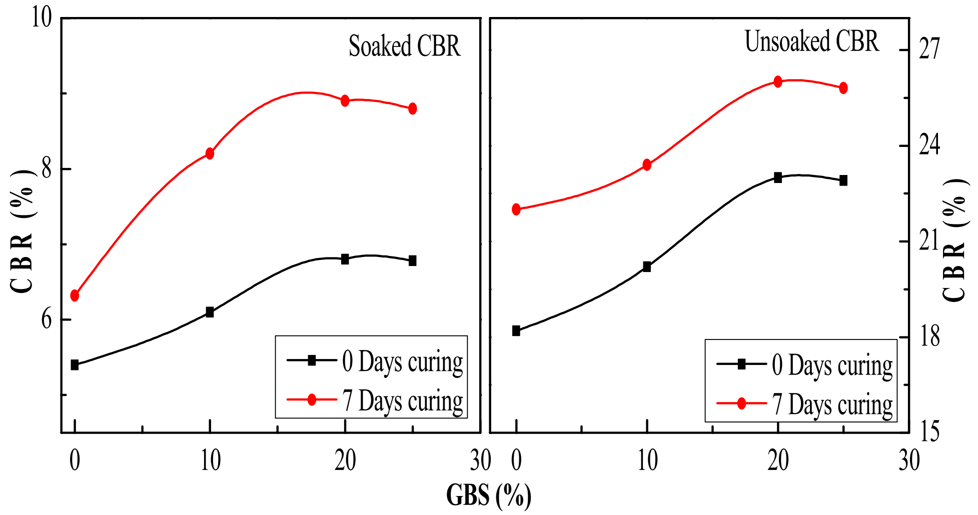


Fig. 14 Variation of CBR values of RM stabilized with GBS at different percentages and curing periods

led to the formation of single grained particles, coupled with silt in a significant amount can affect the dispersion and erosion characteristics [161].

Materials which exhibit dispersive nature are commonly not selected for constructing earthen structures, unless they are adequately stabilized or treated with chemical additives. Erosion resulting from dispersion can be remediated by stabilizing the RM with suitable additives such as lime, cement, and gypsum. Addition of these agents increases the electrolyte concentration and replaces Na^+ with Ca^{2+}, leading to flocculation effect which in turn obviates the dispersivity [82, 103, 162]. Studies conducted by Reddy et al. [20] and Alam et al. [67] demonstrate that 0.5−1% of biopolymers such as guar gum and xanthan gum can effectively control the dispersive nature of RM. The addition of biopolymer by forming hydrogen and ionic bonding prevents the RM exhibiting the dispersion behavior [20, 163]. Ding et al. [22] studied Lignosulfonate's (LS) as a stabilizer and found that it is effective in the prevention of erosion in coarse RM. Alternatively, Rout et al. [164] and Gore [139] have recommended covering the RM with locally available soils to avoid dispersion.

Collapse Potential

Generally, collapsible behavior is associated with an open structure formed by coarse shaped grains, low initial density, low natural water content, low plasticity, relatively high stiffness and strength in the dry state, and often by particle size in the silt to fine sand range and fabric [165, 166]. Natural soil deposits and engineered compacted fills may exhibit volume-moisture sensitivity if compaction specifications and quality control measures are not met appropriately. Compaction to lower dry density reflects in the greatest susceptibility to collapse upon wetting. The major volume change in a practical situation is always triggered by sudden contact with water, which can be anticipated over the waste storage facilities possibly during the torrential rains. RM also comprises of angular particles with considerable finer fractions, apart from showing low plasticity, and thus, it may tend to exhibit collapse potential. Unfortunately, previous studies in the literature that deals with estimating the collapse potential of the RM are nil. Hence, attempts are made to measure the collapse potential of RM with the help of oedometer tests. Figure 15 shows the void ratio versus applied load relationship established on RM samples compacted to two different compaction efforts (SP and MP). The qualitative assessment of soil collapse potential proposed by ASTM D5333 [167] is also given in Table 6. From the results presented in Fig. 15, it is seen that the measured collapse index, I_e, varies from 0.06 to 0.25%. As per the Table 6, the degree of collapse potential for RM can be designated as 'none to slight', indicating that RM may not have a tendency to exhibit collapse potential.

Table 6 Qualitative assessment of soil collapse potential (US Department of Transportation and ASTM D5333 [167])

Degree of specimen collapse	Collapse index, I_e (%)
None	0
Slight	0.1 to 2.0
Moderate	2.1 to 6.0
Moderately severe	6.1 to 10.0
Severe	> 10

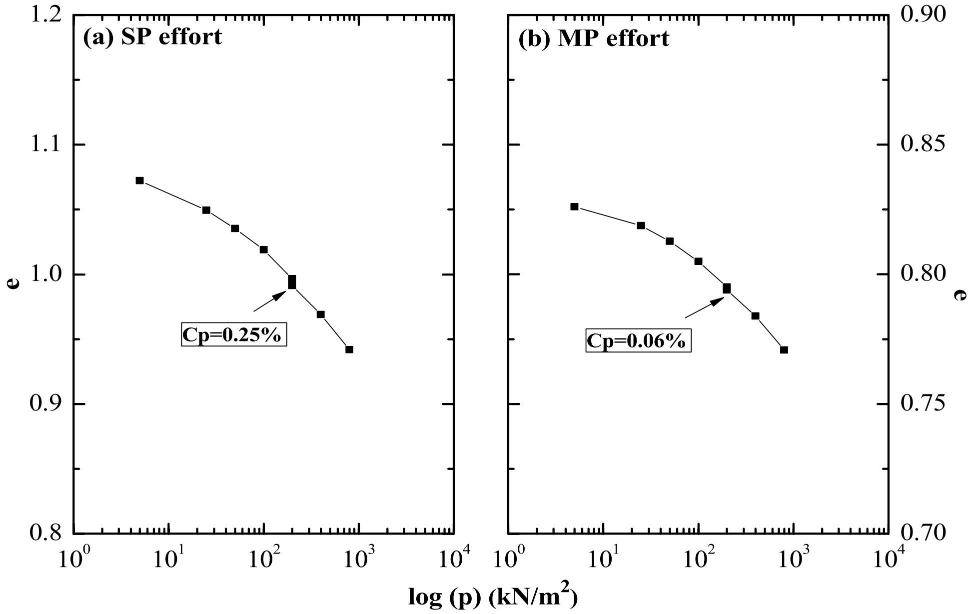


Fig. 15 Determination of collapse potential of red mud at **a** standard Proctor (SP) and **b** modified Proctor (MP) compaction efforts

Assessment of Geotechnical Engineering Applications

As discussed in the context of mineralogical and chemical compositions, in addition to the hydroxy sodalite, electrical charge nature of goethite and hematite minerals do also contribute for the mechanical behavior of RM [29]. Studies of Reddy and Rao [40] and Alam et al. [67] confirm the same fact by comprehensively measuring the zeta potential under variable pH conditions. It is seldom, a waste is selected for a particular geotechnical application based on a single engineering property, rather it must meet requirement of multiple engineering properties. A critical summary on the suitability of RM for a particular field application based solely on (a) code specification(s) and (b) standard with engineering property, in tandem, is shown in Tables 7 and 8. It is obvious from the data presented in these tables that the RM complies with several standard specifications, rendering its suitability as a potential geomaterial in diverse field applications. A closer observation of Table 8 reveals a narrow scope for acceptability of untreated RM and, evidently, wider applicability of treated RM.

Generally, soils having a specific gravity up to 2.7 can be used for constructing the embankments, as it is desirable that the minimal stresses are transmitted safely to the underlying soil layers. As per the values of G_s listed in Table 1, almost all RMs are found to comply with this property. On the other hand, IRC 37 [149] and IRC SP 20 [107] standards recommend w_L and w_{PI} of less than 25% and 6% respectively, while Western Australia 501 [168] (Tables 7, 8) standard suggests the same not exceeding 30% and 10% respectively for selecting geomaterial as a resource material in pavement layers. As such, the consistently greater w_L values shown in Table 1 manifest that RM does not satisfy any of these code specifications. Incidentally, low to high w_{PI} values meet almost every standard specification. Thus, it is prudent to affirm based on the index properties that appropriate stabilization is warranted prior to utilization of RM. A study by Panda et al. [1] proves this fact, where in the study the values of w_L and w_{PI} of sugarcane molasses and microbes treated RM were measured as 10.96% and 0.66%, which very well comply with the guidelines of the above standards. It is important to note that the low values of w_{PI} are beneficial for the RM when it is to be endorsed for constructing subgrade layer of a pavement [164].

Soils exhibiting greater w_{PI} undergo significant compression or settlement [153]. Though w_{PI} values of RMs vary from low (5%) to high range (22%), the compression index vary in the range of 0.0933–0.41 [49, 104, 156]. In fact, the consolidation characteristics of RM were studied only by a few researchers: Somogyi and Gray [156], Nikraz et al. [157], Reddy and Rao [28], limiting the scope to interpret the data in a broader spectrum. Similarly, the coefficient of consolidation is also measured low, ranging from 3.5×10^{-2} to 10.3×10^{-2} cm^2/s. These low compressibility characteristics render the RM as a resource material for constructing embankments, clay liners, foundations, and structural fills (refer to Table 8).

Despite the different origin of RMs, they all commonly consisted of fines (silt and clay size particles) as a major fraction, as evident from Table 1. It can also be reasoned out that the large fraction of fines can significantly contribute for low hydraulic conductivity characteristics. This validates

Table 7 Suitability of RM for different field applications as per the code specifications

Relevant code	Potential application								
	Subgrade	Sub-base	Embankment	Earthen cover	Low volume road	High volume road	Structural fill	Clay liner	Building material
IS 1498 [195]	✓		✓						
IRC SP 20 [107]	✓		✓	✓	✓				
IRC SP 72 [196]	✓				✓				
MoRTH [174]	✓		✓						
IS 1498 [197]			✓		✓	✓			
MoRD [198]	✓		✓						
IRC 37 [149]		✓							
BS 3921 [175]									✓
IRC 36 [199]	✓		✓		✓	✓			
Main Roads Western Australia 501 [168]		✓							
USEPA [124]								✓	

Table 8 Assessment of potential applications of the pre- and post-treated RM based on different geotechnical properties

Property	Potential application								
	Sugrade[a]	Sub-base[b]	Embankment[c]	Earthen cover[d]	Low volume road[e]	High volume road[f]	Foundation[g]	Clay liner[h]	Structural fill
Dry unit weight (kN/m^3)									
Pre	✓	✓	✓	✓	✓	✓	✓	✓	✓
Post	✓	✓	✓	✓	✓	✓	✓	✓	✓
Permeability (cm/s)									
Pre							✓	✓	✓
Post	✓		✓					✓	✓
Index properties									
Pre								✓	
Post	✓	✓	✓		✓		✓	✓	✓
q$_u$ (kPa)									
Pre									
Post	✓	✓	✓		✓				
CBR (%)									
Pre					✓				
Post	✓				✓	✓			
Compressibility									
Pre	✓	✓	✓		✓	✓	✓	✓	✓
Post	✓	✓	✓		✓	✓	✓	✓	✓
Dispersion									
Pre	No	No	No	Yes	No	No	No	No	No
Post	✓	✓	✓	✓	✓	✓	✓	✓	✓
Collapse potential									
Pre	Slight	Slight	Slight		Slight	Slight	Slight	Slight	Slight
Post	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

[a] References [107, 167, 174, 196, 198, 199]

[b] Reference [168]

[c] References [107, 174, 195, 198, 199]

[d] Reference [107]

[e] References [107, 196, 199]

[f] References [149, 195, 199]

[g] Reference [195]

[h] Reference [124]

the data reported by Taha and Kabir [169], who concluded based on the gradation properties that RM can be chosen as a liner material in landfill disposal systems and that the fines could effectively prevent the migration of pollutants into the environment. Hydraulic conductivity is one of the deciding parameters for characterizing the material to be selected as a liner material. Although, soils with high swelling potential show apparently low-hydraulic conductivity, these soils crack upon drying and show susceptibility to chemical attack, resulting in permeation of liquids released from storage unit into the surrounding environment. In this regard, use of RM as a clay liner material gains merit. Further, significantly high iron content, which is active and offers remarkable resistance against chemical attack [170], and low k property qualify the RM to be selected for storage units and compacted liner systems. These observations are in good agreement with the results of Rubinos et al. [49], who have measured low k of RM and, thereby, demonstrated its usability as a clay liner material. Above all, it is seen from Table 1 that the permeability of RM delineated to be low, highlighting a fact that the leaching of toxic metals from it will take a longer time and will be trivial [127]. It is also described that RM possess good sorption properties, with hydroxide phases demonstrably excellent adsorbents [171]. Because of this meritorious trait, RM has been explored for immobilizing a particular contaminant or treating acid drains and contaminated sites [113, 170]. As such, untreated RM is documented excellent for treating of acid drains, contaminated soils, or sewages in comparison to gypsum amended one. RM also exhibits cation exchange capacity in the range of 43.2 –75 mEq/100 g, which apparently close to clayey soils [66, 136, 156].

Besides fulfilling the requirements of low *k*, the material should be compactable and show adequate strength to resist the applied loads, in all practical scenarios. The compaction state is such that permeability at the densest state shall be less than the regulatory levels (i.e. 1×10^{-7} cm/s as per USEPA). Generally, low *k* can be achieved by compacting the material to γ_{dmax} at w_{opt} (2–4%) [146, 172]. Such low *k* ($\leq 1 \times 10^{-7}$ cm/s) value for RM can be attained by compacting to dense homogeneous mass with moderate compaction effort at 0.4–4% of optimum water. However, the presence of iron oxide (above 55%) and abnormally high alkalinity seems to cause contrariety of the density characteristics. To overcome this, Reddy and Rao [28] suggested to applying relatively high compaction energy equivalent to MP compaction energy or alternatively, amending the RM with a suitable additive.

Materials possessing good compaction and strength properties are not only useful for clay liner systems, but they can also be chosen in a wide range of other applications. As evident from Table 8, the suitability of pre- (raw) and post-treated RM (amended) on the basis of dry unit weight found to have versatile applicability. Literature data presented in Table 1 demonstrate that the dry unit weight varies from 12.5 to 17.5 kN/m^3. As such, IRC 36 [173] specifies γ_{dmax} in the range from 15.2 to 20.8 kN/m^3 and w_{opt} from 10 to 20% for ML (i.e. silt of low plasticity) type soils. Similarly, IRC SP 20 [107] (Rural roads) suggests γ_{dmax} of not less than 14.4 kN/m^3 for constructing embankments up to a height 3 m and 15.2 kN/m^3 of embankments exceeding this height. The same standard also recommends γ_{dmax} of not less than 16.5 kN/m^3 of a material to be selected for sub-grade layer or earthen shoulder. As per MoRTH [174] guidelines, γ_{dmax} shall not be < 15.1 kN/m^3 and 17.2 kN/m^3 for ascertaining the suitability of material for an embankment or a sub-grade. From Table 1, it is apparent that the values of γ_{dmax} are a bit higher than the minimum density requirement of IRC 36 [173], but conform to IRC SP 20 standard [107]. Based on the compaction characteristics, it can be concluded that RM qualifies to be used for rural road construction, even without resorting to pre-treatment or amendment. In such cases where it does not meet the prescribed specifications, it is indispensable that RM is amended with suitable additives like fly ash, GGBS, OPC, gypsum, or lime.

High shear strength (i.e. friction angle and cohesion) is also one of the prerequisites for RM as it needs to resist the shear failure against slope instability if used in landfills or embankments [49]. From Fig. 10, it is seen that as the strength varies so does the compaction state of RM. A point is clear from the stress–strain response (Fig. 10) that the untreated RM, in general, seems to exhibit low strength in the range from 102 to 175 kPa (refer to Table 1). Understandably, the strength requirement shall not remain same for all practical scenarios. It is obvious from Table that low strength does not meet the requirements of IRC 37 [149], which specifies 1.5–3.0 MPa for untreated soils and 0.75–1.5 MPa for chemically stabilized soils to be used for granular sub-base course in flexible pavements. Conversely, low strength also marks RM unsuitable as a base course material, for which strength specified is 4.5–7 MPa. This emphasizes that stabilization or solidification of the RM is essential. An important point to be kept in mind pertaining to RM is uncertainty on the formation of reaction products during the stabilization or solidification under extreme alkaline conditions. The alkalinity originating from the associated liquid phase can greatly be reduced with the up-to-date dewatering methods (Bánvölgyi 2015). As such, limited efforts were devoted to stabilize or solidify the RM or per se identify a suitable additive(s) which would develop hydration products under acute pH conditions and thereby, impart desired strength. Additional fundamental studies are needed to investigate these issues.

The large quantity of fine fraction together with low linear and volumetric shrinkage gives the RM to be preferred for building material such as composite brick made of RM and clay [145]. But, interpretation of strength results discard RM suitability as a composite building block because of low strength below 7 MPa as stipulated by BS 3291 standard [175]. These observations further substantiate a fact that stabilization or solidification deemed necessary for RM even to be utilized as a building material.

In addition to the strength, reasonably high CBR is also another prerequisite for a material to be chosen for subgrade layer of a pavement or a road. The prescribed values are 15% under soaked condition as per IRC SP 20 [107] and 8% for roads with traffic ≥ 450 CVPD (commercial vehicles per day) as per IRC 37 [149]. The recorded CBR values of untreated RM (< 3% under soaked condition) obviously did not comply the specifications and thereby, render RM as not acceptable material for subgrade layer. This further stresses the need of prior treatment to the RM. Sahoo and Mohanty [176] and Rao et al. [177] have measured CBR values of RM after treating with 10% and 25% ground granulated blast furnace slag (GGBS) and found that there is a remarkable improvement in CBR values, well above 20% under soaked condition. Similarly, the results presented in Fig. 14 also endorse that 7th day CBR values conform to IRC 37 [150] recommendations for subgrade layer. The performance of subgrade depends not only on CBR value, but also on other properties like swelling. Swelling, which associates with cracking or unpredictable volume change, is other major parameter that affects the performance of geotechnical structures. Generally, swelling potential of a material should be either none or low. As provided in Table 1, RMs of different origin did not exhibit any swelling behavior, giving leverage for their suitability in earthen structures, roads, and landfill cover applications.

The extreme alkalinity of RM might cause induced dispersion, besides accentuating or diminishing the release of ions from the particle surfaces. In this context, Reddy et al. [20] have proposed an economical way of mitigating dispersion behavior by treating with the biopolymers such as guar gum and xanthan gum. As per the results of Reddy et al. [20, 150], biopolymer treatment not only alleviates dispersion successfully, but also causes significant improvement in strength characteristics satisfying the code requirements in all aspects. Besides the dispersion, collapse potential is also a major parameter attracts the attention, especially in materials dominant with silt fractions. Even though, silt fraction (refer to Table 1) is notable amount in RM, yet it is exhibited none to slight collapse potential and thus, making it an appropriate material for civil and infrastructure projects.

As such, the results in Tables 7 and 8 prove that RM is ideally potential material for geotechnical engineering applications. It can be seen from these tables that pre-treated RM found to satisfy only dry unit weight and compressibility criterion, but the post-treated RM apparently makes coherence for almost all geotechnical requirements as per the relevant standards.

Conclusions and Research Needs

The various physical, chemical, mineralogical, leaching and geotechnical properties of RMs, derived from bauxite ores of diverse origin and production processes, were critically reviewed. The review clearly substantiates that concerted efforts for deciding newer applications with a strong focus on circular approach, which is swayed from current linear economic approach, where the end-of-life product is considered to be a feedstock resource for another cycle, would be needed. Most of the studies identify RM possibly after some kind of treatment as a potential geomaterial, specifically to be used in geotechnical engineering applications, without causing negative impacts to the environment.

Conclusions

The following main conclusions have been derived from the comprehensive review of the current literature on various properties of RM:

- To date, there is no comprehensive review on physical, chemical, mineralogical, and leaching characteristics and their affect on geotechnical properties of the RM that would facilitate the research fraternity in identifying perspective geotechnical applications.
- The critical review reveals that the alkalinity of associated liquid phase can substantially be reduced by resorting to improved washing and effective de-watering techniques, possibly by plate and frame pressure filter or hyper-baric filters.
- Presence of poorly crystalline and/or amorphous phases endorse that RM can be considered as a partially pozzolanic material. Presence of such phases is beneficial in exploring its novel applications as a stabilizing agent or building material or partial replacement to cement.
- The comprehensive and critical review reveals that strength and alkalinity are major restrictive factors to accentuate the use of RM.
- The critical review of strength properties, in particular, emphasize that it is imperative to go for stabilization or neutralization or their combination, in tandem, of the RM to enlarge its positive engineering applications.
- It has been noticed that RM exhibits low shrinkage behavior (low critical degree of expansion) when compared to natural soils and other waste materials.
- Distinct mineralogical and chemical compositions identified in RMs of different origin underline the necessity for deeper understanding of these properties and their connotation on engineering behavior.
- Pertinent to gradational characteristics of RMs belonging to diverse origin, it is noticed that percent fractions in them are largely indistinguishable. Thus, the RM, in general, can be characterized as waste containing very fine particles.
- The comparison of compaction curves of RM vis-à-vis with other wastes discloses that RM relatively requires high compaction energy or alternatively amendment with a suitable additive for achieving better or improved engineering properties.
- The interpretation of shear strength data substantiates a fact that RM possesses friction angle very close to sand and that morphology, frictional angle, angularity, alkalinity, age of the deposit etc., are a few major factors seem to be affecting it.
- It has been noticed that biopolymer treatment fetches multiple advantages in terms of mitigating dispersion and collapse behavior, to which RM is susceptible, and concurrently improving the strength properties.
- All reported studies showed that that the concentrations of most of the leachable PTEs are within the permissible limits of USEPA, pointing that usage of the RM causes no harm to the environment.

Research Needs

The physical, chemical, strength, and leaching characteristics of RM samples reviewed in this study are primarily reported by conducting extensive laboratory tests. It can be noted that laboratory scale studies, in general, are executed at controlled environmental conditions, which in many instances do not replicate the field scenarios. Contrarily, RM in the field might be subjected to extreme environmental and climatic conditions, which may or may not possible to be imbibed to laboratory scale tests. It is appreciated, however, that the large scale data compilation and its interpretation as is done in the present study can certainly help for decision making by the waste management authority, developing holistic solutions by researchers or anticipating unforeseen problems to be encountered in the future. Complexities such as high alkalinity and regulations on transportation and storage of alkaline material are found as major compelling reasons for limited studies in the field, in particular on/using the RM. Considering these issues, a small/appropriate quantity of the sample collected from the bauxite residue disposal area as per the guidelines will serves as the representative sample and to make recommendations for field implications.

From the extensive review of literature data, the following ideas have been envisioned to be considered as potential future research works:

- Studies pertaining to understanding the solid alkalinity chemistry or measures to mitigate it are scarce. An opulent scope for mitigating the alkalinity levels either by employing chemical or microbial treatment methods lies exist.
- Contrary to conventional soils, RM demands neutralization followed by stabilization. This can be achieved by resorting to integrated approach wherein neutralization and stabilization will be done together, or in sequential wherein one precedes another method. This can enable high volume utilization of RM in spectrum of civil engineering applications.
- Use of chemical additives for neutralization or stabilization, no doubt, leaves pollution foot-print on the environment or generates secondary reaction products. At this juncture, microbial treatment methods found to be promising as they can able to convert the RM into environmentally benign by simultaneously imparting other beneficial properties.
- Hydraulic conductivity of raw RM and that amended with different additives need to be studied in detail considering different practical scenarios such as RM–liner interaction which would help in assessing the feasibility of RM to be selected in clay liners and hydraulic barrier applications or selection of suitable clay liner systems which would withstand extreme alkaline environments normally encountered in wastes like the RM.
- Previous studies demonstrate variability in mobilization of PTE with a change in pH of the RM. However, studies corroborating the relationship between pH (and amendments) and leaching potential of PTEs are relatively scarce. Such studies bear practical significance in terms of utilizing RM as adsorbent, immobilizing agent, building material, reactive ingredient etc.
- Performance including short-term stability and long-term durability of RM in synergy with various additives are rarely explored.
- Studies investigating the influence of phase composition on the geotechnical and geoenvironmental behavior of the RM addressed in the literature are almost nil. The future works pertinent to the interdependence would need to be defined in order to recycle the RM more efficiently.
- Limited studies explored the effect of alkalinity or neutralization on geotechnical (compaction, consolidation, hydraulic conductivity, shear strength, collapse potential etc.) and geoenvironmental (leaching, pH rebound, settling etc.) properties of RM.
- Studies also highlight the possibility of pH rebound after amending with different additives. Hence, a detailed investigation on physical and geotechnical properties need more emphasis for better implications in practical utilization.
- The high pH and Na^+ content in RM are major challenges in terms of its environment pollution or utilization. More research on fundamental understanding is indeed essential for the amendment of RM with other chemicals or pozzolanic materials in stabilization point of view for the development of a cost-effective technique.
- Long-term leachability of undesirable chemical constituents from RM used in engineering applications under variable environmental and climate impacts in the field need further evaluation.
- New and innovative large-scale engineering applications for RM should be explored and their sustainability should be assessed based on triple bottom line (environmental, economic and social) sustainability considerations.

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References

1. Panda, I., Jain, S., Das, S.K., Jayabalan, R.: Characterization of red mud as a structural fill and embankment material using bioremediation. Int. Biodeterior. Biodegrad. **119**, 368–376 (2017)
2. Rai, S., Wasewar, K.L., Mukhopadhyay, J., Yoo, C.K., Uslu, H.: Neutralization and utilization of red mud for its better waste management. Arch. Environ. Sci. **6**, 13–33 (2012)
3. Bardossy, G.: Karst Bauxites, Bauxite Deposits on Carbonate Rocks, Developments in Economic Geology, vol 14, 1st edn, p. 441. Elsevier, Amsterdam (1982)
4. Kehagia, F.: A successful pilot project demonstrating the re-use potential of bauxite residue in embankment construction. Resour. Conserv. Recycl. **54**, 417–421 (2010)
5. Sun, C., Chen, J., Tian, K., Peng, D., Liao, X., Wu, X.: Geochemical characteristics and toxic elements in alumina refining wastes and leachates from management facilities. Int. J. Environ. Res. Public Health **16**(7), 1297 (2019)
6. Banvoelgyi, G., Huan, T.M., Director, F.G.: De-watering, disposal and utilization of red mud: state of the art and emerging technologies. In: Proceedings of XVIII International Symposium of ICSOBA, Zhengzhou, China, pp. 431–443 (2010)
7. Evans, K.: The history, challenges, and new developments in the management and use of bauxite residue. J. Sustain. Metall. **2**(4), 316–331 (2016)
8. Wang, L., Hu, G., Lyu, F., Yue, T., Tang, H., Han, H., Yang, Y., Liu, R., Sun, W.: Application of red mud in wastewater treatment. Minerals **9**(5), 281 (2019)
9. Power, G., Gräfe, M., Klauber, C.: Review of Current Bauxite Residue Management, Disposal and Storage: Practices, Engineering and Science. CSIRO Document, DMR-3608, pp. 3−4 (2009)
10. Lima, M.S.S., Thives, L.P., Haritonovs, V., Bajars, K.: Red mud application in construction industry: review of benefits and possibilities. IOP Conf Ser Mater Sci Eng **251**(1), 012033 (2017)
11. International Aluminum Institute (IAI): Opportunities for Use of Bauxite Residue in Portland Cement Clinker Production. World Alumina, p. 57 (2018a)
12. European Environment Agency: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Text with EEA Relevance) European Environment Agency (2008)
13. CPCB: Guidelines on Environmental Management of Construction and Demolition (C and D) Wastes, p. 81. Central Pollution Control Board, Ministry of Environment, Forests and Climate Change (2017)
14. USEPA: Sustainable Materials Management Program Strategic Plan. Fiscal Years 2017–2022, p. 8. United States Environmental Protection Agency (2015)
15. Ruyters, S., Mertens, J., Vassilieva, E., Dehandschutter, B., Poffijn, A., Smolders, E.: The red mud accident in Ajka (Hungary): plant toxicity and trace metal bioavailability in red mud contaminated soil. Environ. Sci. Technol. **45**(4), 1616–1622 (2011)
16. Banvolgyi, G.: The lessons learnt from the failure of the embankment of the red mud reservoir at Ajka (Hungary). In: Proceedings of the International Conference and Exhibition on Aluminium (INCAL), Bhubaneswar, India, pp. 88–89 (2019)
17. Mayes, W.M., Jarvis, A.P., Burke, I.T., Walton, M., Feigl, V., Klebercz, O., Gruiz, K.: Dispersal and attenuation of trace contaminants downstream of the Ajka bauxite residue (red mud) depository failure, Hungary. Environ. Sci. Technol. **45**(12), 5147–5155 (2011)
18. Mayes, W.M., Burke, I.T., Gomes, H.I., Anton, Á.D., Molnár, M., Feigl, V., Ujaczki, É.: Advances in understanding environmental risks of red mud after the Ajka Spill, Hungary. J. Sustain. Metall. **2**(4), 332–343 (2016)
19. Gelencsér, A., Kováts, N., Turóczi, B., Rostási, Á., Hoffer, A., Imre, K., Nyirő-Kósa, I., Csákberényi-Malasics, D., Tóth, A., Czitrovszky, A., Nagy, A.: The red mud accident in Ajka (Hungary): characterization and potential health effects of fugitive dust. Environ. Sci. Technol. **45**(4), 1608−1615 (2011)
20. Reddy, N.G., Rao, B.H., Reddy, K.R.: Biopolymer amendment for mitigating dispersive characteristics of red mud waste. Geotech. Lett. **8**(3), 201–207 (2018)
21. International Aluminum Institute (IAI): Sustainable Bauxite Mining Guidelines. World Alumina, p. 116 (2018b)
22. Ding, X., Xu, G., Kizil, M., Zhou, W., Guo, X.: Lignosulfonate treating bauxite residue dust pollution: enhancement of mechanical properties and wind erosion behavior. Water Air Soil Pollut. **229**(7), 214, 1−13
23. Arulrajah, A., Piratheepan, J., Disfani, M.M., Bo, M.W.: Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. J. Mater. Civ. Eng. **25**(8), 1077–1088 (2012)
24. Correia, A.G., Winter, M.G., Puppala, A.J.: A review of sustainable approaches in transport infrastructure geotechnics. Transp. Geotech. **7**, 21–28 (2016)
25. Bhagwan, J., Vittal, U.K.G.: Use of marginal materials for rural road construction—some recent initiatives. In: Proceedings of Indian Geotechnical Conference (IGC-2014), Kakinada, India, pp. 2478−2485 (2014)
26. Qi, J.Z.: Experimental Research on Road Materials of Red Mud. University of Huazhong Science and Technology, Wuhan (2005)
27. Sundaram, R., Gupta, S.: Construction of foundation on red mud. In: Dutta, M., Srivastava R.K., Ramana G.V., Shahu J.T. (eds) 6th International Congress on Environmental Geotechnics, New Delhi, India, pp. 1172−1175 (2010)
28. Reddy, N.G., Rao, B.H.: Compaction and consolidation behaviour of untreated and treated waste of Indian red mud. Geotech. Res. **5**(2), 105–121 (2018)
29. Newson, T., Dyer, T., Adam, C., Sharp, S.: Effect of structure on the geotechnical properties of bauxite residue. J. Geotech. Geoenviron. Eng. **132**(2), 143–151 (2006)
30. Kalkan, E.: Utilization of red mud as a stabilization material for the preparation of clay liners. Eng. Geol. **87**, 220–229 (2006)
31. Rout, S.K., Sahoo, T., Das, S.K.: Design of tailing dam using red mud. Cent. Eur. J. Eng. **3**(2), 316–328 (2013)
32. Reddy, N.G., Chandra, K.S., Rao, B.H.: Assessment of industrial wastes as a road construction material: a review. In: Proceedings of 1st International Conference on Recent Innovations in Engineering and Technology (ICREIAT-2016), 22−23 December, Hyderabad, India, pp. 28−34 (2016)
33. Jitsangiam, P., Nikraz, H., Jamieson, E., Kitanovich, R., Siripun K.: Sustainable use of a bauxite residue (red sand) as highway embankment materials. In: 3rd International Conference on Sustainable Engineering and Science, 9 December, Auckland, New Zealand (2008)
34. Paramguru, R.K., Rath, P.C., Misra, V.N.: Trends in red mud utilization—a review. Min. Process. Extr. Metall. Rev. **26**(1), 1–29 (2005)
35. Oprčkal, P., Mladenovič, A., Zupančič, N., Ščančar, J., Milačič, R., Serjun, V.Z.: Remediation of contaminated soil by red mud and paper ash. J. Clean. Prod. **256**, 120440 (2020)
36. Youssef, N.F., Shater, M.O., Abadir, M.F., Ibrahim, O.A.: Utilization of red mud in the manufacture of ceramic tiles. Key Eng. Mater. **206–213**(Pt. 3, Euro Ceramics VII), 1775–1778 (2002)

37. Villar, L.F.S., Campos, T.M.P., Azevedo, R.F., Zornberg, J.G.: Influence of laboratory techniques on the geotechnical characterization of mining and industrial wastes. In: Proceedings of 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt, pp. 186−189 (2009)
38. ASTM: Standard Test Method D6907-05, Standard Practice for Sampling Contaminated Media with Hand-Operated Bucket Augers, ASTM International, West Conshohocken (2016)
39. Reddy, N.G., Rao, B.H.: Evaluation of the Compaction Characteristics of Untreated and Treated Red Mud. Geotechnical Special Publication 272, Geo-Chicago, ASCE, pp. 23−32 (2016)
40. Reddy, N.G., Rao, B.H.: Assessment of dispersion characteristics of red mud waste from physical tests. In: Proceedings of Indian Geotechnical Conference (GeoNEst), 14−16 December, p. 4. IIT, Guwahati (2017)
41. Reddy, N.G., Rao, B.H.: Characterization of settled particles of the red mud waste exposed to different aqueous environment conditions. Indian Geotech. J. **48**(3), 405–419 (2018)
42. Reddy, N.G., Rao, B.H.: Effect of additives on consistency limits of red mud waste: a comparative study. In: Zhan, L., Chen, Y., Bouazza, A. (eds) Proceedings of 8th International Congress on Environmental Geotechnics, Environmental Science and Engineering, p 3. Springer, Singapore (2019)
43. Reddy, N.G., Rao, B.H., Reddy, K.R.: Chemical analysis procedures for determining the dispersion behaviour of red mud. In: Agnihotri, A., Reddy, K., Bansal, A. (eds.) Recycled Waste Materials. Lecture Notes in Civil Engineering, vol. 32, pp. 19–26. Springer, Singapore (2019)
44. Rao, B.H., Reddy, N.G.: Zeta potential and particle size characteristics of red mud waste. In: Babu, G.L.S., Reddy, K.R., De, A., Datta, M. (eds.) Geoenvironmental Practices and Sustainability, pp. 69–89. Springer, Singapore (2017)
45. Mishra, M.C., Babu, K.S., Reddy, N.G., Dey, P.P., Rao, B.H.: Performance of lime stabilization on extremely alkaline red mud waste under acidic environment. J. Hazard. Toxic Radioact. Waste **23**(4), 04019012 (2019)
46. Terzaghi, K., Peck, R.B., Mesri, G.: Soil Mechanics in Engineering Practice. Wiley, New York (1996)
47. Kumar, H., Cai, W., Lai, J., et al.: Influence of in-house produced biochars on cracks and retained water during drying-wetting cycles: comparison between conventional plant, animal and nano-biochars. J. Soils Sediments **20**, 1983–1996 (2020)
48. Das, S.K., Rout, S., Alam, S.: Characterization of red mud as a subgrade construction material, In: 3rd Conference of the Transportation Research Group of India, Kolkata, West Bengal (3rd CTRG), 17-20 December (2015)
49. Rubinos, D., Spagnoli, G., Barral, M.T.: Assessment of bauxite refining residue (red mud) as a liner for waste disposal facilities. Int. J. Min. Reclam. Environ. **29**(6), 433–452 (2015)
50. Nath, H., Sahoo, P., Sahoo, A.: Characterization of red mud treated under high temperature fluidization. Power Technol. **269**, 233–239 (2015)
51. Borra, C.R., Pontikes, Y., Binnemans, K., Gerven, T.V.: Leaching of rare earths from bauxite residue (red mud). Miner. Eng. **76**, 1–8 (2015)
52. Wagh, A.S.: Settling properties of dilute Bayer process muds of alumina industry in Jamaica. Part. Multiphase Process. **3**, 461–469 (1987)
53. Wehr, J.B., Fulton, I., Menzies, N.W.: Revegetation strategies for bauxite refinery residue: a case study of Alcon Gove in Northern Territory, Australia. Environ. Manag. **27**(3), 297–306 (2006)
54. Alam, S., Das, S.K., Rao, B.H.: Characterization of coarse fraction of red mud as civil engineering construction material. J. Clean. Prod. **168**, 679–691 (2017)
55. Donoghue, A.M., Frisch, N., Olney, D.: Bauxite mining and alumina refining: process description and occupational health risks. J. Occup. Environ. Med. **56**(5 Suppl), S12 (2014)
56. Pradhan, J., Das, S.N., Rao, J., Thakur, R.S.: Characterization of Indian red muds and recovery of their metal values. In: Hale, W. (ed.) Light Metals, pp. 87–92. TMS, Anaheim (1996)
57. Wang, P., Liu, D.: Physical and chemical properties of sintering red mud and Bayer red mud and the implications for beneficial utilization. Materials **5**(10), 1800–1810 (2012)
58. Benson, C.H., Trast, J.M.: Hydraulic conductivity of thirteen compacted clays. Clays Clay Miner. **43**, 669–681 (1995)
59. Daniel, D.E.: Summary review of construction quality control for earthen liners. In: Bonaparte, R. (ed.) Waste Containment Systems: Construction, Regulation, and Performance, vol. 26, pp. 175–189. ASCE, Reston (1990)
60. Benson, C.H., Othman, M.A.: Hydraulic and mechanical characteristics of a compacted municipal solid waste compost. Waste Manag. Res. **11**(2), 127–142 (1993)
61. Tong, L., Wang, Y.H.: DEM simulation of shear modulus and damping ratio of sand with emphasis on the effect of particle number, particle shape and aging. Acta Geotech. **10**, 117–130 (2015)
62. Zhuang, L., Nakata, Y., Kim, U.G., Kim, D.: Influence of relative density, particle shape, and stress path on the plane strain compression behavior of granular materials. Acta Geotech. **9**, 241–255 (2014)
63. Jitsangiam, P., Nikraz, H.: Coarse bauxite residue for roadway construction materials. Int. J. Pavement Eng. **14**(3), 265–273 (2013)
64. Arnepalli, D.N., Shanthakumar, S., Rao, B.H., Singh, D.N.: Comparison of methods for determining specific-surface area of fine-grained soils. Geotech. Geol. Eng. **26**(2), 121–132 (2008)
65. Snars, K., Gilkes, J.R.: Evaluation of bauxite residue (red mud) of different origin for environmental applications. Appl. Clay Sci. **46**(1), 13–20 (2009)
66. Gräfe, M., Power, G., Klauber, C.: Bauxite residue issues: III. Alkalinity and associated chemistry. Hydrometallurgy **108**(1–2), 60–79 (2011)
67. Alam, S., Das, B.K., Das, S.K.: Dispersion and sedimentation characteristics of red mud. J. Hazard. Toxic Radioact. Waste (2018). https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000420
68. Li, L.Y.: Properties of red mud tailings produced under varying process conditions. J. Environ. Eng. **124**, 254–264 (1998)
69. Banvolgyi, G.: Opportunities within the alumina refineries to make bauxite residue easy to downstream use. In: Proceedings of the Bauxite Residue Valorization and Best Practices Conferences, Leuven, Belgium, pp. 89–100 (2015)
70. Li, Y.C., Min, X.B., Ke, Y., Chai, L.Y., Shi, M.Q., Tang, C.J., Wang, Q.W., Liang, Y.J., Lei, J., Liu, D.G.: Utilization of red mud and Pb/Zn smelter waste for the synthesis of a red mud-based cementitious material. J. Hazard. Mater. **344**, 343–349 (2017)
71. Liu, Z., Li, H.: Metallurgical process for valuable elements recovery from red mud—a review. Hydrometallurgy **155**, 29–43 (2015)
72. Feret, F.: Selected Applications of Rietveld-XRD Analysis for Raw Materials of the Aluminium Industry. JCPDS-International Centre for Diffraction Data, Newtown Square (2013)
73. Pascual, J., Corpas, F.A., Lopez-Beceiro, J.: Thermal characterization of a Spanish red mud. J. Therm. Anal. Calorim. **96**, 407–412 (2009)
74. Patel, S., Pal, B.K., Patel, R.K.: A novel approach in red mud neutralization using cow dung. Environ. Sci. Pollut. Res. **25**(1–8), 12841–12848 (2018)
75. Serjun, V.Z., Mladenovic, A., Milacic, R., Scancar, J., Asler, A., Zupancic, N., Nikolic, I., Oprckal, P.: Red mud as an alternative

material for the production of a geotechnical composite. In: 2nd Conference of Bauxite Residue Valorization and Best Practices (BR-2018), 7−10 May, Athens (2018)
76. Santini, T.C.: Application of the Rietveld refinement method for quantification of mineral concentrations in bauxite residues (alumina refining tailings). Int. J. Miner. Process. **139**, 1–10 (2015)
77. Liu, Y., Lin, C., Wu, Y.: Characterization of red mud derived from a combined Bayer process and bauxite calcination method. J. Hazard. Mater. **146**(1–2), 255–261 (2007)
78. CSIRO: Review of Bauxite Alkalinity and Associated Chemistry. CSIRO Document 3610, p. 60. National Research Flagship, CSIRO, Australian Government (2009)
79. Castaldi, P., Silvetti, M., Santona, L., Enzo, S., Melis, P.: XRD, FTIR and thermal analysis of bauxite ore-processing waste (red mud) exchanged with heavy metals. Clays Clay Miner. **56**(4), 461–469 (2008)
80. Garau, G., Castaldi, P., Santona, L., Deiana, P., Melis, P.: Influence of red mud, zeolite and lime on heavy metals immobilization culturable heterotrophic microbial populations and enzyme activities in a contaminated soil. Geoderma **142**(1–2), 47–57 (2007)
81. Hu, X., Peng, T., Sun, H., Zhao, E.: Synthetic mechanism of hydroxy sodalite. Kuei Suan Jen Hsueh Pao **44**(8), 1200–1206 (2016)
82. Kumar, S., Prasad, A.: Parameters controlling strength of red mud–lime mix. Eur. J. Environ. Civ. Eng. (2017). https://doi.org/10.1080/19648189.2017.1304280
83. Singh, M., Upadhyay, S.N., Prasad, P.M.: Preparation of special cements from red mud. Waste Manag. **16**(8), 665–670 (1996)
84. Rubinos, D.A., Barral, M.T.: Fractionation and mobility of metals in bauxite red mud. Environ. Sci. Pollut. Res. **20**(11), 7787–7802 (2013)
85. Pontikes, Y., Angelopoulos, G.N.: Bauxite residue in cement and cementitious applications: current status and a possible way forward. Resour. Conserv. Recycl. **73**, 53–63 (2013)
86. ASTM: Standard Test Method C595/C595M, Standard Specification for Blended Hydraulic Cements. ASTM International, West Conshohocken (2019)
87. Alam, S., Das, S.K., Rao, B.H.: Stabilization of red mud using low ash coal fly ash. In: Proceedings of Indian Geotechnical Conference. IIT, Guwahati (2017b)
88. Addai-Mensah, J., Li, J., Zbik, M., Rosencrance, S.: Sodium aluminosilicate solid phase specific fouling behaviour. In: ECI Conference of Heat Exchanger Fouling and Cleaning. Fundamentals and Applications, Santa Fe, New Mexico, USA, Paper 11 (2003)
89. Peng, H., Seneviratne, D., Vaughan, J.: Role of the amorphous phase during sodium aluminosilicate precipitation. Ind. Eng. Chem. Res. **57**, 1408–1416 (2018)
90. Feret, F.R.: Red mud (bauxite residue). In: International Tables for Crystallography, Volume H, Chapter 7.6, pp. 785–787 (2019)
91. Dobra, G., Kiselev, A., Filipescu, L., Alistarh, V., Anghelovici, N., Iliev, S.: Full analysis of Sierra Leone bauxite and possibilities of bauxite residue filtration. J. Sib. Fed. Univ. Eng. Technol. **9**(5), 643–656 (2016)
92. Lin, C.: Bauxite residue (red mud) from the Pingguo alumina refined China: characteristics and potential uses. In: Pasamehmtoglu, A.G., Ozgenoglu, A., Yesilay, A.Y. (eds.) Proceedings of International Symposium on Environmental Issues and Waste Management in Energy and Mineral Production, p. 551. Atilim University, Ankara (2004)
93. Sglavo, V.M., Campostrini, R., Maurina, S., Carturan, G., Monagheddu, M., Budroni, G., Cocco, G.: Bauxite 'red mud' in the ceramic industry. Part 1: thermal behaviour. J. Eur. Ceram. Soc. **20**(3), 235–244 (2000)
94. Atasoy, A.: The comparison of the Bayer process wastes on the base of chemical and physical properties. J. Therm. Anal. Calorim. **90**(1), 153–158 (2007)
95. Pera, J., Boumaza, R., Ambroise, J.: Development of a pozzolanic pigment from red mud. Cem. Concr. Res. **27**, 1513–1522 (1997)
96. Liu, X., Zhang, N.: Utilization of red mud in cement production: a review. Waste Manag. Res. **29**(10), 1053–1063 (2011)
97. Ribeiro, D.V., Labrincha, J.A., Morelli, M.R.: Potential use of natural red mud as pozzolan for Portland cement. Mater. Res. **14**(1), 60–66 (2011)
98. Subhashree, S.: Geo-engineering properties of lime treated plastic soils. Master's Thesis, NIT, Rourkela (2014)
99. Negussey, D., Wijewickreme, W.K.D., Vaid, Y.P.: Contact volume friction angle of granular materials. Can. Geotech. J. **25**(1), 50–55 (1988)
100. Stark, N., Hay, A.E., Cheel, R., Ake, C.B.: The impact of particle shape on the angle of internal friction and the implications for sediment dynamics at a steep, mixed sand-gravel beach. Earth Surf. Dyn. **2**(2), 469–480 (2014)
101. Jerves, A.X., Kawamoto, R.Y., Andrade, J.E.: Effect of grain morphology on critical state: a computational analysis. Acta Geotech. **11**(3), 493–503 (2016)
102. Kirwan, L., Hartshorn, A., Mcmonagle, J.B., Fleming, L., Funnell, D.: Chemistry of bauxite residue neutralisation and aspects to implementation. Int. J. Miner. Process. (2013). https://doi.org/10.1016/j.minpro.2013.01.001
103. Kushwaha, S.S., Kishan, D.: Stabilization of red mud by lime and gypsum and investigating its possible use in geoenvironmental engineering. In: Geo-Chicago, pp. 978−988 (2016)
104. Gore, M.S., Gilbert, R.B., McMillan, I., Parks, S.L.I.: Geotechnical characterization of compacted bauxite residue for use in levees. In: Geo-Chicago, pp. 299−310 (2016)
105. Pan, S.Y., Chung, T.C., Ho, C.C., Hou, C.J., Chen, Y.H., Chiang, P.C.: CO_2 mineralization and utilization using steel slag for establishing a waste-to-resource supply chain. Sci. Rep. **7**(1), 17227 (2017)
106. Bai, Y., Milestone, N.B., Yang, C.: Sodium sulphate activated GGBS/PFA and its potential as a nuclear waste immobilisation matrix. MRS Online Proc. Libr. Arch. (2006). https://doi.org/10.1557/PROC-932-38.1
107. IRC SP 20: Rural roads manual. In: Indian Road Congress, New Delhi, India (2002)
108. IRC SP 58: Guidelines for use of fly ash in road embankment. In: Indian Road Congress, New Delhi, India (2001)
109. Babu, K.S.: Characteristics study of stabilized red mud waste as a resource material for pavement. Master's Thesis, IIT, Bhubaneswar (2018)
110. Kutle, A., Nad, K., Obhodas, J., Orescanin, V., Valkovic, V.: Assessment of environmental condition in the waste disposal site of an ex-alumina plant near Obrovac, Croatia. X-Ray Spectr. **33**(1), 39–45 (2004)
111. Bartha, A.: Investigation of toxic and heavy metal content and mobility of the red mud in Ajka (Hungary). In: Presentation at the Colloquium Spectroscopicum Internationale XXXVII (CSI XXXVII), Buzios, Brazil (2011)
112. Bánvölgyi, G.: The red mud pond dam failure at Ajka (Hungary) and subsequent developments. ICSOBA Newsl. **7**, 14–23 (2012)
113. Hua, Y., Heal, K.V., Friesl-Hanl, W.: The use of red mud as an immobilizer for metal/metalloid-contaminated soil: a review. J. Hazard. Mater. **325**, 17–30 (2017)
114. Tuazon, D., Corder, G.D.: Life cycle assessment of seawater neutralized red mud for treatment of acid mine drainage. Resour. Conserv. Recycl. **52**(11), 1307–1314 (2008)

115. Palmer, S.J., Frost, R.L.: Characterization of bauxite and seawater neutralized bauxite residue using XRD and vibrational spectroscopic techniques. J. Mater. Sci. **44**(1), 55–63 (2009)
116. Khaitan, S., Dzombak, D.A., Lowry, G.V.: Neutralization of bauxite residue with acidic fly ash. Environ. Eng. Sci. **26**(2), 431–440 (2009)
117. Khaitan, S., Dzombak, D.A., Swallow, P., Schmidt, K., Fu, J., Lowry, G.V.: Field evaluation of bauxite residue neutralization by carbon dioxide, vegetation, and organic amendments. J. Environ. Eng. **136**(10), 1045–1053 (2010)
118. Cusack, P.B., Healy, M.G., Ryan, P.C., Burke, I.T., O'Donoghue, L.M.T., Ujaczki, E., Courtney, R.: Enhancement of bauxite residue as a low-cost adsorbent for phosphorus in aqueous solution, using seawater and gypsum treatments. J. Clean. Prod. **179**, 217–224 (2018)
119. Barrow, N.J.: Possibility of using caustic residue from bauxite for improving the chemical and physical properties of sandy soil. Aust. J. Agric. Res. **33**, 285–295 (1982)
120. Courtney, R., Mullen, G., Harrington, T.: An evaluation of revegetation success on bauxite residue. Restor. Ecol. **17**(3), 350–358 (2009)
121. Clark, M.W., Johnston, M., Reichelt-Brushett, A.J.: Comparison of several different neutralisations to a bauxite refinery residue: potential effectiveness environmental ameliorants. Appl. Geochem. **56**, 1–10 (2015)
122. Abel, J.S., Stangle, G.C.: Sedimentation in flocculating colloidal suspensions. J. Mater. Res. **9**(2), 451–461 (1994)
123. Martinez, E.L.: Investigation of sedimentation behaviour of microcrystalline cellulose. Master's Thesis, Chalmers University of Technology (2012)
124. USEPA/600/4-90/027F: Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms. USEPA (1993)
125. USEPA: Health Effects Assessment Summary Tables (HEAST). U.S. Environmental Protection Agency, Washington, DC (1997)
126. USEPA: Drinking Water Standards and Health Advisories EPA 822-F-18. USEPA, Washington, DC (2018)
127. Kolencsik-Tóth, A., Gonda, N., Fekete, Z., Tóth, M., Székely, I., Zákányi, B., Móricz, F., Kovács, B.: Physical and chemical characterization of red mud in terms of its environmental effects. Geosci. Eng. **3**(5), 129–137 (2014)
128. Qu, Y., Lian, B., Mo, B., Liu, C.: Bioleaching of heavy metals from red mud using *Aspergillus niger*. Hydrometallurgy **136**, 71–77 (2013)
129. Mohapatra, B.K., Rao, M.B.S., Rao, R.B., Paul, A.K.: Characteristics of red mud generated at NALCO Refinery, Damanjodi, India. In: Light Metals, Proceedings of Sessions, TMS Annual Meeting, Warrendale, Pennsylvania, USA (2000)
130. Li, J., Feng, S., Chen, H., Wang, H.: Chemical and geotechnical properties of red mud at Liulin, China. In: Proceedings of GeoShanghai, pp. 405–414 (2018)
131. Chandra, K.S., Krishnaiah, S.: A detailed geotechnical investigation on red mud and chemical analysis of its leachate. In: Indian Geotechnical Conference, p 10. SVNIT, Surat (2019)
132. Urík, M., Bujdoš, M., Milová-Žiaková, B., Mikušová, P., Slovák, M., Matúš, P.: Aluminium leaching from red mud by filamentous fungi. J. Inorg. Biochem. **152**, 154–159 (2015)
133. Ghosh, I., Guha, S., Balasubramaniam, R., Kumar, A.R.: Leaching of metals from fresh and sintered red mud. J. Hazard. Mater. **185**(2–3), 662–668 (2011)
134. Zhang, J., Liu, S., Yao, Z., Wu, S., Jiang, H., Liang, M., Qiao, Y.: Environmental aspects and pavement properties of red mud waste as the replacement of mineral filler in asphalt mixture. Constr. Build. Mater. **180**, 605–613 (2018)
135. Kim, S.Y., Jun, Y., Jeon, D., Oh, J.E.: Synthesis of structural binder for red brick production based on red mud and fly ash activated using $Ca(OH)_2$ and Na_2CO_3. Constr. Build. Mater. **147**, 101–116 (2017)
136. Gray, D.H., Somogyi, F.: Engineering Properties and Dewatering Characteristics of Red Mud Tailing. DRDA Project 340364, Ann Arbor (1974)
137. Hussain, M., Dash, S.K.: Influence of lime on plasticity behaviour of soils. In: Proceedings of Indian Geotechnical Conference, GEOtrendz, 16–18 December. IIT, Bombay (2010)
138. Li, Y.C., Min, X.B., Ke, Y., Chai, L.Y., Shi, M.Q., Tang, C.J., Wang, Q.W., Liang, Y.J., Lei, J., Liu, D.G.: Utilization of red mud and Pb/Zn smelter waste for the synthesis of a red mud-based cementitious material. J. Hazard. Mater. **344**, 343–349 (2018)
139. Gore, M.S.: Geotechnical characterization of bauxite residue (red mud), Doctoral Thesis, The University of Texas, Austin (2015)
140. Grimshaw, R.W.: The Chemistry and Physics of Clays and Other Ceramic Materials. Wiley, New York (1980)
141. Kola, N., Das, S.K.: Lateral earth pressure due to red mud using numerical analysis. In: Proceedings of Indian Geotechnical Conference, 22–24 December, Roorkee, India, p 4 (2013)
142. Hildebrando, E.A., Souza, J.A.D.S., Angelica, R.S., Neves, R.D.F.: Application of bauxite waste from Amazon region in the heavy clay industry. Mater. Res. **16**(6), 1418–1422 (2013)
143. Chen, F.H.: Foundations on Expansive Soils. Elsevier Scientific Publishing Company, Amsterdam (1988)
144. Reddy, P.V.S., Rao, K.M., Rani, C.H.S.: Identification of expansive soils and assessment of expansion potential by fuzzy approach. Electron. J. Geotech. Eng. **14**, 1–10 (2009)
145. Pinnock, W.R., Gordon, J.N.: Assessment of strength development in Bayer-process residues. J. Mater. Sci. **27**(3), 692–696 (1992)
146. Daniel, D.E.: Geotechnical Practice for Waste Disposal. Chapman and Hall, London (1993)
147. Kaniraj, S.R., Havanagi, V.G.: Correlation analysis of laboratory compaction of fly ashes. Pract. Period. Hazard. Toxic Radioact. Waste Manag. **5**(1), 25–32 (2001)
148. Garg, A., Huang, H., Kushvaha, V., et al.: Mechanism of biochar soil pore–gas–water interaction: gas properties of biochar-amended sandy soil at different degrees of compaction using KNN modeling. Acta Geophys. **68**, 207–217 (2019)
149. IRC: 37: Guidelines for the design of flexible pavements. In: Indian Road Congress, New Delhi, India (2012)
150. Reddy, N.G., Singh, N.R., Rao, B.H.: Application of biopolymers for improving strength characteristics of red mud waste. Environ. Geotech. (2020). https://doi.org/10.1680/jenge.19.00018
151. Jain, S.: Red mud as a construction material by using bioremediation. Master's Thesis, NIT Rourkela (2014)
152. Vogt, M.F.: Development studies on dewatering of red mud. In: Proceedings of 103rd Annual Meeting of AIME, Dallas, Texas, pp. 73–91(1974)
153. Arora, K.R.: Soil Mechanics and Foundation Engineering. Standard Publishers Distributors, New Delhi (2004)
154. Srivastava, R.K.: Geotechnical aspects of soil–industrial waste interaction behavior. In: Proceedings of the International Symposium on Engineering Geology and the Environment, Athens, Greece, vol 2, pp. 23–27 (1997)
155. USEPA 440/5-86-001: Quality Criteria for Water. Office of Water Regulations and Standards, Washington, DC (1986)
156. Somogyi, F., Gray, D.H.: Engineering properties affecting disposal of red mud. In: Proceedings of Conference on Geotechnical Practice for Disposal of Solid Waste Materials, pp. 1–22. ASCE, Ann Arbor (1977)
157. Nikraz, H.R., Bodley, A.J., Cooling, D.J., Kong, P.Y.L., Soomro, M.: Comparison of physical properties between treated and untreated bauxite residue mud. J. Mater. Civ. Eng. **19**(1), 2–9 (2007)

158. Deelwal, K., Dharavath, K., Kulshreshtha, M.: Evaluation of characteristic properties of red mud for possible use as a geotechnical material in civil construction. Int. J. Adv. Eng. Technol. **7**(3), 1053–1059 (2014)
159. Mukiza, E., Zhang, L., Liu, X., Zhang, N.: Utilization of red mud in road base and sub grade materials: a review. Resour. Conserv. Recycl. **141**, 187–199 (2019)
160. Deelwal, K., Dharavath, K., Kulshreshtha, M.: Stabilization of red mud by lime, gypsum and investigating its possible use as a geotechnical material in the civil construction. Int. J. Adv. Eng. Technol. **7**(4), 1238–1244 (2014)
161. Umesh, T., Dinesh, S., Sivapullaiah, P.V.: Characterization of dispersive soils. Mater. Sci. Appl. **2**, 629–633 (2011)
162. Hardie, M.: Dispersive Soils and Their Management: A Technical Reference Manual, p. 41. Department Primary Industries and Water (2009)
163. Chen, R., Zhang, L., Budhu, M.: Biopolymer stabilization of mine tailings. J. Geotech. Geoenviron. Eng. **139**(10), 1802–1807 (2013)
164. Rout, S.K., Sahoo, T., Das, S.K.: Utility of red mud as an embankment material. Int. J. Earth Sci. Eng. **5**(6), 1645–1651 (2012)
165. Houston, S.L., Houston, W.N., Zapata, C.E., Lawrence, C.: Geotechnical engineering practice for collapsible soils. Geotech. Geol. Eng. **19**(3–4), 333–355 (2001)
166. Kalantari, B.: Foundations on collapsible soils: a review. Forensic Eng. **166**(FE2), 57–63 (2013)
167. ASTM: Standard Test Method D5333, Measurement of Collapse Potential of Soils. ASTM International, West Conshohocken (2003)
168. Main Roads Western Australia: Specification 501 Pavements Document 04/10110-04 (2012)
169. Taha, M.R., Kabir, M.H.: Tropical residual soil as compacted soil liners. Eng. Geol. **47**(3), 375–381 (2005)
170. Kajita, L.S.: An improved contaminant resistant clay for environmental clay liner applications. Clay Clay Miner. **45**(5), 609–617 (1997)
171. Zhu, L.L., Kexin, M., Zipeng, X.: Fluoride removal from liquid phase by Fe–Al–La trimetal hydroxides adsorbent prepared by iron and aluminum leaching from red mud. J. Mol. Liq. **237**, 164–172 (2017)
172. Mitchell, J., Hooper, D., Campanella, R.: Permeability of compacted clay. J. Soil Mech. Found. Div. **91**, 41–66 (1965)
173. IRC 36: Recommended practice for the construction of earth embankments for road works. In: Indian Road Congress, New Delhi, India (1970)
174. MoRTH: Specifications for road and bridge works, 3rd revision. In: Indian Road Congress, New Delhi, India (2000)
175. BS 3921: Specification for Clay Bricks. London (1985)
176. Sahoo, S.S., Mohanty, C.: Construction of road sub-base by using industrial waste. Int. J. Eng. Sci. Manag. Res. **3**, 77–83 (2016)
177. Rao, C.H.V.H., Naidu, P.G., Satyanyarana, P.V.V., Adiseshu, S.: Application of GGBS stabilized red mud in road construction. IOSR J. Eng. **2**(8), 14–20 (2012)
178. Zhu, X., Li, W., Guan, X.: An active dealkalization of red mud with roasting and water leaching. J. Hazard. Mater. **286**, 85–91 (2015)
179. Rivera, R.M., Ounoughene, G., Borra, C.R., Binnemans, K., Van Gerven, T.: Neutralisation of bauxite residue by carbon dioxide prior to acidic leaching for metal recovery. Miner. Eng. **112**, 92–102 (2017)
180. Li, H., Wen, Y., Cao, A., Huang, J., Zhou, Q., Somasundaran, P.: The influence of additives (Ca^{2+}, Al^{3+}, and Fe^{3+}) on the interaction energy and loosely bound extracellular polymeric substances (EPS) of activated sludge and their flocculation mechanisms. Bioresour. Technol. **114**, 188–194 (2012)
181. Deihimi, N., Irannajad, M., Rezai, B.: Characterization studies of red mud modification processes as adsorbent for enhancing ferricyanide removal. J. Environ. Manag. **206**, 266–275 (2018)
182. Chen, S., Fang, L., Zhu, Q., Li, L., Xing, Z.: Bromate removal by Fe(II)-akaganeite (β-FeOOH) modified red mud granule material. RSC Adv. **6**(34), 28257–28262 (2016)
183. López, E., Soto, B., Arias, M., Nú Ez, A., Rubinos, D., Barral, M.T.: Adsorbent properties of red mud and its use for wastewater treatment. Water Res. **32**, 1314–1322 (1998)
184. Nadaroglu, H., Kalkan, E., Demir, N.: Removal of copper from aqueous solution using red mud. Desalination **251**, 90–95 (2010)
185. Chaddha, M.J., Rai, S., Goyal, R.N.: National Seminar on Environmental Concern and Remedies in Alumina Industry at NALCO, Damanjodi, India (2007)
186. Sahu, R.C., Patel, R.K., Ray, B.C.: Neutralization of red mud using CO_2 sequestration cycle. J. Hazard. Mater. **179**, 28–34 (2010)
187. Meher, S.N., Rout, A.K., Padhi, B.K.: Recovery of Al and Na values from red mud by $BaO–Na_2CO_3$ sinter process. Eur. J. Chem. **8**, 1387–1393 (2011)
188. Mišík, M., Burke, I.T., Reismüller, M., Pichler, C., Rainer, B., Mišíková, K., Mayes, W.M., Knasmueller, S.: Red mud a byproduct of aluminum production contains soluble vanadium that causes genotoxic and cytotoxic effects in higher plants. Sci. Total Environ. **493**, 883–890 (2014)
189. Burke, I.T., Mayes, W.M., Peacock, C.L., Brown, A.P., Jarvis, A.P., Gruiz, K.: Speciation of arsenic, chromium, and vanadium in red mud samples from the Ajka Spill Site, Hungary. Environ. Sci. Technol. **46**(6), 3085–3092 (2012)
190. Di Carlo, E., Boullemant, A., Courtney, R.: A field assessment of bauxite residue rehabilitation strategies. Sci. Total Environ. **663**, 915–926 (2019)
191. Gruiz, K., Feigl, V., Klebercz, O., Anton, A., Vaszita, E.: Environmental risk assessment of red mud contaminated land in Hungary. In: GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering, pp. 4156−4165 (2012)
192. Higgins, D., Curtin, T., Pawlett, M., Courtney, R.: The potential for constructed wetlands to treat alkaline bauxite-residue leachate: *Phragmites australis* growth. Environ. Sci. Pollut. Res. **23**(23), 24305–24315 (2016)
193. NSF/ANSI 61: Drinking Water System Components-Health Effects (2016)
194. Parekh, B.K., Goldberger, W.M.: An Assessment of Technology for Possible Utilization in Bayer Process Muds. EPA-600/2-76-301, p. 154 (1976)
195. IS 1498: Classification and Identification of Soils for General Engineering Purposes. Bureau of Indian Standards, New Delhi (2007)
196. IRC: SP: 72: Guidelines for the design of flexible pavement for low volume rural roads. In: Indian Road Congress, New Delhi, India (2007)
197. IS 1498: Classification and Identification of Soils for General Engineering Purposes. Bureau of Indian Standards, New Delhi (1997)
198. MoRD: Specifications for Rural Roads. Ministry of Rural Development, Government of India, New Delhi (2014)
199. IRC: 36: Recommended Practice for Construction of Earth Embankments and Subgrade for Road Works, Indian Road Congress, New Delhi, India (2010)
200. Bhumij, R.K.: Compaction characteristics of red mud and pond ash mix as filling and embankment material. Doctoral Dissertation (2015)
201. Jitsangiam, P., Chummuneerat, S., Nikraz, H.: Engineering characteristics of cement modified base course material for Western Australian pavements. Aust. J. Civ. Eng. **11**(1), 13–21 (2013)

202. Liu, S., Li, Z., Li, Y., Cao, W.: Strength properties of Bayer red mud stabilized by lime-fly ash using orthogonal experiments. Constr. Build. Mater. **166**, 554–563 (2018)
203. Consoli, N.C.: Comparison of the measured and predicted performance of tailings sedimentation. Proc. Inst. Civ. Eng. Geotech. Eng. **125**, 179–187 (1997)
204. Somogyi, F.: Dewatering and drainage of red mud tailings. Doctoral Dissertation, University of Michigan (1976)
205. Kehagia, F.O.: Construction of an unpaved road using industrial by-products (bauxite residue). WSEAS Trans. Environ. Dev. **10**, 2224–3496 (2014)
206. Kirkpatrick, D.B.: Red Mud Product Development. Minerals, Metals and Materials Society, Warrendale (1996)