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Characterization and Utilization of Recycled Aluminium Residues for Eco-Friendly Road Construction Practices

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The economic growth of any nation relies heavily on industrialization, but this comes at the cost of a significant increase in industrial waste production, posing a detrimental impact on the environment and natural resources. One such waste, known as red mud, is a byproduct of Bayer's method for aluminum extraction from bauxite ore. Due to its highly alkaline nature, red mud poses a serious threat to the ecosystem. To address this issue, an effective strategy involves utilizing red mud in construction projects with proper stabilization methods. This study specifically explores the endurance of red mud when combined with cement, considering its suitability as a material for highway subgrade and embankment construction. The research involves substituting red mud with varying percentages of cement (3%, 6%, and 9% by dry weight) to thoroughly investigate how cement influences the strength characteristics of red mud. This analysis includes factors such as compaction characteristics, California Bearing Ratio, and Unconfined Compressive Strength. Additionally, embankment stability is assessed using Geo-5 software. The current study delves into the optimization of slope stability, ensuring the required Factor of Safety in accordance with Indian Roads Congress guidelines.

Keywords: Embankment material, Factor of safety, Red mud, SEM, Slope stability

Introduction

On a global scale, the rapid advancement of industrialization coupled with burgeoning population growth has resulted in a substantial upsurge in the production of industrial waste. This prevalent trajectory has engendered a discernible demand for specialized expertise in the field of civil engineering and research, particularly with an emphasis on identifying and implementing feasible applications for industrial waste within the construction sector. The primary objective is to prioritize expansive utilizations rather than strictly commercial purposes. Ensuring the derivation of premium construction materials from these industrial byproducts is of paramount importance, all while steadfastly upholding safety and quality standards.[1–4]

The inaugural phase of this process entails a meticulous evaluation of the suitability of various industrial wastes as potential building materials. Given the precipitous pace of industrialization, a substantial volume of diverse industrial wastes is being generated on a global scale, lying latent and posing ecological threats. In the realm of pertinent scholarly literature, Red Mud (RM) has emerged as a notable industrial waste product harboring considerable potential for integration into road construction endeavors.

Pioneering research endeavors have been undertaken to explore the viability of RM utilization in substantial quantities. These research findings collectively underscore the prospect of RM as a multifaceted solution in the domain of sustainable construction practices.[2,4]

Red mud, a byproduct of bauxite processing for alumina production (a primary material in aluminum manufacturing), is a notable industrial waste. Alumina is commonly produced in India using Bayer's methods, resulting in RM along with excess water content (approximately 50%). This RM, often with a lean slurry consistency, is further combined with water before being deposited into ponds. The production rate of RM is influenced by the source of bauxite[5], with studies suggesting varying production rates ranging from 1–2.5 tons[6,7] of RM per ton of alumina, depending on the processed raw material.[8–10]

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In 2015(11), the world produced nearly 160 million tons of RM, with China emerging as the largest producer[12], contributing around 88 million tons in 2016. Global reserves of RM were estimated to be approximately 40 million tons by 2015(12), with the option of higher undiscovered assets. Despite these quantities, the proper disposal of industrial waste remains a pressing environmental issue in various nations, including the United States, India, China, Japan, Australia, France, and Greece.[10,13] The challenge persists even with ongoing efforts to address environmental concerns associated with waste management.

The continuous disposal of RM in ponds raises concerns about the depletion of limited land resources and contributes to pollution problems. Red mud primarily consists of solid and metallic oxides, with iron oxides constituting a significant portion, accounting for up to 62% of the mud's masses and imparting characteristic reddish color.[14] The mud has a high pH ranging between 10 and 13, indicating its strongly basic nature. Other major components include titanium oxide, unleached residual alumina, and silica, as outlined in Table 1. Red mud is typically generated in bauxite plants at a frequency one to two times higher than alumina production. This underscores the substantial volume of RM produced as a byproduct in the bauxite processing industry.[15]

The ratio of RM components is influenced by extraction conditions and refining process of bauxite ore. Numerous scientists, as referenced in sources[13,14–16], have explored various uses for RM. Their investigations reveal that the physical, chemical, mechanical, particle, morphological, and structural features of RM vary significantly, depending on the grade of bauxite ore and the refinement and extraction processes employed.

Despite these studies, the improper characterization of RM, the presence of heavy metals in some samples, and the lack of established guidelines have hindered its potential use as a civil engineering material. Geotechnical description and the application of RM in construction projects have been the focus of only a limited number of foundational studies, as referenced in sources.[15] This indicates a gap in understanding the full spectrum of RM properties and its potential applications in construction due to insufficient research and guidelines.

Aluminum manufacturing process, RM creation, and its use in India is shown in Fig. 1. The common method of disposing of RM is through specially designed landfills near plants, leading to environmental concerns. The incident in Ajka, Hungary, in 2010, where aluminum sludge was discharged, serves as a reminder of the potential property and human losses associated with mishandling RM.[34] To mitigate the impact of RM on the construction industry, using RM in the production of bricks, along with other waste products and stabilizers, has been practiced for the past two decades.[16] Red mud can be utilized for creating subgrades or sub-bases for roads, helping conserve virgin materials and resources while utilizing waste materials.[16–18]

This paper investigates the incorporation of RM waste material into cement, with concentrations ranging from 3% to 9% (by weight). The study systematically elucidates the physical and geotechnical attributes of RM, both in its stabilized and unsterilized states, with a specific focus on its applicability in the construction of road

Table 1 — Chemical composition of bauxite

Compound	Content (%)
Alumina	34.2 – 75.9
Water	8.7 – 30.4
Iron Oxide	0.2 – 46.8
Silica	0.4 – 35.8
Titania	0.0 – 5.0

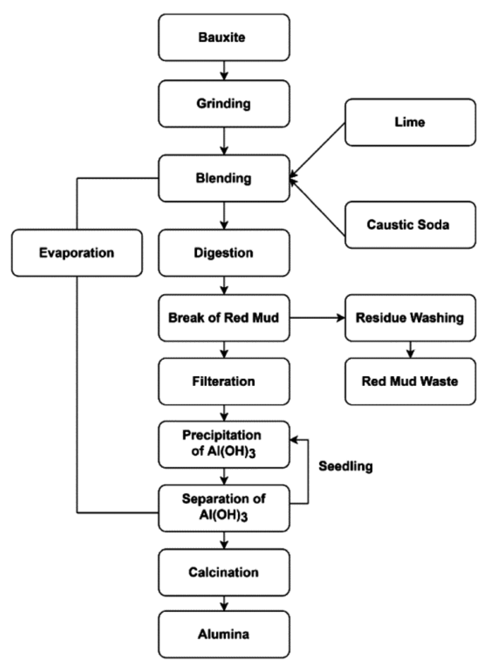

Fig. 1 — Extraction of red mud and alumina from bauxite

embankments, adhering to the guidelines set forth by the Indian Roads Congress (IRC).[19,20] Additionally, the article delves into a microstructural examination of RM, offering insights into its inherent characteristics and behavior under varying conditions.

Materials and Methods

Red Mud (RM)

Solid waste, red mud, was collected from Hirakud in the Sambalpur District of Odisha. Prior to conducting laboratory tests, the collected red mud underwent air-drying to eliminate moisture.

Cement

To achieve the goal of stabilizing various red mud samples, Portland cement of grade 53 was employed. The incorporation of cement into the RM-C combination contributes to enhancing the strength-related parameters of RM and its various combinations. Cement is widely recognized as an effective stabilizer in numerous construction projects, particularly in subgrade and subbase construction for roadways. Its use significantly augments the stiffness and strength of the soil, positively impacting the structural stability of building foundations and pavements. Cement, characterized by an exceptionally high specific gravity of 3.11, is valued for its effectiveness in stabilization applications.

Results & Discussion

Microstructural Characterization

An examination was conducted to analyze the physical properties of RM samples. The surface morphology and microstructural texture features of the particles were investigated using a Scanning Electron Microscope (SEM) as shown in Fig. 2. Before conducting the test, the samples were subjected to a drying process. SEM, equipped with an Emission Dispersive Spectrometer, was employed to obtain detailed imaging information regarding the surface texture and morphology of individual particles within the RM samples.

Geotechnical Characterization

Geotechnical characterization examinations were conducted to evaluate diverse material properties. The determination of natural moisture content and organic content adhered to the specifications outlined in IS 2720-part 2 (2015)[(21)] and IS 2720 – part 22 (2013)[(22)], respectively. Additionally, the assessment of pH value and specific gravity followed the guidelines of IS 2720- part 26 (1987)[(23)] and IS 2720-part 3 (2011)[(24)], respectively. Various geotechnical assessments, including Grain size analysis IS 2720-part 4 (2015)[(25)] as shown in Fig. 3, Free swell indexIS 2720-part 40 (2011)[(26)], Atterberg limit tests IS 2720-part 5& 6(2015)[(27)], Modified Proctor compaction test IS 2720-part 8 (2015)[(28)], California Bearing Ratio (CBR) test 2720-part 16 (2011)[(29)], Direct shear test IS: 2720 -part 13, (2011)[(30)], and Unconfined compressive strength IS 2720 Part 10 (1991)[(31)], were executed on specimens.

Permeability constant was determined in accordance with IS: 2720 (Part 17) -1986, and consolidation tests were conducted following IS: 2720 -Part 15 (2002). These assessments were performed on under double drainage situation. Remoulded samples were made at 95% of Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), saturated for 24 hours at starting seating stress of 0.025 kN/m^2. The seating load was sustained for 24 hours, and the specimen was consolidated under an initial stress of 5 kN/m^2. Settlement dial gauge

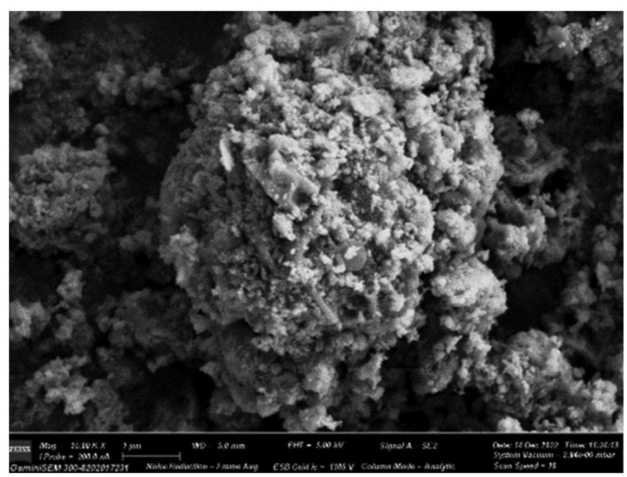

Fig. 2 — SEM view of red mud sample

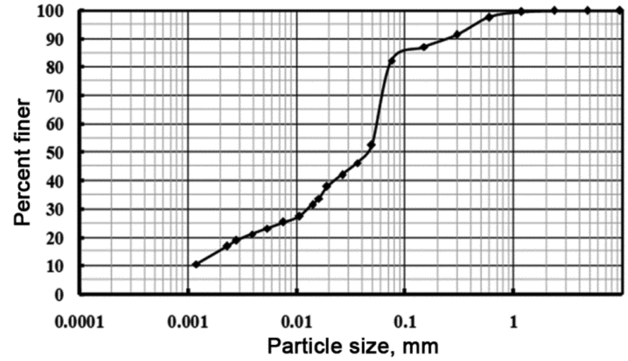

Fig. 3 — Particle size distribution curves of the red mud

readings were documented at various time intervals until equilibrium or up to 1440 minutes. The procedure was iterated for different normal stresses (10, 20, 40, 80, 160, 320, 640 kN/m^2), and settlement readings were recorded for 24 hours each time.

Unconfined Compression Strength (UCS) tests were conducted as per IS: 2720-Part-10 (2015). Three cylindrical specimens with dimensions of 50 mm diameter and 100 mm length were prepared by compacting the sample to 97% MDD and OMC. The compacted specimens underwent testing in a compression machine at a strain rate of 1.25 mm/min.

The SEM analysis revealed the presence of spherical and irregular particles of varying sizes, without distinct surface texture. A number of expected nearly rounded particles were also observed in the mass of RM sample. Similar results were obtained by Qianwei *et al.*[32] concluding that the RM consist of fine particles pertaining later surface area resulting in higher density (Wang and Liu).[33] The percentage of elements (by weight) is presented in Table 2. The surface chemistry of RM was found to be rich in sodium, iron, and calcium.

The majority of the RM consists of silt (65.50%), passing through a 75-micron sieve. The remaining composition comprises clay (6.13%) and sand (17.61%). According to IS classification, the RM falls into the category of Most Low-plasticity silt (ML). Banvoelgyi, and Huan (2010)[(34)] and Qianwei *et al.* (2022)[(32)] also found similar kind of gradation. The specific gravity of the RM is determined to be 3.70. The specific gravity of RM is considerably high[(33)], varying in the range from 2.7 to 3.7, reflecting the different origin of the RM.[34–36]

The RM exhibited a pH measurement of 11.05, signifying its markedly alkaline characteristics. Typically, the pH range of RM falls between 9 and 12.5, occasionally reaching the established threshold limit level of 12.5 (Kumar and Kumar, 2012[(37)], Agrawal and Dhawan, 2021[(38)] explained that the increased value of pH value is observed due to the desilication products such as sodalite and cancrinite, whereas fine particle size deteriorates the settling properties.

Utilizing index properties including Atterberg's limits as provided in Table 3, one can illustrate the plasticity characteristics and deformation of untreated RM. The position of RM on the plasticity chart is depicted in Fig. 4, placing it in the ML category of soil. With a liquid limit less than 50, RM is deemed suitable for embankment construction according to IRC 75 (2015), the Loss On Ignition (LOI) of the RM sample was calculated. The LOI value, determined to be 4.6%, indicates that the tested RM contains very little organic material. The Free Swelling Index (FSI) test, conducted in accordance with IS: 2720-Part 40 (2002), revealed a value of approximately 15%, indicating that the RM has low swelling characteristics.

Table 2 — Chemical composition of red mud

Element	Wt. %
O	46.70
Na	23.98
Al	7.74
Si	3.65
Ti	1.07
Fe	16.86
Total	100

Table 3 — Geotechnical engineering properties of the red mud

Properties	Values	Standard
Liquid limit (%)	27	IS 2720 Part 5
Plastic limit (%)	NA	IS 2720 Part 5
Plasticity index	NA	IS 2720 Part 5
Specific gravity	3.7	IS 2720 Part 3
Gravel	0	IS 2720 Part 4
Sand	17.66	IS 2720 Part 4
Silt	65.50	IS 2720 Part 4
Clay	6.13	IS 2720 Part 4
Free swelling (%)	<5%	IS 2720 Part 40
OMC (%)	17.40	IS 2720 Part 7
MDD (kN/m^3)	21.28	IS 2720 Part 7
UCS (kPa)	306	IS 2720 Part 10
The angle of internal friction	36	IS 2720 Part 13
Cohesion (kPa)	10	IS 2720 Part 13
CBR (%)	18	IS 2720 Part 16

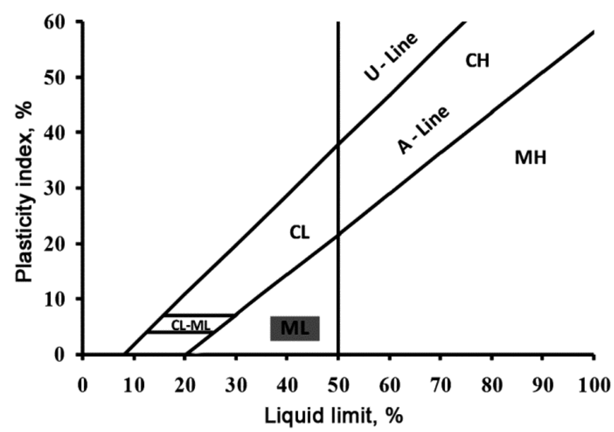

Fig. 4 — Position of red mud on the plasticity chart

Compaction testing, following IS 2720 Part 7, involved modified Proctor compaction tests. The solid RM exhibited a MDD of 21.26 kN/m³ and OMC of 17.40%.The CBR values for soaked and un soaked RM were determined as 18% and 12%, respectively, according to IS 2720 Part 16. The CBR values are comparatively high with respect to conventional soil (Silty soil), this is mainly due to the presence of heavy minerals.

The results indicated a UCS of 306 kPa for the RM after a 28-day curing period. A summary of the geotechnical engineering properties of the RM is provided in Table 3. Similar results were obtained by Sarath *et al.,* 2021.[16]

In all laboratory studies, RM was mixed with different percentages of cement (3%, 6%, and 9% by dry weight of the soil), as outlined in Table 4. The testing findings for untreated and treated RM with varying percentages of cement are as follows:

A permeability test, following IS: 2720 (Part-17) - 1986, yielded permeability coefficients (k) of 5.25 $\times 10^{-7}$ and 4.46 $\times 10^{-5}$ m/s for the RM. Due to its high permeability, RM may find application as fill for embankments, as well as a subgrade or sub-base material. For untreated and treated RM with varying cement percentages (3%, 6%, and 9%), the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) were calculated. The relationship between OMC and the addition of different cement types to the RM is illustrated in Fig. 5. The RM had an initial OMC concentration of 17.40%. The results indicate that the MDD increases from 22.82 kN/m³ to 23.12 kN/m³ as the cement percentage increases up to 9%. According to IRC SP: 20-2002, for a material to be used as both subgrade and embankment material per IRC: 75 (2015), the minimum MDD value must be 14.4 kN/m³, and the OMC value should not exceed 20%. Despite the water content being slightly outside the acceptable range in the current investigation, all samples meet the IRC requirements for MDD. This suggests that the addition of cement enhances the compaction of RM when the proper water proportion is used.

The unconfined compressive strength was resoluted by measuring the load at the point of failure during the test. The Unconfined Compressive Strength (UCS) values for various RM (RM) and cement combinations are presented in Table 5. The samples were cured for 7 days, 14 days, and 28 days at a temperature of 27°C. These three curing durations were chosen to assess how the strengths of different combinations changed over time. The results of the UCS testing device's examination of cured samples are depicted in Fig. 6. For road subgrades ranging

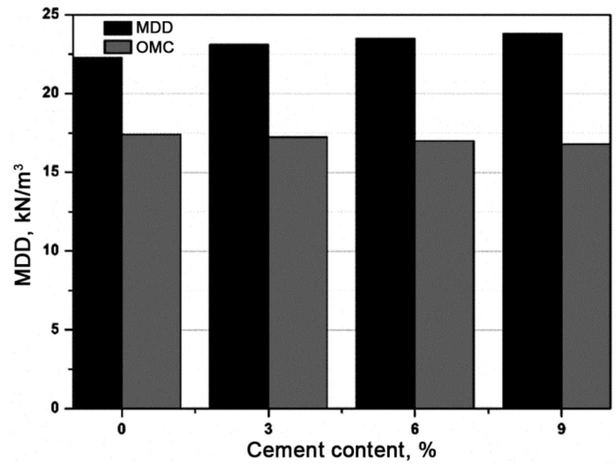

Fig. 5 — Relation between dry density and water content for reinforced red mud with cement

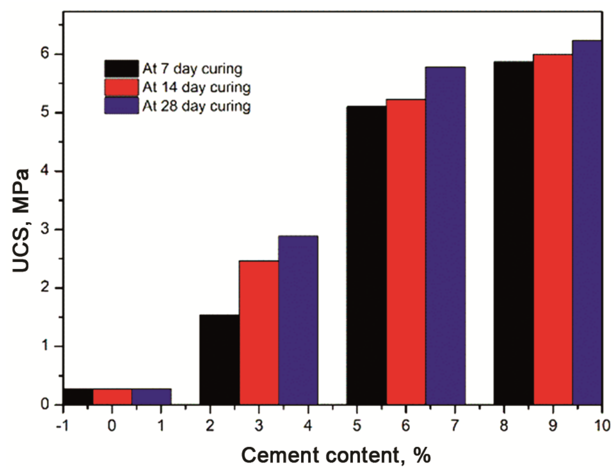

Fig. 6 — Variation of UCS with different content of cement (%)

Table 4 — Different combinations of RM and cement

S. No.	Sample combination (%)	Nomenclature
1	100 RM + 0 CM	RC1
2	100 RM + 3 CM	RC2
3	100 RM + 6 CM	RC3
4	100 RM + 9 CM	RC4

Table 5 — Change in UCS (MPa) of cement-stabilized red mud with respect to curing period

Sample	7 days curing UCS, MPa	14 days curing UCS, MPa	28 days curing UCS, MPa
RC1	0.27	0.27	0.27
RC2	1.54	2.47	2.89
RC3	5.10	5.23	5.78
RC4	5.87	5.99	6.23

from low to high volume, the unconfined strength value should ideally fall between 800 and 3000 kPa, as per IRC: 37-2012 requirements. It can be observed that the combination of RM and cement achieves a maximum strength value of 6230 kPa at 9% cement content. This indicates suitability for the construction of roads with medium to high traffic volumes when used as a subgrade material.

As per the specifications outlined in IRC: 37-2012 and IS 2720 Part-16, any material utilized as a subgrade material must have a minimum California Bearing Ratio (CBR) of 6%, and for embankment material, it should be 2%. The pozzolanic interaction between the RM materials and cement contributes to additional strength enhancement. The strength increases proportionally with the rising cement content in the RM mix, as illustrated in Fig. 7. This indicates that the combination of RM and cement can meet the CBR requirements for both subgrade and embankment materials, making it a promising choice for road construction applications.

Direct Shear test was conducted on a compacted sample of RM in accordance with IS2720 Part-13. The testing was performed under saturated conditions, with the normal stress ranging from 50 to 150 kN/m². The sample underwent shearing at a rate of 0.25 mm/min. The results indicated an internal friction angle of 36 degrees and cohesion of 10 kPa. The shear stress at different strains is illustrated in Fig. 8.

Slope Stability Analyses

The utilization of Geo-5 software facilitated the design of an embankment incorporating RM. Analysis of cross-sections along the alignment revealed varying heights of the road embankment, each featuring side slopes with a ratio of 2 horizontal to 1 vertical. Slope failure assessments were conducted for these embankments, designed as composite structures with RM as the core and flanked by a cover of good earth on both sides. The proposed design includes a 0.5 m thick horizontal soil cover made of local non-plastic soil. The typical embankment model is illustrated in Fig. 9, and the properties of the locally

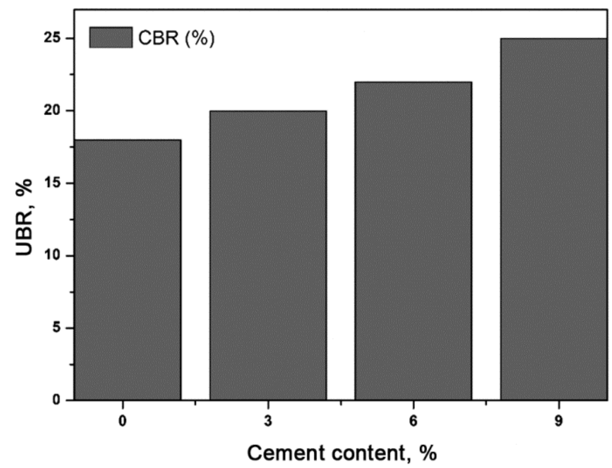

Fig. 7 — Deviation of maximum CBR for red mud with various content of cement

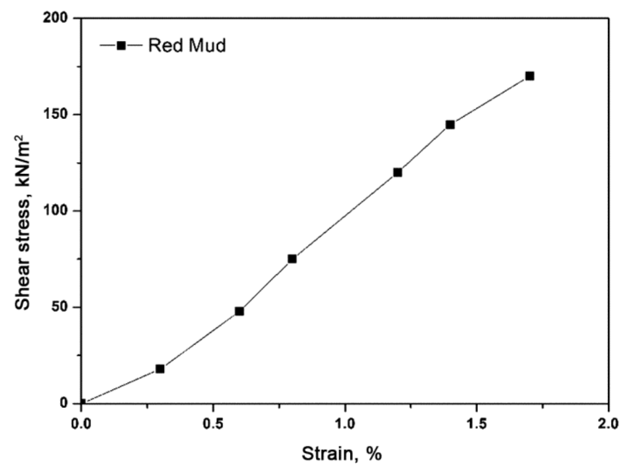

Fig. 8 — Deviation of shear stress with respect to the strain of red mud

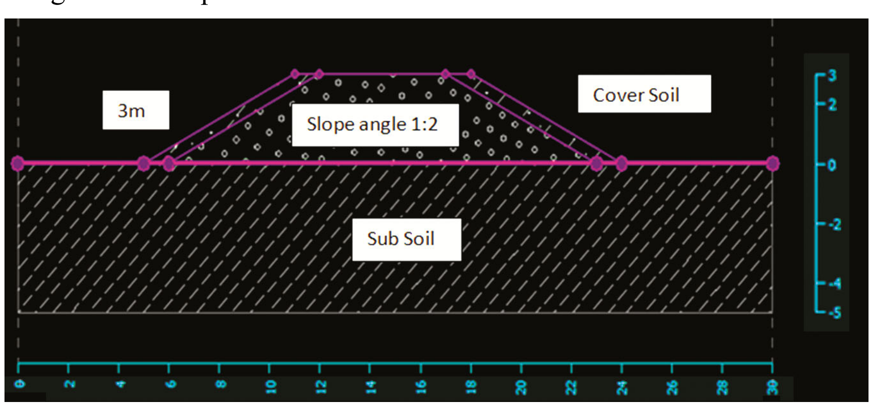

Fig. 9 — Typical cross-section of red mud

Table 6 — Property of material for embankment design

Geotechnical engineering properties		Non-plastic soil	Red mud
Modified proctor test	MDD, (kN/m^3)	19.86	21.28
	OMC, (%)	16.58	17.40
Direct Shear Test	Cohesion (kN/m^2)	0	10
	Angle of friction (°)	38	36

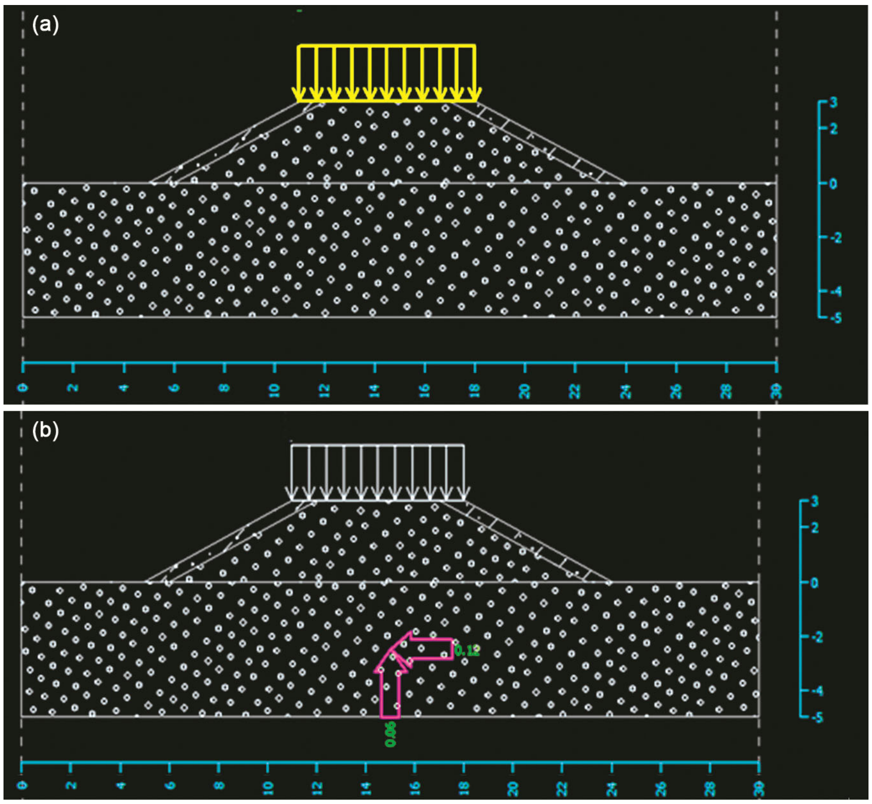

Fig. 10 — (a) Surcharge load, and (b) Seismic load on the cross-section of red mud

available soil and RM are detailed in Table 6. The slope stability analysis employed the Bishop method.

Factors of Safety (FOS)

Typically, the outcomes of stability analysis are presented in the form of a FOS concerning shear strength. The FOS denotes the ratio by which the strength parameters (expressed in expressions of effective stress), namely c' and tan ø', can be reduced before the slope reaches the state of limiting equilibrium. According to the recommendations in IRC: 75-2015, a minimum FOS of 1.4 is advised for static loads and 1.1 for seismic loading.

Loading Conditions

As per IRC 75 (2015), the loads on the top of the embankment, including traffic and other live loads, are rated at 24 kN/m². Additionally, the dead load of the pavement, excluding the subgrade, is considered to be 10 kPa. The study encompassed both static and seismic situations, with Delhi NCR being located in Seismic Zone IV, using a zone factor value of 0.24 for analysis. According to IRC 75, a horizontal seismic coefficient of 0.12 (half of the zone factor) and a vertical seismic coefficient of 0.06 (half of the horizontal coefficient) are employed for seismic slope stability analysis. A total load of 34 kPa (24 + 10 kPa) is evaluated as a surcharge over the embankment top, as depicted in Fig. 10.

The embankment was analyzed under three distinct moisture conditions: continuous seepage, abrupt draw-down, and partial saturation (MDD/OMC), as illustrated in Fig. 11. Such conditions are expected depending on the location/site of the RM embankment construction. The obtained results are presented in Table 7, indicating that the FOS is within acceptable

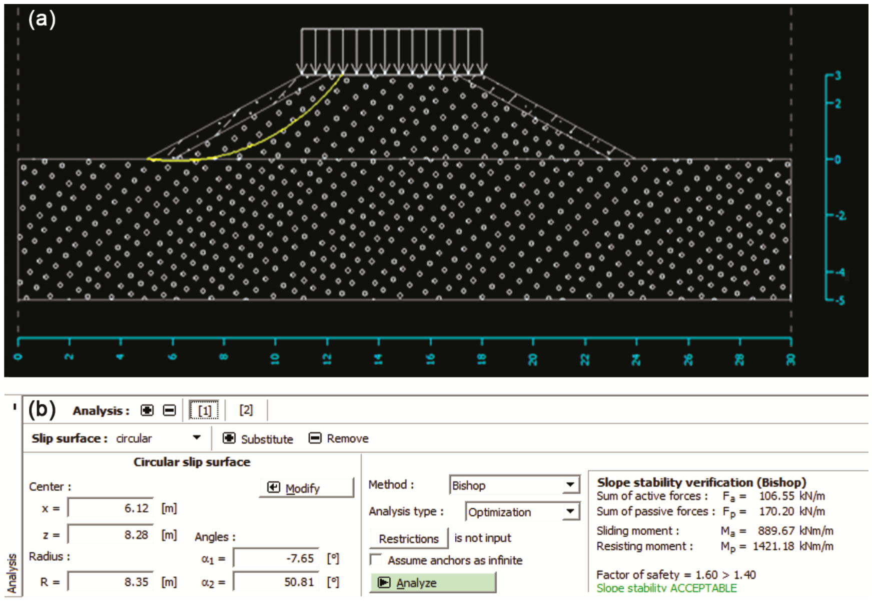

Fig. 11 — (a) Slope stability analysis of embankment, and (b) FOS

Table 7 — FOS at different loading conditions

Loading condition	Static case	Lateral loads
Static case	1.60	1.35
Steady seepage	1.51	1.24
Sudden drawdown	1.36	1.13

limits, being greater than 1.4 under static loading conditions and 1.1 under seismic loading conditions.

Conclusions

A thorough laboratory study assessed red mud's feasibility in road construction and structural fill applications, exploring chemical stabilization to enhance engineering properties. The investigation aimed to evaluate red mud in embankment construction and as a sub-base/base material in road pavement. Tests demonstrated increased strength, high California bearing ratio, and Unconfined Compressive Strength values with cement stabilization (3–9%). The material exhibited low swelling, making it suitable for embankments. Red mud's fine-grained, non-plastic ML classification, comparable density to soil, and free-draining nature support its use in embankments and subgrades. California bearing ratio values exceeded 8% for all red mud-cement combinations, meeting Indian Roads Congress criteria. The study suggests potential applications on rural roads and highways, emphasizing the need for caution, performance monitoring, and field-based evaluations before widespread use.

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