Sustainable Utilization of Bauxite Residue in Road Construction

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Abstract

Utilization of bulk waste as a secondary resource is a crucial aspect of environmental stewardship. Rapid urbanization is driving high demand for aluminium and other construction materials. Depending on the quality of ore and the processes involved, each ton of alumina generates 1–2.5 tonnes of bauxite residue. Globally, more than 3 billion tonnes of bauxite residue are stored, and annual generation is approximately 150 million tonnes, with India accounting for around 10 million tonnes per year.

Utkal Alumina International Ltd., a Hindalco unit, is one of the most cost-efficient refineries in the world and also a major generator of bauxite residue, producing approximately 3 million tonnes per annum. Despite efforts to utilize the residue in cement production, dyke strengthening, backfilling, and brick manufacturing, alternative avenues were required to increase its utilization rate, as there is no cement plant in the vicinity. The feasibility of using bauxite residue in road construction was explored in collaboration with the CSIR-Central Road Research Institute (CRRI). CRRI conducted detailed laboratory tests assessing mechanical and leaching properties along with settlement studies under seismic and varying saturation conditions to assess its suitability for embankments. Laboratory results confirmed that heavy metal concentrations were within the limits. The mechanical properties were within the limits of the Indian Road Congress (IRC) and meeting the embankment and subgrade. Settlement results were also below the National limits.

The performance of Bauxite Residue was evaluated through a pilot test section on the National Highway (NH-130) near Koraput, Odisha. Ambient air, groundwater, and soil were monitored at regular intervals and at multiple sampling locations since the construction stage. A metal analysis on the blood sample of the working personnel involved was conducted to examine exposure to heavy metals, particularly aluminium and iron. The environmental and health parameter will be assessed again in 2026 for any residual impacts.

Keywords: Bauxite residue, Embankment, Subgrade, Circularity, Waste material.

1. Introduction

Bauxite residue is a waste generated during the Bayer process in alumina refining. As per the Indian Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016, it is categorized as a high-volume, low-effect waste. Bauxite residue (commonly referred to as red mud) is characterized by its high alkalinity and the presence of heavy metals, posing potential risks to surrounding ecosystems. Improper handling, storage, or disposal can result in contamination of groundwater, surface water, soil, and air, making its management a critical environmental issue. To address these challenges, industries have adopted sustainable practices for red mud utilization. Examples include its use in cement manufacturing as replacement of laterite, mine backfilling, bricks and aggregate production. Given the rapid pace of infrastructure development in India and the increasing scarcity of natural resources, the National Highways Authority of India (NHAI) has initiated efforts to evaluate the feasibility of using bulk industrial wastes, such as fly ash, jarofix, copper slag, steel slag, zinc slag, red mud, and jarosite,as alternative materials for road construction. Hindalco Industries Ltd. carried out a pilot study to develop a construction methodology with economically viable technology, in collaboration with NHAI, CRRI (Central Road Research Institute) and IMMT (Institute of Minerals & Material Technology). As part of the study, one section of road was constructed using red mud and fly ash (Embankment & Subgrade) while a second section was constructed using a mixture of red mud only (embankment). Based on the study findings, guidelines will be developed by IRC for application of red mud in road construction.

2. Literature Review

Numerous studies have highlighted the potential application of red mud in road infrastructure. For instance, suitability of red mud for use in constructing road bases, embankments, and coastal protection structures like seawall [1]. It has been demonstrated that the stabilization of red mud with up to 4 % with Eko Soil Enzyme (ES) enhances its moisture retention capacity and increases the maximum dry density, thereby improving its engineering properties [2]. Similarly, Panda et al. [3] and He et al. [4] investigated the feasibility of employing red mud in bulk quantities as structural fill and embankment material. Singh et al. [5] explored the feasibility of utilizing bauxite residue to prepare construction materials for highways, showcasing a notable 14.01 % increase in compressive strength, a 6.74 % boost in flexural strength, and a 7.58 % enhancement in split tensile strength following a 28-day curing period in the lab environment.

Further, experiments were conducted using red mud sourced from Muri (Hindalco), India, blended with fly ash in varying ratios (5 to 50 %) [6]. Their findings indicated that the blended material meets the Ministry of Road Transport and Highways (MoRTH) specifications for embankment construction, specifically in accordance with IRC: SP: 84-2014. However, there is a lack of studies that establishes the viability of the red mud usage in actual field conditions. Hindalco Industries Limited, in collaboration with CRRI, New Delhi, undertook an initiative to assess the feasibility of applying red mud in road construction applications. A series of laboratory tests were performed on red mud, both in its natural state with fly ash stabilization, to evaluate its geotechnical characteristics and settlement behaviour, followed by the field trials.

3. Methodology: Lab Trial

3.1 Red Mud Fly Ash Mix

Red mud is a silty and non-plastic fine-grained material. To investigate the improvement in its engineering properties and its workability, it was blended or mechanically stabilized with fly ash (another waste material) in different proportions. Red mud was mixed with fly ash in the ratio of 75:25. Dry density/California Bearing Ratio (CBR) decreases with addition of fly ash in the red mud while the Optimum Moisture Content (OMC) increases. The angle of internal friction of red mud-fly ash mixes varied in the range of 30° to 32° while cohesion value is between 6 to 7 kPa (Table 1).

Table 1. Geotechnical characteristics of red mud (R)- fly ash (F) mix.

Parameters	75R+25F	50R+50F	40R+60F	25R+75F
Specific density G (t/m^3)	3.32	2.97	2.88	2.81
Maximum Dry Density (MDD) (kN/m^3)	19.25	16.73	16.0	14.91
Optimum Moisture Content (OMC) (%)	17.5	18	19	19.5
Cohesion (c) (kN/m^2)	7	6	6	6
Angle of internal friction ϕ (degree)	32	31.5	31.2	30

3.2 Red Mud Cement Mix

To increase the strength property of red mud for the construction of chemically stabilized sub base/base layers, replacing the conventional aggregate layer, 3 to 9 % of cement was added to the red mud. It was observed that maximum dry density slightly increases from 21.28 to 21.5 kN/m^3 with addition of 3 % cement and reached to a maximum value of 21.8 kN/m^3 with addition of 9 % cement while OMC decreases with addition of cement. The unconfined Compressive Strength (UCS) value increases with increase in cement content (3 to 9 percent) and curing periods (7 to 28 days). In durability test, it was observed that all the 3 % cement stabilized samples failed the durability criteria, while the 6–9 % cement stabilized samples passed the durability criteria and have more than 80 percent residual strength.

Table 2. Results of UCS test of cement stabilised red mud samples.

Material		7 days curing		14 days curing		28 days curing	
Sample	Cement Content (%)	UCS, (MPa)	Failure Strain (%)	UCS, (Mpa)	Failure Strain (%)	UCS, (Mpa)	Failure Strain (%)
Red mud	0	0.29	2.33	0.29	2.33	0.29	2.33
	3	1.36	1.67	2.53	2.08	2.82	1.50
	6	4.83	2.83	4.95	2.58	4.99	2.33
	9	4.90	2.33	5.97	2.33	6.06	2.75

3.3 Stability and Settlement Analysis of Red Mud for Embankment Construction

Slope stability analysis was carried out using computer software for a red mud embankment height of 3 m and a two-lane road with side slope of 2 horizontal to 1 vertical. It was observed that the Factor of Safety (FoS) values for critical sudden draw down condition under static/seismic conditions was more than the minimum required with values of 1.4 and 1.0 respectively as per IRC-75 (2015). Considering the Loss on Ignition (LOI) (4.6 percent) value, it was considered that there would be minimum secondary settlement over long time period as organic matter is very low. Settlement was much less than the allowable settlement of 300 mm to 600 mm considered for road embankment (IRC:75, 2013).

Table 3. Factor of safety of embankment without seismic force.

Conditions	R	75R+25F	50R+50R	40R+60F	25R+75F	IRC 75 (2015)
Partially saturated	2.71	2.39	2.28	2.26	2.15	1.4

Steady seepage	1.93	1.92	1.9	1.89	1.86	1.3
Sudden draw down	1.81	1.79	1.75	1.74	1.7	1.3

Table 4. Factor of safety of embankment with seismic force.

Conditions	R	75R+25F	50R+50R	40R+60F	25R+75F	IRC 75 (2015)
Partially saturated	2.58	2.28	2.19	2.18	2.09	1.1
Steady seepage	1.78	1.78	1.77	1.77	1.74	1
Sudden draw down	1.66	1.65	1.62	1.62	1.57	1

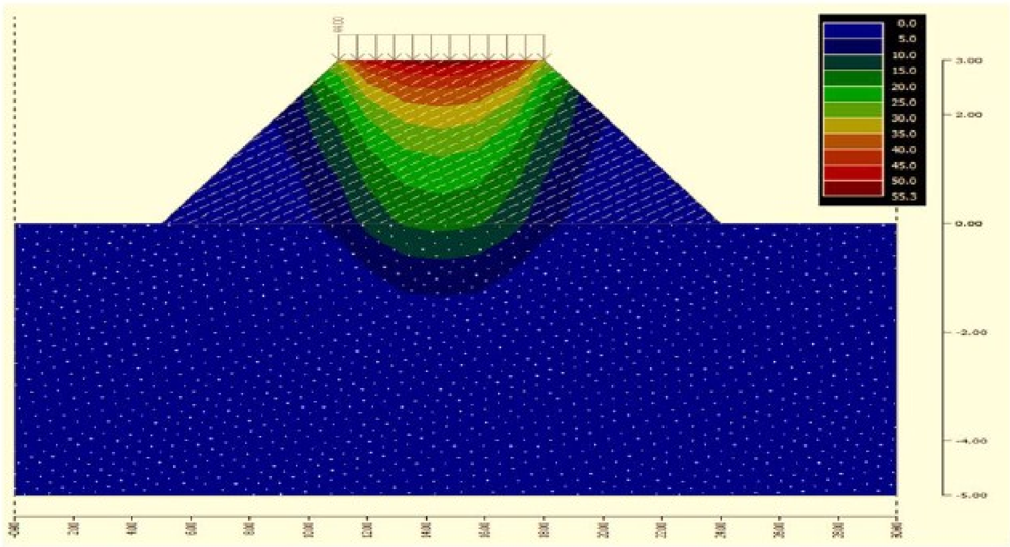

Figure 1. Settlement profile of a 3 m embankment.

3.4 Stability and Settlement Test of Red Mud as a Subgrade Material

To examine the red mud as a structural fill, plate load and dynamic cone penetration tests were carried out in the laboratory on large scale model load test. Density of each compacted layer was measured by core cutter method (IS 2720 part 29, 2005) and average value of 94 % degree of compaction was obtained. No heaving and crack were observed in the compacted surface of the red mud and red mud-fly ash mix. Settlement was observed near the plate and extended up to half the width of the plate. Variation of stress-settlement of red mud and its mix is similar and closely matching with partially saturated cohesive soil as per IS 1888, 2002. Ultimate bearing capacity was noted as 15 000 kg/m^2 (15 t/m^2) from figure 5 of IS 1888 (2002) and safe ultimate bearing capacity (FoS = 3) was estimated as 5 t/m^2. This indicates that this material is suitable for structural fill application.

Characteristics of red mud meet the standard specifications of MoRD (2014) for rural road embankment construction and MoRTH (2013) for national highway embankment and subgrade layer construction.

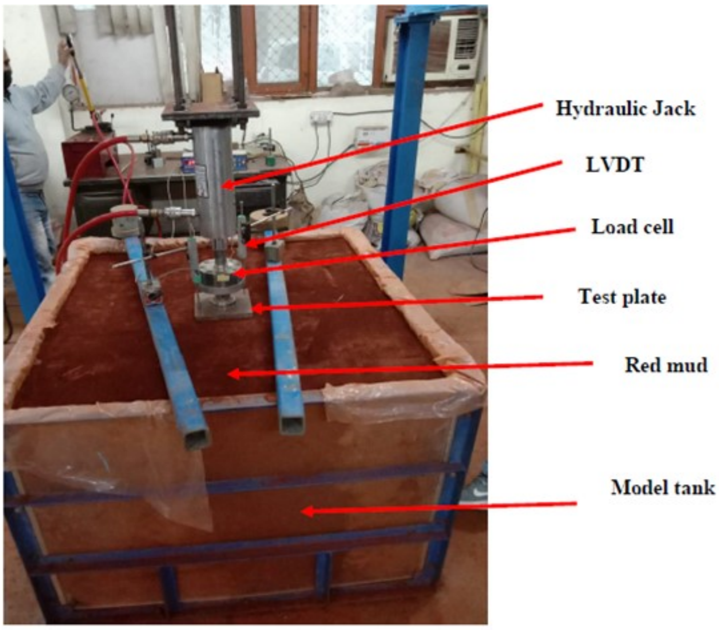

Figure 2. Experimental set up for plate load test on red mud.

The embankment slope stability analysis of red mud and red mud: fly ash (80:20) mix that was carried out using computer software for a typical 6 m height (maximum) of a two-lane road with side slope of 1.5 horizontal to 1 vertical as per the site condition. The embankment was analysed under partially saturated and steady seepage conditions with and without seismic force. However, sudden draw down condition was not considered as per the site condition. Factor of safety (FoS) values obtained are summarized in Table 5. It was observed that FoS values are more than the minimum required value as per IRC 75 (2015).

Table 5. Factor of safety of embankment as per final mix ratio.

Material	Type of Analysis	Obtained FoS		Permissible FoS as per IRC 75 (2015)	
		Static	Seismic	Static	Seismic
Red mud	Partially saturated	2.0	1.8	1.4	1.1
	Steady seepage	1.9	1.7	1.3	1.0
Red mud : fly ash 75:25	Partially saturated	2.4	2.0	1.4	1.1
	Steady seepage	2.3	2.0	1.3	1.0

4. Field Trial Experimental Design

Based on the laboratory study, it was decided that its performance should be examined in the actual field condition with a pilot study. The red mud experimental sections were constructed along the six-lane Kaliagura – Baunsaguar section of National |Highway 130 (NH-130) which is under-construction from 249+000 to 293+000 in the Raipur-Visakhapatanam economic corridor of the state of Odisha. It was decided to construct red mud experimental sections in the loop road of flyover i.e., chainage 290+915.

The cross-sectional design of the red mud pavement as per, per IRC 37 (2014) for National Highway is shown in Figure 3.

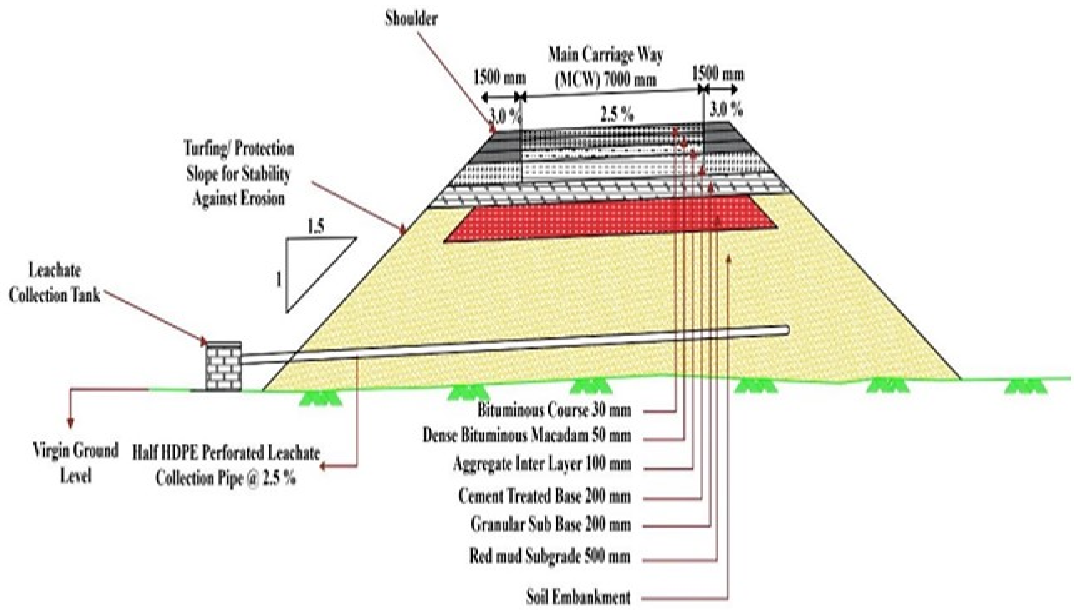

Figure 3. Cross section design of red mud- fly ash embankment.

4.1 Protocol Used for the Construction

After preparation of the ground supporting the embankment, red mud shall be unloaded along the proposed alignment directly from the plant and spread using dozers/graders to the required loose thickness. The fly ash shall then be spread over the same area to the required loose thickness. The loose thicknesses of each of the fill material have to be determined for the specified proportion (by weight, 75:25) and for a compacted thickness of 200 mm as required (MoRTH, 2013). The loose layers of red mud and overlying material should be mixed using a tractor towed harrows or rotavator till until a uniform mix is achieved. 3–4 passes of harrow in either direction (perpendicular) may be sufficient to achieve the uniform mixing. Water should be added as per the optimum moisture content obtained from the modified Proctor compaction test (if required) and compaction should be carried out.

Clearing & Grubbing: cutting, removing and disposal of all trees, bushes, roots, rubbish etc. followed by necessary excavation, backfilling of pits resulting from uprooting of trees and stumps to required compaction

Setting Out: After the site has been cleared, the limits of embankment shall be set out true to lines, curves, slopes, grades and sections as shown on the drawings or as directed by the Engineer. The limits of the embankment shall be marked by fixing batter pegs on both sides at regular intervals

Stripping of Top Soil: Before laying first layer of red mud, the top soil should be stripped to a specified depth not exceeding 150 mm.

Compaction of Supporting Ground & Embankment Fill: The ground supporting the embankment shall be rolled firm using 8–10 tonnes vibratory roller to attain at least 95 % MPD (Maximum Proctor Density). The required amount of water is then added as per OMC, compaction shall be carried out by 8 to 10 tonnes vibratory rollers to achieve a compacted thickness of 200 mm & degree of compaction should be more than 98 %

Subgrade Layer: Total thickness of sub grade layer should be 300 mm (Rural Road) / 500 mm (Highway). The degree of companion achieved should be more than 100 %.

Stabilised Sub Base Layer: Cement (≥ 6 %) stabilized red mud can be tried for the construction of sub base layer of both rural road and National Highway. Through to achieve target UCS value 7 days curing is necessary.

Grassing: Furnishing and laying of live shod of the perennial turf forming grass on embankment slope

Base Layer (WMM): Providing, laying, spreading and compacting graded stone aggregates to wet mix macadam specifications

Bitumen Layers: Applying primer &tack coat of bitumen emulsion, DBM and bituminous concrete

Figure 4. Dumping and in-situ mixing of red mud and fly ash of red mud at the pilot Site.

Figure 5. Left: Compaction of the subgrade section, Right: leachate collection chamber.

Figure 6. Display board at the project site.

5. Results

The feasibility of red mud for utilisation in road construction was investigated and as a structural fill application by carrying out detailed laboratory study. Red mud has lattice and impervious structure of silt and clay size fine particles. Its natural moisture content is very low and is available in an almost dry state. Specific gravity is significantly higher to conventional soil. It has low swelling characteristics which makes it suitable for embankment construction. The Toxicity Characteristic Leaching Procedure (TCLP) test leaching results for concentration of various elements such as nickel, chromium, vanadium, zinc, copper etc. are within the permissible limit stipulated in schedule-II of MEFCC (2016) and as per the manual of United States Environmental Protection Agency (USEPA) - 1311 (1992) for extraction of leachable constituents by wet extraction test (WET). Its density is similar to conventional soil with high value of CBR, which makes it suitable for the construction of embankment and subgrade.

Table 6. Geotechnical characteristics of red mud and fly ash.

Materials	MDD (kN/m^3)	OMC (%)	LL (%)	PL (%)	FSI (%)	CBR (%)	c (kN/m^2)	ϕ (Deg)
Red mud	21.28	18	27.0	NP	15	25	8	32
Fly ash	13.30	20	35.32	NP	--	--	--	24

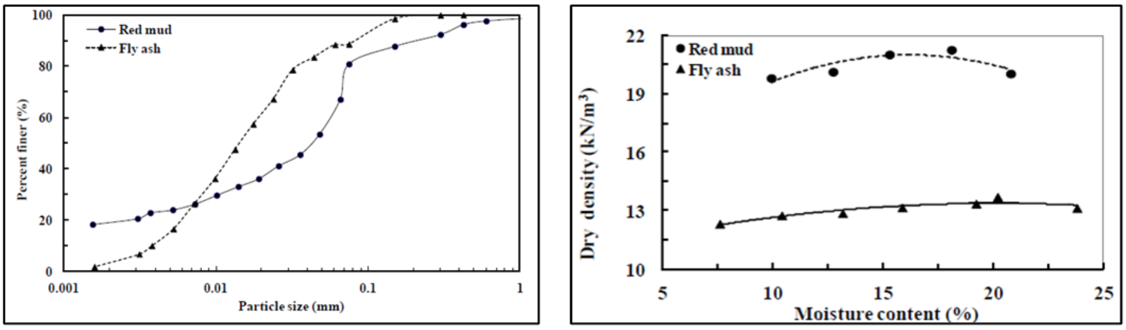

Figure 7. Geotechnical characteristics of red mud and fly ash.

Table 7. Absolute concentration of elements in red mud within permissible limit.

Sl.	Parameters	Result (mg/L)	Method Reference	Permissible limits (mg/L)
1	Arsenic	0.004	TCLP followed by IS 11885-2007; Ed. 2007	5
2	Silver	BQL	TCLP followed by IS 11885-2007; Ed. 2007	5
3	Barium	0.021	TCLP followed by IS 11885-2007; Ed. 2007	100
4	Cadmium	BQL	TCLP followed by IS 11885-2007; Ed. 2007	1
5	Manganese	0.002	TCLP followed by IS 11885-2007; Ed. 2007	10
6	Lead	BQL	TCLP followed by IS 11885-2007; Ed. 2007	5
7	Selenium	BQL	TCLP followed by IS 11885-2007; Ed. 2007	1
8	Mercury	BQL	TCLP followed by IS 11885-2007; Ed. 2007	0.2
9	Beryllium	0.004	WET followed by IS 11885-2007; Ed. 2007	0.75
10	Chromium	0.405	WET followed by IS 11885-2007; Ed. 2007	5
11	Copper	0.36	WET followed by IS 11885-2007; Ed. 2007	25
12	Cobalt	0.021	WET followed by IS 11885-2007; Ed. 2007	80
13	Nickel	0.931	WET followed by IS 11885-2007; Ed. 2007	20
14	Molybdenum	0.12	WET followed by IS 11885-2007; Ed. 2007	350
15	Vanadium	0.644	WET followed by IS 11885-2007; Ed. 2007	24
16	Zinc	0.343	WET followed by IS 11885-2007; Ed. 2007	250
17	Polycyclic Aromatic BDL Pyrene: Naphthalene:	BDL	TCLP followed by US EPA Method 610/8100	0.001
18	Polychlorinated biphenyls (PCBs) (PCB 28, PCB 52, PCB 101, PCB 153, PCB138, PCB 180)	BDL	WET followed by US EPA Method 608/625/8082A	5

Figure 8. Red mud experimental section at chainage 289 & 290.

Figure 9. Experimental chainage 289 & 290, post bituminous concrete layer (BC).

6. Quality Control & Monitoring

The red mud and fly ash was checked for dry density, in situ-moisture content etc. as per Bureau of Indian Standard (BIS) specifications. The tests achieved values within the specifications required by MoRD and MoRTH specifications. Field dry density of red mud alone or red mud-fly ash mix was evaluated either by core cutter or sand replacement method.

Figure 10. Field dry density test (left) and strength test (BBD) under progress (right).

Before construction of the road section using bauxite residue, water, ambient air, soil quality and health impact was recorded as baseline data as per construction standards. Subsequent to the construction of the road section, same parameters were tested to ascertain the environmental impact of bauxite residue used in road construction. The monitoring period extended over two years from the construction time.

Ambient air quality monitoring stations were established at four locations, selected based on the predominant wind direction to ensure representative sampling. Monitoring was conducted at a frequency of two days, with pollutants including PM_{10}, $PM_{2.5}$, SO_2, and NO_2 sampled over a period of 8 hours.

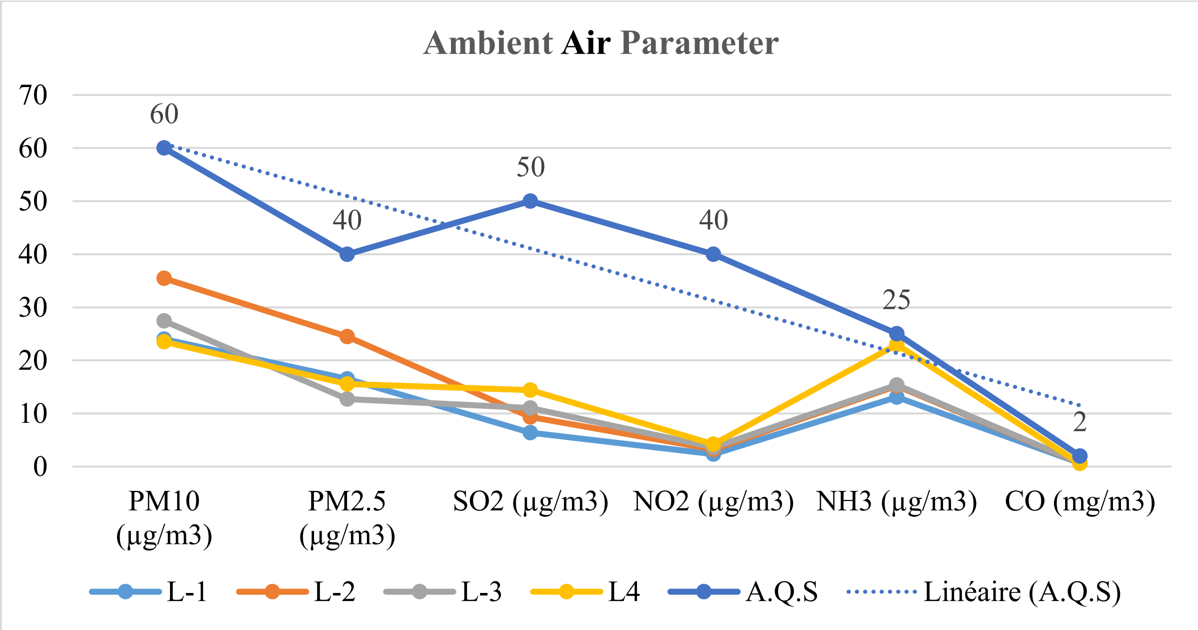

Figure 11. Ambient air quality parameters at the 4 sampling locations.

All observed values were within the permissible limits as specified under the National Ambient Air Quality Standards (NAAQS). Additionally, analysis of heavy metals in $PM_{2.5}$ showed iron concentrations ranging from 0.14 to 1.07 mg/L and aluminium from 0.03 to 0.64 mg/L.

Water samples were collected from six locations to evaluate key physico-chemical parameters. The results were compared against the surface water quality standard IS 2296:1982 (Class C) and drinking water standard IS 10500:2012. The majority of parameters were found to comply with the prescribed limits, indicating acceptable water quality in the monitored areas.

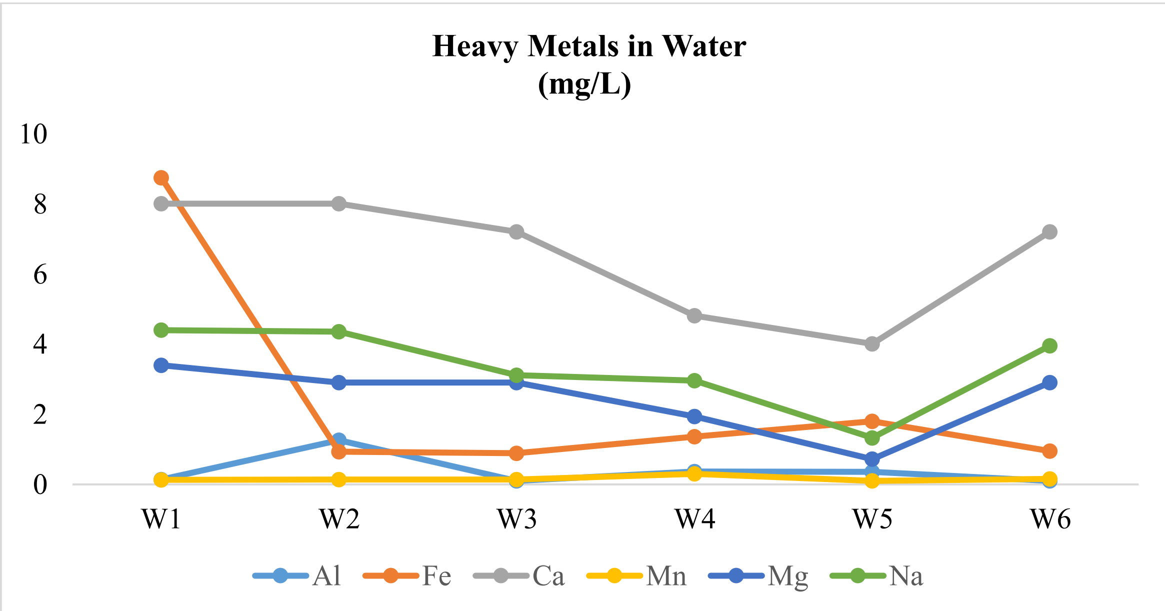

Figure 12. Surface water quality parameters at 6 sampling locations.

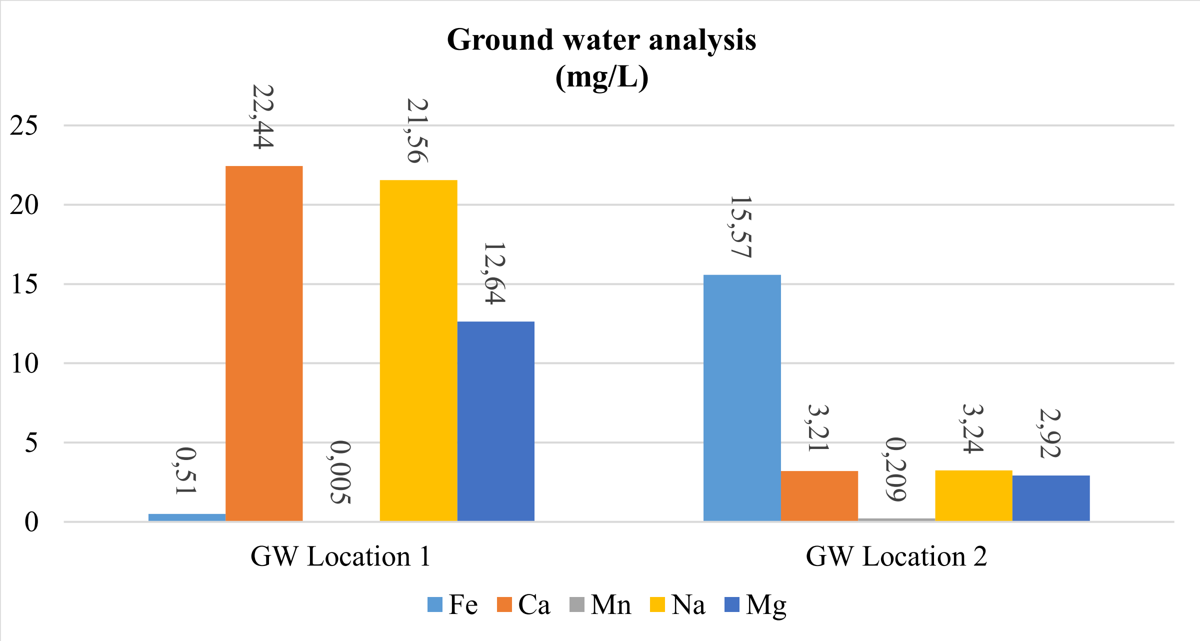

Figure 13. Groundwater quality parameters at 2 sampling locations.

6.1 Soil Quality Assessment

Ten soil samples were collected and analyzed for nutrient content and other relevant parameters. Electrical conductivity results indicated good nutrient availability. Furthermore, concentrations of nitrogen (N), phosphorus (P), and potassium (K) were found to be adequate in nearly all samples, suggesting that the soil surrounding the project area is fertile and suitable for vegetation.

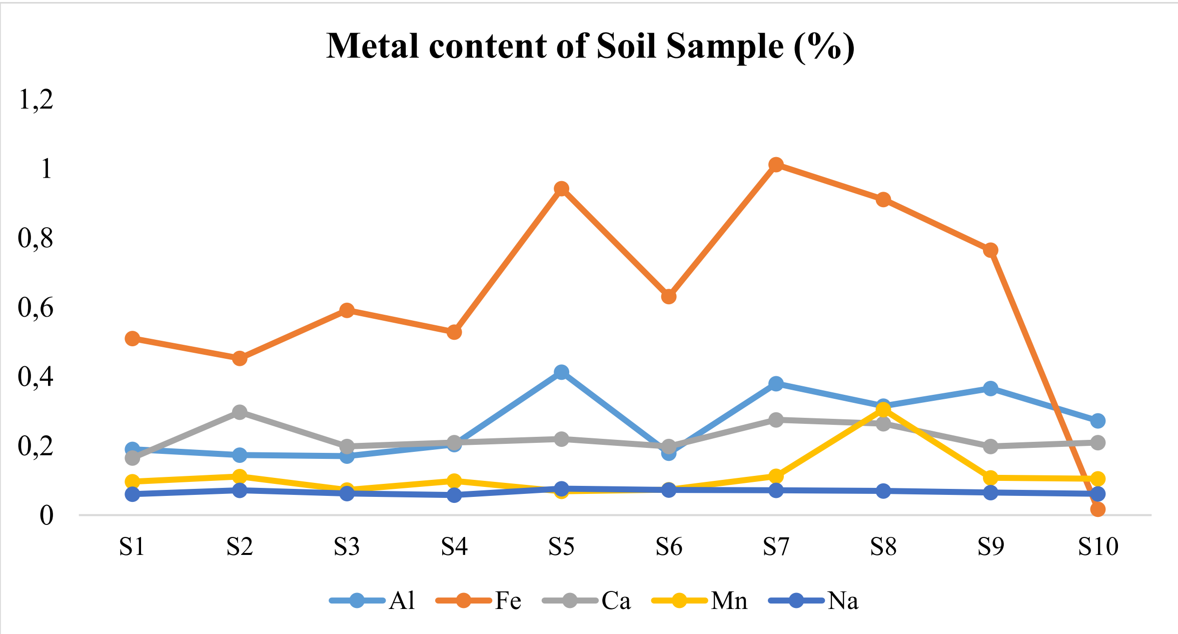

Figure 14. Soil quality parameters at 10 sampling locations.

To evaluate the potential health impacts from red mud exposure, twelve individuals involved in red mud-based road construction activities were selected for the study. Blood samples were collected from these workers and analyzed for heavy metal content, with a particular focus on aluminium and iron concentrations. This analysis aimed to assess the possible bioaccumulation of metals and any related health effects associated with prolonged exposure to red mud.

7. Conclusion & Way Forward

Lab test results have shown suitability of red mud as embankment and subgrade material. TCLP test results confirmed that heavy metal concentrations in the bauxite residue were within the limits specified by USEPA. It had a higher specific gravity (3.2) and CBR (25 %) than soil, with a similar density. The maximum dry density (MDD) and optimum moisture content (OMC) were 21.28 kN/m³ and 18 %, respectively. Settlement (31–51 mm) was well below the Indian Road Congress (IRC) 75 (2015) limit. The factor of safety was found to be greater than 1. It meets the embankment and subgrade specifications as per MORTH (2015) and IRC SP:132 (2022).

For the field trial, performance evaluation by CRRI has shown that all the structural-stability parameters are within norms as per IRC 75 (2013 & 2015). 32 000 t Red Mud has been used in this pilot and Environmental monitoring is ongoing, ending in Dec 2025, and comparative analysis with the baseline parameters after 2 years of monitoring will establish long term sustainability of the bauxite residue use-case in road construction. For this pilot project, red mud and fly ash mix was being used as embankment and subgrade material; however, it can also be used for sub-base construction by mixing it with cement. Suitability of usage of red mud as sub-base construction has been proved through laboratory tests by CRRI. A request letter is submitted to Chairman, NHAI, Delhi for allotment of additional sections of road for utilization of further red mud. Also, in order to streamline the cross-sectoral collaboration and synergy between all the stakeholders, project protocol and SOP will be formulated to be adopted across all sites for consistency and compliance.

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