Study on Mechanical Properties of Lime Stabilized Active Bauxite Residue (Red Mud) and Fly Ash to Use as a Subgrade Material in Road Construction

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Abstract:

Bauxite residue (Red mud) is a waste product produced during the extraction of aluminium from Bauxite by Bayer's process. The huge requirement of aluminium for the various needs of mankind resulted to the enormous production of bauxite residue which is a very fine substance with high alkalinity. The high alkaline nature of this waste material shows a high impact on environment if it not covered or used in an appropriate method. This paper focusses on the usage of bauxite residue with the support of lime and flyash as a stabilizing material to use as a subgrade in road constructions and understand the toxicity levels of it upon leaching. Bauxite residue was stabilized with various ratios of fly ash and lime powder to its dry weight and determined the mechanical properties like California bearing ratio and unconfined compressive strength of all the combinations. Any industrial waste material will pose a environmental threat if the chemical analysis was not made upon using it as a subgrade material. In this study more emphasis was given to study the various hazardous chemicals present in the leachate collected from bauxite residue with fly ash and lime mixture. Leachate was collected by using Total characteristics leaching procedure (TCLP Method) and chemical analysis was performed and compared the results with the various water standards to recommend this material as a chemically safe material in the nature. All the results proved that bauxite residue upon stabilizing with the fly ash and lime is very much suitable to use as a subgrade material and environmentally safe

Keywords: Bauxite residue, Mechanical properties, chemical analysis, Leachate collection, subgrade material, strength, microstructure.

Introduction:

It is important to consider the negative consequences of the rapid growth of industry and urbanisation on both the environment and social life around the world. These negative consequences raise questions about how to safely dispose of industrial waste. The main consequences of these two phenomena are the vast amounts of industrial waste produced and the issues associated with their proper management and disposal [1]. Land, materials, and resources are in short supply, which makes it difficult to carry out continuing development activities, such as building infrastructure. Aluminum is the third most abundant element on Earth, and mining has expanded dramatically [2]. Aluminium's widespread use in modern life has increased extraction. At the present time, bauxite ore is the principal source of alumina around the world. A lateritic mineral rich in aluminium and iron oxide, bauxite is mined around the world. Barite mining, Bayer refining, and subsequently aluminium smelting are the three steps in making alumina. [3] Barite mining and Bayer refining are the first two. Because of its intractable nature after being digested with sodium hydroxide at extremely high pressure and temperature to produce alumina via the Bayer process, the substance produced is known as "bauxite residue" (4). The red colour is due to iron oxide, which is a strongly alkaline waste product [5]. Bauxite tailings, bauxite residue, red sludge, and alumina refinery leftovers are all terms used to describe this material (ARR).

Bauxite residue has a high alkalinity, which makes the discharge of it environmentally harmful and difficult. One of the most important objectives in the quest for a more sustainable environment [6] is to better understand and explain these issues. It is obvious that the wide range of characteristics makes it difficult to categorise the substance (whether bauxite residue is a silt or a clay). There are two main causes for the difficulty: drying of the material in various ways and cementation of the substance that might occur to diverse degrees and over varying time periods. ' The drying effects on bauxite residue are the second problem that has been brought up. Changes in temperature (air-dried, oven-dried, compress-dried) and void fluid pH (caustic, acidic, or neutral based on the environment) tend to impact bauxite residue behaviour [7]. [8].

Because bauxite residue leaches out into the environment, it becomes hazardous. By percolation, soluble elements from various materials (such as rock, soil, or garbage) are dissolved from the solid material into a fluid. Consequently, solid phase components will dissolve in liquid and create a leachate when fill materials are exposed to liquids (including rainwater that has been percolated, groundwater, surface water, and any other liquids included in the fill material). Site- and material-specific circumstances (physical, chemical, and biological factors) and time will determine the extent to which the contents are dissolved into the contact liquid. It is most typically utilised in the context of land-filling of putrescible or industrial waste. The term "leachate" refers to any liquid that, while moving through a substance, removes soluble or suspended particles or any other component of that material.

In this study, afte runderstanding about the index properties of bauxite residue, eventually have a comparative study of the chemical analysis of bauxite residue before and after it hasbeenleachedwhereglacialaceticacid has beenemployedastheleachingfluid.The investigation will be carried out using a variety of routine analysis methods in the field of materials science and engineering, including XRD, SEM, shear strength testing, particle size measurement, and so on. This will signify the elements like heavy metals which makes the behavior of bauxite residue toxic and hazardous after the process of leaching.To improve the usage of bauxite residue in constructional activities such as using it as a subgrade layer or as a component of building materials by using bauxite residue which is considered as a hazardous by-product in the process of extracting alumina from bauxite as a useful material andworking towards a sustainable approach [11] [12]. Utilizingbauxite residue also reduces environmentalimpacts. After determining the geotechnical properties of bauxite residue, made acomparative study on the chemical properties of bauxite residue and the leachate of bauxite residue in ordertoidentifythehazardouschemicalconstituentsthathasbeenformedorincreased after the contact with the leaching fluid, i.e.water.The alumina production is a process by which chemical enrichment occurs while separating alumina from the undesirable components of its bauxite ore. The primary aluminium production is carried out in two stages. In the first stage, alumina is produced by wet chemical, caustic leach method (Bayer process). Followed by the second step wherein aluminium is produced from alumina by smelting in the Hall-Heroult process. Components like oxides of iron, titanium, silicon, calcium, vanadium, manganese etc. are components of the sludge or residue produced as a by-product of the Bayer extraction process and is commonly referred to as bauxite residue.

In the waste stream, approximately 35-40 percent of the bauxite ore is converted to alkaline bauxite residue slurry, with the remaining 15-40 percent comprising of solids. For every tonne of alumina produced, between 0.3 to 2.5 tonnes of bauxite residue are generated..This rangevariesgreatlywiththetypeoforeused.Globally,thereisanestimated70million tons of bauxite residue being produced every year [13]. It has been estimated that the world productionofbauxitewasat248milliontonsin2012andIndiaaloneaccountedfor12,877 thousandtonsin2012-13.The presence of large amounts of industrial alkali, fluoride, heavy metals and other potential pollutants in bauxite residue residue, which when stored for an extended period of time, would not only take up valuable land space but also have the potential to pollute the soil, air and groundwater in the surrounding area. The continuous growth in stacking height has been demonstrated to enhance the risk of geological calamity.Thus, intensive studiesonthephysicalandchemicalpropertiesofbauxite residuealongwithitscomprehensive utilization is demanding immediate attention with the development in science and sustainable engineering technologies. The most appropriate method of using a waste material is application of it in civil engineering constructions and specifically in the construction of various layers of pavements. In the construction of pavement layers huge of amount of bauxite residue or any other industry waste material can be used upon stabilizing in the suitable forms [14].

Materials:

Bauxite residue:

The Bauxite Residue (BR) utilised in this study was recovered from the waste collection pond of HINDALCO Industries Ltd., Belgaum, Karnataka. The samples were collected in a dry state and contained more particles with a moisture level of 3-5 percent.. The specific gravity (G), liquid limit (LL) and plastic limit (PL) values are 2.86, 39% and 28%, respectively. BR is classified as ML (low plasticity silt) based on the coefficient of uniformity (0.67) and coefficient of curvature (0.71) according to USCS classification. BR has a pH of 11.06. Standard Proctor compaction test results portrayed the OMC and MDD values as 34.39% and 1.59 g/cc. The unsoaked and soaked CBR values of BR were determined as 5.48% and 1.56%. These values show that BR cannot be used as a geomaterial due to its low strength. SEM, XRF and XRD analyses performed to identify the microstructure, chemical, and minerals present. Figure 1a depicts a SEM picture of BR, revealing very loose microstructures and significant porosity. Figure 2 shows XRD patterns of main mineral phases of the BR waste are Chantalite ($Na_5Al_3CSi_3O_{15}$), Gibbsite ($Al(OH)_3$), Muscovite ($KAl_2(FOH)$), Calcite ($CaCO_3$), Hematite- Fe_2O_3.

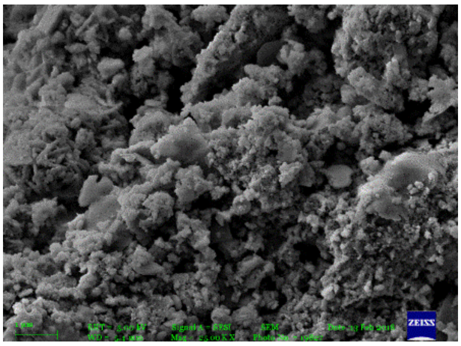

Fig 1: Scanning Electron Microscope (SEM) image of Bauxite residue

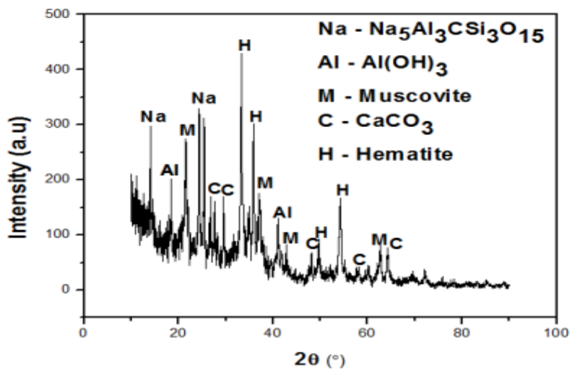

Fig 2: X-Ray Diffraction (XRD) of Bauxite residue

The chemical composition of BR is shown in table 1. The main chemical constituents of BR are Fe_2O_3, Al_2O_3, SiO_2, CaO, Na_2O, TiO, K_2O, and MgO. The percentage of these chemical components will fluctuate over time based on the method, property, and phase of the bauxite.

Table 1. Chemicalcompositions of bauxite residue, fly ash and lime

S. No	Chemical constituent	Bauxite residue (%)	Flyash(%)	Lime (%)
1	Fe_2O_3	44.3	13.43	0.35
2	Al_2O_3	18.2	19.54	0.65
3	SiO_2	14.5	46.5	1.36
4	TiO_2	10.5	1.04	-
5	Na_2O	9.29	1.56	-
6	CaO	1.11	7.61	92.7
7	P_2O_5	0.74	2.48	-
8	SO_3	0.37	0.9	-
9	V_2O_5	0.35	0.05	-
10	Cr_2O_3	0.18	-	-
11	K_2O	-	-	-
12	MgO	-	4.6	1.89

Flyash:

RTPS, a coal-fired electric power station located in the Raichur region of Karnataka, India, provided fly ash (FA) for this project. Fly ash is utilised as a stabilising material because it has a pozzolonic character when it combines with water, which makes it a good choice for this use. The chemical makeup of FA is shown in Table 1. Silica and mullite are the most active constituents, with trace levels of hematite and calcium oxide also present.

Lime:

Lime is rich in CaO content, so it can be used as a binder to stabilize Redmud mixes. For this study the lime with 92.7% CaO was purchased from a local vendor which is a high quality with respect to the stabilization of materials. Lime has been used in the construction of buildings for thousands of years as a strong and durable mortar. The strength of lime-based mixes can be altered as per the needs of the particular application. Lime powder was mixed with bauxite residue and prepared various mixes or combinations which are to be used as base and subbases in pavement construction. The detailed chemical composition of lime is presented in table 1 for the better idea on the parameters of stabilizing the material and chemical analysis.

Methodology:

The geotechnical parameters of virginBRmaterial were initially investigated in depth in order to determine whether the material could be used as a subgrade material in road building. Then BR is substituted with FA by percentages of 10%, 20%, and 30% of the dry weight of the product, respectively. BR-FA strength qualities were determined by re-stimulating the same combinations with 1 percent, 3 percent, and 5 percent of lime to determine the strength properties of the BR-FA. Table 2 contains a list of possible combinations, as well as the nomenclature for each one. In order to examine their compaction characteristics, such as OMC and MDD, all of the combinations were subjected to a modified Proctor Compaction test. Using the OMC obtained from the compaction test, the researchers ran an unsoaked CBR and a soaked CBR over a 4-day period on all of the combinations. The findings of CBR were compared with the standard values of the construction of subgrade according to IRC 37. The UCS of all the samples was determined for the curing periods of 1 day, 7 days, and 28 days by producing the samples with the OMC of theUCS samples were made in accordance with the UCS test technique and then covered with a polythene cover to allow for curing for one day, seven days, and 28 days, depending on the time frame. It was determined that all of the samples had sufficient compressive strength by testing them with an unconfined compressive strength testing machine and recording the results. Following the completion of all geotechnical testing, the optimal combination of tests was TCLP (Toxicity Characteristics Leaching Procedure) testing was chosen since it collects the leachate from the sample.BR-FA was researched and compared to various water quality requirements in order to ensure that it could be utilized in road subgrades in the future without posing a threat to human health or the environment.

Table 2: Nomenclatures for BR-FA and Lime Combinations

S. No.	Sample Combination (%)	Nomenclature
1	100BR+0FA+0L	BFL1
2	90BR+10FA+0L	BFL2
3	90BR+10FA+1L	BFL3
4	90BR+10FA+3L	BFL4
5	90BR+10FA+5L	BFL5
6	80BR+20FA+0L	BFL6
7	80BR+20FA+1L	BFL7
8	80BR+20FA+3L	BFL8
9	80BR+20FA+5L	BFL9
10	70BR+30FA+0L	BFL10
11	70BR+30FA+1L	BFL11
12	70BR+30FA+3L	BFL12
13	70BR+30FA+5L	BFC13

Results and discussion:

Compaction test:

For all of the combinations, a modified proctor compaction test was expected to characterize the optimal moisture content (OMC) and maximum dry density (MDD). It is observed that the OMC was reducing with the addition of FA to BR as the water obsoption capacity of FA is less compared to the BR. It is also observed that the improvement in the dry density figures with the addition of FA but many studies proves that the addition of FA to be restricted upto 30% maximum as further will not show any improvement in MDD [15] . The addition of lime also indicated the reduction of OMC and increase of MDD in all the cases of BFL combinations. The table 3 presents the OMC and MDD values of all the combinations used in this study.

Table 3: OMC and MDD of BR-FA with and without Lime in a series of assays

S. No.	Sample Name	OMC (%)	MDD (kN/m^3)
1	BFL1	30.39	16.00
2	BFL2	29.11	17.10
3	BFL3	29.12	17.15
4	BFL4	29.00	17.20
5	BFL5	28.66	17.30
6	BFL6	28.88	17.35
7	BFL7	27.45	17.85
8	BFL8	26.99	17.91
9	BFL9	26.55	18.10
10	BFL10	25.99	17.80
11	BFL11	25.03	17.80
12	BFL12	24.66	17.79
13	BFL13	24.01	17.70

California Bearing Ratio (CBR) Test:

All of the samples were subjected to a California bearing ratio test to determine the CBR value, which is a crucial metric for a material's acceptance as a subgrade material in road construction. CBR test was performed by mixing the BR-FA and Lime with the OMC which is obtained in the modified proctor compaction. As per conventional conduction protocol, all samples were soaked in water for four days with a surcharge load of 5kg. CBR value of various combinations were presented in figure 3. It shows that the addition of fly ash increased the CBR value and further the study proves that the addition of lime upto 5 percent with 20 percent replacement of FA showed the best results among all the combinations The minimum CBR necessary for the building of subgrade using any material, according to IRC 37-2012, is 8, and the combination BFL9 produces the greatest results of all the trails.

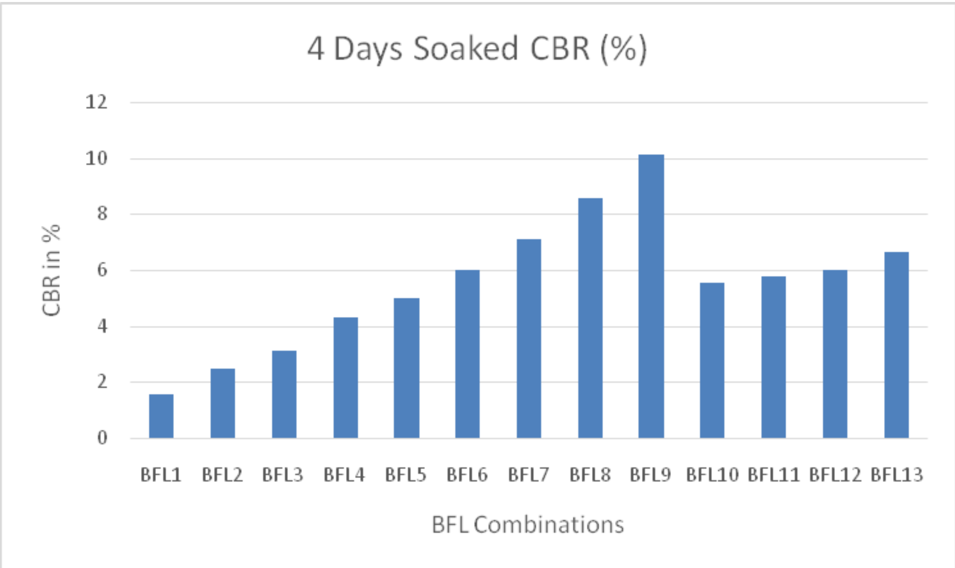

Fig 3: CBR value of various combinations of BR, FA and Lime

Unconfined Compressive Strength (UCS):

UCS test was conducted to investigate the strength property of BR with FA and lime. All the UCS samples were prepared by using the OMC obtained for the specific combinations which is presented in table 3. All the samples were cured for 1day, 7days and 28days as per the standard procedure of estimating the strength improvement in materials. It is observed that the strength of lime and fly ash stabilized bauxite residue samples increased exponentially with the increase of curing periods which directly indicates that the chemical present in lime and fly ash are supporting to the improvement in the strength. All the combinations with the different curing periods were presented in Fig 4. BFL9 has shown the best results among all the combinations with the 28days of curing period. It shows that the chemicals like silica and aluminum in BR and FA has reacted well with the CaO present in the lime to get a better boding and improving the strength.

Fig 4: UCS of various combinations of BR, FA and Lime

Methods of collecting the leachate:

In this paper authors envisaged on various methods of collecting the leachate before conducting the chemical analysis of leachate. The procedures for collecting leachate vary depending on the materials utilised in the research.This chapter gives a clear idea to the reader about the possible methods of collecting the leachate and importance of it in the geo environmental study. The extent of dissolution chiefly depends on site- and material-specific conditions and to a great extent on the length of time in contact. It is important to know the composition of the leachate formed by the material and its possible impact on water quality in order to evaluate its acceptability as a subgrade substance. Batch leaching and continuous flow column leaching have been used for leaching tests. A single extraction may be used in some batch leaching procedures, whereas others need numerous extractions [16]. Toxic Characteristic Leaching Procedure (TCLP) is mandated by the Michigan Environmental Response Act Administrative Rule 299.5711(2). Subrule (b) authorises the Department of Environmental Quality to accept the use of other methodologies in lieu of TCLP if they are more closely aligned with site conditions.

Table 4: Types of leachate collection methods based on materials.

Test Method	Extraction fluid	Appropriate for	In appropriate for
Total methods	As per each analytical method	All See MERA operational memo #6 for correct methods	
Toxicity Characteristic Leaching Procedure (TCLP) EPA method 1311	Buffered acetic acid pH 2.88 or 4.93	Metals, semi volatiles, pesticides, PCB's, volatiles	Cyanide, sulfides, hexavalent and chromium
Synthetic Precipitation Leaching Procedure (SPLP) EPA method 1312	H_2SO_4 and HNO_3	Metals, semi volatiles, pesticides, PCB's,	
	Reagent water	Cyanide, sulfides, hexavalent and chromium	
ASTM D3987-85 (ASTM Neutral Leach)	Reagent water	semi volatiles, pesticides, PCB's, Cyanide, sulfides, hexavalent and chromium	
ASTM D 5233-92 (ASTM Single Batch)	Buffered Acetic acid (Ph 2.88 OR 4.93	Metals, semi volatiles, pesticides, PCB's,	Volatiles, Cyanide, sulfides, hexavalent and chromium

In a TCLP test, 100g of a size-reduced waste material sample is measured and combined with an extraction fluid of choice. A 20:1 liquid to solid ratio is used. The leaching fluid is selected based on extent of solubility of constituents. Solubility of inorganic materials primarily depends on the pH and the redox potential whereas solubility of metals is influenced by the competency characteristics of the other metals in the solution. Contaminated waste water enriched with non-ferrous elements like lead, cadmium, zinc and copper is probable to cause secondary pollutionA clear distinction between leaching at different pH of organic acids such as sulfuric acid, nitric acid, and hydrochloric acid, and inorganic acids such as citric acid, malic acid, succinic acid, and acetic acid has been explained in the past, where tests showed that an optimum pH of 2-3 gives the best leachate characteristics, above which leaching concentrations tend to flatten out [17]. Heavy metals are detected in trace concentrations in bauxite residue.

It was noticed that the leaching concentrations differ for different metals. This means that the extent of leaching of one metal need not be the same for all the metals despite showing maximum leaching at a particular range of pH. For example, concentrations of Zn, Cd and Pb in leachate was 50-100 times, 400-600 times and 10-15 times as large as Cu [18]. Organic acids showed better leaching performance than inorganic acids. Lead, cadmium and zinc was 50-200, 1.5-2.0, 1.8-2.0 times more leached by organic acids than by inorganic acids. For exceptional metals like arsenic and copper, inorganic acids showed better affinity.

Chemical Analysis of Leachate:

The Toxicity Characteristics Leaching Procedure was selected leachate collection from bauxite residual waste because of the presence of metals, volatiles, semi-volatiles, and PCBs in the waste (TCLP- U.S EPA- Test Method 1311). Leachate is collected in the laboratory using a variety of procedures, as shown in Table 3. The TCLP test uses an extraction solution to remove pollutants from a 100-gram sample of waste material. Liquid to solids (L/S) ratios of 20:1 are used in this experiment, and the combination is rotated for 18 hours at 30 revolutions per minute (rpm). The alkalinity of the waste material determines the extraction fluid utilised. Acetic acid buffered at pH 4.93 0.05 with 1-N sodium hydroxide is used to leach alkaline waste materials, while acetic acid buffered at pH 2.88 0.05 is used to leach alkaline waste materials. Filtration takes place when the final pH is determined and the liquid is centrifuged. Preservative can be applied to the filtrate once it is collected in the proper container. A wide range of constituents are examined in the filtrate. Toxic waste is defined as that which has constituent concentrations that are equivalent to or greater than the standards indicated.

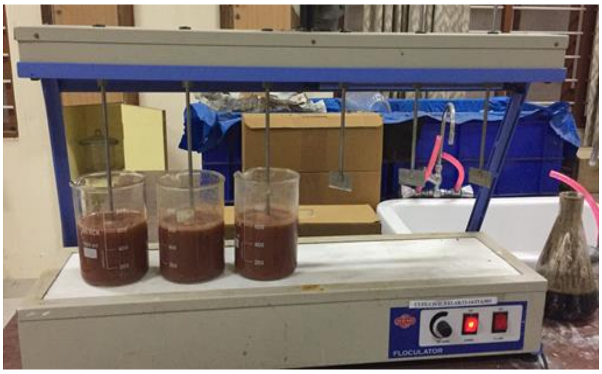

Figure 5. Beakers containing mixture with vertical axis rotary machine

This approach of increasing pH by adding additional alkaline water is depicted in Table 5. From 100 ml to 600 ml of alkaline water was supplied to increase from a pH of 2.15 to 2.88 in order to collect the leachate from bauxite residual waste as required by the TCPL method A glass fibre filter is used to collect the filtrate in a suitable container. This is followed by an examination of the leachate for the required parameters.

Table 5. Trail and Error method to increase in pH

Water in ml	pH
100	2.15
120	2.17
140	2.21
160	2.22
180	2.24
220	2.34
300	2.34
320	2.44
520	2.76
600	2.88

In this study, BFL9 combination shows the best results with the respect to strength and CBR, it is used to study the leachate characteristics. TCLP approach was used to gather the waste leachate from the bauxite residue waste. Leachate collected in the laboratory is more effective than leachate collected on site, according to research. It was chosen to test the collected leachate for heavy metals such arsenic, cadmium, chromium, lead, mercury, sodium, calcium, silica, and copper based on the results of the literature review and the degree of toxicity. TCLP hazardous waste limits and WHO drinking water standards are all used to compare the heavy metal concentrations in the leachate from the bauxite residue waste (as well as the fly ash and lime) with those in the primary drinking water standards. Table 6 presents the levels of various heavy metals and comparisons with the various water quality standards. It demonstrates that even in leachate, a significant quantity of calcium, silica, and sodium can be retained.

Table 6. Heavy metals present in leachate and comparative limits

Heavy Metals	Results obtained mg/l	Primary drinking water standard mg/l	TCLP hazardous wastelimit mg/l	WHO standards of drinking water mg/
Arsenic	<0.02	0.05	5.0	0.01
Cadmium	0.05	0.005	1.0	0.003
Chromium	0.8	0.1	5.0	0.05
Lead	0.2	0.015	5.0	0.01
Mercury	<0.001	0.002	0.2	0.001
Copper	0.1	1.3	-	2
Sodium	3.99	20	40	20
Silica	118	100	200	100
Calcium	198	20-208	-	20-208

Conclusions:

The high alkaline nature makes the BR into a toxic material if it exposed freely. The geotechnical results show that the bare BR can be used as a geo material with the appropriate method of stabilizations. The results of CBR and UCS confirms that the BR in combination with 20% fly ash and 5% lime shows the best results and can be most suitable as a subgrade material in the pavement constructions. The leachate study confirms that the hazardous chemicals present in the suggested combination are less harmful even upon mixing with the ground water. Although few heavy metals are beyond the WHO standards, which shows that the water is not suitable for drinking but the appropriate combination can be safely used as they are not toxic according to TCLP. This work concludes that the BR with fly ash and lime can be effectively used as a subgrade material.

Data Availability:

The data used to support findings of this study are included within the article.

Conflict of Interest:

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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