

Research Article

Utilization of Red Mud-Fly Ash Reinforced with Cement in Road Construction Applications

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Received 12 July 2021; Accepted 17 August 2021; Published 26 August 2021

Academic Editor: Samson Jerold Samuel Chelladurai

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Industrialization is the key to the growth of any country's economy. However, on the other hand, the production of industrial waste is increasing enormously, which adversely impacts the environment and natural resources. Red mud is also a widespread industrial waste produced during aluminium extraction from bauxite ore in Bayer's process. Red mud is a highly alkaline material that creates a massive environmental threat in nature. To reduce the impact of this solid waste material, the ideal method is to use it in construction works with appropriate stabilization. This study envisages the strength properties of red mud with fly ash and cement to use it as a road construction material in the subgrade. The influence of fly ash and cement on improving the strength properties of red mud was studied in detail by replacing red mud with 10%, 20%, and 30% with fly ash and 1%, 3%, and 5% of cement to its dry weight. The CBR (California bearing ratio) value was increased from 1.58% to 11.6% by stabilizing red mud with fly ash and cement, which can be used as a road construction material. The UCS (unconfined compressive strength) of red mud was increased from 825 kPa to 2340 kPa upon curing for 28 days with the right mix of fly ash and cement. Along with the strength properties, the chemical analysis of leachate for the best suitable mix was performed according to the TCLP method to understand the hazardous materials present in the red mud when it is injected as ground material. Both strength properties and the leachate characteristics prove that the red mud with suitable fly ash and cement is an excellent material in road constructions.

1. Introduction

The cost for construction of rigid and flexible pavements with subgrade of low California bearing ratio (CBR) values is exceptionally higher because of the high thickness of the pavement required. Expulsion and substitution of low CBR soils is one of the methods to increase the CBR of the subgrade. The subgrade soil having low CBR values is expelled and placed with the soil of high CBR values, in the event that it is accessible in the adjacent zones monetarily. But, every time, it is not practicable to discover soils of high CBR values to be utilized as subgrade over low CBR soil. Also, taking the soil from a region where the soil is utilized for agricultural purpose will decrease the yield. Also, it will make many depressions in the ground which may result in

land degradation. The disposal of tremendous amounts of solid wastes like red mud and flyash which comes from manufacturing industries makes a number of geo-environmental issues such as groundwater contamination and surface water and neighborhood air contamination, other than loss of profitable land close to the plant site. These solid wastes can be combined to deliver a composite material of high CBR values and good compressive strength which can be utilized as subgrade instead of soils of low values.

Red mud (RM) is an industrial waste produced from Bayer's technique of extracting aluminium from bauxite ore. It is also known as bauxite residue. The quantity of RM generated varies between 60 and 70% of the prepared metals, depending on the purity and immaculateness of the bauxite minerals [1]. More than 150 million tonnes of RM are

produced worldwide, with India contributing 9 million tonnes each year [2]. Every tonne of alumina produced produces 0.8–1.6 tonnes of RM [3]. When RM is dumped directly into the land surface, its high alkalinity (pH: 11–13) poses an environmental concern. The total annual production of red mud from various countries was estimated and presented in Figure 1.

Figure 2 depicts the production of aluminium, the generation of RM, and its use in India, revealing a significant discrepancy between production and utilization of RM. In most countries, the most prevalent way of RM disposal is to dump it into specially prepared landfills adjacent to plants, which produces air pollution from very fine particles and groundwater pollution if leaching occurs. In 2010, an aluminium sludge discharge occurred near Ajka in Hungary. Another spillover incident in January 2018 in Belem has served as a reminder to everyone that storing large quantities of RM can result in unanticipated property and human loss [6, 7]. Using RM in the construction sector is the most effective way to lessen its impact [8]. For the past 20 years, bricks manufactured using RM, as well as other waste materials and stabilizers, have been in use [9]. Even still, as seen in Figure 2, there is a significant disparity between output and use. If RM is used to make subgrade or subbase in roads, a large proportion of it can be employed, which can assist to prevent the conservation of virgin materials and resources on the one hand and the utilization of waste materials on the other hand [10].

Many research studies have been conducted on the utilization of red mud and proved that the RM alone will not give the desired strength for any construction and it should be treated with any of the neutralizing methods to reduce the impact of it on environment [11]. In order to this, RM is mixed with the another industry waste material called fly ash (FA) which gives a pozzolonic nature to the virgin RM. Fly ash is a byproduct of coal combustion that can be obtained from coal-fired power plants and other coal-burning facilities. The availability of FA in India is expected to be between 80 and 100 million tonnes per year. Every thermal power station that generates 1000 MW of power produces 3500 tonnes of FA per day on average [12]. On average 28,000 ha of land has been used to dump the fly ash near the industries and the presence of fine particles will result a destruction to plant and human life directly by creating air pollution [13]. RM is rich in iron and FA is good at silica and aluminium which helps to develop and good strength when both are used in a right combination.

The FA used in this work is a class F fly ash which is low in pozzolonic reaction. So, an attempt was made to add another geotechnical stabilizer called cement to improve the strength properties of RM-FA in a very minimum amount [14]. A Portland cement is generally used for the purpose of stabilization [15]. Here, a small amount of cement was used to get better strength values to RM-FA and recommend it as a competitive subgrade material in road constructions. A thorough laboratory investigation was made on various combinations of RM-FA with cement and determined the strength properties of all the combinations by using UCS and CBR as the parameters. Upon finding the strength

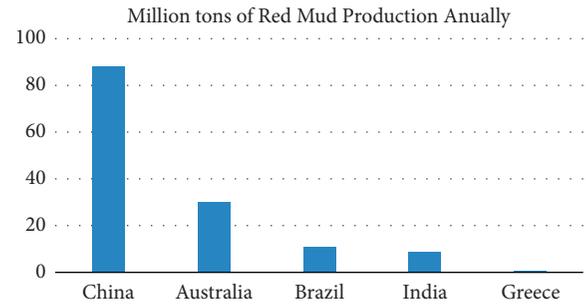


FIGURE 1: Annual production of red mud from various countries [4].

properties, the most suitable combination was used to collect the leachate and performed the chemical analysis of it to understand the presence of hazardous materials in it. Comparison of these hazardous chemicals with the WHO standards was made to use the RM-FA reinforced with cement effective in environmental perspective also.

2. Materials

2.1. Red Mud. The Hindalco Aluminium Industry in Belgaum, Karnataka, India, provided a solid RM waste. The collected RM is allowed to air-dry before starting the laboratory testings in order to remove the moisture which is present in it. According to ASTM-D422-63, gradation of bare RM sample is performed to understand the percentage of various geotech materials [16]. The majority of the RM is silt (75%) that passes through a 75 μ m sieve, with the remaining fractions of 10% clay and 15% sand. As per Unified Soil Classification System (USCS), RM has the most silt, which is classed as silt of low plasticity (ML). The specific gravity of RM has been determined to be 2.85. Compaction tests are performed by using modified proctor compaction tests, as per ASTM D 1557-12 [17]. The maximum dry density (MDD) and optimum moisture content (OMC) of bare RM were 31.39 % and 16 kN/m³, respectively. The pH of the RM which was used in this research study was 11.05 which shows the nature of highly alkaline material. The CBR values of unsoaked and soaked RM were 5.76% and 1.58%, respectively. UCS samples were prepared based on the OMC and MDD of the RM, and the results show that the UCS of RM is 815 kPa for the 28 days curing.

Scanning electron microscopy (SEM), X-ray fluorescence (XRF), and X-ray diffraction method (XRD) were performed on the bare RM to have a better understanding of the material. SEM and XRD of RM are presented in Figure 3. The SEM image depicts the loose structure of the RM, and the same was presented in Figure 3(a). The XRD pattern of the RM waste presented in Figure 3(b) reveals chalcite ($\text{Na}_5\text{Al}_3\text{CSi}_3\text{O}_{15}$), gibbsite ($\text{Al}(\text{OH})_3$), muscovite ($\text{KAl}_2(\text{FOH})$), calcite (CaCO_3), and hematite (Fe_2O_3) as the primary mineral phases. It identifies the minerals in the RM with pinpoint accuracy. The chemical composition of RM is measured by the XRF analyzer. Fe_2O_3 , Al_2O_3 , SiO_2 , CaO , Na_2O , TiO , K_2O , and MgO are the primary chemical components of RM. The percentage of these

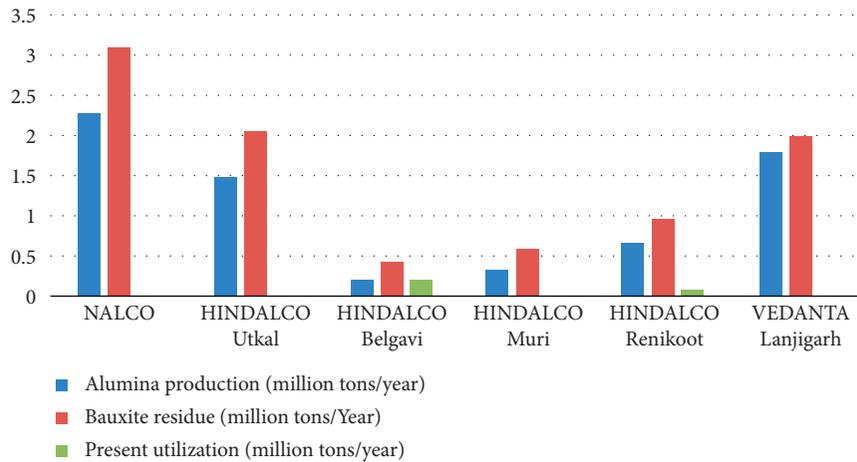


FIGURE 2: Production of aluminium and red mud and its utilization annually [5].

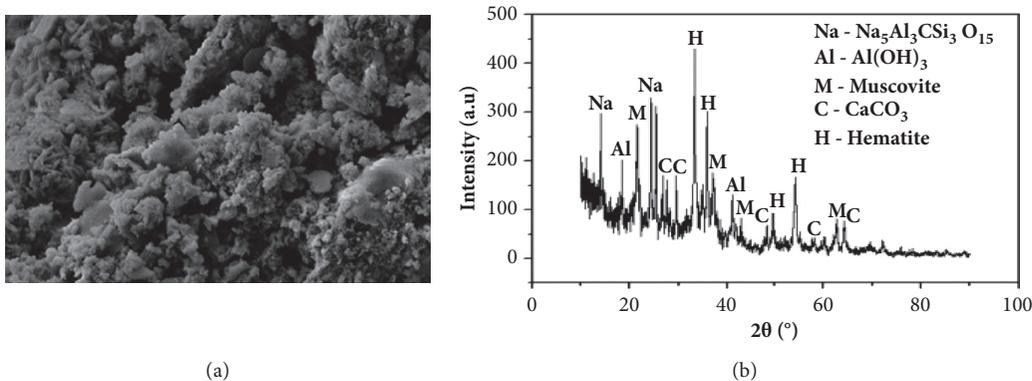


FIGURE 3: (a) SEM of red mud and (b) XRD of red mud.

chemical elements in bauxite will vary based on the procedure, property, and phase of the bauxite and will alter over time.

2.2. Fly Ash. Raichur Thermal Power Plant in Shakthinagar, Raichur District, Karnataka, India, provided the FA. The Karnataka Power Corporation Limited (KPCL) operates a coal-fired electric power station that produces 1.5 million tonnes of FA every year [18]. The principal chemical composition of the FA employed in this study is 46.2% SiO_2 , 19.54% Al_2O_3 , 13.46% Fe_2O_3 , and 7.61% CaO which are obtained by performing an XRF analysis. FA was classed as class F according to ASTM C618-12 [19] because the total chemical composition of SiO_2 , Al_2O_3 , Fe_2O_3 , and CaO was greater than 70% and CaO was less than 10%. FA has the specific gravity of 2.51. The SEM and XRD images of FA are presented in Figure 4. The SEM image depicted in Figure 4(a) shows that the shape of the particles are sphere, whereas the shape of particles in RM are angular, which directly proves a better combination to use both of them in construction works. The XRD of the FA is shown in Figure 4(b), with peak values for the principal amorphous phases: quartz, calcite, mullite, hematite, and calcium sulphate.

2.3. Cement. Portland cement of 53 grade was used for the purpose of stabilization of various combinations of RM-FA. Induction of cement in the RM-FA combination helps to increase the strength parameters of RM and its various combinations. Cement is used as a good stabilizer in many construction works and highly acceptable material in the stabilization of soils in subgrade and subbase construction of roads. Cement stabilization significantly enhances soil stiffness and strength to the point that it aids pavement and building foundations structurally. The specific gravity of cement is very high which is of 3.11 g/cc. The chemical composition of cement was determined by XRF analyzer and identified CaO , SiO_2 , Al_2O_3 , and Fe_2O_3 are the major proportions of it.

3. Methodology

Geotechnical properties of bare RM were studied initially in detail to analyze the usage of the material as a subgrade material in road construction. Then, RM is replaced with FA by 10%, 20%, and 30% to its dry weight. Same combinations were again stabilized with 1%, 3%, and 5% of cement to determine the strength properties of RM-FA. The list of combinations and their nomenclature is presented in Table 1. Modified proctor compaction test was

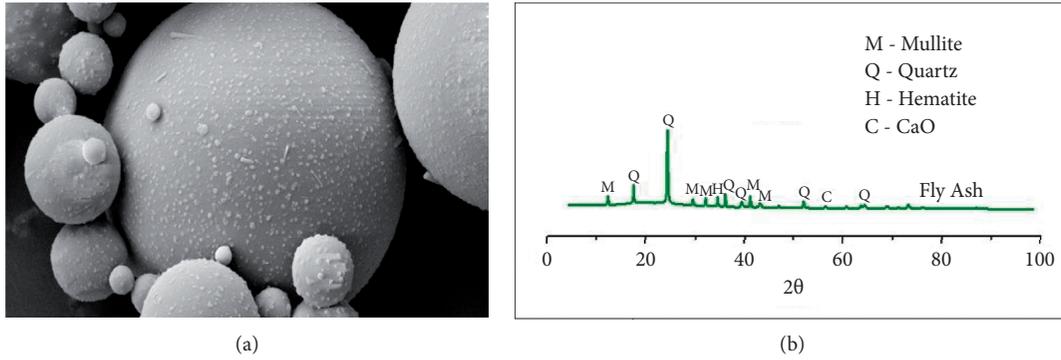


FIGURE 4: (a) SEM of fly ash and (b) XRD of fly ash.

TABLE 1: Combinations of RM-FA and cement with nomenclatures.

S. no.	Sample combination (%)	Nomenclature
1	100RM + 0FA + 0CM	RFC1
2	90RM + 10FA + 0CM	RFC2
3	90RM + 10FA + 1CM	RFC3
4	90RM + 10FA + 3CM	RFC4
5	90RM + 10FA + 5CM	RFC5
6	80RM + 20FA + 0CM	RFC6
7	80RM + 20FA + 1CM	RFC7
8	80RM + 20FA + 3CM	RFC8
9	80RM + 20FA + 5CM	RFC9
10	70RM + 30FA + 0CM	RFC10
11	70RM + 30FA + 1CM	RFC11
12	70RM + 30FA + 3CM	RFC12
13	70RM + 30FA + 5CM	RFC13

used to determine the compaction characteristics such as OMC and MDD for all the combinations. Unsoaked CBR and soaked CBR of 4 days were conducted on all the combinations by compacting with the OMC obtained from the compaction test. UCS of all the samples were determined for 1 day, 7 days, and 28 days of curing period by making the samples with the OMC of respective combination. UCS samples were prepared as per the UCS test procedure and covered in a polythene cover to allow the curing for 1 day, 7 days, and 28 days. All the samples were tested for compressive strength using unconfined compressive strength testing machine, and the reading was noted. Upon conducting all the geotechnical tests, the best combination was used to perform the TCLP (Toxicity Characteristics Leaching Procedure) test was performed, and the leachate was collected from the sample. The hazardous chemicals present in the leachate were studied and compared with the various water quality standards for the safe utilization of RM-FA in subgrade of roads.

4. Results and Discussion

4.1. Modified Proctor Compaction Test. All combinations were subjected to a modified proctor compaction test to determine the compaction characteristics, and the results are reported in Table 2. The OMC and MDD values are presented in Table 2, in percentage and kN/m^3 for various

trials of RM and FA without and with cement reinforcement, respectively. OMC of RM was reduced with the increase of FA and MDD was increased upto a substitution of 20%. The 30% substitution of FA to RM does not show any effect on the MDD, but the OMC was decreased further. The trend of increasing the MDD and reduction of OMC was even continued with the addition of cement also but the change was very minimum compared with and without cement. The nonplastic character of FA resulted in a decrease in OMC, but the particle size of FA, which acts as a padding material up to a point, resulted in an increase in MDD.

According to IRC SP: 20-2002, the minimum MDD value should be 14.4 kN/m^3 and OMC should not be more than 20% to select any material as a subgrade. In the present study, all the samples satisfy the IRC specifications with respect to MDD though water content is not in the limits. Though the OMC is higher than the specified values, the RM-FA with cement can be confidently used as a subgrade material because of the satisfying values of dry density. MDD of RM-FA has increased from 16 kN/m^3 to 17.1 kN/m^3 with the 20% replacement of FA and 5% of cement, which is a sample combination of RFC9. OMC was reduced to 27.55% from 31.39% with the replacement of 20% FA and 5% cement. It proves that the addition of FA and cement increases the compaction and strength of RM with the right proportion of water.

TABLE 2: OMC and MDD of various trails of RM-FA with and without cement.

S. no.	Sample name	OMC (%)	MDD (kN/m ³)
1	RFC1	31.39	16.00
2	RFC2	30.11	16.10
3	RFC3	30.12	16.15
4	RFC4	30.00	16.20
5	RFC5	29.66	16.30
6	RFC6	29.88	16.35
7	RFC7	28.45	16.85
8	RFC8	27.99	16.91
9	RFC9	27.55	17.10
10	RFC10	26.99	16.80
11	RFC11	26.03	16.80
12	RFC12	25.66	16.79
13	RFC13	25.01	16.70

4.2. California Bearing Ratio. The CBR test was administered on all the samples by mixing with the water based on OMC obtained for the respective combination. All the samples were soaked in water for 4 days by keeping a surcharge weight of 5 kg as per the standard procedure. 50 kN proving ring was used to determine the CBR value of all the combinations. The soaked CBR values of various combinations of RM-FA with cement are presented in Figure 5. The minimum CBR required to use any material as a subgrade material is 8% as per the guidelines of IRC 2012 specifications. RM with 20% replacement of FA showed the CBR value of more than 8% for with and without cement combinations. The presence of cement further increased the strength by creating the pozzolonic reaction among the RM-FA samples. RFC9 shows the highest CBR value of 11.6% which is highly accepted for the construction of subgrades in the road construction. The effect of cement reinforcement is well distinguished in the CBR properties of RM-FA samples. The soaked CBR values of RM with 30% replacement of FA were reduced because of higher absorption of water which results in the loss of bearing capacity of the material upon soaking. The results present in Figure 5, indicate that the RM-FA reinforced with cement can be a subgrade.

4.3. Unconfined Compressive Strength. Figure 6 shows the UCS values of various combinations of RM-FA with cement. UCS samples were produced using the combinations listed in Table 1 and the OMC, MDD combinations listed in Table 2, in accordance with the standard UCS validation process. All the samples were cured for 1 day, 7 days, and 28 days of curing period at a room temperature of 27°C. Three curing times were chosen to see how the strength of various combinations increased over time. C-S-H gel is produced with the increase of time in silica-based materials, and this gel helps to impart the strength in the combinations by densifying the materials. Cured samples were tested by using the UCS testing machine, and the values are presented in Figure 6. UCS values of RM-FA without cement are presented in Figure 6(a). With better curing time and temperature, high strength can be attained [20]. It is observed that the UCS values are increased with the increase of fly ash upto 20%, and at 30% replacement, it is observed that the reduction in strength

because of higher consumption of water, even the same trend, was observed with the cement stabilization.

According to IRC: 37-2012 specifications [21], the compressive strength value should be between 800 and 3000 kPa for low volume to high volume road subgrades. It is observed that the combination of RFC9 with 80%RM, 20%FA, and 5% cement shows the maximum strength value of 2340 kPa, which is highly acceptable for the construction of mid to high volume traffic roads as a subgrade material. It is observed that the strength improvement in RFC9 was approximately three times more than the virgin RM. These results confirm that the RM-FA with 5% of cement will surely satisfy the IRC specifications of road subgrade constructions. Higher amount of cement stabilization can be made but limited the work to only 5% addition by taking low-cost stabilization method as the key factor.

4.4. Geoenvironmental Study. The pH of RM is very high, and it is observed as alkaline in nature. This indicates that the RM may impose the environmental threat by polluting the ground water with the seepage. Addition of FA to RM helps to neutralize the RM and reduces the effect of its hazardous content in leachate. Utilization of any waste material may pose ground water pollution without proper liners and protective measure. In this study, the best combination is RFC9, which shows the better values of CBR, and UCS is used to collect the leachate from the TCLP procedure. The TCLP test includes extracting pollutants from a 100 gram sample of waste material using a suitable extraction fluid. A liquid to solid ratio of 20 : 1 is used, and the mixture is rotated at 30 rpm for 18 ± 2 hours by using an apparatus called rotary agitation device. The extraction fluid utilized for TCLP test is based on the level of alkaline nature of the waste material. High alkaline waste materials are leached with a set quantity of acetic acid at $\text{pH } 2.88 \pm 0.05$, whereas other waste materials are leached using acetic acid buffered with 1-N NaOH at $\text{pH } 4.93 \pm 0.05$. The ultimate pH of the mixture is determined after spinning, and it is filtered, then the leachate was collected from the sample, and the hazardous chemicals present in it were presented by performing the chemical analysis of it. Selected list of hazardous chemicals is used to understand the concentration of each hazardous chemicals, and the same are presented in Table 3. The results were compared with the

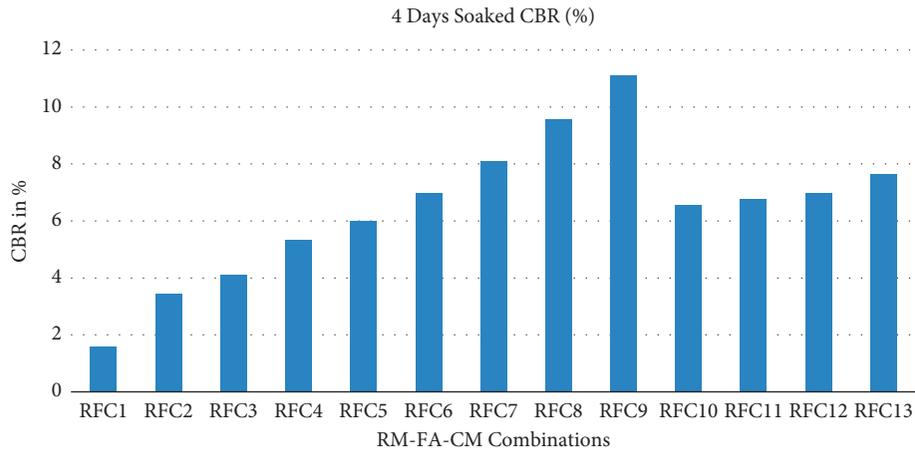
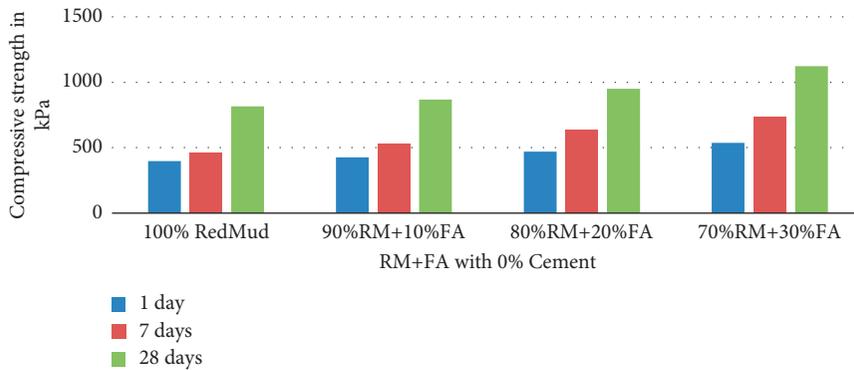
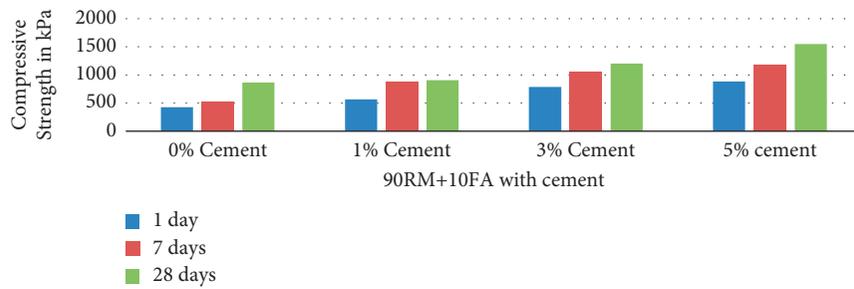


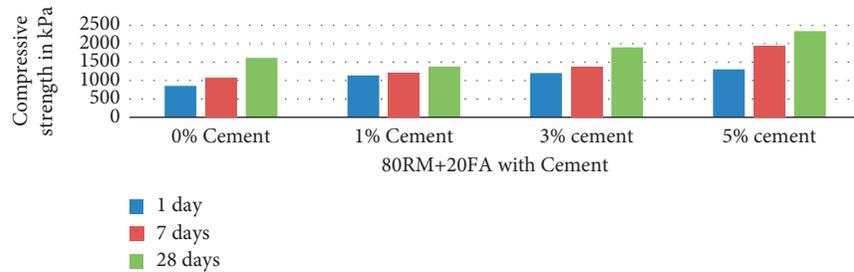
FIGURE 5: CBR values of RM-FA reinforced with cement.



(a)



(b)



(c)

FIGURE 6: Continued.

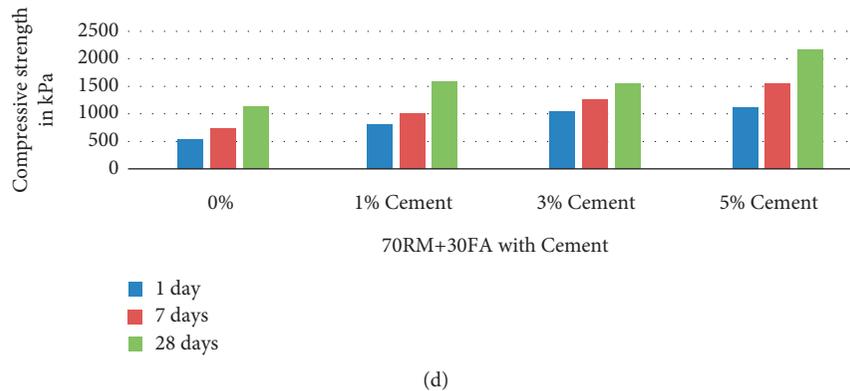


FIGURE 6: UCS of RM-FA reinforced with cement.

TABLE 3: Chemical analysis of leachate of RM and RFC9 in comparison with the various standards.

Analytes	Results obtained (mg/l)		Drinking water standards (mg/l)	TCLP limits (mg/l)	WHO standards of drinking water (mg/l)
	RM	RFC9			
Arsenic (As)	0.001	0.160	0.05	5.0	0.01
Cadmium (Cd)	0.04	0.23	0.005	1.0	0.003
Chromium (Cr)	0.76	1.16	0.1	5.0	0.05
Lead (Pb)	0.70	1.98	0.015	5.0	0.01
Mercury (Hg)	0.001	0.02	0.002	0.2	0.001
Sodium (Na)	4.12	6.76	20	40	20
Calcium (Ca)	216.8	234	20–208	—	20–208
Silica (SiO ₂)	116.9	145.77	100	200	100

TCLP standards and WHO standards. The results show that the hazardous chemicals are within the permissible limits of TCLP standards. This confirms that the RM-FA with cement reinforcement can be highly recommended to use as a subgrade material in construction of roads with respect to geotechnical and geoenvironmental studies.

5. Conclusions

The strength development of the red mud and fly ash as a sustainable material for subgrade application with varied ratios of cement to its dry weight was evaluated in this work through a series of experiments. FA replacement to RM showcased the improvement in strength of RM by resulting very good values of CBR and UCS. The addition of FA to RM reduces the OMC and increases the MDD, and the same trend was continued with the addition of cement. The addition of cement in this work was limited to only 5% to develop a low-cost sustainable material from the industrial solid wastes. The CBR value of all the combinations of RM with 20% FA shows more than 8%, which shows that the RM-FA combinations are accepted to use as a subgrade material. The UCS values of 28 days cured samples of RM with 20% FA and 5% cement show the highest values among all the combinations and will fall in the limits given by the IRC in relation to strength parameters. Geoenvironmental study shows that the RFC9 sample has all the toxic metals are within the allowable limits and concludes

that the RM-FA with cement will be a very good sustainable material.

Data Availability

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

Conflicts of Interest

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

Acknowledgments

The authors thank the Department of Civil Engineering, School of Engineering and Technology, Christ University, Bangalore, for providing the laboratory facilities to conduct all the experiments.

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