Potential Application of Treated Bauxite Residue

Sujeet Kumar[1] Abhay Kumar Verma[2] Arun Prasad[2]

[1] *Civil Engineering Departmen, Shiwalik College of Engineering, Dehradun-248197*

[2] *Civil Engineering Department, Indian Institute of Technology (BHU), Varanasi-221005*

Sujeet.rs.civ14@iitbhu.ac.in

Abstract. Bauxite residue is a significant industrial solid waste residue produced by the Bayer process for the extraction of alumina from bauxite ores. It is usually disposed-off in the form of slurry in the nearby areas of the alumina industry. About 400 million tons of bauxite residues are produced annually worldwide. However, it has some environmental and logistical problems in handling and disposal due to high alkalinity (pH 10-13.5), sodicity, fine particles, and some trace metal content. Thus, it cannot be used directly and requires pre-treatment before any civil engineering applications. In view of the given above, an attempt has been made to explore the potential of the bauxite residue for some civil engineering application. The present study investigates the effect of various parameters on the strength and durability of bauxite residue. Further, a series of laboratory tests considering various parameters were carried out. The results indicate that treated bauxite residue with a certain combination of parameters (dry density, moisture content, and curing time) can be used as an unfired brick for low-cost housing.

Keywords: *Bauxite Residu, Strength, Durability, Unfired Brick, Subbase.*

1 Introduction

Most of the developing nations have one of the significant challenges to fulfill the demands of the rapidly increasing population. Industrialization and urbanization are the two common phenomena for these nations. Although it is quite essential for the betterment of the society regarding infrastructure, ongoing developmental activities at the same instance (time), we have to consider their negative impacts leading to disposal, environmental and health problems. In the present scenario, the global researcher community is also dedicating its research to find out new ways to reduce the industrial wastes by using them as an alternative construction material. Bauxite residue is a major industrial solid waste produced during the extraction of alumina from bauxite ores. The worldwide deposits of bauxite ore are estimated approximately to be 55 to 75 billion tones; whereas, India shares about 7% of global inventory [17]. Worldwide generation of this industrial waste was about 4 billion tons per annum till 2016 [21]. Whereas, Indian alumina plants generate approximately 14 million tones of bauxite residue every year.

Various researchers have examined the chemical compositions of bauxite residue and found that it mainly contain minerals of ferrous (hematite, magnetite and goethite), silica (quartz and sodalite), alumina (gibbsite, diaspore, and boehmite), calcite, anatase, rutile, perovskite, water, oxilate, occulants, some organic and inorganic carbon and some trace and rare earth elements [8, 17]. From the literature, it appears that bauxite residue predominately composed of oxides of iron, alumina, and silica. The availability of such elements (aluminate and/or silicate) is an essential constituent in any pozzolanic reactions in the presence of water and alkali. However, this waste has some environmental and logistical concerns with handling, storing and disposal due to its characteristics such as high alkalinity (pH 10−13.5), sodicity, fine particles, heavy metals content [18]. Thus, bauxite residue cannot be used without treatment/stabilization and require pre-treatment for any mass utilization. In view of the given above, researchers have carried numerous studies covering various aspects such as metals recovery, water, and wastewater treatment, production of construction and building materials. However, civil engineering is one of the promising areas where mass utilization of these waste can be utilized with some modification in different forms such as pavement materials, bricks, paving blocks, embankment materials, etc. Several investigators have been trying to develop construction and building materials using bauxite residue in conjunction with different types of industrial rejects (fly ash, silica fume, stone dust and lime, cement, gypsum, clay etc) and additives (traditional and non-traditional) [6, 2, 4, 14]. However, in case of multivariate (multi-parameter) studies, conducting experiments and recording of results are bit expensive and time-consuming. In such situation, design of experiment can be used as alternative for planning and design the experiments which also overcome the deficiencies of conventional methods. Various researchers have applied design of experiment (DOE) in different areas such as sewage sludge ash optimization [3], Optimize amount of lime, rice husk ash [9], fermentation and bios option process [12, 20]. The present work is an attempt on treated bauxite residue. In this paper, experimental designed approach is used to assess the strength of treated bauxite residue. Finally, different possible applications of treated materials have also been tried for the possible utilization as construction and building materials.

2 Materials and Methodology

2.1 Material

Bauxite residue used in the study was collected from Hindalco Industries Limited, Renukoot, and Uttar Pradesh, India. It appears reddish and contains mostly fine particles on visual examination. Commercial grade dry hydrated lime ($CaOH_2$) is used as the cementing agent, and it consists mainly of oxides of Ca and Mg. The physical and geotechnical properties of bauxite residue are summarized in Tables 1.

Table 1: Geotechnical properties of the bauxite residue.

Properties	Value
Maximum dry density (kN/m^3)	1.50
Optimum moisture content (%)	30
pH	10.2
Specific gravity	3.1
Sand content (%)	28
Silt size particle (%)	60
Clay size particle (%)	12
Effective diameter D10 (mm)	0.007
Coefficient of uniformity, C_u	8.57
Coefficient of curvature, C_c	0.69
Unified soil classification system (USCS)	ML
Unconfined compressive strength (kPa)	138.6

2.2 Sample Preparation

Firstly, the required amount of bauxite residue and lime were mixed in a dry state to a uniform consistency. Water was then added while continuing the mixing process until a uniform, homogeneous mixture was obtained. After mixing, it was compacted in three layers in a split mold. After the molding process, the sample was extracted from the mold and placed in an airtight polythene bag. The sample was allowed to cure for desired curing periods in desiccators at room temperature (23 ±3°C) by maintaining the relative humidity of more than 95%. After the molding and curing processes, the sample was tested in an automatic load compression device of 50 kN capacity with a proving ring of 10 kN capacity.

2.3 Selection of Factors

Five factors were selected for the investigation of evaluation of strength and durability of bauxite residue on the basis of the literature review and were included in the experiment. Table 2 summarizes the factors and their range used in the present study.

Table 2: Factors and their ranges selected for the study.

Factor	Variable Type	Purpose
Additive content (%)	Quantitative	Influence of cementing agent
Curing time (days)	Quantitative	Effect of curing
Molding moisture content (%)	Quantitative	Effect of molding moisture
Dry unit weight (kN/m^3)	Quantitative	Effect of packing of particle

2.4 Design Methodology

Different experiment design methods may be used for the design of the experiment, but it solely depends on nature and operability region of the problem. In this study, Box-Behnken design (BBD) is used to design the experiment. It is a three-tier factorial method used in experiment design. The methodology of design of experiment is available in details in [7], and thus, these are not described here. Input variables employed for this study are the lime content (L) and molding moisture (w) in percentage, dry density (γ_d) in kN/m^3 and curing time (t) in day. The operating ranges are taken as 3 to 11 % for L, 26 to 30 % for w, 13 to 15.5 kN/m^3 for γ_d and 7 to 60 days for t. The experimental levels of independent variables are given in Table 3.

Table 3 Experimental level of independent variables used in the design of experiment.

Input parameter	Range		
	-1	0	1
w	26	28	30
L	3	7	11
[illegible]	13	14.3	15.5

t	7	34	60

3 Results and Discussions

Based on the experimental design, laboratory tests are performed and results are recorded for each combination. Results of the laboratory tests are presented as the response in Table 4.

Table 4 Design matrix of input and output based on the design of experiment.

Run No.	Input Parameters				Response
	w	L	[illegible]	t	UCS (kPa)
1	30	11	14.25	33.5	2381.09
2	28	3	14.25	60	1679.35
3	26	7	15.5	33.5	2295.68
4	28	7	14.25	33.5	1576.36
5	28	7	14.25	33.5	1464.13
6	28	7	14.25	33.5	1531.05
7	28	11	14.25	60	2568.24
8	28	11	15.5	33.5	3335.25
9	30	3	14.25	33.5	1108.35
10	26	7	13	33.5	947.02
11	28	7	15.5	7	1704.47
12	28	3	14.25	7	702.14
13	28	7	14.25	33.5	1347.08
14	30	7	13	33.5	1123.16
15	26	7	14.25	60	2214.05
16	28	7	14.25	33.5	1482.51
17	28	7	14.25	33.5	1525.4
18	28	7	15.5	60	3308.29
19	28	7	13	7	838.59
20	28	11	14.25	7	1387.41
21	30	7	14.25	7	1124.23
22	30	7	14.25	60	2189.8
23	26	3	14.25	33.5	997.38
24	26	7	14.25	7	1051.8
25	28	3	13	33.5	737.26
26	26	11	14.25	33.5	1856.25

27	30	7	15.5	33.5	2537.24
28	28	7	13	60	1549.35
29	28	3	15.5	33.5	1725.69
30	28	11	13	33.5	1324.05

After successful experimental design and development, a predictive equation is to establish the relationship between input parameters and response for the range of study. Thus, various linear and non-linear empirical models were tried, and the details are presented in Table 5.

Table 5: Summary of various predictive models based on Box Behnken (BB) experimental design approach.

Source	Std. Dev.	p-value	R^2	Adj R^2	Pre R^2	Remarks
Linear	247.18	< 0.0001	0.96310	0.95460	0.92660	Significant
2FI	116.15	0.11130	0.97920	0.96680	0.90910	Insignificant
Quadratic	61.84	0.00340	0.99670	0.99250	0.95490	Opted
Cubic	21.02	0.04120	0.99950	0.99800	0.84960	Aliased

From Table 5, it is seen that quadratic models better satisfy the statistical criteria (as correlation coefficient (R^2=0.92)) and hence selected as predictive equations for the range of study. Further, the selection of the statistically significant input variables after choosing the best predictive model is the key step in the experiment design. It tells us if the independent variables and their interaction have significant influence on the dependent variables. In this case, variance analysis (ANOVA) could be beneficial in describing the interactions between variables. Thus, ANOVA was performed to establish the parameters found as statistically significant in the predictive model and their relative contributions to the dependent parameter (response) and the results are presented in Table 6.

Table 6: ANOVA results for BB design.

Source	Sum of Squares (SS)	df	Mean Square (MS)	F Value	p-value Prob > F	Remarks

Model	1.36E+07	14	9.68E+05	83.09	< 0.0001	significant
w	1.01E+05	1	1.01E+05	8.68	0.01	significant
L	2.90E+06	1	2.90E+06	249.23	< 0.0001	significant
[illegible]	5.86E+06	1	5.86E+06	503.3	< 0.0001	significant
t	3.74E+06	1	3.74E+06	321.22	< 0.0001	significant
W*L	42822.09	1	42822.09	3.68	0.0744	not significant
W* [illegible]	1.07E+03	1	1.07E+03	0.0919	0.766	not significant
W*t	2336.76	1	2336.76	0.2006	0.6606	not significant
L* [illegible]	2.62E+05	1	2.62E+05	22.45	0.0003	significant
L*t	1.04E+04	1	1.04E+04	0.8899	0.3604	not significant
[illegible]	1.99E+05	1	1.99E+05	17.12	0.0009	significant
w^2	1.05E+04	1	10495.56	0.9011	0.3575	not significant
L^2	8973.05	1	8973.05	0.7704	0.3939	not significant
[illegible]	3.92E+05	1	3.92E+05	33.66	< 0.0001	significant
t^2	69371.46	1	69371.46	5.96	0.0276	significant
Residual	1.75E+05	15	11647.39			
Lack of Fit	1.43E+05	10	14319.33	2.27	0.189	not significant
Pure Error	31517.56	5	6303.51			
Cor Total	1.37E+07	29				

From Table 6, it is also observed that the proposed models contain some statistically insignificant terms which have no active role in the prediction of the response. Thus, this term is discarded in during the development of predictive equation. Hence, entire insignificant factors are discarded, and only significant parameters are considered for the development of predictive equations. Finally, a mathematical relationship linking all selected parameters can be given as Eqs.1:

$$q_u = 31558.15 - 44.63w - 967.89L - 4214.54\gamma_d - 83.67t + 12.93w * L + 51.14L * \gamma_d + 6.74\gamma_d * t + 147.01{\gamma_d}^2 + 0.13t^2 \quad \text{(Eq. 1)}$$

From the above results, it is seen that treated bauxite residue has good unconfined compressive strength ($460 \leq q_u \leq 4350$ kPa), for the range of studies ($3 \leq L \leq 11$ %, $13 \leq \gamma_d \leq 15.5$ kN/m^3, $26 \leq t \leq 60$ days and $13 \leq w \leq 30$ %). Hence, treated bauxite residue may have potential to be used in some of the civil engineering applications.

3.2 Unfired Bricks

Since the unconfined compressive strength of some of the mix of stabilized red mud is more than 3500 kPa; these mixes have the potential to be used as unfired bricks. Thus, scaled bricks of size (100 × 50 × 50 mm) was prepared in accordance with IS 12894:2002 [5]. It was fabricated in our institute workshop. For preparing mix for brick, the required amount of red mud and lime were mixed in a dry state to a uniform consistency and water was then added while continuing the mixing process until a uniform, homogeneous mixture was obtained. After mixing, it was transferred in the mold and compacted using hydraulic press to achieve the correct dimension. After the molding process, the sample was extracted from the mold, wrapped in an airtight polythene bag and kept in a desiccator to cure for desired curing period at room temperature (23 ± 3 ◦C) while maintaining the relative humidity of more than 95%. After the molding and curing processes, the sample was tested in an automatic load compression device of 50 kN capacity with a proving ring of 10 kN capacity. The results of various mix of red mud -lime used for preparation of unfired bricks are shown in Table 7.

Table 7: Mix compositions using for preparation of unfired brick

Sr. No.	Moisture content (w) %	Curing time (t) days	Dry density (γd) kN/m3	Lime content (L) %	Average Compressive Strength	Water absorption (%)
1	26	28	15.5	11	3408.25	19.05
2	26	60	15.5	7	3755.18	17.89
3	26	60	15.5	9	3924.15	15.68
4	26	60	15	11	3398.68	18.78
5	26	60	15.5	11	4075.58	13.81
6	28	28	15.5	11	3789.03	18.85
7	28	60	15.5	7	3645.48	17.94
8	28	60	15.5	9	3756.24	18.58
9	28	60	15	11	3623.08	17.90
10	28	60	15.5	11	4436.29	11.85
11	30	28	15.5	11	3845.72	17.87
12	30	60	15.5	7	4048.91	14.09
13	30	60	15.5	9	4124.19	12.68
14	30	60	15	11	4621.78	11.35
15	30	60	15.5	11	4989.27	12.82

Further, it is also seen that the stabilized red mud unfired bricks fulfill the requirement of compressive strength (>3.5 MP a) and water absorption (<20 %) as per IS 12894:2002 [5]. Thus, the brick can be used in low-cost housing which will save not only the conventional constructional materials but also solve the storage problem. The discussed mix will also reduce the chance of contamination of surface and subsurface water bodies.

4 Conclusions

The primary objective of this work is to study the possible potential of treated bauxite residue for different civil engineering applications. An attempt has also been made to incorporate an alternative approach based on the design of the experiment to study the effects of multiple parameters on the compressive strength of bauxite. Further, the results reported in the previous section indicate that the treated bauxite can have scope in pavement layers and brick applications. However, the present study is limited to laboratory test only, and it will require detailed studies to validate these results with various model tests and field studies. Further, the proposed predictive equations work well within the range of However, the proposed equation may or may not efficient for the outside the range of study like any other techniques.

References

1. Altundoguan, H.S., Altundoguan, S., Tumen, F., Bildik, M.: Arsenic adsorption from aqueous solutions by activated red mud. Waste management 22(3), 357-363 (2002).
2. Feng, Y.L., Yu, L.J., Gao, J.P., Wang, P., Luo, Q.W., Huang, B., Wang, M.: Study on the preparation and properties of red mud unburned brick. Materials Research Innovations 19(sup8), S8297 (2015).
3. Güllü, H., Fedakar, H.: Use of factorial experimental approach and effect size on the CBR testing results for the usable dosages of wastewater sludge ash with coarse-grained material. European Journal of Environmental and Civil Engineering 22(1), 4263 (2018).
4. Hongying, C.: Formula of environment-friendly red mud-brick or ceramsite, environment-friendly red mud-brick or ceramsite and preparation method thereof. Google patents (2017), cN107056241 A.
5. IS-12894: Pulverized fuel ash-lime bricks. Bureau of Indian Standards, New Delhi, India (2002).
6. Jupei, X., Lixuan, G., Zhaoshu, Z.: Unburned brick prepared from main materials of red mud and magnesium slag. Google patents (2012), cN102381864 A.
7. Kumar, S., Prasad, A.: Strength retrieval of artificially cemented bauxite residue using machine learning: an alternative design ap-

proach based on response surface methodology. Neural Computing and Applications, (2018). https://doi.org/10.1007/s00521-018-3482-5.

8. Mandal, A., Sinha, O.: New-generation aluminum composite with bottom ash industrial waste. JOM pp. 16 (2018).
9. Olgun, M.: The eË™ects and optimization of additives for expansive clays under freeze-thaw conditions. Cold Regions Science and Technology 93, 36-46 (2013).
10. Pera, J., Boumaza, R., Ambroise, J.: Development of a pozzolanic pigment from red mud. Cement and Concrete Research 27(10), 1513-1522 (1997).
11. Samal, S., Ray, A.K., Bandopadhyay, A.: Proposal for resources, utilization and processes of red mud in India review. International Journal of Mineral Process-ing 118, 4355 (2013).
12. Sen, R., Swaminathan, T.: Application of response surface methodology to evaluate the optimum environmental conditions for the enhanced production of surfactin. Applied Microbiology and Biotechnology 47(4), 358-363 (1997).
13. Sglavo, V.M., Campostrini, R., Maurina, S., Carturan, G., Monagheddu, M., Bu-droni, G., Cocco, G.: Bauxite `red mud' in the ceramic industry. Part 1: thermal behavior. Journal of the European Ceramic Society 20(3), 235-244 (2000).
14. Shichao, C., Mianlian, B., Dongyang, M., Hui, S., Zhicheng, C., Xun, X., Daohong, W.: Method for manufacturing perforated brick by using red mud. Google patents (2017), cN106747317 A.
15. Snars, K., Gilkes, R.: Evaluation of bauxite residues (red muds) of diË™erent origins for environmental applications. Applied Clay Science 46(1), 1320 (2009).
16. Srikanth, S., Ray, A.K., Bandopadhyay, A., Ravikumar, B., Jha, A.: Phase constitution during sintering of red mud and red mud˛y ash mixtures. Journal of the American Ceramic Society 88(9), 2396-2401 (2005).

17. Sutar, H., Mishra, S.C., Sahoo, S.K., Chakravarty, A.P., Maharana, H.S.: Progress of red mud utilization: an overview. American Chemical Science Journal 4(3), 255- 279 (2014).
18. Sutar, H., Mishra, S.C., Sahoo, S.K., Maharana, H.: Progress of red mud utilization: an overview. Master's thesis, National Institute of Technology- Rourkela (Jan 2014).
19. Vachon, P., Tyagi, R.D., Auclair, J.C., Wilkinson, K.J.: Chemical and biological leaching of aluminum from red mud. Environmental science & technology 28(1), 2630 (1994)
20. .Witek, A., Chojnacka, K., Podstawczyk, D., Dawiec, A., Pokomeda, K.: Application of response surface methodology and artificial neural network methods in modeling and optimization of biosorption process. Bioresource technology 160, 150-160 (2014).
21. Zhu, X., Li, W., Guan, X.: An active de-alkalization of red mud with roasting and water leaching. Journal of hazardous materials 286, 8591 (2015).