Development of Polymer Composite from Bauxite Residue and Plastic Waste for Sustainable Utilization

Vaishali Surawar[1], Abhishek Dash[2], Chiradip Roy[3], Devendra Narain Singh[4] and Bibek Chand[5]
1. Chief Sustainability Officer
2. Lead Environment Research
Hindalco Industries, India
3. Manager- Alumina Operations
Hindalco Industries, Belagavi, India
4. D. L Shah Chair Professor for Innovation
5. Master of Technology Scholar
Indian Institute of Technology, Bombay, India
Corresponding author: vaishali.surawar@adityabirla.com
https://doi.org/10.71659/icsoba2025-br021

Abstract

The increasing accumulation of bauxite residue (BR), a by-product of alumina extraction from bauxite ore at Hindalco Industries Limited presents significant storage and environmental challenges. Simultaneously, plastic waste management remains a critical issue for municipalities. This study investigates the potential of utilizing BR and plastic waste to develop Bauxite Residue Waste Plastic Composite (BR-WPC) bricks as a sustainable construction material. The feasibility of using BR with plastic waste was explored in collaboration with the Indian Institute of Technology, Bombay (IITB). The physicochemical, thermal, and toxicity characteristics of BR-WPC bricks were analysed to assess their environmental viability. Additionally, unconfined compressive strength (UCS) tests were conducted to evaluate their structural performance.

Composite samples were prepared with varying BR content (15 %, 20 %, 25 %, 30 %, 40 %, and 50 %) to determine the optimal mix for strength and durability. The study emphasized the minimal leaching potential of these composites, ensuring environmental safety. The water absorption study indicated their hydrophobic nature, i.e., water-resistant properties, making them suitable for use in extreme weather conditions. The UCS test findings showed that compressive strength was around 15 MPa which surpassed the strength standard for Class I bricks (10.5 MPa) as per IS 1077:1992, suggesting that BR-WPC bricks offer a viable solution for sustainable construction while contributing to both industrial waste management and circular economy initiatives.

Keywords: Bauxite residue, Plastic waste, Polymer composite bricks, Unconfined compressive strength, Sustainable construction.

1. Introduction

Urbanization and industrialization have significantly contributed to economic growth but have also led to the excessive exploitation of natural resources, resulting in substantial amounts of industrial and municipal waste. Among these, Bauxite Residue (BR), a by-product of alumina extraction from bauxite, presents severe environmental and storage challenges due to its alkalinity and potential metal leaching. The specific generation of BR per tonne of alumina from the plants (more than 95 %) which use the Bayer process ranges between 1 and 1.5 metric tonne globally. The Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 (HOWM Rules 2016) notified by the Govt. of India under the Environment (Protection) 29 Act, 1986, exempts Red Mud from the scheduled category of hazardous waste and instead classifies it as a "High Volume Low Effect Waste" [1]. Similarly, plastic waste accumulation in landfills poses a major problem for municipalities. Traditional waste disposal methods such as landfilling, dumping, and stockpiling are no longer sustainable due to limited space, environmental concerns, and resource depletion.

This study explores an innovative approach to address these challenges by developing bauxite residue–plastic composites using BR as a filler in polymer matrices. Past research has shown the potential of industrial waste as fillers in polymer composites to enhance mechanical properties and durability while preventing harmful leaching [2]. However, limited studies have investigated BR in combination with plastic waste for sustainable applications [3].

The present work focuses on the physicochemical, mechanical, and thermal properties of BR-WPC with varying BR content (15–50 %). Additionally, unconfined compressive strength (UCS) tests and leaching assessments are conducted to ensure the environmental viability of the developed BR-WPC. By transforming industrial and municipal waste into a valuable construction material, this study aligns with sustainable development goals and promotes a circular economy approach to waste management.

2. Materials and Methods

2.1 Materials

The primary materials used in the study include bauxite residue (BR) and waste plastic. BR, a byproduct of aluminium production, is rich in iron oxide, making it a potential candidate for composite materials. The sample of the BR was collected from the filter feed unit of Hindalco Industries Limited, Belagavi (Karnataka), India. The main chemical composition of the bauxite residue is Fe_2O_3, Al_2O_3, SiO_2, and CaO followed by Na_2O, MgO and K_2O. Waste plastic, including polyethylene (PE) and polypropylene (PP), was also sourced from the same plant.

2.2 Preparation of BR-WPC Bricks

The preparation involved blending BR with different proportions of waste plastic i.e., 15–50 %, followed by moulding and curing processes. Field-scale demonstration of the technology to manufacture recycled polymer composites consists of a pilot plant comprising of a shredder, a mixer cum preheater, and an extruder to obtain the fresh binder filler composite to shred the plastic waste, mix and preheat plastic waste and red mud mixture, and melt the mixture followed by pressing in moulds at the end, respectively. The temperature required for melting depends on the plastics added.

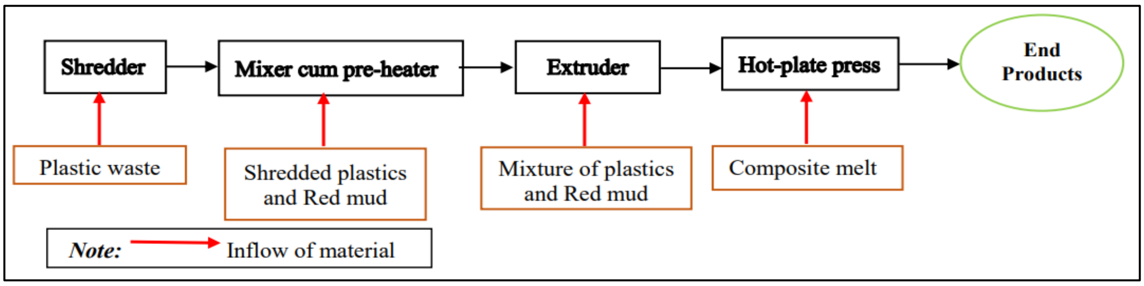

Figure 1. Flowchart of the BR-WPC production process.

2.3 Testing Methods

2.3.1 Physical Properties

The physical properties of the developed plastic composite bricks were assessed through specific gravity and water absorption tests. The specific gravity of the BR-WPC specimens was determined using a Helium Gas Pycnometer (Quanta Chrome) following the ASTM D5550 standard [4].

Water absorption, a critical property influencing the durability and performance of composite bricks, was evaluated in accordance with ASTM D570 [5]. The bricks, prepared with varying BR compositions, were first dried in an oven at 100 °C for 24 h, after which their dry weight (W_2) was recorded. The samples were then immersed in water for another 24 h before measuring the wet weight (W_1). The percentage of water absorption was calculated using the following equation:

$$\text{Water absorption (\%)} = \frac{W_1 - W_2}{W_2} \times 100 \quad (1)$$

where:

W1 Wet weight

W2 Dry weight

2.3.2 Chemical Properties

The chemical properties of BR-WPC bricks were evaluated through batch leaching tests to assess potential environmental risks. These tests were conducted at a liquid-to-solid (L/S) ratio of 20, with samples placed in sealed bottles and subjected to mechanical agitation. Supernatant samples were collected at time intervals of 1, 5, 14, 21, and 120 days. The collected supernatant was filtered using Whatman 42 filter paper and analysed for pH, total dissolved solids (TDS), electrical conductivity (EC), and salinity using standard glass electrodes (EU tech pH700 and Oakton).

Additionally, an accelerated batch leaching test was performed to simulate extreme weather conditions. This involved heating the BR-WPC specimens at 100 °C while adjusting the liquid-to-solid ratio from 30 to 20. The resultant solution was then analysed to determine variations in leaching behaviour under harsh conditions.

To further evaluate the environmental impact, heavy metal leaching was assessed using inductively coupled plasma-atomic emission spectrometry (ICP-AES). Two samples of each BR-WPC specimen, submerged in water for four months, were analysed for heavy metal concentrations as per USEPA 1311, ensuring compliance with environmental safety standards. The results are compared with Toxicity Characteristic Leaching Procedure (TCLP) limits stipulated in schedule-II of MEFCC (2016) [9].

2.3.3 Thermal Properties

The thermal stability of BR-WPC was evaluated using thermogravimetric analysis (TGA). Composite samples weighing between 1 g and 5 g were heated from 30 to 1000 °C at a controlled heating rate of 10 °C/min under an inert nitrogen atmosphere, maintained at a flow rate of 200 mL/min. The results of this analysis provide insights into the thermal decomposition performance and potential applicability of BR-WPC in high-temperature environments.

2.3.4 Mechanical Properties

The mechanical strength of the BR-WPC bricks was assessed through unconfined compressive strength (UCS) tests. The specimens, prepared with a diameter (Ø) of 38 mm and a length of 76 mm, were evaluated while maintaining an aspect ratio (L/D) of approximately 2. The UCS tests were conducted at a constant strain rate of 0.5 mm/min following ASTM D2166-00 [6]. This evaluation helped determine the structural integrity and load-bearing capacity of the developed composite bricks, making them suitable for potential construction applications.

3. Results and Discussion

3.1 Physical Properties

The specific gravity of BR-WPC exhibits an increase from 1.2 to 1.6 as the BR content rises from 15 % to 50 %. This trend is illustrated in Figure 2, which presents the specific gravity measurements for BR-WPC at varying BR content levels. As BR content increases in BR-WPC, specific gravity rises, and mechanical properties like tensile and flexural strength improve due to better filler-matrix interaction.

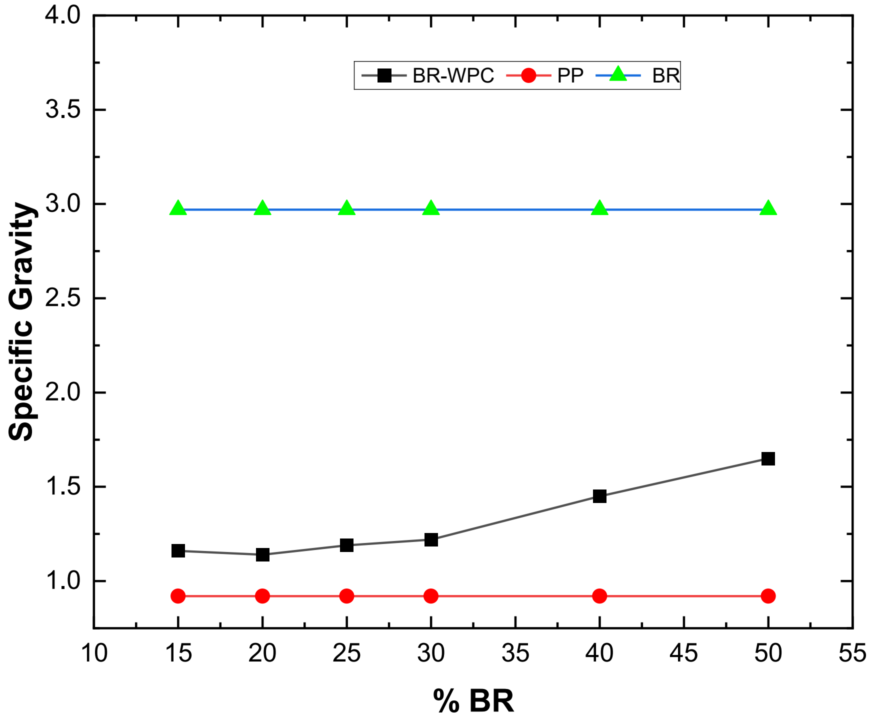

Figure 2. Specific Gravity of BR-WPC with varying BR content along with individual specific gravity of PP and BR for comparison.

Table 1 presents the water absorption values for various BR-WPC bricks. The data was compared with acceptable limit for burnt clay bricks as per IS 3495 (Part 2) [7] and it indicated that BR-WPC specimens exhibit minimal water absorption, attributed to the effective encapsulation of polymers with BR. The hydrophobic nature of the polymer repels water, enhancing the water resistance of the material.

3.2 Chemical Properties

The chemical properties include study of pH, EC, TDS, salinity and leaching behaviour of BR-WPC bricks. The results for pH, EC, TDS, and salinity are presented in Figures 4–7. These figures indicate that the values of pH, EC, TDS, and salinity in BR-WPC remain consistent with those of the tap water used to dissolve the composite specimens.

Figure 3. Water absorption test.

Table 1. Water absorption with variation in BR content in the BR-WPC.

Composition (% by weight) (BR:WP)	Water absorption (%)	Acceptable limit for burnt clay bricks. Water absorption (%) IS 3495 (Part 2): 1992
15:85	0.62	15–20
20:80	0.38	
25:75	0.10	
30:70	0.44	
40:60	0.41	
50:50	0.85	

The long-term batch leaching study, conducted over 120 days, indicates that the chemical properties of BR-WPC bricks exhibit significantly lower values compared to raw BR. The pH of the leachate remains within the range of 7.5–8.5, while the electrical conductivity (EC) increases up to 400 μS/cm. Furthermore, the total dissolved solids (TDS) and salinity levels of the BR-WPC bricks remain below 300 ppm. These findings suggest that the incorporation of waste polymer composites in BR bricks effectively stabilizes the material, reducing the leaching potential of key chemical parameters.

Based on the ICP-AES analysis of BR-WPC bricks with varying BR:PW compositions, most heavy metals including Ni, Ti, Cd, As, and Hg were not detected across all formulations, indicating low toxicity risk from these elements. Cu, Fe, and Zn were present in detectable amounts but remained well below TCLP limits [9], demonstrating controlled incorporation of these metals within the BR and plastic matrix.

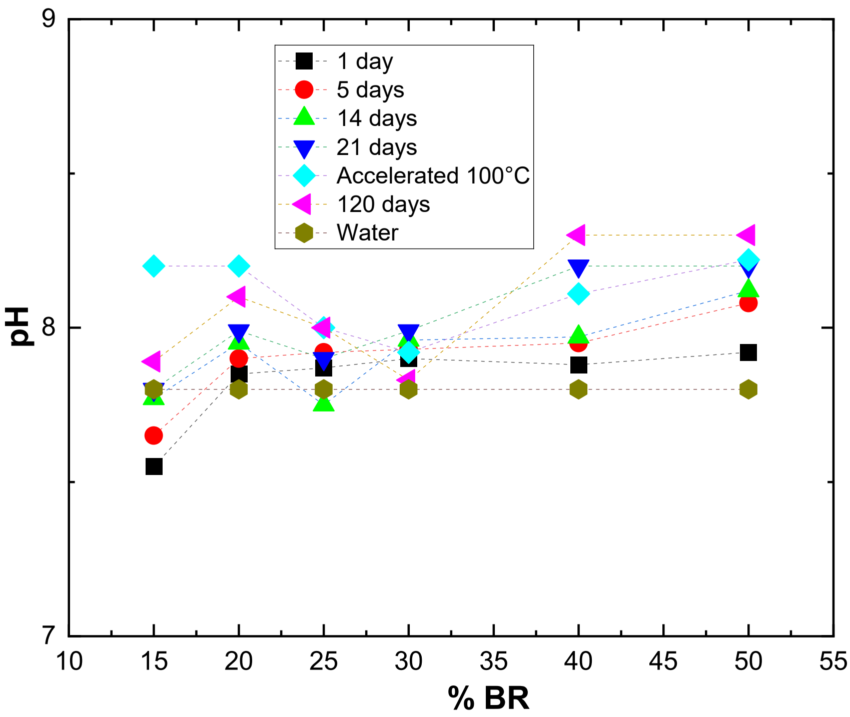

Figure 4. pH of BR-WPC with varying BR content.

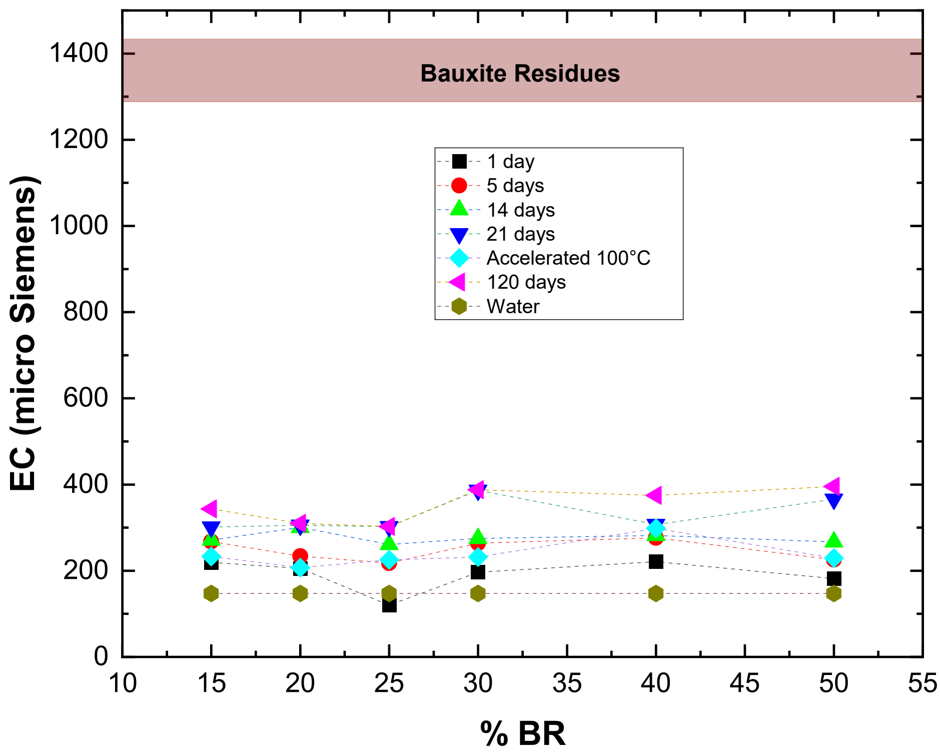

Figure 5. Electrical Conductivity (EC) of BR-WPC with varied BR content.

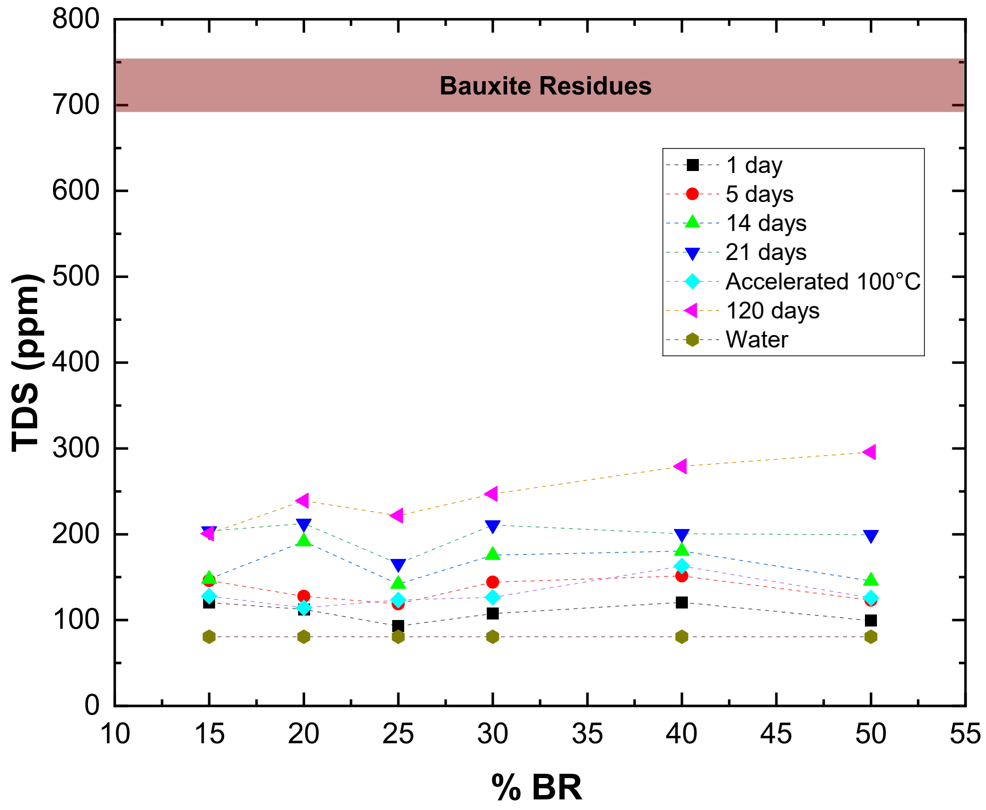

Figure 6. Total Dissolved Solids (TDS) of BR-WPC with varying BR content.

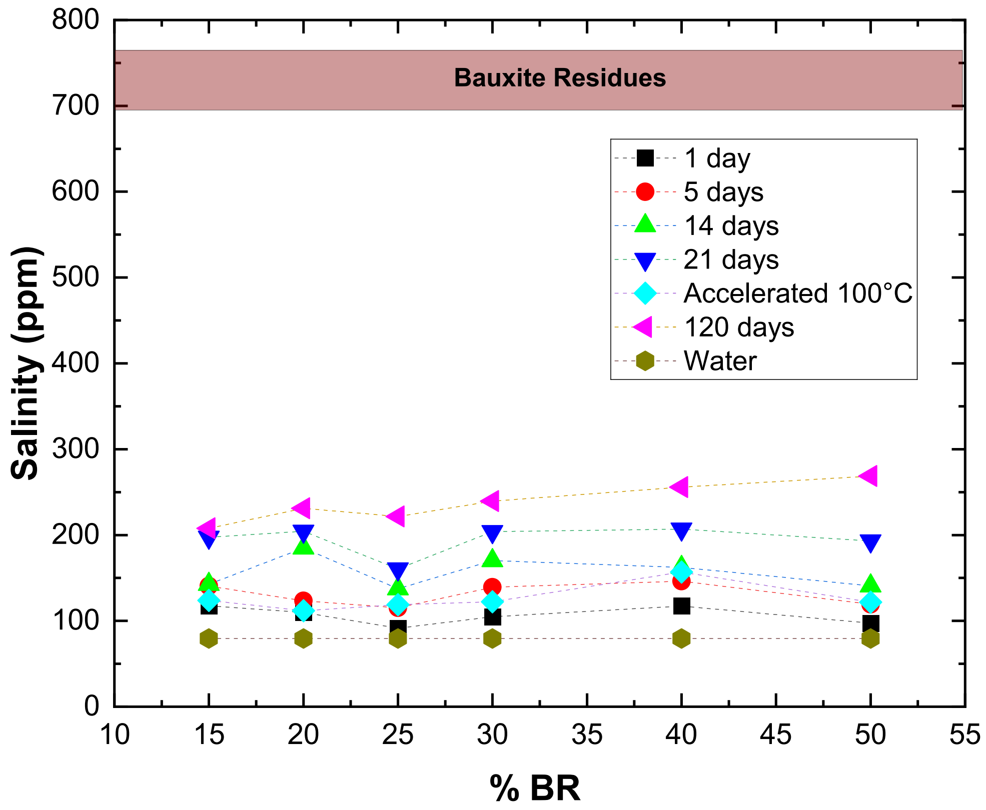

Figure 7. Salinity of BR-WPC with varying BR content.

Table 2. Heavy Metals detected in the BR-WPC brick leachate at various compositions of BR.

Composition BR: PW	Heavy Metals (ppm)									
	Ni	Cu	Ti	Cd	Fe	Zn	Pb	As	Hg	Cr
15 : 85	-	0.03	-	-	0.02	0.04	0.03	-	-	0.01
20 : 80	-	0.06	-	-	0.01	0.28	0.05	-	-	0.01
25 : 75	-	0.08	-	-	0.02	0.37	0.07	-	-	0.01
30 : 70	-	0.08	-	-	0.02	0.28	0.08	-	-	0.02
40 : 60	-	0.01	-	-	0.02	0.21	0.08	-	-	0.01
50 : 50	-	0.07	-	-	0.02	0.07	0.08	-	-	0.12
100 : 0	3.43	10.5	7.5	5	41.2	15	0.61	8.6	0.5	5.19
TCLP limit*	20	25	-	1	-	250	5	5	0.2	5

*As per Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 (Schedule II)

3.3 Thermal Properties

The TGA results demonstrated superior thermal stability, with BR-WPC bricks exhibiting higher decomposition temperatures compared to traditional materials. Studies on polymer-based composites typically report weight loss in three stages:

I. Minimal loss due to moisture evaporation (< 300 °C)
II. Decomposition of organic/polymeric components (300–600 °C)
III. Decomposition of inorganic constituents such as carbonates and clay minerals (> 600 °C).

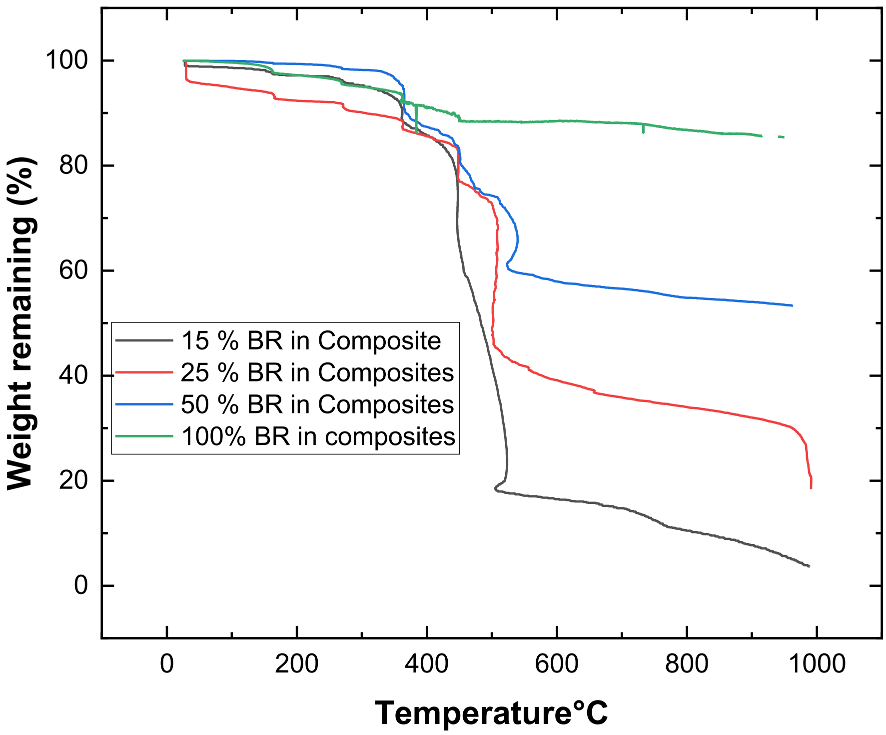

Figure 8. Thermal gravimetric analysis (TGA) profiles of BR-WPC with varying BR content.

The TGA analysis reveals minimal weight loss up to 300 °C. Between 300 and 600 °C, a noticeable weight reduction is observed, primarily due to the decomposition of polymeric components within the composites. Beyond 600 °C, up to 1000 °C, further weight loss is attributed to the breakdown of calcite and clay minerals. The residual mass at 1000 °C consists of stable inorganic oxides, including Fe_2O_3, Al_2O_3, SiO_2, and TiO_2. These stable inorganic oxides enhance thermal stability by resisting decomposition at high temperatures, acting as a heat barrier. These findings indicate that as the red mud content in BR-WPC increases, the overall weight loss during thermal degradation decreases, demonstrating enhanced thermal stability. Figure 8 shows the percentage of remaining weight of BR-WPC as a function of temperature.

3.4 Mechanical Properties

Figure 9. UCS test specimen undergoing unidirectional loading.

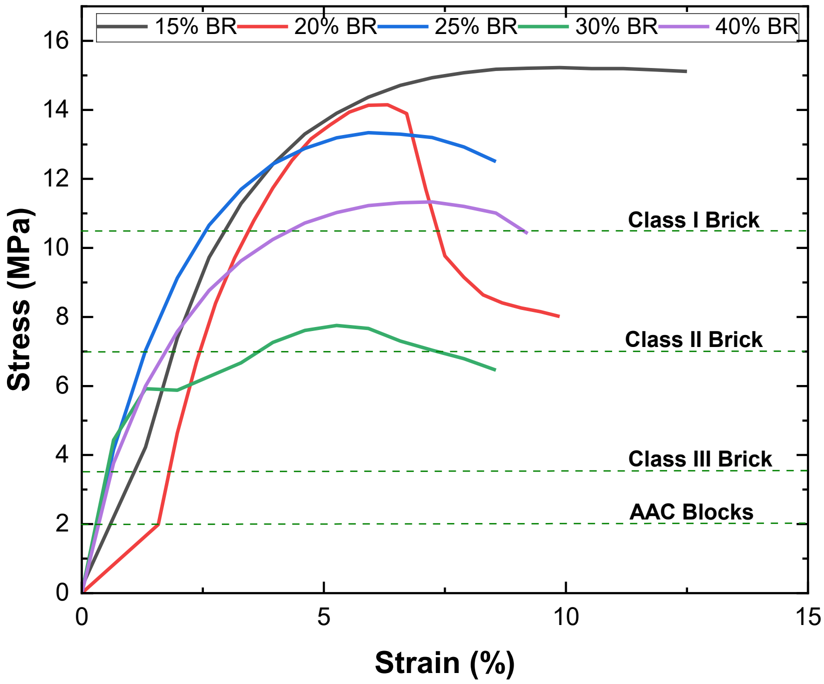

Figure 10. Stress-strain plot of the BR-WPC brick specimens with varying BR content.

The compressive strength of BR-WPC bricks was observed to be higher than that of conventional clay bricks, making them suitable for load-bearing applications. Figure 9 indicates compressive strength test set-up and Figure 10 shows the results of UCS test.

The UCS of BR-WPC containing 15 %, 20 %, 25 %, and 40 % red mud exceeds 10.5 MPa, thereby meeting the requirement for Class I bricks as per IS 1077:1992 [10]. Notably, the UCS of BR-WPC with 30 % red mud content surpasses the standard for Class II bricks. These findings indicate that BR-WPC exhibits superior compressive strength compared to conventional bricks.

4. Conclusion

The study demonstrates that BR-WPC bricks, developed using varying proportions of red mud and waste plastic, exhibit promising physical, chemical, and mechanical properties. The low water absorption confirms the effectiveness of the adopted methodology for making bricks. Long-term batch leaching tests (up to 120 days) reveal significantly lower values of pH, EC, TDS, and salinity in BR-WPC bricks compared to raw red mud, indicating improved chemical stability. ICP-AES analysis confirms that most heavy metals are either undetectable or within permissible limits making this as a non-leachable product. Unconfined compressive strength tests further show that BR-WPC bricks surpass conventional burnt clay bricks in strength, highlighting their potential as a sustainable alternative in construction applications.

The primary objective of this study is the large-scale utilization of bauxite BR accumulated within industrial premises. To achieve this, efforts have been made to develop mechanically and chemically stable materials by converting BR into synthetic aggregates. These aggregates offer significant advantages in terms of bulk utilization, ease of transportation, and long-term durability. Additionally, BR can be employed in the production of paver blocks, which are suitable for direct application in road construction. Furthermore, high-strength composite bricks incorporating BR demonstrating compressive strength sufficient can support the movement of heavy vehicles.

5. References

1. Guidelines for Handling and Management of Red Mud Generated from Alumina Plants, Central Pollution Control Board (CPCB), New Delhi, May 2023.
2. Venkata Siva Naga Sai Goli and Devendra Narain Singh, Landfill-mined-soil-like-fractions and red mud as anthropogenic resources in polypropylene composites, *Process Safety and Environmental Protection*, Vol. 184, April 2024, 542-559. https://doi.org/10.1016/j.psep.2024.02.012
3. Dan Xu et al., Catalytic conversion of plastic wastes using cost-effective bauxite residue as catalyst into H2-rich syngas and magnetic nanocomposites for chrome(VI) detoxification, *Journal of Hazardous Materials,* Vol. 413, 5th July 2021, Article 125289. https://doi.org/10.1016/j.jhazmat.2021.125289
4. ASTM D5550-14. Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer. 2023.
5. ASTM D570-22. Standard Test Method for Water Absorption of Plastics. 2022.
6. ASTM D2166/D2166M-24. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. 2024.
7. IS 3495-1 to 4. Methods of tests of burnt clay building bricks: Part 1 Determination of compressive strength and Part 2 Determination of water absorption. 1992.
8. ASTM C67/C67M-23a. Test Methods for Sampling and Testing Brick and Structural Clay Tile. 2021.

9. Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016, Ministry Of Environment, Forest And Climate Change, *Gazette of India*, Government of India, New Delhi, India, 2016.
10. IS 1077:1992. Common Burnt Clay Building Bricks – Specification. Fifth Revision. 2007.