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Red Mud Particles' Impact on the Mechanical Properties and Microstructure of AA6005 Composites for Brake Rotor Applications

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Abstract

There is increasing focus on utilizing industrial waste as reinforcement in metal matrix composites, driven by the demand for eco-friendly and cost-effective materials in automotive applications. With an emphasis on their possible use in braking rotors, this study examines how red mud particles affect the microstructure and mechanical characteristics of AA6005 aluminum alloy composites. Red mud, a byproduct of the Bayer process, is a good low-cost ceramic reinforcement because it is high in silica, alumina, and iron oxides. The stir casting method was used to create the composites, which contained different weight percentages of red mud particles (2%, 4%, 6%, and 8%). A consistent distribution of red mud particles and notable grain refinement were found by microstructural analysis, which enhanced the material's hardness and resistance to wear. Although there was a slight decrease in ductility at higher reinforcement levels, mechanical tests showed that the hardness and tensile strength increased as the red mud content increased. Significant improvement was seen in the tribological performance under dry sliding circumstances, indicating improved compatibility for high-friction applications like brake rotors. The study's overall findings highlight the potential of red mud-reinforced AA6005 composites as an effective and environmentally friendly substitute material for vehicle braking systems.

Keywords: Aluminum, Red mud, Brake Rotor, Composites, Mechanical

INTRODUCTION

In the context of composite materials, the term "composite" denotes the macroscopic combination of two or more constituents to create a usable substance. Although various materials can be mixed together on a microscopic level, as in alloying, the final product is homogeneous on a macroscale [1]. The benefit of composite materials is that they combine the greatest features of each of their elements with additional attributes that each one lacks. A substance that meets the following criteria will be referred to as a composite material [2].

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The automotive industry's need for high-performance, affordable, and sustainable materials has prompted research into the creation of metal matrix composites (MMCs) reinforced with industrial waste. The abundance and high concentration of oxides like Fe_2O_3, Al_2O_3, and SiO_2 in red mud, a byproduct of the Bayer process used to produce alumina, have made it a promising reinforcement material [3, 4]. A by-product of the caustic leaching of bauxites during the manufacturing of industrial alumina is red mud. For every ton of alumina, roughly 1-2 tons of red mud residues are created, and millions of tons of red mud have been accumulated so far, the majority of which have been kept or dumped into the sea with little to no reuse [5].

Because of its high alkalinity, which causes soil alkalization and water contamination, red mud storage in wetlands presents significant environmental risks. Additionally, direct discharge to the sea contaminates seawater, which threatens the fishing industry [6], and dry storage can produce a lot of dust and harm the atmosphere. Better cleanup procedures are therefore desperately needed, and red mud recycling has generated a lot of interest.

Advanced metal matrix composites (MMCs) have developed more quickly as a result of the automobile industry's increasing need for lightweight, high-performance, and environmentally acceptable materials [7]. Brake rotors, among other automotive parts, are essential to vehicle performance and safety and call for materials with high mechanical strength, wear resistance, and thermal stability [8]. Cast iron has long been the preferred material because of its superior wear properties and resistance to heat. Its great density, however, adds a substantial amount to the weight of the vehicle, increasing emissions and fuel consumption. Conversely, aluminum alloys in particular, AA6005 present a viable substitute because of their low density, strong resistance to corrosion, and adequate mechanical qualities.

The use of industrial wastes as reinforcing materials has gained popularity recently as a way to lower production costs and support environmental sustainability. Red mud was utilized in aluminum 6082 alloy composite, where it was observed that it has improved the mechanical strength and wear resistance of the composite materials [9]. Similarly, Sharma et al. [10] fabricated Aluminum 2024-red mud composites, where it was reported that the composites exhibited excellent wear properties in dry sliding wear conditions. Moreover, Huang et al. [11] investigated the influence of thermal properties and microstructure of ZL109 aluminum composites reinforced with red mud particles. With the help of uniform dispersion and strong interfacial bonding, the composites exhibited a potential application for high-temperature usage.

Because of its alkaline nature and environmental impact, red mud, a waste byproduct of the Bayer process used in alumina extraction, is produced in huge quantities and presents serious disposal issues. Red mud, which is mostly composed of Fe_2O_3, Al_2O_3, SiO_2, TiO_2, and Na_2O, has characteristics that are comparable to those of traditional ceramic reinforcements. It is a desirable option for usage in MMCs due to its availability, hardness, and thermal stability [12]. By using industrial waste, adding red mud to aluminum matrices not only improves material performance but also advances sustainable material development [13].

MATERIALS AND METHODS

The matrix material employed in this study is AA6005 aluminum alloy, chosen for its excellent extrudability, moderate strength, and corrosion resistance, making it suitable for automotive brake rotor applications. The 6xxx series of precipitation-hardenable aluminum alloys, including AA6005, is renowned for its excellent formability and strength-to-weight ratio. The AA6005 alloy is primarily alloyed with silicon as a typical 6xxx series, with the chemical composition given in Table 1 below. These compositions are consistent with standard specifications for AA6005 aluminum alloys.

Table 1. Basic chemical composition of AA6005.

Element	**Composition Range (%)**
Silicon (Si)	0.6 – 0.9
Iron (Fe)	0.35
Copper (Cu)	0.10
Manganese (Mn)	0.15
Magnesium (Mg)	0.4 – 0.7
Aluminum (Al)	Balance

Red mud, an industrial byproduct generated from the Bayer process during alumina production, was utilized as the reinforcement material. The red mud used in this study was sourced from a local alumina refinery (shown in Figure 1) and primarily composed of Fe_2O_3 (30–60%), Al_2O_3 (10–20%), SiO_2 (10–20%), Na_2O (2–10%), and TiO_2 (trace amounts), with particle sizes ranging from 100 to 200 µm before processing. High-purity argon gas (99.99%) was employed as an inert atmosphere during casting to prevent oxidation. The chemical composition of as-received red mud is shown in Table 2.

Figure 1. As-Received Red mud.

Table 2. Composition of red mud.

Compound	Typical Composition Range (%)
Iron oxide (Fe_2O_3)	30 – 60%
Aluminum oxide (Al_2O_3)	10 – 20%
Silicon dioxide (SiO_2)	10 – 20%
Sodium oxide (Na_2O)	2 – 10%
Calcium oxide (CaO)	2 – 8%
Titanium dioxide (TiO_2)	0.5 – 8%
Trace elements (Cr, V, Mn, etc.)	< 1%

Commercially pure aluminum powder (99.7% purity, average particle size 50 µm) is used as a carrier for nano-sized red mud particles to enhance wettability and distribution during casting. Silicon carbide (SiC) particles with an average size of 5–10 µm are incorporated in hybrid composites to improve wear resistance. All materials are preheated to 200 °C for 2 hours to remove moisture and improve interfacial bonding during processing.

Composite Fabrication

AA6005-red mud composites were fabricated using the stir casting technique, chosen for its cost-effectiveness and ability to achieve uniform particle distribution. The AA6005 alloy was melted in a graphite crucible using an electric resistance furnace at 750°C under an argon atmosphere. Preheated red mud particles (at 400°C for 1 hour) were added to the molten alloy in weight fractions of 2%, 4%, 6% and 8%. To enhance wettability and reduce agglomeration, 1 wt.% magnesium was added to the melt prior to reinforcement addition. The melt was stirred at 550 rpm for 5 minutes using a stainless-steel impeller to create a vortex, ensuring homogeneous dispersion of red mud particles. The composite melt was then poured into preheated (200°C) cast iron molds to produce cylindrical specimens (diameter: 20 mm, length: 100 mm). For comparison, unreinforced AA6005 samples were also cast under identical conditions.

Heat Treatment

To optimize mechanical properties, the cast composites were subjected to T6 heat treatment. The samples underwent solution treatment at 530°C for 2 hours, followed by water quenching at room temperature. Artificial aging was performed at 175°C for 8 hours in a muffle furnace, followed by air cooling. This heat treatment was designed to promote the formation of strengthening precipitates, such as Mg_2Si, in the AA6005 matrix.

Microstructural Characterization

The microstructure of the composites was analysed to evaluate particle distribution, interfacial bonding, and phase formation. Specimens were sectioned, polished using standard metallographic techniques (SiC papers up to 2000 grit, followed by diamond paste polishing), and etched with Keller's reagent (2.5% HNO_3, 1.5% HCl, 1% HF, 95% H_2O). Optical microscopy and scanning electron microscopy (SEM) were used to examine the microstructure.

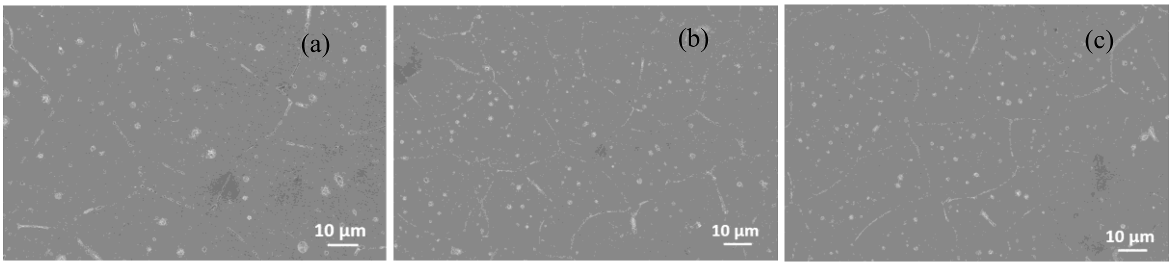

Figure 2. SEM micrographs of AA6005-Red Mud Composites (a) 2 wt%, (b) 4 wt%, (c) 6 wt%.

- *Particle Dispersion:* The SEM micrographs involving Al/Red mud composites are shown in Fig. 2. The uniform dispersion of red mud particles within the aluminum matrix plays a crucial role in determining the final mechanical performance of the composite material. Homogeneous distribution ensures consistent load transfer between the matrix and the reinforcement particles, which directly influences properties such as tensile strength, hardness, wear resistance, and fracture toughness. Conversely, poor dispersion can lead to the formation of agglomerates or clusters, which act as stress concentrators, initiating microcracks under mechanical loading and compromising the integrity of the composite [14].
- *Fracture Mechanism:* The composites' fracture behavior is greatly impacted by the addition of red mud. A hybrid failure mechanism with both brittle and ductile characteristics is shown by scanning electron microscopy (SEM) study of broken surfaces. Red mud particles may improve energy absorption during failure, as seen by the development of dimples and micro-voids, which are indicative of localized plastic deformation typical of ductile fracture. Concurrently, the development of cleavage planes and acute cracks indicates brittle behaviour, most likely as a result of stress concentration surrounding the stiff red mud particles. Red mud may change the fracture pattern and encourage a mixed-mode failure in the composites, according to this combination [15, 16].

Mechanical Testing

Mechanical properties were evaluated to assess the suitability of the composites for brake rotor applications. Microhardness was measured using a Vickers hardness tester with a 500 g load and a dwell time of 10 seconds. At least 10 indentations were made on each sample to ensure repeatability. Tensile properties were determined using a universal testing machine. Cylindrical tensile specimens were machined from the cast samples and tested at a crosshead speed of 1 mm/min. Compressive strength was evaluated on cylindrical specimens using the same testing machine at a strain rate of 10^{-3} s^{-1}, following ASTM E9 standards. Wear behaviour was investigated using a pin-on-disc tribometer under dry sliding conditions with a normal load of 20 N, sliding speed of 1.5 m/s, and sliding distance of 1000 m. Wear rate was calculated by measuring mass loss, and worn surfaces were analyzed by SEM to identify wear mechanisms.

Mechanical Properties

Hardness And Tensile Strength

Vickers micro-hardness values (measured in HV) of various AA6005 composite samples with the designations. When evaluating a material's durability and wear resistance, the Vickers hardness test is essential since it gauges the material's resistance to plastic deformation. Figure 3 shows that the hardness values from A1 to A4 clearly show an ascending trend. As the weight percentage of red mud reinforcement in the AA6005 aluminum matrix increases, the experimental study demonstrates a progressive rise in hardness, as shown in the Vickers hardness bar graph. The hardness of the basic alloy was 65 HV, and for 2%, 4%, 6%, and 8% red mud-reinforced samples, it progressively increased to 72 HV, 79 HV, 86 HV, and 92 HV, respectively. The dispersion of hard ceramic elements found in red mud, such as Fe_2O_3, Al_2O_3, and SiO_2, is mostly responsible for this increase in hardness. These constituents serve as efficient barriers to dislocation motion, enhancing the composite's resistance to plastic deformation.

This steady rise indicates that changes made to the composite, including adding reinforcement or using different processing methods, help to improve the material's hardness. Hardness may have been raised by the use of reinforcing particles or better thermal-mechanical treatment, which may have enhanced the dislocation density, decreased porosity, or refined the grain structure. The graph showing the Vickers micro-hardness of AA6005 composites reinforced with different weight percentages of red mud particles. The increasing trend in hardness from A1 (2 wt% red mud) to A4 (8 wt% red mud) reflects the strengthening effect of red mud reinforcement.

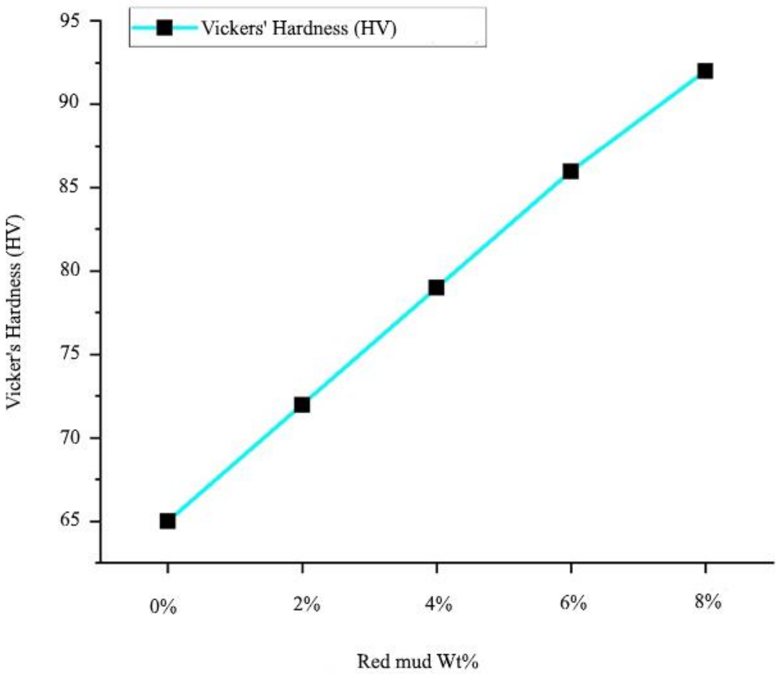

Figure 3. Micro-Hardness of AA6005/Red Mud Composites.

Figure 4 shows a graphic representation of the tensile characteristics of AA6005 aluminum alloy composites reinforced with different weight percentages of red mud particles (2%, 4%, 6%, and 8%). Yield Strength (YS) and Ultimate Tensile Strength (UTS), two important mechanical performance measures, are depicted in the graph. The stress at which the material starts to distort plastically is represented by the blue bars, which stand for yield strength. The red bars represent the material's ultimate tensile strength, which is the highest stress it can withstand before failing. The trends that have been observed offer important information on how the structural integrity of the composite is affected by increasing red mud reinforcement.

With an increase in reinforcement content, the tensile strength behavior of AA6005 aluminum alloy and its composites reinforced with red mud particles clearly improves. The graph shows that the base AA6005 alloy has an ultimate tensile strength (UTS) of 270 MPa and a yield strength (YS) of 190 MPa. The findings show that when the red mud concentration rises from 2% to 8%, yield strength and UTS both clearly and consistently improve. The base alloy shows a UTS of 285 MPa and a yield strength of 205 MPa at 2 weight percent. This demonstrates the first efficacy of the ceramic red mud particles in fortifying the matrix and already represents a notable improvement over the unreinforced base alloy. The reinforcement probably improves the composite's resistance to deformation by preventing dislocation movement and promoting regional grain refinement.

Both strength metrics significantly increase when the red mud concentration is raised to 4 weight percent. While UTS increases to 305 MPa, the yield strength reaches 220 MPa. This ongoing development points to a more uniform particle distribution and more efficient load transfer between the ceramic particles and the aluminum matrix. A finer and more equiaxed grain structure that increases overall strength may result from the red mud particles at this stage serving as nucleation sites during solidification.

The greatest performance increase is obtained with additional reinforcement at 6 weight percent, with UTS peaking at 325 MPa and yield strength increasing to 235 MPa. This suggests that particle content and dispersion are working in perfect harmony to produce the highest possible resistance to yielding and fracture. The material's mechanical improvement is largely dependent on the enhanced particle-matrix interaction and interfacial bonding at this level.

With the yield strength at 240 MPa and UTS at 330 MPa, the strength values at 8 weight percent continue to rise, albeit slightly. A possible approach to saturation, where the advantages of additional reinforcement start to level out, is suggested by the slower rate of progress at this point. This could counteract the benefits of a higher ceramic content and could be caused by mild matrix embrittlement or particle aggregation. However, the strength values are the greatest among all samples, showing that 8 weight percent red mud still improves tensile performance without materially sacrificing integrity.

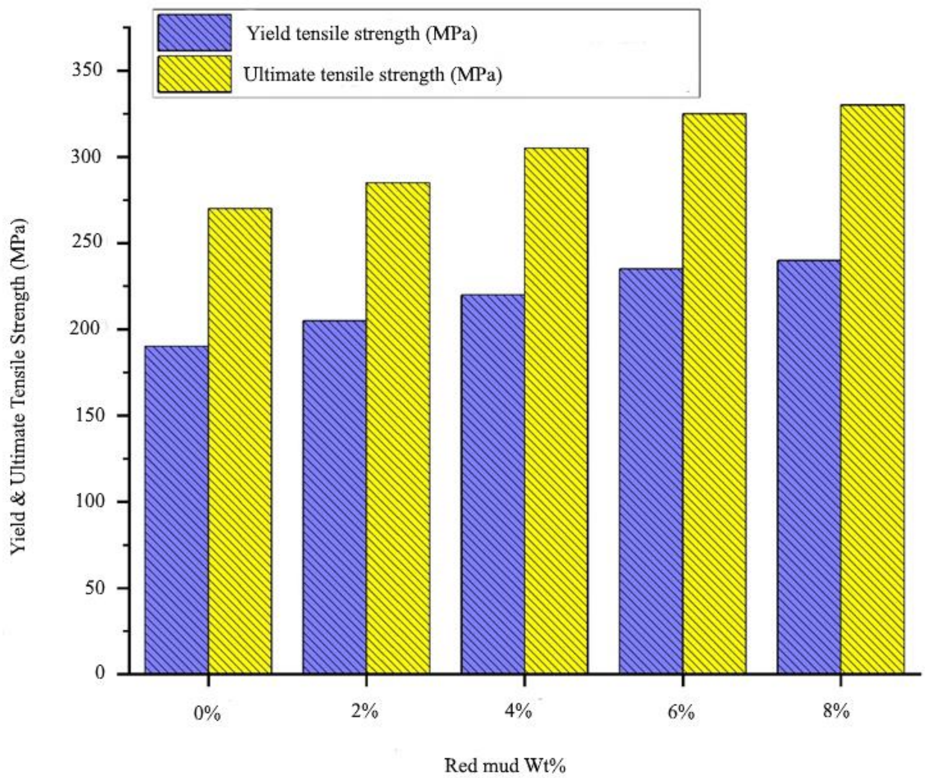

Figure 4. Yield Strength and Ultimate Tensile Strength of AA6005 Composites.

The graph shows the Yield Strength and Ultimate Tensile Strength of AA6005 composites with varying weight percentages of red mud particles from samples with all concentrations of red mud in Figure 4.

- *Impact Strength:* The variation of impact strength with red mud addition is given in Figure 5. Red mud can have a negative impact on impact strength, even though it enhances qualities like hardness and tensile strength in aluminum matrix composites. Because ceramic reinforcements are fragile, composites with a higher red mud component demonstrated lower impact energy [17]. This is mostly because red mud, a ceramic-based substance, is naturally fragile and can lead to stress concentration areas inside the matrix. The composite may fracture or fail under dynamic loading as a result of these stiff particles' decreased capacity to absorb and release energy during abrupt impacts. Particularly in applications like brake rotors, where materials must tolerate high mechanical loads and abrupt shocks without sacrificing performance or safety, this trade-off between increased strength and decreased toughness is crucial.

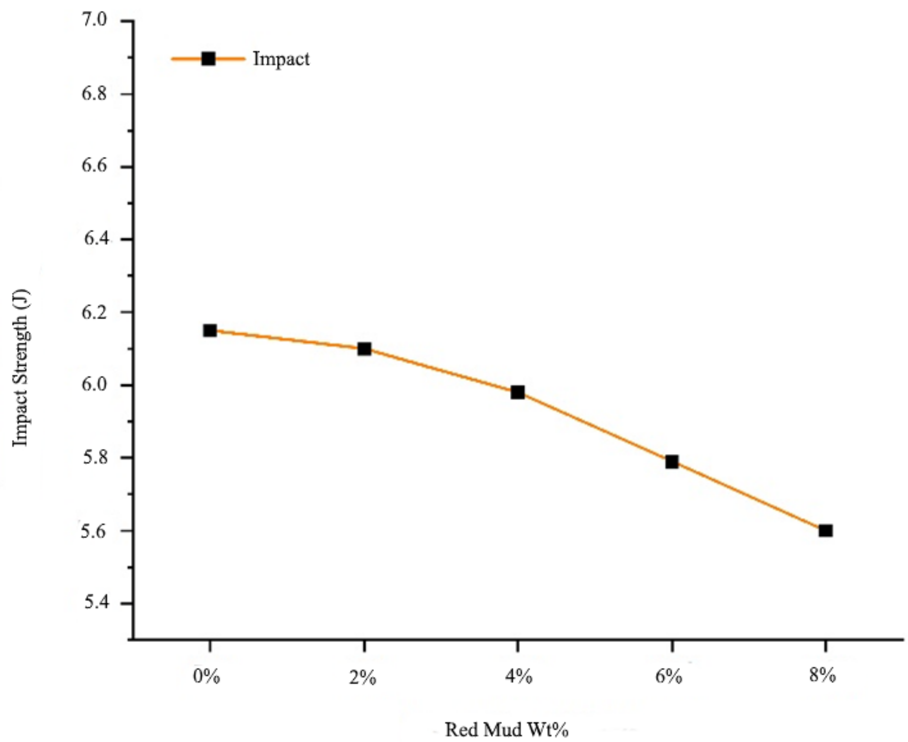

Figure 5. Variation of Impact Strength with Red Mud Content.

RESULTS AND DISCUSSION

Mechanical Properties

The mechanical behavior of the aluminum alloy AA6005 was greatly affected by the addition of red mud particles. Up to an ideal weight percentage (usually 10–15 wt%), the inclusion of red mud improved the composites' tensile strength and hardness. This improvement is explained by the dispersion strengthening effect, in which the hard red mud particles increase load-bearing capacity by preventing dislocation movement. When compared to the unreinforced matrix, the Vickers hardness values showed a discernible increase, demonstrating the reinforcement's ability to withstand localized plastic deformation. Red mud's ceramic composition causes brittleness, which lowers the material's resistance to shock or dynamic stress. In brake rotor applications, where strength and toughness must be balanced, this discovery is crucial.

MICROSTRUCTURAL ANALYSIS

When red mud was added, the shattered surfaces' microstructural behavior changed significantly, according to scanning electron microscopy (SEM). Unreinforced AA6005's fracture surfaces showed deep dimples and wide plastic deformation zones, which are typical ductile features. The composites augmented with red mud, on the other hand, showed mixed-mode fracture behavior. Whereas cleavage facets and microcracks showed brittle fracture zones, shallow dimples and micro-voids revealed ductile failure regions.

Red mud particles were evenly distributed throughout the aluminum matrix, which enhanced load distribution and refined grain structures. Higher reinforcement levels, however, showed some micro-porosity and particle agglomeration, which could serve as fracture initiation sites and impair mechanical performance.

Comparative Analysis

Aluminum metal matrix composites (AMMCs) provide a distinctive blend of low weight, superior strength, and excellent wear resistance, rendering them essential for applications in aerospace, automotive, and construction industries. This comparative analysis (Table 3) examines critical attributes, including mechanical performance, thermal endurance, and fabrication methods, to elucidate the strengths and constraints of different AMMC compositions.

Table 3. Comparative Analysis with previous literature.

Study (Year) & Alloy	Red Mud wt%	Hardness	UTS (MPa)	Microstructural & Key Observations
Kumar et al. [19], AA6063 hybrid	Al alloy + red mud + fly ash (wt% NR)	Hardness ↑ with reinforcement (HRB)	UTS & YS ↑	Well-dispersed particles hinder dislocations
Kar & Surekha [12], Al7075/TiC/red mud	3–12%	Microhardness ↑ (HV)	UTS ↑ with TiC, red mud caused 71% UTS ↓	SEM: dimples, cracks, voids, clusters
Samal et al. [15], AA6082	0–6%	↑ significantly (e.g., 80 → 104 HV)	260 → ~310	Ductile fracture mode (dimples, micro-voids)
Karuna et al. [18], AA2024	1–4%	149 → 166 HV (@4 wt%	Tensile ↑ (6-10%)	Uniform dispersion enhances properties, and impact toughness declines

CONCLUSION

This study shows that red mud has a promising future as a sustainable reinforcing material for automotive braking applications in AA6005 aluminum alloy composites. By using the stir casting method to incorporate red mud particles, the mechanical and tribological properties were significantly improved, the particle distribution was uniform, and the grain structures were refined. Higher red mud content was associated with increased hardness, tensile strength, and wear resistance; however, ductility was slightly reduced at higher reinforcement levels. The enhanced performance in dry sliding situations, which is especially important for brake rotor operation, indicates that red mud-reinforced AA6005 composites provide a practical, affordable, and environmentally responsible substitute for traditional materials. These results encourage more research and possible industrial use of these composites in sustainable and high-performing vehicle parts.

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