

## Green Specialty Alumina for Greener Energy Products

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<https://doi.org/10.71659/icsoba2024-aa026>

### Abstract

Alumina and their derivatives were researched and engineered with different formulations using advanced processes for the last 4 decades, offering a wide spectrum of applications in aerospace, automobile, energy, petrochemical, steel, defence, solar, and mining segments. Amongst various efforts to address, the challenges of optimum energy utilization, materials selection and design play a crucial role in energy-related engineering applications. Special grades of Alumina (including hydrates), as a raw material, offer numerous advantages for energy conservation and efficiency having a potential more than 12 000 kt global market in 2030.

As the world shifts towards green and renewable energy, lithium-ion batteries (LiBs) play a significant role. Hindalco has developed high quality alumina and offered for very high-end applications, for example, Sub-Micron Alumina (SMA) and Ultra Fine Boehmite (UFB) are used as a separator coating on polyolefin films for Li-ion batteries to enhance performance and safety. High purity alumina (IC : Industrial Ceramic) is used in thermal interface materials to dissipate heat faster from batteries and other electronic devices, ensuring safety and longevity. In applications like spark plugs and insulators, High Crystalline Alumina (HCA) offers electrical insulation and high-temperature stability. It's also crucial in high-voltage insulators due to its low dielectric constant and high dielectric breakdown voltage.

Additionally, Super Fine Hydrate (SFH) of trihydrates and the UFB are finding applications as catalyst support materials in petroleum refining, indirectly aiding the energy sector.

On the other hand, by effective utilization of red mud it is possible to develop sustainable and green aluminium company. Advanced R & D and fully automated process control enable the development of a wide range of calcined alumina for various applications. The cumulative impact of green alumina refining process and products contributes significantly to achieving sustainability goals.

**Keywords:** Alumina, Boehmite, Energy, Green product, Specialty alumina.

### 1. Introduction

Amongst various industrial ceramics, alumina is one of the most important engineering materials due to its diverse and beneficial properties, which result in a wide range of applications [1, 2]. In industry, there is always a high demand for suitably designed materials due to their ease of application and high performance [3]. In some cases, this high performance leads to energy-saving processes, which is also a factor in designing materials for a greener approach.

Electric vehicles and rechargeable electronic gadgets heavily rely on the use of Li-ion batteries [4]. Ramasubramanian et al. [5] described major challenges for the sustainability of the Li-ion battery in their paper. They discussed the main criteria for the sustainability of Li-ion batteries, including maximizing battery performance and prolonging battery life with safety. Alumina and boehmite play very important roles here [6, 7]. While improved cathode materials and electrolytes

are being designed to improve current density coating a suitable separator on the polypropylene or polyethylene film can also enhance current density. Both alumina and boehmite improve the performance (current density), safety, and prolonged cycle life of Li-ion batteries [8, 9]. Due to the use of such ceramic coated separator thermal runaway can be prevented, and also ensure thermal stability at high working temperature. Additionally, separator coating improves the mechanical strength and wettability of the separator. Therefore, use of alumina and boehmite help to meet the sustainable criteria of Li-ion battery.

EV (Electric Vehicle) batteries and other electronic devices face problems due to heat generation during operation. The device's performance and safety are at substantial risk due to the generation of excessive heat. Therefore, heat dissipation is the most significant factor for to safely using the device for a prolonged life cycle. Alumina with high dielectric strength and moderate thermal conductivity can resolve this issue [10–12]. For Thermal Interface Materials (TIMs), Alumina is used a filler in the resin matrix (silicone, Epoxy, Nylon) to remove the generated heat from the devices. It helps to efficiently transfer heat away from the components, reducing the risk of overheating and ensuring stable operation. In power electronics, alumina substrates are widely used to mount semiconductor devices, enhancing their thermal management and reliability.

Thermocouples are used to measure the temperature from ambient to elevated conditions. The wire of the thermocouple needs thermal protection during the operations at high temperature. Alumina being thermally stable and inert can provides such protection to thermocouple wires [13–16]. Heat loss can be minimized if the temperature measurement is accurate. Accurate temperature measurement is needed to minimize heat loss, which ensures accuracy of the system. In this way, the use of alumina is a greener approach which helps to reduce energy loss. Alumina can withstand very high temperature (1600–1800 °C) temperatures without degradation makes it suitable as refractory materials in industries such as metallurgy, glass manufacturing, and chemical processing, where temperature control heat loss is crucial.

Sparkplugs are used for the ignition of fuel in engine of the cars. Alumina with thermal and electrical insulations can host the high-temperature spark and minimize the damage. Alumina due its effective electrical insulation properties prevent electrical leakage, ensuring generation of spark for ignition [17, 18]. Use of Alumina ensure the lifespan of the sparkplug with any degradation over the application period. This helps the internal combustion engine to run with better fuel economy and low emission of green-house gases.

High dielectric strength is required for the transmission of high voltage lines. Porcelain bodies with Alumina as a filler material can attain such high dielectric strength required for the transmission. Alumina containing insulators helps long distance transmission without any leakage and failure [19]. Their durability and resistance to environmental factors such as moisture and temperature variations make the alumina containing insulators ideal for outdoor applications.

Alumina is a significant raw material for the refractory industry, the use of alumina has significantly increased for the clean steel production. Alumina provides high-temperature insulation, inertness, strength, and stability [20, 21]. Effective insulation saves a significant amount of energy at high temperature and completes processes in minimal time. Therefore, alumina as one of the major components of refractory raw materials, helps in energy saving [22]. Alumina based refractories finds applications in industries like steelmaking, cement production, and glass manufacturing where for lining furnaces, kilns, and reactors [23]. These alumina containing refractories withstand high temperatures and provide protection from the corrosive environments, ensuring process efficiency and longevity of the kiln, furnace and equipment, leading to reduced energy consumption and operational costs.

Similarly, the use of alumina as a grinding media enables many industrial processes to be completed in a short time and energy saving manner [24]. Alumina grinding media are widely used in milling processes to crush, grind, and blend materials in finer fractions. The high hardness and wear resistance of alumina minimize the contamination of the milled products and ensure efficient grinding. This type of grinding efficiency translates into lower energy consumption and faster processing times, therefore, benefiting industries such as mining, ceramics, and pharmaceuticals.

The petrochemical industry has wide application of catalyst. Both, alumina and boehmite are widely used as catalyst support materials [25], which also helps to purify the petroleum products and thus reduce energy consumption indirectly. Alumina and Boehmite serves as a support for catalysts by providing a high surface area and stable environment for catalytic activity [26]. This enhances the efficiency of processes such as oil refining, chemical synthesis, and pollution control. The use of alumina-based catalysts considerably improves reaction rates and selectivity, leading to energy savings and reduced environmental impact.

Finally, the alumina refining process was hazardous due to the significant deposition of red mud, a byproduct of alumina refining. However, after technological advancement the red mud is now being utilized for cement production, making the alumina refining process itself a green process. The integration of red mud into cement manufacturing not only reduces the environmental impact of alumina production but also provides a valuable raw material for the construction industry [27]. This kind of approach aligns with circular economy principles, turning waste into a valuable resource and thus improving the environmental sustainability for both the industries.

In addition to the lowering the carbon footprint, use of biomass-based steam and wind power can further improve the effort towards a sustainable world.

Efforts have been invested to develop a versatile and environmentally friendly alumina powder that is suitable for a broad range of applications, as evidenced by its extensive use in various high-tech and industrial processes. The innovation involved for the development is not only a testament to quality but also a dedication towards a sustainable future. By incorporating advanced manufacturing techniques, it is possible to produce alumina powder that meets the highest standards of performance and sustainability, helping other industries achieve their greener product development goals.

This paper discusses a few grades of alumina powder, highlighting their wide range of applications where alumina plays a crucial role in energy conservation.

## **2. Experimental Process**

The feedstock for calcined alumina is aluminium hydroxide (hydrates), a product derived from the Bayer process at the refinery. The hydrates are thoroughly washed and then calcined in a rotary kiln to produce various alumina products. The quality of the final product depends on the processing parameters within the rotary kiln, which are adjusted according to the specific application requirements. Post-calcination, the alumina powders have undergone grinding or milling operations to achieve the desired particle size distribution for its final application. The entire process is highly automated and closely monitored to ensure the highest quality products. These developmental activities are supported by a dedicated R&D team, ensuring continuous improvement and innovation in product quality and application suitability.

The final products are characterized using a comprehensive suite of advanced techniques to ensure they meet stringent quality standards and application requirements. These include X-ray Diffraction (XRD) for phase identification, X-ray Fluorescence (XRF) for chemical analysis,

Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) for trace element analysis and Scanning Electron Microscopy (SEM) for examining microstructure. Additionally, Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) are used to study thermal stability and phase transitions. Dielectric properties and thermal properties characterizations are also performed to assess the material's suitability for electronic applications. In the following sections different product grades are mentioned for various applications.

In case of flux, a standard composition was produced using kaolin clay (50 wt%), Dolomite (40 wt%) and Talc (10 wt%), the resultant mixture was wet milled along with HCA grades separately for 8 h in a pot mill. The resultant slurry was dried at 90 °C/24 h, then ground using a pestle and mortar to break the agglomerates and to homogenise the mixture, finally the latter was sieved (200 mesh) to remove the remnant aggregates before making the green compacts at 50 MPa in a uniaxial press. The green compacts were sintered at 1600 °C/4h in a muffle furnace, the heating profile is as follows, the samples were heated to 5 °C/min and ramped up to 1400 °C at a rate of 8 °C/min and finally raised to 1600 °C at 6 °C/min and held for 4 h and consecutively cooled down to 1000 °C at 10 °C/min and allowed the furnace to cool to the ambient temperature.

The sintered samples were used to analyse the shrinkage and density using Archimedes method. A Nanovea tribometer was used for testing wear resistance of the sintered compacts, a 6-mm Yttria Stabilised Zirconia (YSZ) ball was used to wear alumina in a Ball-on-disk configuration. For Dielectric strength, a ceramic sample measuring 60 mm × 3.8 mm disks were prepared and a rapid rise method (ASTM D149-20) used to measure dielectric strength at 50 Hz. Volume resistivity was measured as per ASTM D257-14, and Di-electric constant and loss tangent were obtained using ASTM D150-18 standards using similar dimension samples.

### **3. Results & Discussion**

#### **3.1 High Crystalline Alumina (HCA)**

Figure 1a shows the XRD pattern of the high crystalline alumina, it clearly shows that the materials are phase pure alpha in nature and hence not displaying any secondary phases. The difference between the grades is the extent of calcination which had resulted in different morphologies. Figure 1b shows the SEM images of the HCA series products, HCA1 and HCA2 are crystallized into spherical morphology whilst the HCA3 and HCA4 displayed platelet structures with different aspect ratios (diameter to thickness). This allows various applications possible to obtain different performances, the results of the study are tabulated in Table 1.

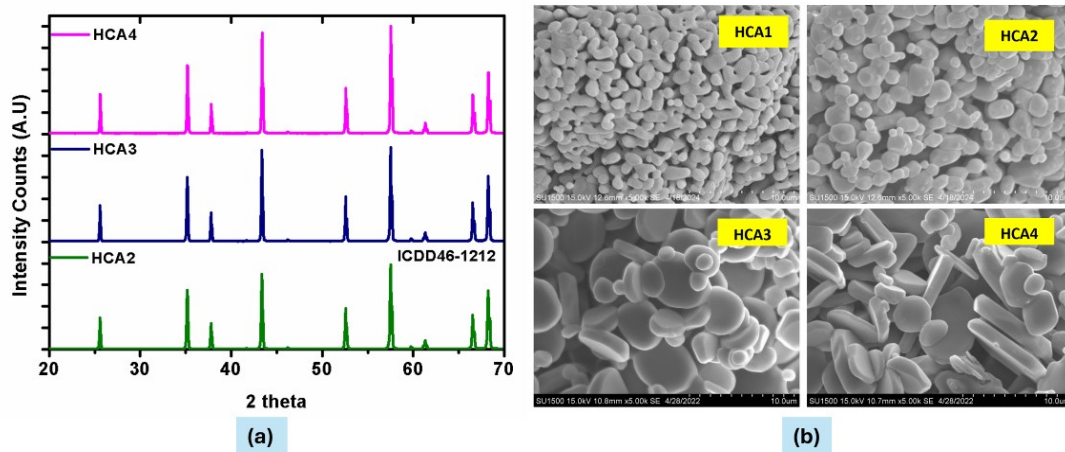


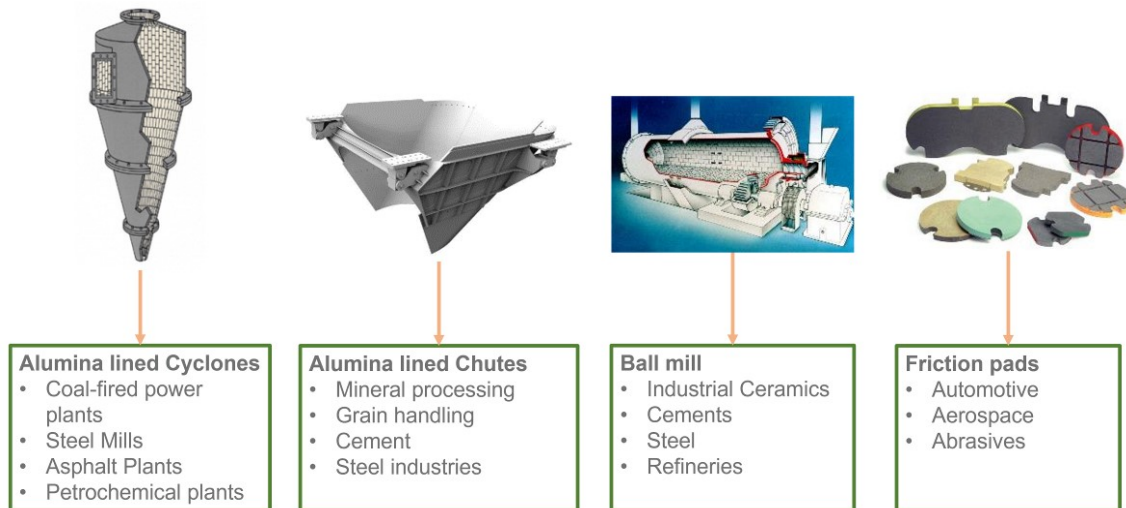
Figure 1. (a) XRD pattern of High Crystalline Alumina (HCA) series  
(b) SEM images of HCA series.

Table 1. Performance of HCA Series

Chemical Properties	HCA2	HCA3	HCA4
Na <sub>2</sub> O, %	0.1	0.1	0.1
Fe <sub>2</sub> O <sub>3</sub> , %	0.02	0.02	0.02
SiO <sub>2</sub> , %	0.02	0.02	0.02
CaO, %	0.03	0.03	0.03
Physical Properties			
SSA, m <sup>2</sup> /g	0.7	0.6	0.4
Primary Particle Size, μm	2	3	5
Green Density, g/cc & 50 MPa	2.31	2.31	2.36
Fired Density, g/cc @ 1600 °C/4 h	3.70	3.70	3.70
Porosity (%)	0.1	0.1	0.1
Co-efficient of Friction	0.56	0.62	0.64
Wear Resistance,	4.50e-05	5.50e-05	6.02e-05
Electrical properties			
Dielectric Strength, kV/mm	8.73	8.67	8.46
Volume resistivity, Ω·cm	4.67e+10	8.36e+12	5e+12
Dielectric constant	4.94	5.59	5.88
Loss tangent	0.001392	0.00229	0.003385

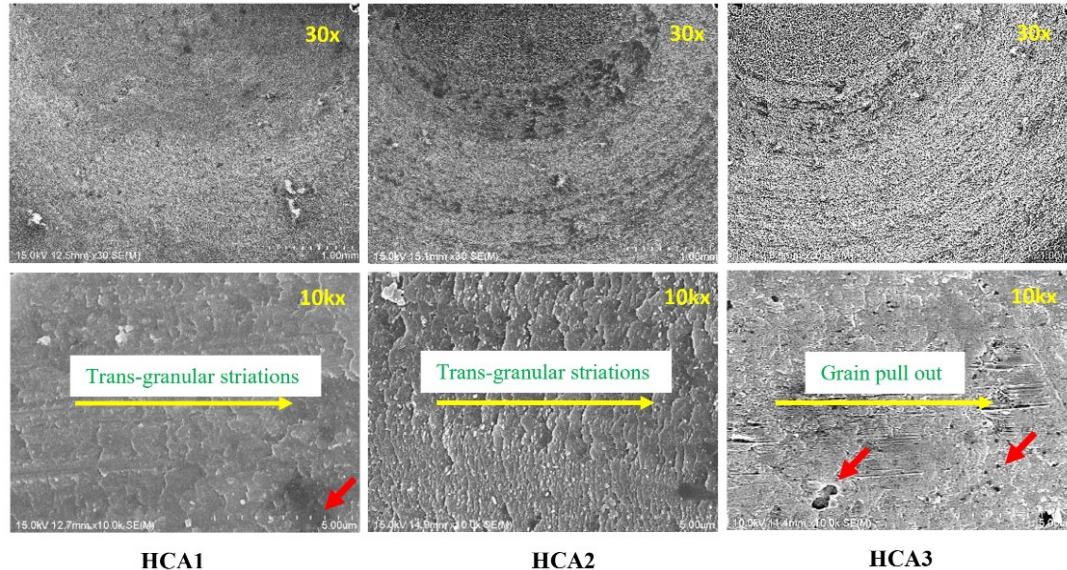
### 3.1.1 Wear Ceramics

Alumina has been widely used in wear-resistance applications such as cyclone separators, ceramic-lined chutes, ball mills, and in friction pads, refer Figure 2. These products are used in various industries, i.e., steel industry, petrochemical, cement, automotive, and aerospace. This application is a complex function of grain size, shape, microstructure, toughness, hardness, and operating conditions. The HCA series has been tested and the effect of particle shape and sintered grain size have been investigated in this study and the results are discussed.



**Figure 2. Wear Ceramic Applications [28, 29]**

In this study, both spherical and platelet morphologies have been investigated to study their effects on wear resistance. All the alumina products were densified with 10 % flux and the sintered bodies were used for the wear resistance test. The HCA1 and HCA2 allow progressive wear whilst the HCA3 resulted in bulk material removal by grain pullout. The results are shown in Figure 3. The SEM images show the wear pattern of HCA3 and HCA2 & HCA1, the former show grain pullout mechanism whilst the latter shows striations of grains and displaying a clear progressive wear which resulted in high wear resistance. This high wear-resistant alumina ensures energy-efficient grinding and optimal processing conditions.

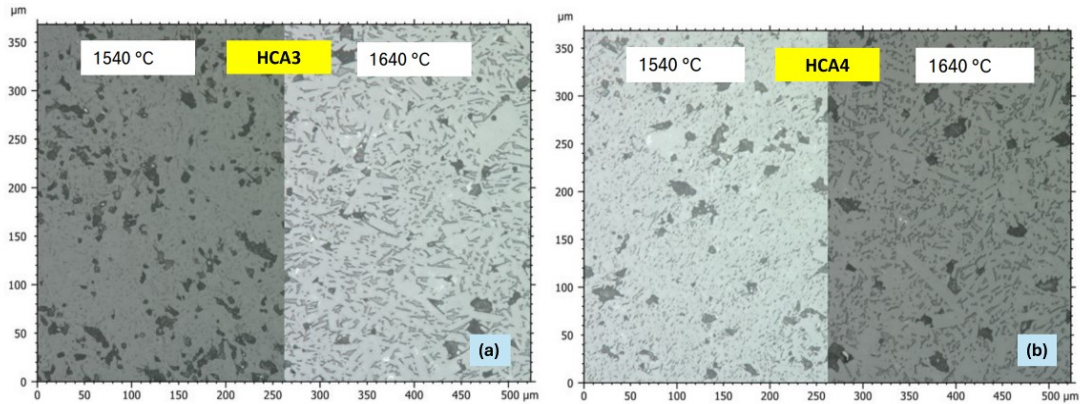


**Figure 3. Resultant SEM images of the wear patterns of HCA1, HCA2 and HCA3.**

### 3.1.2 Electroceramics (HCA Series)

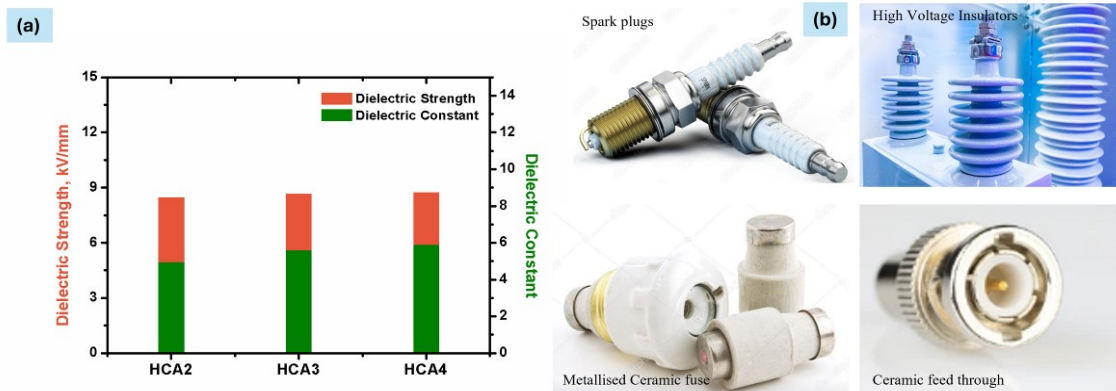
Alumina ceramics have emerged as a critical component in the electronic industry for the last three decades. Alumina products such as spark plugs, insulators and ceramic substrates need exceptional electrical insulation and thermal conductive properties along with high mechanical strength. HCA2, HCA3 and HCA4 have been studied for electrical applications, these materials contain high alpha and low soda impurities. Figure 4 shows the sintering kinetics and SEM images

obtained after sintering at 1540 and 1640 °C/2 h and obtained fired density of 3.7 g/cm<sup>3</sup> with 4 % flux. The results suggest that there were no pores observed in the sintered ceramics and the difference being the grain growth, with columnar grains when sintered at 1640 °C.



**Figure 4. Sintered microstructures of HCA3 and HCA4 after sintering at 1540 °C and 1640 °C**

The samples sintered at 1640 °C/4 h have been chosen for studying electrical properties. Table 1 shows the results of the resultant ceramics and Figure 5a shows the graphical illustration of dielectric strength and dielectric constant with respect to the HCA grades. It is very clear that the HCA3 and HCA4 have excellent dielectric strength and dielectric loss due to the higher degree of crystallinity and the alpha content was more than 99 % with minimal impurities. This suggests that the HCA produced is superior in quality and it can be used to obtain the electrical properties close to theoretical and supplied for various electronic applications, Figure 5 b.



**Figure 5. (a) Electrical properties of HCA series alumina and (b) electro-ceramic applications**

### 3.1.3 Thermal Ceramics (HCA, SMA and IC Series)

As mentioned earlier, Alumina being the critical component in the electronic industry, due to the better electrical and thermal properties find application in heat sinks, thermal pads and few other applications. The primary role of alumina in this application is to dissipate heat from the electronic components and stay dielectric as possible to avoid short circuits.

In this study, IC03SG (Industrial Ceramics: IC, Super Ground: SG), SMA3 and HCA4FG (Fine Ground) grades of milled alumina was taken for the thermal interface material study, these three

grades are single phase alpha alumina products, Figure 6a, whilst the difference being the particle size, shape and particle size distribution, refer to Figure 6b.

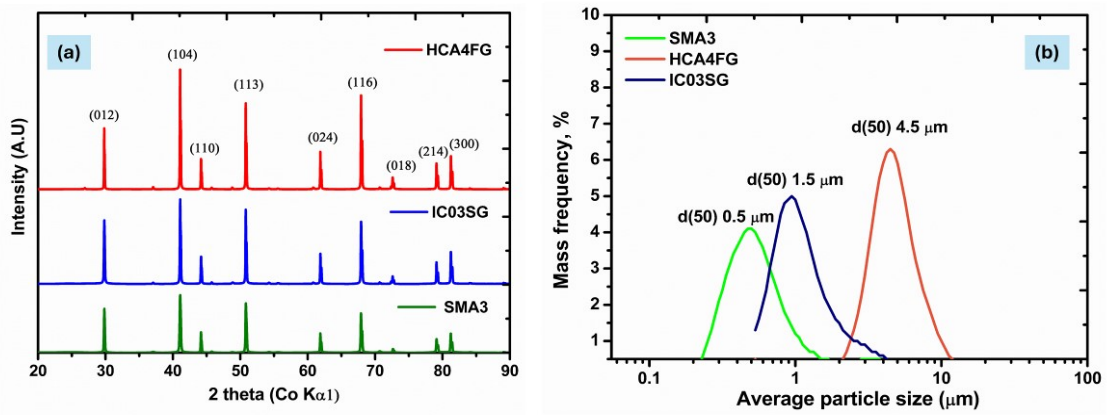


Figure 6. (a) XRD patterns of SMA3, IC03SG and HCA4FG and (b) PSD of SMA3, IC03SG and HCA4FG

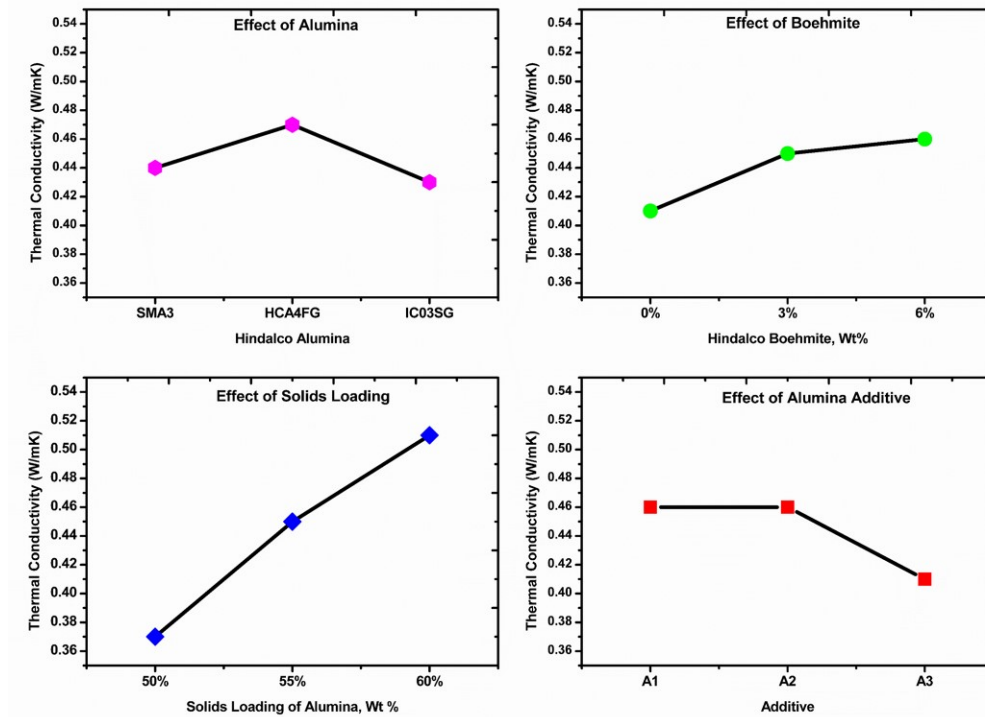
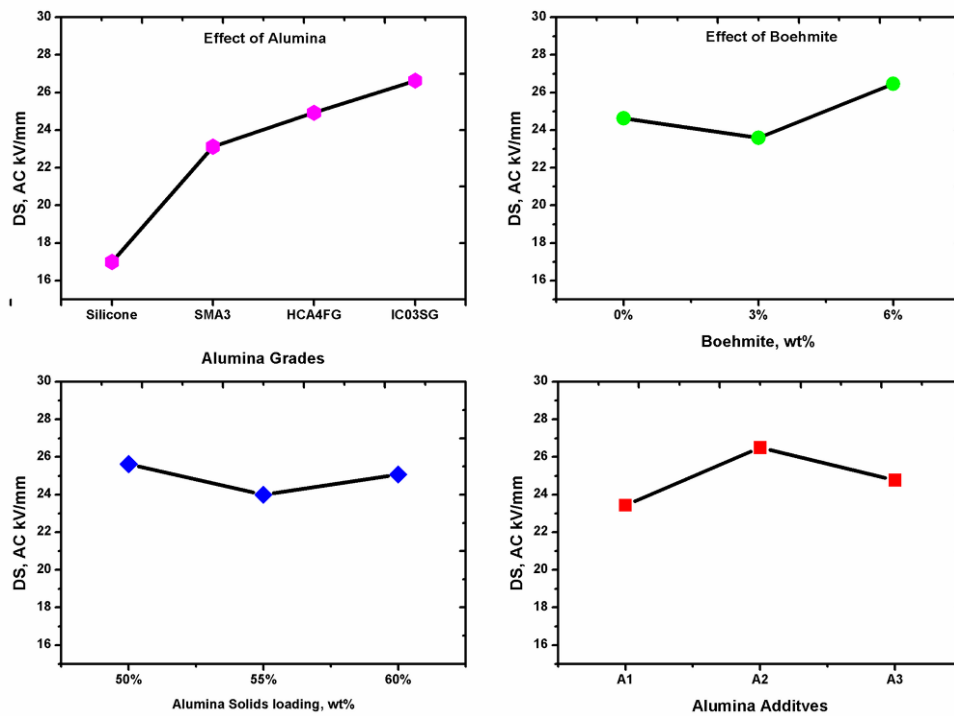


Figure 7. Influence of Alumina grades, Boehmite content, solids loading and Additive on Thermal conductivity.



**Figure 8. Influence of Alumina grades, Boehmite content, solids loading and Additive on dielectric strength.**

Figure 7 and Figure 8 show the effect of factors affecting thermal conductivity and dielectric strength of the composites produced using Alumina and silicone rubber compound. The material was loaded with 50, 55 and 60 wt% and the composites were very much flexible after curing them at 180 °C/10 mins at the maximum temperature. The results suggest that HCA4 was resulting in high thermal conductivity and moderate dielectric strength. Whilst Boehmite also helps in retarding the degradation of polymer at temperatures above 250 °C.

Similarly, HCA4FG was used in the making of nylon-6 compounding, the mechanical performance was studied. It was noticeably clear that about 70 wt% alumina can be loaded into Nylon-6 matrix, it is evident that 60 wt% compounding resulted in better mechanical strength whilst 70 wt. % (Table 2) alumina results in lower mechanical properties. To enhance the mechanical properties, it was decided to reinforce alumina/glass fibers to increase whilst maintaining the physical properties higher.

**Table 2. Results of HCA4FG alumina with Nylon-6 material.**

Test Description	Units	Test Method	HCA4FG 70 wt%	HCA4FG 60 wt%
Alumina Content	%	ISO 3451	70.3	60.9
Tensile Strength	MPa	ISO 527	24.2	31.4
Tensile Elongation	%	ISO 527	12.0	12.0
Flexural Modulus	MPa	ISO 178	7200	5800
Flexural Strength	MPa	ISO 178	55	64
Notched Charpy Impact, 23 °C	kJ/m <sup>2</sup>	ISO 179	4.2	4.2
Specific Gravity	g/cm <sup>3</sup>	ISO 1183	2.26	2.01
Thermal conductivity @ 25 °C	W/m·K	ISO 22007-4	1.33	0.74

Thermal interface materials play a crucial role in EV batteries, semiconductors, and other electronic applications by protecting devices from overheating and ensuring safe and efficient operation.

### 3.2 Boehmite for EV applications

Boehmite produced in this study is a high purity material having Boehmite assay of around 99.9 %, these are crystallized to single phase material under a control processing condition Figure 9a. The SEM image show in Figure 9b that the boehmite crystals are platelet in shape with a thickness of 10–20 nm. These products are used for edge coatings and battery separator coatings.

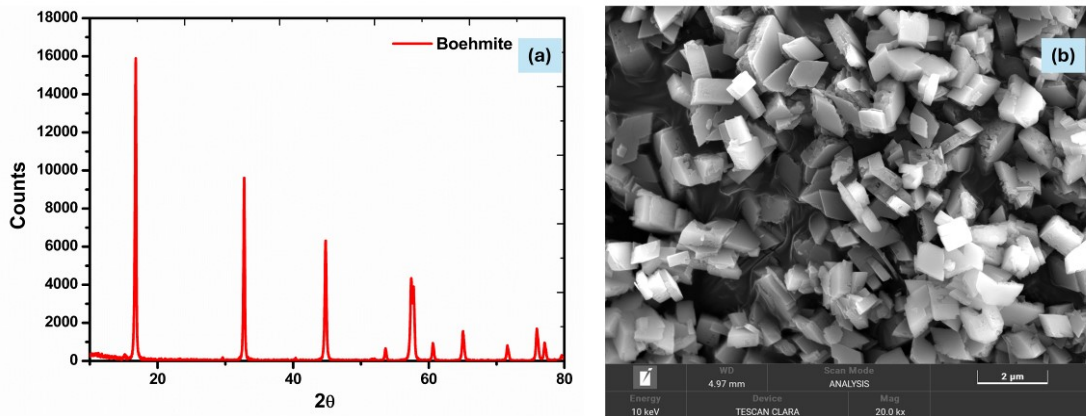


Figure 9. Characterization of Boehmite produced in this study (a) XRD pattern of Boehmite and (b) Morphology of Boehmite obtained using SEM

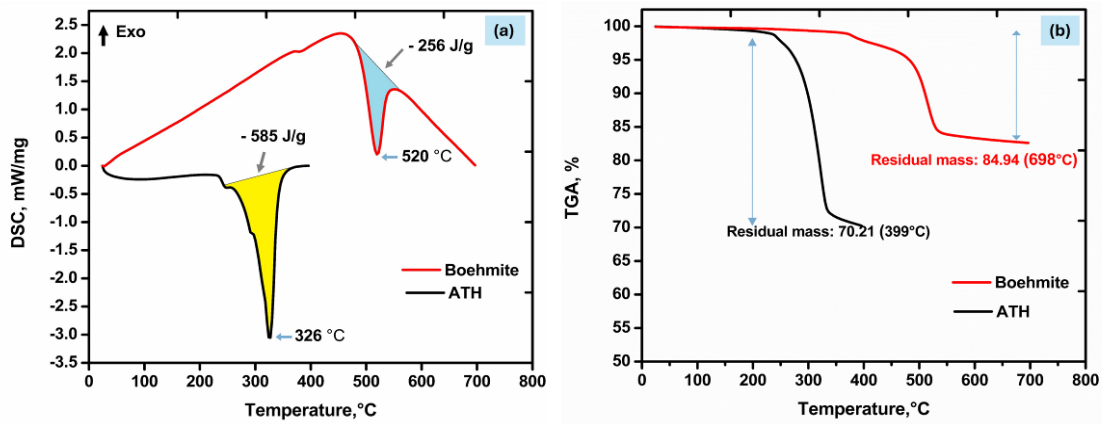


Figure 10. Thermal properties of ATH & Boehmite produced in this study a) DSC, b) TGA

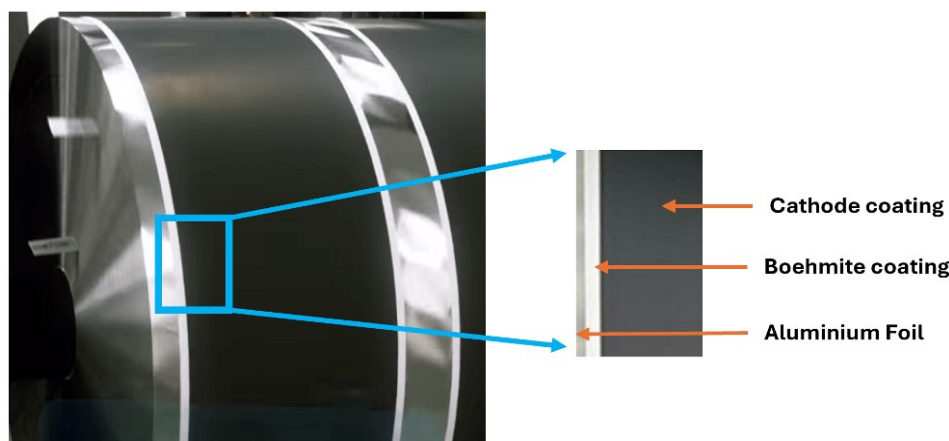


Figure 11. Edge coating is produced using Boehmite.

#### 4. Conclusions

HCA series with their high degree of crystallinity and controlled morphologies allow to achieve better mechanical, thermal and electrical properties which finds many applications in the advanced ceramics and in composites. Due to its high dielectric strength, it is suitable for manufacturing insulators bodies and metallized ceramics providing hermetic sealing and electrical conductivity in applications such as spark plugs, switch gears, feedthroughs, vacuum tubes, heaters and other electrical applications for microwaves and radio frequency components. Both HCA and IC series exhibited very good thermal and electrical management with good mechanical properties when composites made by incorporating these dispersed alumina fillers into different polymer matrices.

The boehmite series products with very high crystallinity, phase purity (100 % Boehmite) and with high dissociation temperature ( $\sim 450$  °C) are very suitable for cathode-edge coatings and separator coating materials in LiBs. The platelet microstructure and narrow particle size distribution of Boehmite allowed to produce stable slurries in both aqueous and nonaqueous systems made them suitable for coating on polymer films.

From the above discussion, it is evident that alumina (including hydrate phases of alumina) serves for versatile applications in various industries. Due to its unique combination of mechanical, thermal, chemical and electrical properties, it is profoundly used in large volumes across different product segments. These properties enable industries to run operations and manufacture products that consume less energy compared to those made from other materials, resulting in cost-effective solutions. Alumina is produced mostly from renewable resources, and it is believed that it will go towards greener operation in 2025 with the initiatives being undertaken. Consequently, products made with alumina are often considered greener, contributing to the sustainable growth of organizations.

#### 5. Acknowledgements

The author would like to thank Mr. Sagar Pandit, Dr. Shekhar Nath and Dr. Prabhu Ramanujam of Hindalco Industries Ltd., for their continuous support and guidance during writing the paper. Special thanks to Analytical Science and Technology Department of ABSTC for their support in characterization.

## 6. References

1. M. Abyzov et al., Properties of Al<sub>2</sub>O<sub>3</sub> and commercial production of dispersed Al<sub>2</sub>O<sub>3</sub>, Aluminum oxide and alumina ceramics (Review). Part 1-2019, Vol. 60(1), 24-32
2. A. M. Abyzov et al., Foreign manufacturers of alumina ceramics. Technologies and research in the field of alumina ceramics, *Aluminum oxide and alumina ceramics (Review). Part 2. 2019*, Vol. 60(1), 33-41.
3. P. B. Parikh et al., Engineering applications and domestic market potential, *Alumina ceramics 1995*, Vol. 54(5), 179-184.
4. B. Ramasubramanian et al., Ten major challenges for sustainable lithium-ion batteries, 2024, *Cell Reports, Physical Science*, 5, 102032.
5. C. M. Costa et al., Recycling, and environmental issues of lithium-ion batteries: Advances, challenges, and opportunities, 2021, *Energy Storage Materials*, 37, 433-465.
6. D. W. Lee et al., Preparation of a high-purity ultrafine  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> powder and characterization of an Al<sub>2</sub>O<sub>3</sub>-coated PE separator for lithium-ion batteries, 2017, *Powder Technology*, 320, 125-132.
7. C. Yang, et al., Boehmite particle coating modified microporous polyethylene membrane: A promising separator for lithium-ion batteries, 2017, *Journal of Power Sources*, 348, 80-86.
8. J. Holtmann et al., Boehmite-based ceramic separator for lithium-ion batteries. 2016, *Journal of Applied Electrochemistry*, 46, 69-76.
9. G. Sharma et al., Lithium-ion batteries with alumina separator for improved safety, 2017, *Journal of The Electrochemical Society*, 164(6), A1184.
10. Y. Ouyang, et al., Recent progress of thermal conductive polymer composites: Al<sub>2</sub>O<sub>3</sub> fillers, properties, and applications, 2022, *Composites Part A: Applied Science and Manufacturing*, 152, 106685.
11. Y. Zhang, et al., Recent progress in the development of thermal interface materials: A review, 2021, *Physical Chemistry Chemical Physics*, 23, 753-776.
12. Y. Zhou et al., Recent advances in thermal interface materials, 2020, *ES Materials & Manufacturing*, 7, 4-24.
13. A. J. Palmer et al., Thermocouple testing in support of the AGR-5/6/7 experiment, 2017.
14. S. Riley et al., Influence of microstructure and phase morphology on the stability of high-temperature irradiation resistant thermocouples, 2023, *Materials Today Communications*, 35, 105972.
15. Thermo-Kinetics, 2020, Protection tubes. Retrieved from <https://thermo-kinetics.com/wp-content/uploads/2020/03/ProtectionTubes.pdf>.
16. Vulcan Electric, 2017, High temperature brochure. Retrieved from [https://www.vulcanelectric.com/wp-content/uploads/2017/08/High\\_Temp\\_Brochure\\_English-1.pdf](https://www.vulcanelectric.com/wp-content/uploads/2017/08/High_Temp_Brochure_English-1.pdf).
17. B. Fryskowski et al, Spark plug reliability improvement with regard to ceramic insulator form factor, 2021, *Proceedings of the IMechE Part D: Journal of Automobile Engineering*, 235(2-3), 1-14.
18. J. Destefani et al, High-alumina ceramic insulator at heart of new spark plug, 2013, Ceramic Tech Today. Retrieved from <https://ceramics.org/ceramic-tech-today/high-alumina-ceramic-insulator-at-heart-of-new-spark-plug/>.
19. M. Touzin et al. Alumina-based ceramics for high-voltage insulation, 2010, *Journal of the European Ceramic Society*, 30, 805-817. Retrieved from <https://hal.science/hal-00850929/document>.
20. IspatGuru, Alumina and alumina refractories, 2017, Retrieved from <https://www.ispatguru.com/alumina-and-alumina-refractories/>.
21. J. C. Southern, A review of alumina production, characterization, and use, 2001, In W. M. Carty (Ed.), *Alumina production, characterization, and use*. doi: <https://doi.org/10.1002/9780470294673.ch12>.

22. Q. Chen et al. Improved comprehensive properties of Al<sub>2</sub>O<sub>3</sub>-MgO-C refractories containing lightweight tabular alumina aggregates. *Ceramics International*, 2023, 49(11), Part A, 17818-17826.
23. CUMI, Murugappa Group. High alumina refractories. Retrieved from <https://www.cumi-murugappa.com/refractories/products/high-alumina-refractories/>.
24. BeadsZirconia.com. Maximizing efficiency with ceramic alumina balls: A guide to energy-saving milling and grinding, 2023, Retrieved from <https://www.beadszirconia.com/how-do-ceramic-alumina-balls-affect-energy-consumption-in-milling-and-grinding-processes.html>.
25. W. Lueangchaichaweng et. al., High surface area, nanostructured boehmite and alumina atalysts: Synthesis and application in the sustainable epoxidation of alkenes, 2019, *Applied Catalysis A: General*, 571, 180-187.
26. M. Trueba & S. P. Trasatti,  $\gamma$ -Alumina as a support for catalysts: A review of fundamental aspects, 2005, *European Journal of Inorganic Chemistry*, 2005(17), 3393-3403.
27. X. Liu, & N. Zhang, Utilization of red mud in cement production: A review, 2011, *Waste Management & Research*, 29(10), 1053-1063.
28. P. Ramanujam et al. High Crystalline Alumina (HCA) for electro-ceramic applications”, 2022, *InCers*, 86<sup>th</sup> annual Conference Proceedings
29. R Halder et al. Effect of particle morphology on the wear resistance mechanism of Alumina Ceramics, 2021, *InCers*, 85<sup>th</sup> annual Conference Proceedings.