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A Review on the Synthesis, Properties, Applications, and Harmful Effects of Alumina

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ABSTRACT

Alumina is an inert, white amorphous solid that occurs naturally in various minerals like corundum. Alumina has been recognized as an excellent material that has countless industrial applications and has improved human life in several ways. Due to extraordinary strength, inertness, and excellent biocompatibility, it is used extensively in the medical field. Its use in armour ranks it to be a life-saving material. In this review, we have thoroughly discussed the synthesis, crystal structure, properties, applications, and harmful effects of alumina. We believe this article will give insight to alumina to the researchers.

KEYWORDS: *Aluminium Oxide, Alumina, Bauxite, Properties, Applications, Harmful Effects*

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1. INTRODUCTION

Aluminium oxide (Al_2O_3) also known as alumina, is an amorphous white powder that is highly stable and is amphoteric in nature. Aluminium is a highly reactive metal that, when exposed to air, combines readily with atmospheric oxygen to form aluminium oxide. A white powdery thin covering of aluminium oxide on the surface of aluminium metal containers is a common sight. The passive nature of alumina shields aluminium metal and prevents further weathering. Alumina also occurs in nature as the mineral corundum. Corundum is a crystalline and one of the naturally occurring transparent substances. It is a very hard material used as an abrasive for grinding and polishing. Synthetically produced alumina is white or nearly colourless, but corundum may be white or coloured. It acquires colour when an impurity is present in it. Several precious stones like ruby, sapphire, amethyst, and topaz consist of Al_2O_3 with metal ion impurities that impart colour. Rubies acquire their typical rich red colour and shimmer due to traces of chromium. Sapphires are found in different colours due to a variety of impurities like iron and titanium.

Traditionally, alumina was used as an abrasive and a pottery raw material. Advances in material science appreciated its unusual physical and chemical properties and today it is a valuable constituent in the manufacturing of a variety of products. Due to extraordinary toughness, chemical inertness, and biocompatibility, alumina has proved to be an outstanding material that has improved modern life in several ways. It is employed in the fabrication of prosthetic bones and tissues and is also a major constituent of material used to make surgical devices. Its use as a favourable biomedical material and as armour in modern warfare has provided it the status of a life-saving entity. This review article thoroughly discussed the properties, production, applications in various fields, and hazards of aluminium oxide.

2. Synthesis

Bauxite, an ore containing hydrous aluminium oxide, is refined using Bayer's process to produce aluminium oxide. In this process, the bauxite ore is ground, washed, dried, and then mixed with caustic soda. The slurry formed is then heated to 150-200^{o}C in a pressure vessel. At this temperature, aluminium dissolves because of the formation of sodium aluminate.

$Al(OH)_3$ (s)+NaOH (aq)→$NaAl(OH)_4$ (aq)

Filtration removes the impurities as residue called red mud and filtrate is transferred into a vessel for cooling and seeding. Putting aluminium hydroxide crystals from previous crystallization into alumina solution leads to faster precipitation. Once precipitation is complete, caustic soda is removed and the solid aluminium hydroxide is washed multiple times and then filtered. Finally, calcination at around 1100°C removes the water molecules bonded to Al_2O_3 and produces anhydrous alumina [1]. Presently, bauxite is the only source for large-scale production of alumina. However, scientists are working on the feasibility of extracting alumina from clay and coal fly ash.The various steps involved in the large-scale production of alumina are shown as a flow diagram given in Fig. 1.

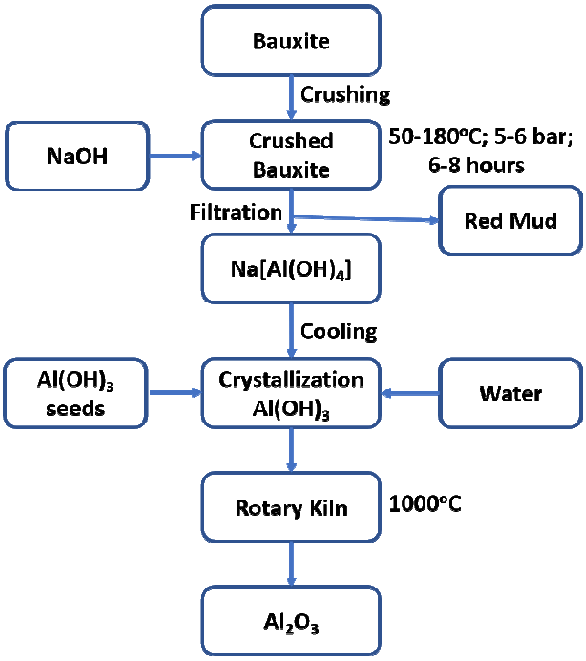

Fig. 1: Flow diagram showing the various steps involved in the large-scale production of alumina.

3. Crystal Structure

Alumina exists in many allotropic forms named α, δ, η, θ, ρ, γ and χ. These forms emerge due to different heat treatments of the alumina sample. Out of these, α-alumina is the most common and thermodynamically most stable form. The oxygen atoms are in hexagonal close packing (hcp) and the aluminium ions occupy two-thirds of the octahedral sites of the lattice. The six oxide ions surround each aluminium ion. Each octahedron is attached to the top layer as well as the bottom layer (Fig.2). Such close packing of aluminium and oxygen atoms makes it thermodynamically stable over a wide range of a temperature.

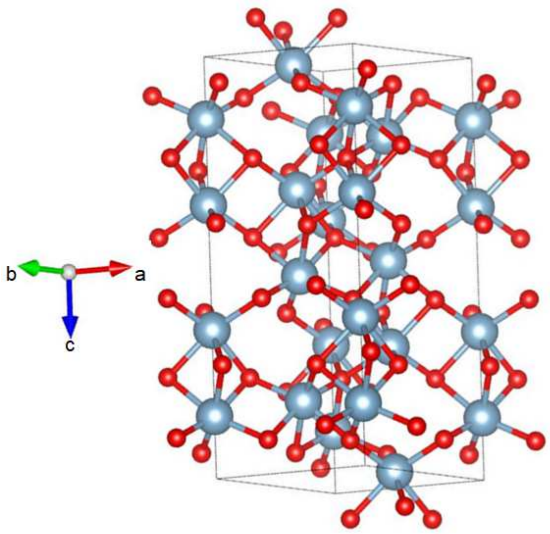

Fig.2: Crystal structure of α-alumina

4. Physical Properties

The physical properties of alumina are tabulated and shown in Table 1 [2].

Table 1: Physical Properties of Alumina

Physical state	Solid
Colour	White
Molar Mass	101.96 g/mol
Density	3.95g/cm^3
Solubility	Insoluble in water as well as non-polar organic solvents, slightly soluble in aqueous alkaline solutions
Flammability	Non-flammable
Melting point	2072°C
Boiling point	2977°C
Hardness	15-19 GPa [9 on Mohs scale]
Thermal conductivity	20-30 W/mK
Strength (Compressive)	2000-4000 MPa
Strength (Mechanical)	300-630 MPa
Electrical Resistivity	10^{12} -10^{13} Ωm

5. Applications

Alumina is exceptionally hard, non-porous, non-reactive, scratch-resistant, and has a very high density. Resistance to corrosion, fatigue, and crack make it a preferred material over other materials having similar properties. Commercially, many varieties of alumina, each having distinct properties and hence different applications, are produced. A major percentage of alumina produced is smelter-grade is electrolyzed to produce aluminium metal. Activated alumina, a granular porous variety is used as an adsorbent and as catalysts substrate. For most of the ceramic products, including laboratory ware, refractory lining, polishing, grinding abrasives, spark plug insulators, integrated circuits, and biological implants, calcined alumina is used. To improve the toughness of alumina ceramic, to make it suitable for industrial cutting tools, a very small quantity of zirconia or silicon carbide is added.

A major portion (approximately 90%) of aluminium oxide produced is utilized to manufacture aluminium metal. Aluminium metal, being lightweight yet strong, is used to make foil and utensils. Aluminium oxide's use in the ceramic industry is also quite well known. In addition to these traditional applications, aluminium oxide is extensively employed in various other industries.

5.1. Medical Industry

Bones, like other body parts, are dynamic entities that keep rejuvenating and reconstructing. This self-repair ability decreases with age and any prolonged physical stress or illness, combined with nutritional deficiency, causes irreparable damage to joints and bones. Serious problems arise due to accidents leading to multiple fractures and, in severe cases, causing demolition of critical support bone structures like hip joints and knee joints. Advancements in the medical field have made the insertion of a prosthetic replacement a viable option to reduce suffering. Amalgamation with surrounding tissues and the long-term survival of implants depends on the properties of the material used in their manufacture. Corrosion of metal causes localized dermatitis, swelling, pain, and inflammation in the implant site and makes metallic implants less suitable [3].

Bio-ceramics are ceramics used for producing orthopaedic and dental implants used for human beings [4]. These ceramics are inert to the neighbouring tissue's biochemical response towards the implant. Based upon the type of response induced in the body, these ceramics are categorized into three types; biodegradable, bioactive, and bio-inert. Calcium phosphate ceramics fall in the biodegradable category. The bone gets revived and grows through the pores of implants, leading to a total fusion between natural bone and artificial insertion. Bioactive ceramics, for example, hydroxyapatite (HA), stimulate the surrounding tissues and bone formation. This leads to strong bonding between bone and implant. However, because of their low strength, these materials cannot be used in heavy load-bearing areas. The bio-inert group, which also includes alumina ceramics, is inert towards biochemical reactions and has been accepted to be favourable material for fabricating replacement for parts of the human skeletal system [5]. Bio-compatibility, high load-bearing strength, good wear resistance, and immunity to corrosion, make alumina ceramics ideal clinical material.

High alumina ceramics (containing over 99% Al_2O_3) having a compressive strength of around 4500 MPs fulfils all the conditions to be accepted as a popular material for bone replacement. In a hip replacement, the alumina ceramic is used in combination with metal. For ball and socket, either alumina-alumina combination or alumina-UHMWPE (Ultra High Molecular Weight Polyethylene) is used, and the cup is fitted on an acetabular cup [6]. Due to its chemical inertness, alumina does not induce any biochemical activity at the interface with natural organic tissues. This results in smooth osteointegration and facilitates bone ingrowth. For knee and ankle replacement, alumina is used in combination with polyethylene. Alumina implants are also used in prosthetic dentistry, ear, nose, throat surgery, and reconstruction of injured face and skull bones.

Recently, alumina-silver composite nanoparticles were reported to show antimicrobial behaviour [7]. The antibacterial activity of nano form is much greater than in bulk form. This significant property of alumina nanoparticles needs to be tested vigorously before their clinical application.

5.2. Electronic Industry

A conducive blend of chemical, electrical, thermal, and mechanical properties make alumina ceramics a popular substitute for conventional porcelain, like steatite [$H_2Mg_3(SiO_3)_4$], forsterite (Mg_2SiO_4), and zirconia (ZrO_2) for the electronic industry. The alumina ceramics are also preferred over beryllia (BeO) ceramics due to inferior mechanical properties of later.

The alumina produced by Bayer's process contains substantial amounts of impurities and hence is not acceptable for electronic applications. However, the purity and properties of commercial alumina can be improved by various processes and material satisfactory for the manufacturing of electronic ceramics can be obtained. For making alumina parts suitable for electronic use, both fused as well as calcined, alumina is used as raw material. It is recommended that the impurity of alkali metal compounds should be negligible (< 0.01%) as the volatile nature of these impurities lowers the strength of the ceramic. Iron oxide has negative effects on the electrical properties and titanium dioxide is undesirable because of the colour imparted by it, so their percentage in raw material should be as low as possible. Silicon dioxide and alkaline earth oxide are added to produce a glassy phase used in ceramic to metal seal bodies. For use in a thin-film substrate, magnesium oxide is added to curb grain growth and get a smooth surface finish. Some of the applications of alumina ceramic in the electronic industry are discussed below.

5.2.1. Insulators

The dominant application of alumina in the electronic industry is the insulation of various parts of any assembly [8]. Alumina is widely used to make spark plug insulators as well as insulators for power transmission systems. In electronic devices, it is used for making insulating substrates for microchips. A coating of alumina acts as a heater insulator in an electron tube. For uniform and thick coating, electrophoresis is preferred over spraying or dipping.

5.2.2. Ceramic-metal Seal

Another use of alumina in electronic appliances is as spacers, supports, envelopes, and windows in electron tubes. Various parts of a tube assembly need to be isolated by placing a bushing or an envelope. These separating structures must have high dielectric strength and effective insulating power at various temperatures. Glass sealings have high dielectric loss even at low temperatures, making them susceptible to accidents. Unlike glass, the dielectric loss of ceramics does not increase with increasing temperature and is substantially low at normal temperature. The mechanical strength of ceramics makes these bushings less susceptible to damage caused by thermal and physical shocks.

5.2.3. Microwave Windows

Being transparent to microwave radio frequencies, alumina ceramics are a good choice as microwave windows material. In high-power microwave tubes like klystrons and magnetrons, ceramics of thickness ranging between 0.05–0.06 inches are used as windows. Even with such a low thickness, ceramics are vacuum-tight and have almost nil electrical loss [9].

5.3. Refractories

Refractories are being used for ages. Early civilization saw the use of clay-based brickwork in fireplaces at home and at pottery kilns for containment of heat. Various modifications were introduced to use refractories for iron smelting, which ultimately evolved as a blast furnace. The industrial revolution commanded the need to look for newer and advanced refractory material. Today, the refractory industry is a very large, extremely diverse, and indispensable part of the present-day manufacturing sector.

Refractories are ceramic materials created to cope with extremely high temperatures (>1000°F or 538°C) commonly used in contemporary manufacturing. These are used to optimize the utilization of heat and to reduce the damage to the inner lining of industrial furnaces and boilers. Industrial furnaces and boilers need to be resistant to thermal stress and other physical changes induced by extreme heat. In addition to this, resistance to corrosion caused due to chemicals is also a mandatory requirement. Refractory products are produced from natural as well as synthetic material or a combination of various materials. Based on their chemical composition and ability to resist attack by fired material, refractories are classified as acidic, basic, or neutral [10]. Silica and zirconia rich refractories are acidic, magnesia and calcia rich are basic, and alumina rich ones are neutral in nature. Alumina-rich refractories are manufactured by adding alumina-rich raw materials like bauxite (Al_2O_3□$2H_2O$) and gibbsite ($Al(OH)_3$) to kaolinite clay mineral (Al_2O_3□$2SiO_2$□$2H_2O$). Fire clay has 25-45%, aluminous fire clay 45-65% and high-alumina has > 72% alumina (Al_2O_3) content[11].

Presently, the use of monolithic refractories has become very common. It is a concept where instead of making bricks, ready-to-mix refractory powder mixed with a binder is supplied. Monolithic refractory is supposed to be mixed with water and then it can be cast in the desired shape, sprayed, or simply applied as an instant refractory layer [12].

5.4. Military Equipment and Armour

Body armours made of metal were commonly used until mid of the fifteenth century. The invention of battlefield handguns and the introduction of advanced military weapons using high-speed ammunition made traditional metallic body armours ineffective. Slowly, these became obsolete and were finally abandoned. Material engineers successfully explored the possibility of using ceramics in life-saving body armours for ground troops. When used against armour-piercing rifle bullets, ceramics have been found to show better performance than steel. Compared to metals, ceramics absorb and disperse the energy more effectively and thus the force of a high-speed bullet gets reduced drastically. Later on, ceramics in combination with some other highly complex materials were also used as a vehicle (both lightweight and heavy) and aircraft armour. Alumina was the first ceramic used as armour and because of its effectiveness and low cost, even today it is a major player. The other two ceramics used for this purpose are SiC (silicon carbide) and B_4C (boron carbide). Boron carbide having a density of 2.5g/cm^3 is lighter than alumina (3.9 g/cm^3) and silicon carbide (3.2g/cm^3). Having hardness comparable to the other two options, the light-weight, B_4C was seen as an ideal armour ceramic, but its inherent shock-loading problem makes it a risky option. Silicon carbide ceramics are considered being perfect for stopping supersonic bullets but are not employed freely as it is very expensive ceramic. Alumina dominates the ceramic armour segment due to weight efficiency and lower price than its competition.

Any ceramic armour is not used in isolation as better protection is achieved by using ceramic sheets or coating in combination with other shielding layers. This is called composite ceramic armour. For example, the body armour breastplates are used after wrapping in fibre-reinforced polymer (FRP) covering. For alumina composite armour, the alumina should be at least 85% pure. For better protection, >90% alumina is recommended. Lightweight and capable of facing multiple hits make alumina ceramic an ideal armour for light-weight military vehicles, aircraft, and helicopters. Precisely crafted ceramic panels are wrapped in an FRP layer and attached to the metallic frame of a vehicle to be protected using Velcro. Synthetically produced, single crystal sapphire is used as bullet-proof glass for armoured vehicles. For heavily armoured vehicles, like tanks, where threats levels are high but weight is not a consideration, even heavy ceramic (e.g., tungsten carbide) can be used. In these systems also deployment of alumina ceramic is quite significant.

5.5. Gem Industry

For ages, precious gems like sapphires and rubies have fascinated people around the world. Their colour and shine enhance the beauty of jewellery. Natural corundum giving quality gems is rare, making these jewels very expensive. Looking at the demand, chemists started synthesizing these jewels in a lab about a century ago. The major advantages of growing gems in a laboratory are control over cost, quality, size, and speed. High purity aluminium oxide is the base element for these precious jewels and impurities are added under required physical conditions to get the desired colour. The deep red colour of rubies is due to chromium impurities, while traces of iron and titanium impurities give a variety of sapphires.

Two common methods used to produce artificial gems are melt processes and solution processes

5.5.1. Melt Process

The traditional and most commonly used melt process is also called the flame fusion process or Verneuil process. In this process, highly pure Al_2O_3 along with a pinch of impurity is introduced into high-temperature flame. The contents melt and form a droplet called “boule” which on cooling gives teardrop-shaped gems. A modified melt process is the Czochralski process. In this method, instead of flame, radio waves are used to melt the mixture of aluminium oxide and impurity used. A seed crystal is dipped into a molten mixture and rotated slowly to create a bigger piece of sapphire. Though expensive, this process can create sapphires and rubies much larger than those commonly found in nature.

5.5.2. Solution Process

Imitating the natural formation of these gems, a solution process called hydrothermal synthesis was introduced. Minerals are subjected to extreme heat and pressure in a steel pressure vessel. Hanging a tiny seed into this vessel results in the formation of big size crystal around the seed.

Nowadays, another method known as a flux-growth process is used to create synthetic gems. Here, Al_2O_3 (flux) is melted and traces of impurities required are dissolved in it. Gradual cooling of dissolved chemical mixture gives crystals of desired gem [13].

5.6. Abrasive Industry

The use of an efficient and effective abrasive is of supreme importance to remove surface inconsistencies and attain the quality finish of any product. Aluminium oxide is extensively used in a variety of industrial abrasive materials used for polishing and shaping components. It is also an ideal choice for removing old fainting layers of paint, rust, and other unwanted contaminants from the surface of an object. Abrasive grains (having >98% purity alumina) of particle sizes ranging between 3 to 10 μm are produced by sintering [13]. Coarse grit aluminium oxide sandpaper can be used by hands or can be cut to size and fitted onto the sanding block of a machine. It is effective in removing surface accumulations and produces a smooth exterior ideal for subsequent painting/coating. Aluminium oxide having negligible iron content (0.01–0.05%) does not leave any rust (which may cause hindrance to further processing) on the surface Having tough cutting edges, it is commonly applied for most of the metals including steel, marble, granite, glass, and wood. Due to its hard-wearing properties, it produces lesser dust during use and is an ideal abrasive medium, which to our advantage, also chemically inert and non-toxic. Another significant property is that it can be recycled and used again, thereby reducing wastage and disposal costs.

Alumina ceramic abrasives are considered to be the best in performance because of their robustness and fastest cutting rate [14]. It provides excellent value for money due to longer cutting life than its competitors and needs less frequent replacement. Alumina ceramic coating is used to protect industrial machines from abrasion. Zirconia-Alumina ceramic, commonly referred to as zirc, is produced by melting alumina (59%) and zirconia (40%) at about 2000^{o}C temperature in an electric arc furnace followed by cooling [15]. The very fine and homogeneous microstructure of particles provides high toughness to the material. Though not as hard as the diamond, it is an economical replacement for industrial diamond. It is used for cutting stainless steel, high-pressure rough grinding and snagging, snagging of alloyed steel castings, disk grinding, and sanding of belts and flap discs.

5.7. Glass industry

Glass is an exceptionally versatile substance and has become an integral part of our everyday life. Glass tumblers are commonly used to drink water and store food. Glass is the common material used in windows at home and automobiles. Unique properties of glass, like durability, optical transparency, and low electrical conductivity make it an outstanding product. However, the utility of glass becomes restricted due to its inherent brittleness. Soda-lime glass is the most common kind of glass used for containers and window panes. The borosilicate glass is better than soda-lime glass in terms of strength, acid resistance, and thermal shock resistance, but remains susceptible to breakage. Toughened or tempered glass is prepared by controlled thermal and chemical treatments that lead to enhanced strength compared to ordinary glass. Toughened glass is known as safety glass due to its ability to withstand heavy external impacts and high-temperature changes. Though this glass is robust and has high durability but it is not indestructible. When toughened glass breaks, it shatters in entirety, forming small harmless globules, thereby reducing the possibility of harm in case of an accident. Keeping in view the extensive use of glass, scientists have been constantly working on improving the quality of glass. Although to date unbreakable glass is not a reality, the addition of alumina (5-10%) has been found to lend increased strength and durability to the glass [16]. Aluminosilicate glasses containing 20-40% aluminium oxide are very hard and have a better thermal resistance. Frankberg et al. reported a dense glassy material using alumina, which deforms rather than breaking[17]. The new product has been found to have higher ductility and is seen as a potential damage-proof glass material. Glasses having approximately 78-80 mol % alumina, rare-earth metal (lanthanum, gadolinium, and yttrium) oxides, and zirconium oxide have been prepared by a flame spraying technique [18]. These alumina-rich glasses are transparent and much harder than conventional silica-based glasses.

5.8. Cement Production

Natural minerals along with some industrial products are used for the production of cement. The main components of cement are lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). Portland cement, the most common variety of cement used throughout the world contains only 3-8% of Al_2O_3. Alumina serves as a flux, reduces the temperature required for clinkering, and provides the quick-setting quality to cement. High Alumina Cement and Portland are entirely different from each other in composition, method of manufacturing, as well as properties. HAC contains 40% lime, 40% alumina, and around 8% silica along with traces of iron oxide [19]. The raw materials employed for HAC production are limestone and bauxite, which are first converted into small pieces, then mixed in the desired ratio and fused in a kiln at about 1600^{o}C. Heating drives off moisture and carbon dioxide and complete fusion of material takes place. The molten material comes out of the furnace and solidifies on cooling. These solid pieces are then shattered into smaller pieces and grounded. During grinding, the iron particles are segregated with the help of magnetic separators. Due to the high hardness of the HAC clinker, the power consumption for a grinding process is very high. Due to the high cost of fuel used in the furnace to maintain high temperature and the high cost of power for crushing and grinding, the production cost of this cement is very high. This makes HAC much costlier than ordinary cement.

Excess alumina in any cement lowers the setting time but also reduces its strength. The main reason for loss of strength is the formation of mono-calcium aluminate decahydrate ($CaO\cdot Al_2O_3\cdot 10H_2O$), dicalcium aluminate octahydrate ($2CaO\cdot Al_2O_3\cdot 8H_2O$), and alumina gel during the setting process of HAC. These aluminates are unstable and gradually get converted to tri-calcium alumina hexahydrate ($3CaO\cdot Al_2O_3\cdot 6H_2O$) which is more stable. The change in composition and crystalline structure results in the loss of strength of cement. People associated with construction and civil engineering call this loss of strength as “conversion” and attribute it to high alumina content. The rate of chemical decomposition or conversion depends on temperature and water-cement ratio. Higher the temperature, the faster the conversion. Also, the higher the water-cement ratio, the greater the rate of decomposition [20]. Many countries have banned the use of high alumina cement (HAC) in the construction of load-bearing buildings and structures. However, calcium aluminate cement containing as high as 40-50% alumina is preferred where rapid strength development is required even at low temperatures. It is also used as a protective layer in sewer lines to combat microbial corrosion [21].

5.9. As an adsorbent, desiccant and catalyst

γ-alumina is a kind of activated alumina that is porous, inert, resistant to high temperature, and has a high surface area. These properties make it an effective adsorbent in both gas-solid and liquid-solid in adsorption chromatography employed for the separation of compounds in many industries [22]. Due to its amphoteric nature, it is suitable to be used for the separation of neutral, acidic as well as basic compounds. One of the most important applications of alumina is in water purification where, as an adsorbent, it removes contaminants like fluorides, heavy metals, toxic waste, colours or dyes, insecticides, and also radioactive waste [23]. Having an excellent adsorbing capacity, alumina can absorb moisture from the air and is used as a desiccant to keep items dry. Alumina is employed to remove water vapours from gases used in industries. Adsorbed water can be removed by heating and alumina can be re-used.

Activated alumina is used as a catalyst in many chemical reactions. In some reactions, alumina itself acts as a catalyst (For example in Claus reaction) and in some cases, it is used as an inert carrier for another catalyst. α-alumina, β-alumina and γ-alumina all act as catalyst support, but γ-alumina is more effective [24].

5.10. Other Industrial applications

The aluminium oxide coating is used on wooden flooring to protect it from damage and increase durability. Being scratch-resistant t is the best finishing option for areas that are used extensively or get higher footfall. The aluminium oxide finish forms an impermeable layer on the surface which prevents decolouration, oxidation, and degradation of wood [25]. These floorings are much safer than polyurethane finished floors as no harmful vapours or volatile organic compounds (VOC'S) are released.

Due to hardness and wear resistance, alumina is widely used in the production of water-resistant pump boosters, baffle plates, machining tools, and high-speed cutting tools. Alumina retains its hardness even at the melting point of steel, and this property makes it superior to all other materials used for machining and cutting tools. Several plumbing components, like nozzle, elbows, tees, straight pipes, and valves, are manufactured using alumina [26].

Being chemically inert, alumina is used as a filler in bricks, plastics, and clay ware. It plays the role of cementing material and provides flexibility to starting material so that bricks can easily be moulded [27]. However, excess alumina causes shrinkage and on drying cracks appear in the bricks. In plastics, alumina trihydrate is used as filler to change the properties of the original plastic. It is frequently used as a filler in paints and varnishes

Alumina is used as an abrasive, anticaking agent, absorbent and bulking agent in cosmetics [28]. Because of its ability to absorb, scatter and reflect both UV-A and UV-B radiations, alumina amplifies the Sun Protection Factor (SPF) of a sunscreen formulation.

Table 2: Summary of percentage of alumina in the raw material used in various industries

Industry	Percentage of Alumina and other contents	Product
Medical industry	>99.8 % Al_2O_3 + MgO	Ball and socket of joints, Dental implants, bone replacements for vertebra, ear, nose and throat
Electronic Industry	94-99.5 % Al_2O_3 +SiO_2, MgO	Insulators, Spacers, Windows, substrate for integrated circuits
Refractories	25-75% $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ + $Al_2O_3 \cdot 2H_2O$ or $Al(OH)_3$	Refractories for petrochemical processing, iron and steel industry, cement production and waste incineration
Gem Industry	>99% Al_2O_3 + Traces of Na/Cr/Fe/Ti/V/Mn	Manufacturing of precious stones like Diamonds, Rubies, Sapphires, Emeralds
Military Equipment and Armour	>90-94 % Al_2O_3 (6.4-9.5 mm thickness) >99% Al_2O_3 (8.5 mm thickness)	Body armour plates Ceramic tiles for vehicle armour
Industrial Abrasive	>98% Al_2O_3+ ZrO_2 59% Al_2O_3 + 40% ZrO_2	Abrasive (Sand Paper) Industrial Cutter
Glass	5-10 % Al_2O_3 +SiO_2+ CaO 20-40% Al_2O_3 + SiO_2 + CaO	Glass with improved strength Alumino-silicate glass
Cement	3-8% Al_2O_3+17-25% SiO_2+ 60-67 % CaO+ Traces of Fe_2O_3 40% Al_2O_3 +40% CaO+8% SiO_2+ Traces of Fe_2O_3	Portland Cement High Alumina Cement[HAC]

6. Harmful Effects of Al_2O_3

Alumina, a material with exceptional properties, is employed widely in many manufacturing units and this has increased occupational exposure of people involved in these industries. Aluminium oxide dust causes skin irritation. Though it is not classified as a hazardous substance, chronic inhalation has been found to cause eye irritation, nasal discomfort, and inflammation of the back throat [29]. Chronic inhalation of Al_2O_3 may cause scarring of lungs, cough, and restrictive pulmonary function. In severe cases, death may result from respiratory failure. Studies suggest that chronic aluminium oxide exposure leads to increased aluminium load in the body and may be associated with neurophysiological dysfunction.

7. Conclusion

Unusual physical and chemical properties make alumina a wonder product having a variety of applications. Currently, alumina ceramics are used in the electronics and electrical industry, refractories, glass production, cement production, artificial gem production, armours, and the medical field. Another admirable quality of alumina is its non-toxic nature, as even in cases of chronic exposure, no significant damaging effect has been reported.

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