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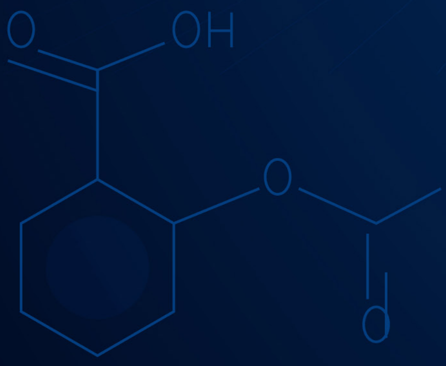

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A Summarized Review of Refractory Materials and Their Chemical Components

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ABSTRACT

Refractories are non-metallic ceramic materials capable of withstanding temperatures higher than 1500 °C, where the refractoriness is defined by the pyrometric cone equivalent. Silica fume and fly ash are used in industries as cost-effective raw materials to fabricate refractory composites. Mullite ceramic ($3Al_2O_3 \cdot 2SiO_2$) is a widely used engineering ceramic material with high strength and high creep resistance at high temperatures, low thermal expansion coefficient, and thermal stability. Cordierite ceramics ($Mg_2Al_4Si_5O_{18}$) can be used as the carrier of environmental catalysts because of their low coefficient of thermal expansion and stable structure. Therefore, it is an important way to reduce the generation of waste pollutants (Silica fume, fly ash, etc.), reflecting the basic idea of the transformation of solid waste into valuable products. The components of refractory materials are discussed alongside their utilizations, properties, and characteristics.

INTRODUCTION

The development of metals, polymers, and ceramic materials has significantly contributed to the progress of human civilization. The emergence of metals and ceramics is historically interconnected. The high temperatures involved in metallurgical processes lead to the development of suitable refractories of molten metal containers. These refractory materials are non-metallic with suitable physical and chemical properties used for components of systems that are exposed to high temperatures of above 538 °C (Chandra & Sarkar, 2019; Dana *et al.,* 2014; Nwannenna *et al.,* 2015). The properties of these refractory materials remain unaltered at elevated temperatures of sustained operations. Refractory ceramic materials are classified into chemical nature (acid, basic, neutral), implementation method (shaped and unshaped), manufacturing method (sintered or fused), and porosity of the material (porous and dense) depending on the physicochemical nature of the starting materials (silica, aluminosilicate, magnesia, etc.) utilized in the manufacturing process (Biswas *et al.,* 2020; Sarkar, 2023). These materials are resistant to heat when exposed to different degrees of mechanical stress and strain, corrosion from liquids and gases, and mechanical abrasion at high temperatures. The scarcity of basic refractory materials imported from Europe during World War II brought about the development of aluminosilicate refractories associated closely with the development of bauxite-based refractories in North America (Garbers-Craig, 2008; Sengupta, 2020).

The advancement of aluminosilicate refractory materials from bauxite began in North America when there was a shortage of refractory materials in Europe during the second world war. The overall consumption and utilization of refractories are a result of the sustained development of starting materials and processing technology in the refractory industry. In recent times, aluminosilicate refractories are mainly produced in developing countries and imported to developed nations. The knowledge obtained from the results of experimental research in materials science is essential for use in the fields of engineering and technology in modern days. The anticipation of industrial engineers to develop materials that have the advantage to resist high operating conditions began with the commencement of ceramics, polymers, refractories, etc. The fabrication of these latest materials has the purpose to produce good and reliable products with easy processing and low-cost operation (Bramsiepe *et al.,* 2012; Jandyal *et al.,* 2022; Zhong, 2021). Refractory ceramics are suitable for use in furnace linings or melting pots due to their ability to withstand physical and chemical conditions at high temperatures in metal casting industries and other applications with critical thermochemical properties. The properties of these materials are contingent on the properties of the starting reagents and formulations (chemical and mineralogical composition, particle size, and shape distribution), forming process, and sintering temperature (Colomban, 2020; Danninger *et al.,* 2017; Kamara *et al.,* 2025; Mohd Mortar *et al.,* 2022; Sun *et al.,* 2024; Ulusoy, 2023).

The fabrication of different types of refractory ceramic materials is dependent upon the starting materials utilized and the stoichiometric processing parameters (Kamara, 2025; Kamara *et al.,* 2020; Nanda *et al.,* 2023; Shackelford & Doremus, 2008). Studies on silica and alumina-containing compounds show that mullite ($3Al_2O_3.2SiO_2$) mineral phase is one of the most outstanding refractory ceramics (Hossain & Roy, 2020; Vakalova *et al.,* 2004) due to a combination of such distinct properties as elevated melting point (1800°C), low thermal expansion coefficient,

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excellent mechanical and thermal shock resistance, chemical stability, etc., making it useful in many applications from refractories to electronic substrates (Kamara *et al.,* 2025; Kamara *et al.,* 2020). The significant amounts of silica (SiO_2) and alumina oxides (Al_2O_3) in clay minerals make clay material a suitable low-cost natural raw material to fabricate mullite refractory ceramics. The SiO_2/Al_2O_3 ratio in the clay material is low and therefore requires the addition of suitable stoichiometric compositions to produce the major mullite phase (Zhang *et al.,* 2022).

In recent decades, concerns about environmental issues have grown around the world, particularly in the field of education and researchers have now given much attention to sustainable methods aimed at recycling inorganic waste (Debrah *et al.,* 2021; Townsend, 2011). They are coarse-grain ceramics having a microstructure that consists of large grains joined by fine materials (Lan *et al.,* 2016). The major starting materials used to fabricate refractories are the oxides of silicon, aluminum, etc. Nitrides, borides, silicates, graphite, etc, are some non-oxide refractories (Guanghui, 2024). As stated earlier, the choice of refractories by engineers is solely based on the operational conditions to which they are being exposed. For instance, at extreme temperatures zirconia can be utilized to withstand such conditions. Also, silicon carbide and carbon are employed for such applications but they should be used in the absence of oxygen because of their oxidative properties. Refractories are a special form of ceramic materials which mainly differs from any normal ceramic because their coarse grain structure is joined by larger grog particles made of fine intermediate materials (bonding). The qualities of refractories depend on their physical, chemical, mineralogical, and thermal properties (Sengupta, 2020; Yurkov, 2015). Refractories are normally made based on process parameters (temperature profile, mode of operation, and operating atmosphere), expected quality characteristics, and best techniques for engineering application so that the final physical, chemical, and thermal properties are compatible with the application (Chandra & Sarkar, 2019). Refractories are expensive, and any failure in the refractories results in a great loss of production time, equipment, and sometimes the product itself (Chandra & Sarkar, 2019; Horckmans *et al.,* 2019; Yurkov, 2015). The energy consumed and the quality of the product is also determined by the type of refractory involved. The main objective of this work is to review the components of refractory material that provide the basis for its suitability in the production of engineering materials. It is therefore very significant to produce suitable refractory materials for a particular application. The suitability of a refractory material does not imply durability but rather the balance between the initial cost and its performance. This balance is never achieved but is continuously moving as a result of the introduction of new processes or new types of refractories.

LITERATURE REVIEW

Refractories are non-metallic ceramic materials capable of withstanding temperatures higher than 1500 °C, where the refractoriness is defined by the pyrometric cone equivalent. Most modern refractories are based on one or more non-metallic oxides, which can be divided into basic and non-basic refractories. All basic products are based on either calcium oxide (CaO) or MgO, whereas non-basic materials are based on Al_2O_3, silicon dioxide (SiO_2), or zirconium oxide (ZrO_2). This is a fundamental differentiation, as the correct refractory material is always based on the basicity of the medium in contact with the lining. Refractory materials are both economically and socially strategic materials as they enable the production of other crucial products, including steel, non-ferrous metals, cement clinker, lime, glass, and many others. They are designed to operate at high temperatures, temperature gradients, and under severe chemical and mechanical loadings.

The main raw materials used in the production of refractories are: the oxides of silicon, aluminum, magnesium, calcium, and zirconium, and some non-oxide refractories like carbides, nitrides, borides, silicates and graphite. The main types include fire-clay bricks, castables, ceramic fiber, and insulating bricks that are made in varying combinations and shapes for diverse applications. The value of refractories is not judged by the cost of the material itself, but by the nature of the job and/or its performance in a particular situation. Atmosphere, temperature, and the materials in contact are some of the operating factors that determine the composition of refractory materials.

Refractories are utilized by the metallurgy industry in the internal linings of furnaces, kilns, reactors, and other vessels for holding and transporting metal and slag. In non-metallurgical industries, the refractories are mostly installed on fired heaters, hydrogen reformers, ammonia primary and secondary reformers, cracking furnaces, incinerators, utility boilers, catalytic cracking units, coke calciner, sulfur furnaces, air heaters, ducting, stacks, etc. The majority of these listed equipment operates under high pressure, and operating temperature can vary from very low to very high (approximately 900°F to 2900°F). The refractory materials are therefore needed to withstand temperatures and above these temperatures.

Important properties of refractories are: chemical composition, bulk density, apparent porosity, apparent specific gravity, and strength at atmospheric temperatures. These properties are often among those which are used as ‘control points’ in the manufacturing and quality control process. The chemical composition serves as a basic for classification of refractories and the density, porosity and strength is influenced by many other factors. Among these are type and quality of the raw materials, the size and fit of the particles, moisture content at the time of pressing, pressure at mould, temperature, duration of firing and the rate of cooling.

Some of the important characteristics of refractories include melting point, size and dimensional stability, porosity, bulk density, cold crushing strength, pyrometric cone equivalent (PCE), refractoriness under load, creep at high temperature, volume expansion stability and shrinkage at high temperature, reversible thermal expansion, thermal conductivity, etc. Refractory materials are characterized as ceramic materials, exposed during their use to high temperatures, and often to other extreme chemical and physical exposures that limit their operation life. The intensive use of refractories in steelmaking plants is due to the properties these compounds exhibit such as high starting melting point, high structural strength at high temperatures and in highly corrosive environments, and an intensive stability in temperature variations. What is common for refractory materials in terms of not only various applications but also their material and structural nature is described by a set of properties of refractory materials.

Previous use of refractories, particularly aluminum oxide (Al_2O_3) and magnesium oxide (MgO), has exposed challenges in terms of corrosion mainly due to the formation of cobalt aluminates ($CoAl_2O_4$) using Al_2O_3 as a refractory material and lithium diffusion within the crucible walls using MgO. Corrosion, generally defined as the chemical attack on refractory material by a liquid phase such as slag, metal or alloy, occurs when the melt infiltrates the refractory matrix, creating capillaries that weaken the material's mechanical strength. During this process, the fine grain of the refractory is washed out leaving the coarse grain exposed. This process occurs due to the chemical reaction between the liquid slag and solid refractory phases. It continues until the saturation point of the slag or the metal bath occurs through the refractory material. Such issues can lead to contamination of the input material and significantly impact refractory stability and reusability. Furthermore, diffusion-related constraints can hinder lithium removal rates, thereby diminishing the overall process efficiency.

MATERIALS AND METHODS

Several articles related to refractory technology were downloaded from various online publishing sources, of which 53 topically related papers were selected and systematically reviewed. The work was summarized based on the research objectives, which focuses on the components of refractory materials.

Classification of Refractory Refractories

They are categorized based on their chemical composition and chemical properties.

Chemical Composition

Silica refractories are fabricated in the form of quartz and it is composed of 92% of SiO_2. The iron and steel industries extensively utilize SiO_2 refractories due to their outstanding resistance to thermal shock. The raw materials for this class of refractories are high-grade rocks and fly ash. Fireclay refractories are formed by heating a particular type of clay and it comprises less than 78% of SiO_2 and 44% of Al_2O_3. They are cost-effective and popular industrial materials. Alumina refractories are also made of Al_2O_3 and SiO_2 with a minimum of 50% Al_2O_3. They are subdivided into seven different percentages such as 50% Al_2O_3, 60% Al_2O_3, 70%Al_2O_3, 80%Al_2O_3, 85%Al_2O_3, 90% Al_2O_3, and 99% Al_2O_3. Magnesia refractories have magnesium oxide (MgO) and their principal sources are brines, seawater, and sintered and fused magnesia with magnesia-carbon refractory identified as the most important. Dolomite refractories comprise MgO and CaO as their main components. These refractories are fabricated from sintered dolomite. Magnesia-chrome refractories mainly consist of MgO and chromium oxide (Cr_2O_3). They are named magnesia chrome or chrome-magnesite depending on the percentages of MgO and Cr_2O_3 present in the refractory. About 15% to 35% Cr_2O_3 and 42% to 50% of MgO are contained in magnesite chrome while magnesite-chromite has about 60% MgO and 8% to 18% of Cr_2O_3. They are utilized to construct critical parts of high-temperature furnaces due to their abilities to withstand corrosive slags and gases and their high refractoriness. Magnesite-chrome has better-spalling resistance than chrome-magnesite refractories in some cases. Silicon carbide refractories are manufactured from silicon carbide (SiC) obtained by reacting silica and carbon in an electric furnace at a high temperature of over 25000 °C. Zirconia refractories have zirconium oxide (ZrO_2) as their principal component and are utilized as high-temperature construction materials. Nozzles, gates, crucibles, furnace liners, and kilns, etc., are cast at high temperatures greater than 1900°C from these class of refractories. It is a suitable insulating material due to its lower thermal conductivity at high temperatures, and they do not react with liquid metals. Carbon refractories have carbon as the principal component, existing in the form of graphite or semi-graphite. They can resist the action of slags and have high thermal stability.

Chemical Reactivity

There are several typical chemical reactivities of refractories based on the chemical reactivity of their constituent substances.

Acidic refractories contain silica and alumina, which tend to react with basic slags. They are resistant to acid slags and are therefore utilized in an acidic environment and slags.

Basic refractories constitute calcium oxide, magnesia refractories, dolomite refractories, magnesia-chrome refractories, etc. They react with acidic slags but are resistant to alkaline (basic) slags, specks of dust, and fumes at extreme temperatures. Steel manufacturers make use of this class of refractory to construct furnace linings in an alkaline medium.

Neutral refractories are chemically stable in both acidic and basic media and can be utilized in acidic or basic environments and slags. Carbon graphite (most inert), chromite refractories, and alumina are typical examples of these refractories, among which graphite is the least reactive and is suitably utilized in metallurgical furnaces where oxidation processes are controlled.

Special refractories include pure alumina, sialons (Si-Al-O-N), beryllia (BeO), zirconia, boron nitride, spinel, etc. They are costly refractory materials that are fabricated using pure synthetic (fused/sintered) suitable production parameters and conditions. They have especially used refractories in the construction of crucibles, research and development purposes, etc. where the cost of a refractory is not considered.

Cordierite (2MgO. 2Al$_2$O$_3$. 5SiO$_2$) and Mullite (3Al$_2$O$_3$. 2SiO$_2$)

These are technologically popular aluminosilicate refractory materials due to their suitable properties (thermal shock resistance, low thermal conductivity, creep resistance, low thermal expansion, elevated thermal and chemical stabilities, etc.) for various engineering purposes. Their raw materials are easily obtainable at cheap prices. The low production costs of these materials influenced their potential use as an alternative material to alumina. They are used in welding shapes, electrical insulators, furnace liners, etc. The high thermal coefficient of expansion of mullite renders it a suitable refractory utilized to ameliorate the thermal operational problems encountered at the silicon-substrate overlap of integrated circuit devices (Fahlman, 2023; Rahman *et al.,* 2014). What is normally done in this case is to decrease the thermal expansion coefficient to equalize the thermal coefficient of silicon by adding cordierite as a second phase, since it has a low thermal expansion coefficient. A cordierite-mullite refractory composite is superior to mullite refractory because of the high thermal conductivity of the former (mullite). An adequate liquid phase is formed between 1290-1550^{o}C to form a density. Another important factor to note is that both mullite and cordierite co-exist in thermal equilibrium, which means mullite can exist in the cordierite phase and cordierite can exist in thermal equilibrium with the mullite phase. Cordierite-mullite composite ceramics were fabricated from commercially available cordierite and mullite powders (Xu *et al.,* 2017) in which the mullite content in the composite was about 65% (Xu *et al.,* 2017). The electrical conductivity of the composite was studied based on the influence on porosity, mullite glass phase, and grain size. The composition of refractory composite renders them suitable for thermal expansion behavior.

The consequence of starting materials on the morphology of mullite crystals in the composite refractories (cordierite-mullite), and was observed the morphology of the mullite crystals became different contingent on the type and source of aluminum utilized in the fabrication of the composite refractories (Chermat *et al.,* 2025; Sun *et al.,* 2022). It was revealed that alumina-sol mixtures give rise to acicular grains while Al(OH)$_3$ powder mixtures show the appearance of angular or granular mullite mixtures. A lower mullitization temperature of a composite made with alumina sol shows better reactivity and dispersibility than those with Al(OH)$_3$ powder. Cordierite and mullite powders obtained from commercial vendors have been used by Phatthamon Kiattisaksophon and Sukdiphon Thiansem as raw materials in different ratios of up to 100 wt% (Kiattisaksophon & Thiansem, 2008). The raw material was combined, mixed, processed, and taken to a ball grinding mill for composite formation. The samples were then sintered at temperatures between 1250 and 1400 at an interval of 50°C. The samples were heated at extreme temperatures and cooled down to room temperature to study their thermal actions to measure the thermal expansion coefficient. It was learned from the thermal behavior of the samples that the fabricated cordierite-mullite composite showed good physical and chemical properties at 70:30 wt% sintered at 1400°C. The fabricated cordierite-mullite composite also shows improved densification of cordierite and mullite structures, thermal shock resistance, pore size variation, bulk density, and apparent low porosity. The crack and microstructural characteristics suitably attract the utilization of cordierite-mullite composite in the swift firing of porcelain whiteware. One significant concern pointed out by the refractory industries is the thermal shock degeneration of commercial refractories that results in to decrease in stiffness, mechanical strength, and degradation when subjected to high industrial thermal conditions. The use of high-quality starting reagents ignited the cost of refractory composites in the market. Considerations are now made for the use of non-destructive testing to determine damages caused by thermal shocks. The thermal degeneration of commercial refractory composites was investigated by (Boccaccini *et al.,* 2008; Cioangher *et al.,* 2024; Flores-Jacobo *et al.,* 2023) exposed to harsh industrial thermal conditions by comparing the degenerated curves acquired from the non-destructive testing, e.g. comparing images acquired from ultrasonic velocity testing (UPVT) with those secured from measuring the flexural strength and fracture toughness by three-point bending test and chevron notched method, respectively.

Table 1: Physical properties of cordierite and mullite (Camerucci *et al.,* 2001; da Silva *et al.,* 2019)

Property	**Cordierite**	**Mullite**
Chemical formula	3Al$_2$O$_3$. 2SiO$_2$	2MgO.2Al$_2$O$_3$. 5SiO$_2$
Density	3.03g/cc	2.60 g/cc
Thermal expansion coeff.	4.5- 5.6 (x10-6/ °C)	1.7(x10-6/°C)
Thermal Conductivity	4-6 W/m K (100-1400°C)	3 W/m K (room temp.)
Max. Operating temp.	1725 °C	1371°C

Mullite has suitable thermal and mechanical properties which account for its importance in traditional and advanced refractory material. It is not widely distributed in nature because of its high temperature and low pressure. Many methods are used to fabricate refractory composite materials. The two methods employed to fabricate mullite-cordierite composite refractory: (1) by a combination of raw material, and (2) by joining of pre-made mullite and cordierite powders (Bilung, 2012). The ground raw materials are heated at low temperatures between 550°C to 900^{0}C to enhance the densification of the materials. The microstructure, crystalline, dielectric, and mechanical properties of the composite manufactured from the various raw materials were analyzed. Crystals were easily formed refractory composites made of finely ground precursors than those from aluminum sulfate reagents. A composite refractory fabricated from a raw material made of composite materials attains a better density at lower temperatures due to the gummy or sticky flow of the ceramics. Mechanical properties of a composite can be accounted for from microstructures while strength and hardness are correlated to the composition, grain size, and porosity. In a solid-state reaction, a refractory composite with its desired properties is incompletely transformed into another composite having another set of desired properties. The product from this process has the benefit of carrying the advantages of both the starting materials. It is observed from various cordierite-mullite ceramics that an increase in cordierite causes a decrease in the thermal expansion coefficient. Preferably, we can keep the percentage of cordierite-mullite ratio at the constant of 70:30%. Shock resistance is supported by the cordierite while strength is aided by mullite. The existence of the cordierite reduces the temperature and the firing shrinkage (El-Fadaly *et al.,* 2022; Sadik *et al.,* 2016). (Zemánek *et al.,* 2021) in their work combined cordierite and mullite in various proportions either as reactants or grog and studied the effect of the percentage of grog added. Components with 50-70 & grog acquired improved mechanical, thermal, and physical properties. Table 1 above shows some physical parameters of cordierite and mullite.

Ternary Phase Diagrams for Cordierite and Mullite

A ternary phase diagram is a complex diagram captured in a three-dimensional plot in which each side of the plot represents a pure component in the system. Figure 1 below is the ternary diagram of the magnesium oxide aluminum silicate system. The $MgO.Al_2O_3.SiO_2$ system has been studied for so many years through the extensive experimental system. The compositions within the system are important for many reasons. They are important to geologists looking for mineralogical systems and also many of the compounds within the system have important applications such as high-temperature ceramics and structural ceramics in kilns or ovens. Most of the compositions in the system form transparent glass ceramics and from the geologic point of view, they contribute many of the lower mantle minerals. Understanding the melting behavior and crystallization part of the system is therefore important. It is also a great test system to see if we can apply our knowledge to read the crystallization part from the liquidus projections.

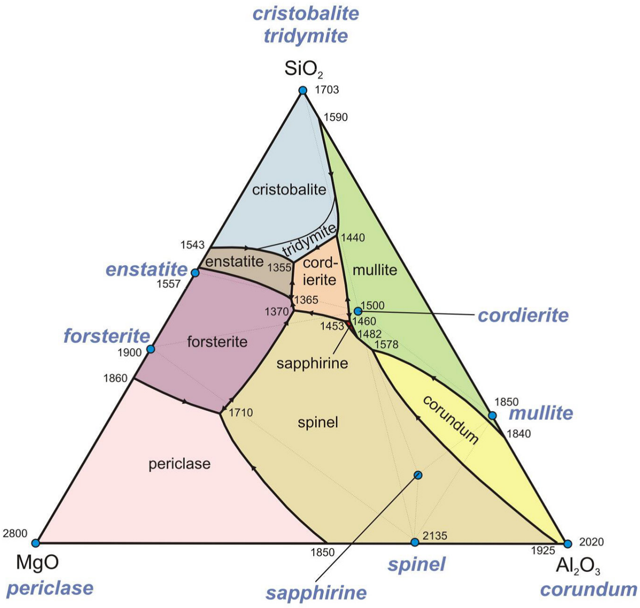

Figure 1: Modified ternary phase diagram of refractory composites (Dudnik *et al.,* 2014)

Many years of studies lead to the experimental determination of the system and detailed characterization of the phase stability in melting temperatures. The objectives here are to read and interpret all of the information in the diagram and then track some solidifications. The three compositions (MgO, Al_2O_3 & SiO_2) in the diagram are shown in percent weight or mass percent and not moles. It is observed that the part where you have the cordierite ($2MgO.2Al_2O_3.5SiO_2$) with blue dotted lines is a little bit congested. Along the MgO and SiO_2 binary are two compounds which are $MgO.SiO_2$ mineral called enstatite and $2MgO.SiO_2$ is known as forsterite. Both of these compounds do not show solubility. Between the MgO and Al_2O_3 is a well-known phase called spinel ($MgO.Al_2O_3$) which shows a very significant solid solution. The compound along Al_2O_3 and SiO_2 is mullite ($3Al_2O_3.2SiO_2$). There are two ternary compounds, one is the cordierite mineral ($2MgO.2Al_2O_3.5SiO_2$) which has ceramic applications, and immediately below the cordierite mineral is sapphirine ($4MgO.5Al_2O_3.2SiO2$). Between the spinel ($MgO.Al_2O_3$) and Al_2O_3 is a solid solution. A significant amount of solid solution is also found around the mullite and the cordierite.

The Structural Chemistry of Alumina

Aluminum oxide is an oxide obtained from bauxite and occurs in mineral corundum alongside some impurities from ruby and sapphire(Abyzov, 2019; Giuliani *et al.,* 2020; Panasyuk *et al.,* 2019; Simonet *et al.,* 2008). The oxides of alumina obtained from bauxite with varying particle sizes are reactive alumina, low bauxite, calcined alumina, etc. They have properties such as particle size, surface area, surface reactivity, catalytic properties, etc., which account for their structural differences. The illustration in figure 1 below shows the thermal conversion of aluminum hydroxide into various forms when subjected to heat (Castruita *et al.,* 2013; Shirai *et al.,* 2010).

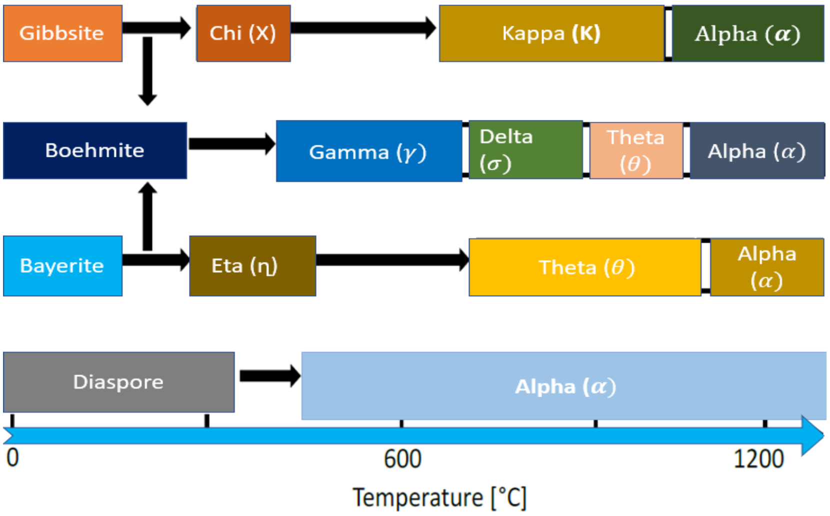

Figure 2: shows the thermal transformation of aluminum hydroxides (modified).

There are many allotropes of Al_2O_3, and α-Al_2O_3 is the most stable thermodynamic phase which is formed at high temperatures by metastable or transition alumina precursors such as γ-alumina, β-alumina, δ-alumina, σ-alumina, etc. Aluminum hydroxide thermally decomposes to form these metastable phases (Castruita *et al.,* 2013; Yang *et al.,* 2024). For instance, heating gibbsite (γ-trihydrate; γ-$Al(OH)_3$), boehmite (γ-monohydrate; γ-AlOOH), bayerite (α-trihydrate; α-$Al(OH)_3$), and diaspore (α-monohydrate; α-AlOOH) convert to various crystalline phases when calcined at high temperatures (Atanga, 2013). The crystalline form of alumina is hexagonal in structure, as shown below, flocked by O2- anions and Al3+ cations (Baronskiy *et al.,* 2022; Nestler *et al.,* 2019). The Al atoms are in an octahedral arrangement with six oxygen rings as shown in the diagram below(Gutierrez & Johansson, 2002; Rustad *et*

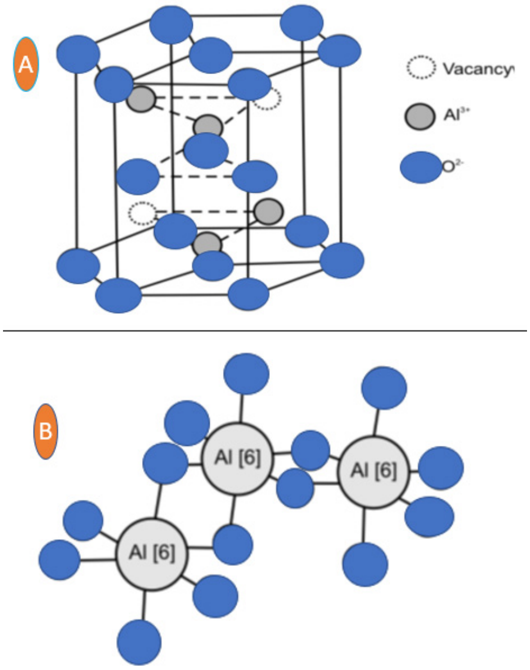

Figure 3: (A) Modified corundum structure in alpha-Al_2O_3 and (B) Modified octahedral coordination of alpha-alumina (Abdelkader & Abdecharif, 2012; Ahmed *et al.,* 2021; Khosravi Mardkhe, 2014).

al., 2004). The dimensions of the unit cells in the trigonal lattice structure are a = 4.7587 Å, b = 4.7587 Å, and c = 12.99 Å.

Properties of Al_2O_3

The typical properties of alumina are: high hardness, chemical inertness, high thermal stability, low coefficient of thermal expansion, good thermal conductivity, good wear and abrasion resistance, high corrosion resistance, a high melting temperature (2050°C), and its commercial availability in different purity ranges and grain sizes, makes it attractive for a great variety of engineering application. The suitability of alumina to resist thermal fatigue is related to its geometric arrangement and strength, controlled by its thermal properties like thermal conductivity and thermal expansion characteristics (Czerwinski, 2020; Kamara *et al.,* 2025; Sobczak *et al.,* 2002; H. Wang *et al.,* 2020).

Applications of Al_2O_3 Ceramics

The applications of alumina ceramics in engineering are as follows:

- as a refractory material for the lining of furnaces (Sengupta, 2020; Slovikovskii & Gulyaeva, 2018).
- as an abrasive material and cutting tool (Hosseini & Kishawy, 2014; Toenshoff & Denkena, 2013)
- as substrate material for electronic parts and packing materials for integrated circuits (e.g. silicon chips, electrical insulators, and spark plugs) (Pulugurtha *et al.,* 2022; Yin *et al.,* 2024)
- alumina also has widespread applications as a porous ceramic and catalyst support (Wang *et al.,* 2022).

The suitability of alumina for all these applications is due to the properties listed in table 2.

Structural Chemistry of SiO_2

Silica (SiO_2) is a compound made of silicon and oxygen atoms, which occurs in nature as quartz, silica sand, or sandstone(Götze, 2012; Pan *et al.,* 2022), and can also be obtained from various sources in different forms like silica fume, fused silica, colloidal silica, and gel silica (Hyde *et al.,* 2016). The reaction in equation 1 below shows the formation of silica from alkoxide.

$$Si(OR)_4\,(l) + 2H2O\,(l) \rightarrow SiO_2\,(s) + 4ROH \qquad (1)$$

Efficient nucleation and heterogeneous growth of the amorphous material lead to the fabrication of stable mullite phases. A mullite refractory fabricated from amorphous silica is more stable than mullite from crystalline silica reagent. The formation of mullite with better microstructure is dependent on the silica precursor, the alumina precursor, and processing conditions. There are several crystalline forms of silica, but the three major crystalline phases are quartz, tridymite, and cristobalite. The low and high-temperature crystalline forms or polymorphs are represented as the α-form and the β-form. The β-cristobalite is stable at around 1705 °C and melts at temperatures equal or equal to 1705 °C (Fernandes *et al.,* 2024; Ortiz-Bravo *et al.,* 2022; Wiberg *et al.,* 2001).

Table 2: Mechanical and thermal properties of alumina (Gudlur *et al.,* 2012; Xie *et al.,* 2011)

Characteristics	**Measured values**
density, [g cm^{-3}]	3.95-4.10
melting point, [°C]	2072
microhardness, [GPa]	20
hardness, [GPa]	9
young's modulus, [GPa]	260-410
bending strength, [MPa]	150-600
fracture toughness, [MPa m0.5]	4-6
thermal conductivity from 25 °C to 1000 °C, [W m^{-1} K^{-1}]	30-40
coefficient of thermal expansion from 20 °C to 1000 °C, *10^{-6} [K^{-1}]	5.4-9.5

Table 3: Silica and some properties (Pabst & Gregorová, 2013; Polyakova, 2014)

Form	**Crystal symmetry**	**Stable range**	**Density (g cm-3)**
α-quartz	hexagonal	< 573 °C	2.65
β-quartz	hexagonal	573 °C - 870 °C	2.53
α-tridymite	monoclinic	metastable	2.36
β-tridymite	hexagonal	870 °C - 1470 °C	2.25
α-cristobalite	tetragonal	metastable	2.32
β-cristobalite	tetragonal	1470 °C - 1705 °C	2.20
Silica melt	-	≥ 1705 °C	-

Figure 4 represents the stable crystalline phase of silica at extreme temperatures in which each silicon atom is bonded to four oxygen atoms to form a tetrahedral structure (Norman *et al.,* 2013; Polyakova, 2014; Schnurre *et al.,* 2004).

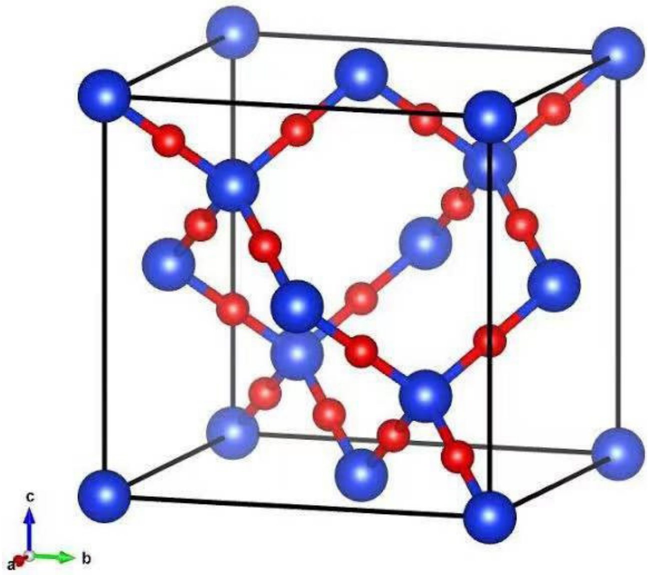

Figure 4: Modified crystal structure of cristobalite (a high-temperature crystalline form of silica)(Aleem *et al.,* 2014).

The silica group in the structure constitutes various minerals with different structures, symmetries, and physical properties but with the same composition. An increase in temperature causes a shift in the positions of the atoms in the crystal lattice structure. The bond angle between the SiO_4 tetrahedra) change from 153° (β-quartz) via 180° (β-tridymite) to 151° (β-cristobalite). A shift is induced in the bond length of Si-O, resulting in a contraction from 0.161 nm (α-quartz) to 0.158 nm (β-cristobalite). A corresponding decrease in density and an increase in hardness have been discussed by some researchers. Silica is the most significant component of mullite, which has many industrial applications. It has a high melting temperature, used to produce molds and cores for the production of metal castings in ferrous and non-ferrous industries. It is the main component of ceramic products. Silica is used to regulate drying and shrinkage; it modifies thermal expansion and improves structural and mechanical properties (Hou *et al.,* 2025; Tran *et al.,* 2021; J. Wang *et al.,* 2020).

CONCLUSION

Refractories are well-known for their superior engineering properties. They involve low production costs due to the reasonable source of raw materials involved. The most common and widely used refractory composites are cordierite and mullite. They are prepared through various methods such as the combustion process, mechanical route, sol-gel route, the effect of pH, etc. These compounds can also be studied in a ternary system to understand important applications such as those in high-temperature ceramics. They are made of aluminosilicate compounds.

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