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Manufacturing of cement and petrography of its raw materials

Hasnain Haider[1], Shamim Akhtar[2], Enayatallah Emami[1], Khadija Masood[3], Khaliq Hussain[1]

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ABSTRACT

Cement is an adhesive, chemical substance used as a binder during construction. So it's important to know about the raw materials used to manufacture cement. Quantity and quality of different raw materials affects the strength of cement. For geologists it is interesting to know about the chemical composition of raw materials and their source rocks. Limestone, silica, iron oxide, gypsum and clay minerals in specific quantities are used to manufacture cement in different cement industries. Therefore it is also important to know the mineralogical composition of these manufacturing materials that help us to explain the chemical composition of cement. This study explores the intricate relationship between the petrographic characteristics of raw materials and their impact on enhancing the quality and efficiency of cement production. By conducting a comprehensive petrographic analysis of key raw materials such as limestone and clay, we can delve into the detailed mineralogical composition and textural attributes that define these materials. The primary objective of the following investigation is to determine whether variations in mineral content and physical properties significantly influence the strength and sustainability of the final cement product. Our findings indicate that optimizing raw materials, characterized by competent minerals with favorable textures, can notably enhance cement quality while mitigating manufacturing inefficiencies. Furthermore, the study reveals a substantial presence of calcite cement interspersed with bio clasts in limestone, alongside an enriched concentration of aluminum-bearing minerals such as kaolinite, boehmite, and gibbsite in bauxite. Additionally, the analysis highlights the enrichment of iron-bearing hematite minerals in conjunction with kaolinite, which collectively improving settling times and overall cement quality. To achieve the production of sustainable and durable cement, it is crucial to exercise caution in the selection of both the quantity and quality of raw materials. An inadequacy of essential minerals or their excessive presence can lead to the creation of cement that is not only of low strength but also lacks durability. Thus, careful consideration is vital for optimizing cement production processes.

KEYWORDS

Cement, Gypsum, Limestone, Manufacturing, Petrography

I. INTRODUCTION

Materials that are used for manufacturing cement are mainly Lime, Silica, Alumina, and Iron oxide (Aldieb & Ibrahim, 2010). The cement manufacturing process typically comprises four key stages: extracting and preparing raw materials, producing raw materials, producing clinker, and the final grinding process to create cement (Habert et al., 2010). The raw materials usually include limestone, clay, and other essential minerals, which undergo physical and chemical changes throughout the process. As technology advances and becomes more reliable, researchers are increasingly focusing on optimizing these stages to enhance efficiency, reduce energy consumption, and minimize environmental impacts (Favier et al., 2016) When oxides, present in raw materials comes to high temperature, form complex compounds on mixing. Moreover, the major raw materials that are used in the manufacturing of cement, may also mixed with some minor compounds that formed in the kiln. The influence of these minor compounds is not enough. Two of the minor compounds are oxides of alkalis (Potassium K2O and Sodium Na2O) (Kolovos, Tsivilis, & Kakali, 2002). Petrographic analysis is crucial in identifying mineral phases and understanding how their behavior changes during cement production. This information allows us to evaluate the quality of raw materials, assess their suitability and stability for cement production, and analyze their impact on the clinker formation process (Morales et al., 2013).

Proportion of each constituent isn't same, yet it varies with location or industry. Limestone, Laterite, Bauxite, Gypsum and Clay minerals are considered as significant ingredient. They are used in manufacturing in specific amount that's provided by QC (Quality Control) unit cell in Cement Industry. The proportion of ingredients is maintained carefully. Above or below that specific proportion may affect the strength or setting time of Cement. Excess quantity of lime expands and disintegrates it, while deficiency of lime may decrease

[1] University of Yazd, Yazd, Iran, [2] University of Sargodha, Pakistan, [3] National Center of Excellence in Geology, University of Peshawar, Pakistan
H. Haider: haider.cca@gmail.com

the strength and cause quick setting (Faija, 1893). Recent studies have highlighted the importance of the mineral composition of limestone and clay, which are essential raw materials in cement production. Impurities such as silica, alumina, and iron oxide can influence the sintering behavior of the raw mix and ultimately affect the mineralogy of the resulting clinker (Gholami et al., 2020). Moreover, the widespread use of petrographic techniques to analyze additional raw materials, such as bauxite and gypsum, has provided valuable insights into how these materials behave in the cement kiln (Sinter et al., 2021).

Silica is also an important ingredient in a way of providing strength. Excess quantity of silica increases the strength yet it also enhances its setting time (Vora & Dave, 2013). Alumina also contributes in quick setting yet using it in large proportion may reduce the strength (Lawrence, 1998). Recent studies have demonstrated that incorporating petrographic analysis techniques into the selection of alternative raw materials can significantly enhance the performance of blended cement, resulting in improved durability and strength (Bounkhel et al., 2016).

Gypsum used as calcium sulfate enhances the initial setting time (Ioannou et al., 2014). Iron oxide is used in cement mainly to contribute in coloring of cement (Jahagirdar, Patki, & Metan, 2019). Recently, more sustainable and efficient kiln systems have replaced older models. For instance, using rotary kilns powered by alternative fuels has gained attention (Moncaster et al., 2019).

Laterite is used as oxides of iron and alumina. Iron oxide also helps in increasing strength and hardness of cement. Many researchers have developed unique models to interpret the petrographic characteristics of the raw materials used in cement production, aiming to predict the performance of durable cement during the hydration process (Zhao et al., 2019).

This study aims to provide a comprehensive understanding of the cement manufacturing process and the petrographic characteristics of its raw materials. This research illustrates how different mineral compositions in cement affect the sustainability and performance of the final product. By combining insights from the manufacturing process and petrographic studies, we can enhance the sustainability and efficiency of cement production.

Previous studies typically focused on either the manufacturing process or the material properties in isolation; however, this research bridges that gap by examining how the mineral composition of raw materials, such as limestone and clay, influences cement performance. The findings will assist in selecting raw materials based on petrographic analysis, providing innovative ideas to optimize manufacturing efficiency and reduce waste.

A. *Manufacturing of cement*

Manufacturing of cement involves different stages that are categorized into dry process and wet process. Followings are the common stages that involved in both processes.

B. *Raw Material Preparation*

The initial step to make cement is to excavate raw materials, such as limestone, shale, clay, laterite and bauxite. Materials are mined in quarries and transported to a crushing plant for further processing. Crushed Ingredients are transported to the cement plant by conveyors. They are blended in proper proportions to create a raw mix, usually 70 -75% limestone, 15-20 % iron oxides and silica, 5% gypsum and less than 5% clay. These quantities may vary in specific amount that's provided by QC (Quality Control) unit cell in different cement industries.

C. *Raw Material Grinding*

Fine powder is created by crushing and combining the raw materials in a precise ratio. Afterwards, components are introduced into the raw mill and transformed into a finely powdered substance.

D. *The Preheating Stage*

Fine powder is heated to 2000°C and it turns into clinker at 1500°C, and then rapidly cooled with air fans. Raw mix is burn to produce clinker which is essential in cement production. This is a crucial process. Raw material ingredients are heated at high temperatures before further processing in the kiln. This occurs in the pre-heater tower, a tall unit for pre-heating. Raw materials are heated as they came into contact with hot gases introduced at the bottom of tower. The temperature of the tower can reach up to 800-900°C. Preheating reduces moisture in raw materials saving energy and promoting necessary chemical reactions in cement production (Zhang, Cheng, & Lo, 2014).

E. *Calcination*

Calcination heats raw materials to release CO_2. Calcination is crucial in cement manufacturing. Raw materials are heated in a kiln, then cooled and ground to produce the product. During calcining, limestone is heated to 1450°C causing decarbonation and release of carbon dioxide gas.

$$CaCO_3 = CaO + CO_2 \tag{1}$$

This reaction creates calcium oxide, or quicklime, a vital cement ingredient. The lime reacts with silicon dioxide to produce dicalcium silicate and tricalcium silicate.

$$2CaO + SiO_2 = 2CaO \cdot SiO_2 \quad (2)$$
$$3CaO + SiO_2 = 3CaO \cdot SiO_2 \quad (3)$$

Later on, lime also reacts with aluminum oxide to form tricalcium aluminate.

$$3CaO + Al_2O_3 = 3CaO.Al_2O_3 \quad (4)$$

Finally, calcium oxide, aluminum oxide, and ferric oxide react together to form cement.

$$4CaO + Al_2O_3 + Fe_2O_3 = 4CaO.\ Al_2O_3.\ Fe_2O_3 \quad (5)$$

Other materials like clay, shale, sand, iron ore, and fly ash are heated and transformed. Clinker is cooled and ground to make cement powder. Calcining cement must be controlled for quality. Advancements in technology have enabled more efficient and eco-friendly cement calcination, reducing its carbon footprint. Calcination is vital in cement manufacturing. It occurs in the rotary kiln of the plant after preheating raw meal. Rotary kiln heats raw material to 1450°C, causing reaction series that create cement clinker. The kilns burner, powered by natural gas or coal, produces high temperature flames that calcinate the raw material. After calcination, the clinker will cool in a cooler.

A similar rotary kiln is used to burn slurry, with a longer drying zone due to added water. Moisture is removed before undergoing the same process as the dry method (Berriel et al., 2016).

F. Cooling

Clinker cooling is the process of reducing its temperature after heating in a kiln. This is crucial for cement production as high temperatures may cause cracking. The cooling process cools hot clinker by passing it through a rotating cylinder sprayed with water or air until it reaches a suitable temperature for storage and processing. The cooling process prevents unwanted minerals in clinker and enhances cement quality. After exiting the kiln, clinker is cooled and additives are combined for final cement production. Gypsum is added to clinker to regulate setting time and enhances compressive strength of cement. It prevents powder agglomeration and coating mill surfaces. Organic additives like Triethanolamine (0.1 weight percent) prevent powder clumping. Other additives include ethylene glycol, oleic acid, and dodecyl-benzene sulfonate. Clinker heat is recycled to save energy and final grinding finishes cement production. Cooler clinker is ground with steel balls rotating drums, resulting in 150 billion grains per pound. This powder called cement, cooled in great cooler with forced air from fans. Cooled clinker is stored and ground after reaching 120°C from 1350-1450°C. Recirculated hot air saves energy in rotary kiln of cement plant. Cooled clinker is fed to cement mills for final grinding, with many factories using ball mills due to their small product particle size distribution and ease of operation (Shao, Cui, & Ma, 2020).

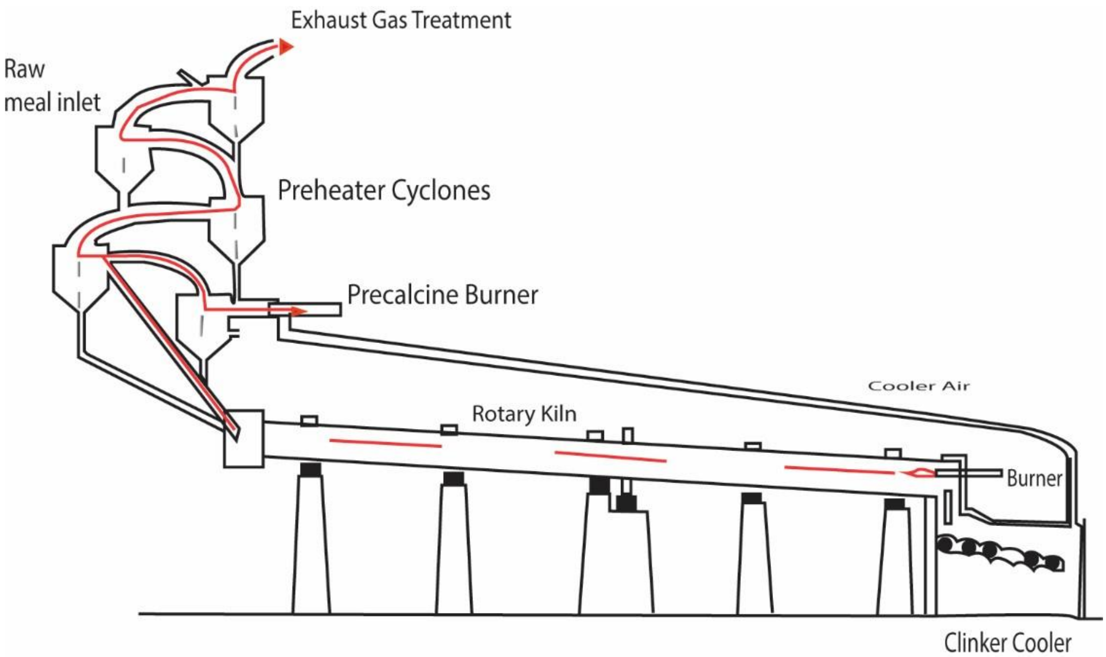

Fig.1. Model diagram to show the function of rotary kiln

G. Grinding of Clinkers

Clinker grinding is essential for making cement. It is ground with gypsum using various to make fine powder. Grinding with vertical roller mills creates smaller particles for faster water reaction. Clinker is ground with gypsum in roller press to produce final product. Grinding produces even particles, strengthening the cement. Clinker and gypsum are horizontally milled ground. Material is ground with an aid in open or closed-circuit grinding. Additives are added to cool clinker for cement production. Gypsum strengthens the cement while Triethanolamine prevents clumping. Recirculate clinker heat to the kiln for energy savings. Finally grind into fine powder using rotating drums with steel balls. This final product is called cement. Grind clinkers, add 2-3 percent gypsum as retarding agent. Ground clinkers and gypsum resist settling in water, creating a pure final product.

$$3CaO.Al_2O_3 + xCaSO_4.7H_2O = 3CaO.Al_2O_3.xCaSO_4.7H_2O \quad (6)$$

Gypsum controls the setting to allow time for concrete placing. Gypsum is added to a slow cement setting (Lamond & Pielert, 2006).

H. Cement Silo

This unit cell is used to store cement elevated by buckets elevator chains. Cement silos employ compressors and blowers for blending and aeration. The cement is transported via bucket elevator and pneumatic conveyor.

I. Packing and Storage of Cement

Cement packing involves filling and packaging into bags or containers for transportation and distribution. The bags are woven polypropylene or paper with sizes from 25 to 50 kg. After grinding, mixing and adding gypsum and other additives, cement is packed into machines at packing plant. Modern packing machines can fill and seal bags of cement at a precise weight of 50KG with a speed of 2000 bags per hour. Bags are stacked, wrapped and stored for distribution. Most of this cement is transported in bulk via trucks, trains or ships with only a small amount sold in smaller bags. Materials move from mills to silos, then to small bags for customers with minimal requirements. Cement is shipped in bulk by trucks, rails, or ships or is transferred from mills to silos and packaged or transported. Rotary packers are popular for quick, large-scale cement packing (Hekkert, Joosten, & Worrell, 2000).

II. PETROGRAPHY OF RAW MATERIALS

The petrography of raw materials is important to know the chemical and mineralogical composition of cement. The main constituents of cements with their mineralogical description are as follows:

A. Limestone

Limestone is a sedimentary rock composed of calcium carbonate with organic remains. Limestone varies in color, texture and composition, with common variations like chalk, marl, and oolitic limestone. The limestone that is rich in calcium increase the setting time and strength of cement while impurities like sulfur magnesium carbonate can make cement less durable. Limestone is abundant in nature, cost-effective, and enhances cement strength and durability.

B. Laterite

Laterite is soil formed in hot regions, containing iron and aluminum hydroxides. Laterite varies in color and structure due to iron oxide content and weathering. Petrographic characteristics of cement may differ by deposit (Shah et al., 2013). Laterite, rich in iron oxide, contributes to the formation of C4AF, enhancing the mechanical properties of cement, especially its strength and resistance to chemical attacks in environments with high sulfate levels or seawater (Mehta & Monteiro, 2014). Furthermore, laterite is readily available in tropical regions, where it is abundant and easy to mine, making it a cost-effective alternative to more expensive sources of iron ore (Sathia et al., 2017).

C. Bauxite

Bauxite is a primary source of aluminum in cement production. It's composed of aluminum hydroxides, including gibbsite, boehmite and diaspore mixed with clay minerals, iron oxide and silica. Bauxite varies in color and texture based on mineral composition and weathering.

Good quality bauxite contains a high aluminum content and low level of impurities, which enhances clinker formation and ensures high cement quality. The high alumina content also contributes to an early increase in the setting time of the cement. Additionally, bauxite reduces the clinker melting temperature, which improves energy efficiency in cement production (Mehta & Monteiro, 2014). However, the presence of high impurities such as silica and iron in bauxite can negatively impact the setting time, color, and strength of the cement. Despite this, bauxite improves the durability of cement, enhances resistance to chemical attacks, and is essential for high alumina cement.

Clay minerals like Kaolinite, illite and montmorillonite are used in cement production. Clay is formed from weathered rocks and its properties vary based on its source. Clays for cement are known for their plasticity, water retention, and high silica, alumina and iron oxide content. These characteristics determine raw materials' suitability, influencing cement quality and performance. High-quality clay can enhance the setting time, durability, and efficiency of cement, while clay rich in impurities can negatively affect the final product (Jones & Clark, 2018).

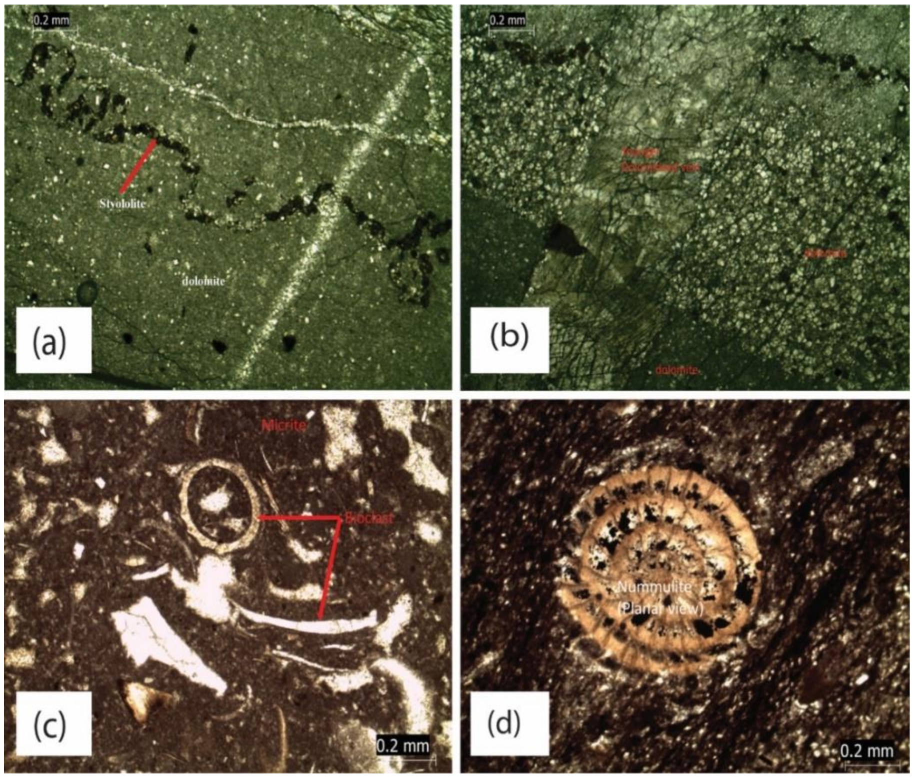

Fig. 2. Thin section study of limestone. (a) Indicates stylolite and dolomite, (b) indicates Dolomite and younger dolomitized vein, (c) Indicates Micrite and Bioclast, and (d) indicates planner view of Nummulite present in limestone

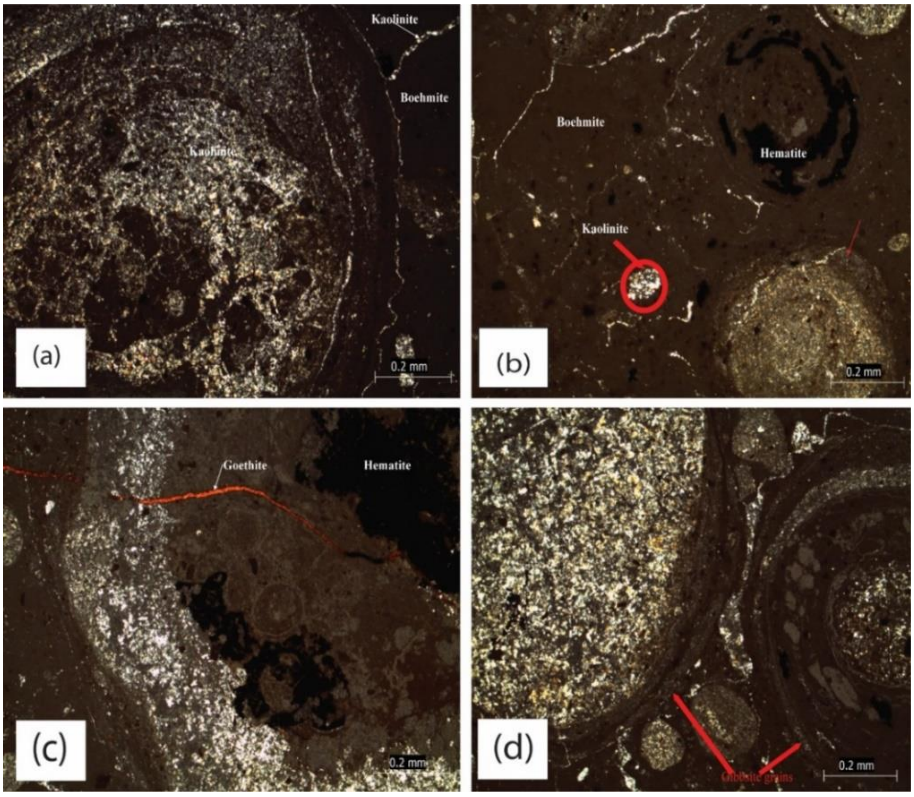

Fig.3. (a) Indicates Kaolinite and Boehmite minerals from petrography of lateritic bauxite, (b) Indicates Hematite, aolinite and Boehmite minerals, (c) Showing Goethite vein and Hematite, and (d) Showing Gibbsite grains

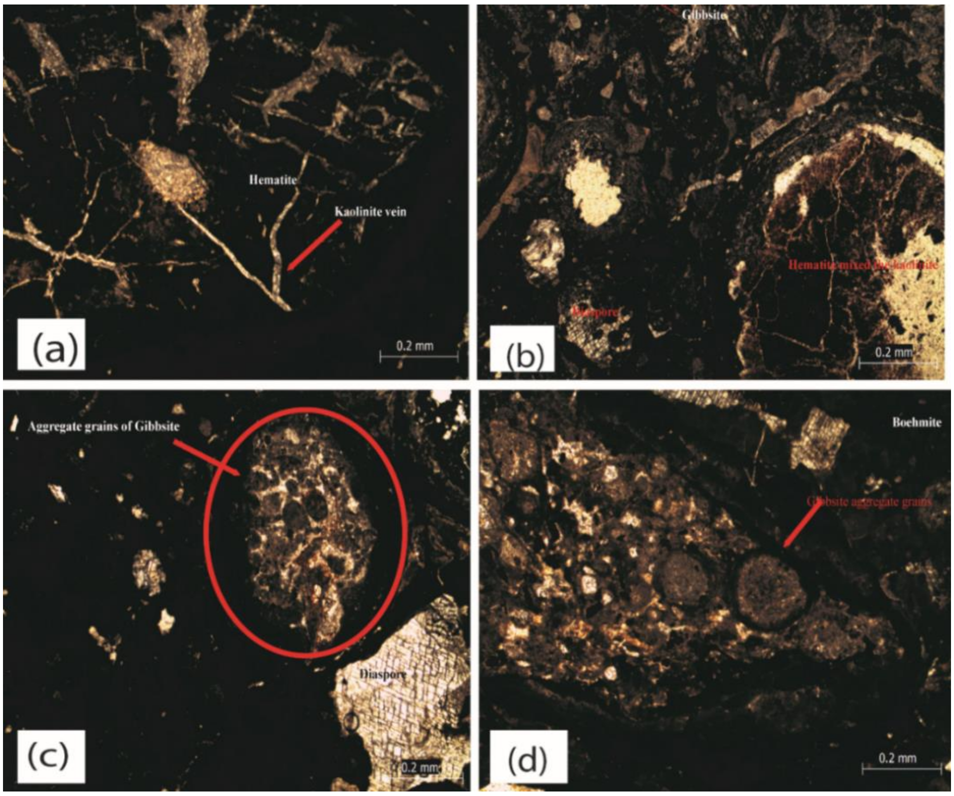

Fig. 4. (a) showing Hematite, Kaolinite veins, (b) showing Gibbsite, Diaspore and Hematite mixed with Kaolinite, (c) Indicates aggregate grains of Gibbsite, and (d) showing Boehmite

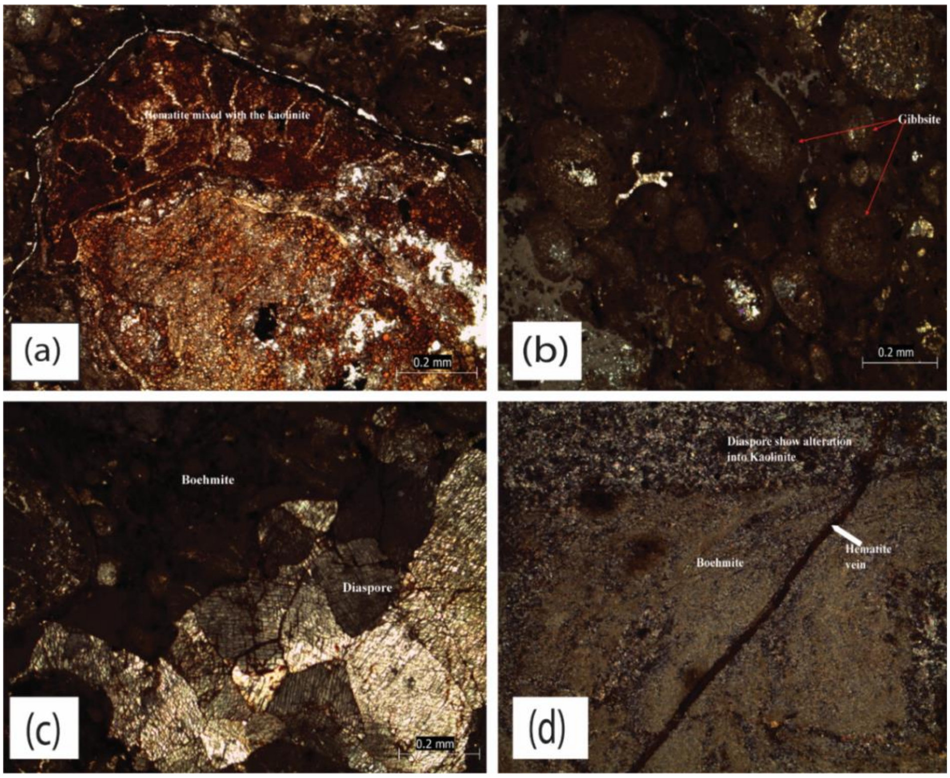

Fig. 5. (a) Hematite mixed with kaolinite, (b) Showing gibbsite, (c) Showing boehmite and diaspore, and (d) Showing boehmite, hematite vein and diaspore showing alteration into kaolinite

III. Discussion

The production of cement is a complex process that requires careful selection of raw materials. Typically, production occurs in four main stages: extraction and preparation of raw materials, selection of raw materials, production of clinker, and grinding cement. It is crucial to choose raw materials that are cost-effective and readily available in the region. Before selecting these materials, it is important to examine their chemical and mineralogical composition, as this can significantly impact the overall durability and sustainability of the cement. Petrographic studies are useful for analyzing the mineralogical composition of the raw materials. By carefully evaluating the results from these studies, we can choose raw materials that make cement more efficient and environmentally friendly. This paper discusses both the manufacturing process of cement carried out at the DG Cement Factory in Pakistan and the petrographic analysis conducted in the petrographic lab at the University of Sargodha, also in Pakistan. The results indicate that the cement produced after conducting petrographic studies is more sustainable, durable, and environmentally friendly. The primary components used in cement production—limestone, laterite, and bauxite—are studied using petrographic techniques. During the petrographic examination of limestone, we observed calcium carbonate with dolomite, which consists of calcium magnesium carbonate. Stylolite surfaces (Fig. 2) are formed due to pressure dissolution during compaction or tectonic stress, marking areas where minerals, primarily calcite, have dissolved, leaving behind impurities (Boggs, 2011). Limestone rich in calcium can enhance the strength and setting time of the cement, while impurities such as magnesium and sulfur can negatively affect these properties (Siddique & Chahal, 2017). Additionally, micrite, which refers to microcrystalline calcite, and bioclasts—remains of organisms like shells, coral, and algae—are observed (Fig. 2). The results suggest that the dolomite content, indicating the presence of magnesium carbonate, is low. At the same time the limestone has high calcium content, making it a suitable raw material for cement production. Higher calcium carbonate contributes to better clinker formation, reducing the energy required to convert it into lime (CaO) (Jones & Clark, 2018). Laterite, commonly found in tropical regions, is a rich source of iron oxide and alumina—both vital for cement production. The iron oxide content in laterite contributes to forming the C4AF phase in clinker, influencing the cement's color, setting time, and strength (Rao, 2016). However, laterite often has high moisture content, complicating processing and increasing drying costs (Sathia et al., 2017). Bauxite is another key raw material used to produce high-alumina cement, known for its quick setting time and superior strength compared to other cement. The alumina content in bauxite helps form calcium aluminate phases, like C3A, which enhance the early strength and setting characteristics of the cement (Kumar & Singh, 2019). However, obtaining high-quality bauxite with fewer impurities can be challenging, as it is not widely available in nature (Siddique & Chahal, 2017). In the petrographic analysis of lateritic bauxite (Fig. 3), kaolinite ($Al_2Si_2O_5(OH)_4$) and boehmite (AlO(OH)) were identified as significant sources of alumina and silica, which can improve strength, and resistance to sulfur attack, and setting time of the cement. Additionally, the presence of hematite (Fe_2O_3) and goethite (FeO(OH)) serves as excellent sources of iron oxide, further enhancing the sustainability and strength of the cement. Other aluminum sources observed during the petrographic studies include gibbsite ($Al(OH)_3$) and diaspore (AlO(OH)) (Fig.s 4 and 5). The findings from our petrographic studies suggest that cement produced from these raw materials exhibits high resistance to chemical attacks and favorable setting times. However, it is important to consider certain factors during cement preparation. Excessive use of minerals can lead to complications; for instance, too much iron oxide may alter the color and slightly reduce strength, while excessive clay or silica can make clinker harder, increasing energy consumption and resulting in poor grinding and low-strength cement. High sulfate content may lead to expansion and cracking, while alkalis can react with aggregates in concrete, causing alkali-silica reactions that can result in cracking.

IV. Conclusion

Cement is a basic need in construction industry being a good adhesive and binding material. Many cement manufacturing industries produce cement of different quality and in different quantities annually. Quantity depends on mechanical strength of each industry but quality of cement depends on raw material.

Basically 70-75% limestone, 15-20% iron oxides and silica, 5% gypsum and less than 5% clay minerals are used as a raw material. These quantities may vary in specific amount that's provided by QC (Quality Control) unit cell in different cement industries.

Above or below that specific proportion of these raw materials may affect the strength or setting time of Cement. Excess quantity of lime expands and disintegrates it, while deficiency of lime may decrease the strength and cause quick setting.

Petrographic studies are beneficial for selecting raw materials that enhance the sustainability and durability of cement production. They can also help reduce energy consumption costs and minimize environmental impacts. Limestone with high calcium carbonate content is particularly effective for clinker formation and enhances the strength of the resulting cement. Its abundance in nature makes it a cost-effective choice while also promoting effective clinker formation.

Silica and alumina enhance strength of cement. While a good quantity of silica and alumina increases strength, it also enhances setting time. However, excessive use of these minerals can contribute to cracking and initiating different chemical reactions.

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