A LEGACY OF LEADERSHIP: A SPECIAL ISSUE HONOURING THE TENURE OF OUR VICE CHANCELLOR, PROFESSOR ARMAYA'U HAMISU BICHI, *OON, FASN, FFS, FNSAP*

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RECENT ADVANCES IN CEMENT CHEMISTRY AND APPLICATIONS: A REVIEW

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ABSTRACT

This study provides a survey of the chemistry and applications of the various kinds of cement produced by various industries in recent times. Cement-based products are widely used in the construction of buildings, roads, bridges and oil well drilling. The primary components of cement are limestone, clay and shale. Cement forms a composite known as mortar when mixed with water and sand. When mixed with water, sand and gravel it forms concrete. There are various types of cement produced and marketed worldwide. Ordinary Portland cement is the most widely used type of cement in various construction works. This cement is a fine grey/white powder consisting of a mixture of calcium silicates, aluminates, and aluminoferrites. It is a mixture of different inorganic oxides such as CaO, SiO_2, Al_2O_3 and Fe_2O_3, The ability to understand the different properties of the various types of cement helps one to make informed decision when selecting materials for a particular application.

Keywords: Cement chemistry, Limestone, Concrete, Portland cement, Cement production, Clinker formation

INTRODUCTION

Cement is a hydraulic binder composed of finely ground inorganic materials. When combined with water, it forms a paste that undergoes various exothermic hydration reactions, allowing it to set and harden. This enables it to bind solid particles together into a cohesive, compact mass (Cadix & James, 2022). Once combined with water and fine aggregate (such as sand), it forms a composite known as mortar. When mixed with water, sand, and gravel (small stones), it creates concrete (Krishnya *et al*., 2021). Among the different types of cement, ordinary Portland cement (OPC) is the most widely used one. (Liu *et al*., 2022). Although cement technology appears well-established, recent advancements in nanotechnology and materials science. This development opens the door for their use in advanced technological applications, such as self-healing systems (Xue, 2022). The demand for more ecologically friendly materials drives many contemporary approaches to cement chemistry in addition to their scientific and industrial significance. The cement industry currently contributes significantly to climate change by emitting carbon dioxide into the atmosphere. (Hammerl & Kromoser, 2021)

This study aims to offer a comprehensive overview of the chemistry involved in cement and cement-based materials, the recent literature (Xia et al., 2023) (Zheng *et al*., 2023) (Lavagna & Nisticò, 2023) clearly highlights the pivotal interest still present in the development of new advanced cement and cementitious materials.

Chemical Composition of Cement

The chemical composition of cement is regularly analyzed in both clinker and cement forms. ASTM C114 provides the standard for the chemical analysis of hydraulic cements (CSI-ECRA, 2017). The chemical composition of cement with percentage can vary depending on the type of cement, but a typical composition of cement for Ordinary Portland Cement (OPC) includes approximately 60-67% CaO, 17-25% SiO_2, 3-8% Al_2O_3 and 0.5-6% Fe_2O_3. (CSI-ECRA, 2017). The chemical compounds percentages are tabulated below in Table 1.

Table 1: The chemical composition of cement in percentage

Ingredients	Chemical formula	Percentage
Lime	CaO	60-67
Silica	SiO_2	17-25
Alumina	Al_2O_3	3-8
Iron oxide	Fe_2O_3	3-4
Gypsum	$CaSO_42H_2O$	1-4

Cement Raw Materials

Cements and cement-containing materials comprised some of the first structural materials exploited by humanity (Yi *et al*., 2022). Sand, lime and water are common elements that go into making cement. Cement is essentially a paste made of calcium silicate hydrates that have been polymerized into a strongly crosslinked matrix (Zunino *et al*., 2022). Its capacity to set and stay insoluble under water is known as hydraulicity, and it is its most significant characteristic. (Wilkie & Dyer, 2024).

4 Chemical Composition and Properties of Limestone ($CACO_3$)

The main component of limestone, a sedimentary rock, is calcium carbonate ($CaCO_3$) in the form of the mineral aragonite and calcite. It is one of the most prevalent and extensively dispersed rocks on Earth, having a broad range of use in both natural and industrial contexts. Over millions of years, the accumulation and compaction of marine organisms, mostly the remains of shellfish and coral, results in the formation of limestone. (Zheng *et al*., 2023).

$$CaO + CO_2 \rightarrow CaCO_3 \quad (1)$$

Composition of Limestone

Depending on its composition, this sedimentary rock can display a vast range of patterns and colours, limestone is a rock with a weight percentage of at least 50% calcium carbonate in the form of calcite. Every limestone has some additional components which could be tiny quartz, feldspar, or clay mineral particles that have been carried to the location by streams, currents, or waves. (Bonewitz, 2012). Limestone's high calcium carbonate content provides it a characteristic that is frequently used to identify rocks, when it comes into contact with a cold solution of 5% hydrochloric acid, it effervesces. (Ibrahim *et al*., 2020). The image of limestone is shown in Figure 1.

Figure 1: Limestone (Bonewitz, 2012)

Types of Limestone

There are various types of limestone, each with its unique characteristics. Some common varieties include chalk, marl, travertine, and tufa, which differ in terms of texture, origin, and usage. (Casella *et al*., 2018)

Properties of Limestone

Calcium Carbonate Content: Limestone is primarily composed of calcium carbonate ($CaCO_3$), which gives it its fundamental chemical composition. (Series & Science, 2018)

Colour: Limestone can vary in colour, from white and grey to yellow, brown, and even black. The colour often depends on impurities and mineral content.

Texture: Limestone can have a variety of textures, ranging from fine-grained to coarsely crystalline. This texture impacts its suitability for different uses.

Durability: Limestone is a durable and long-lasting material, making it suitable for many construction and architectural applications.

Hardness: Limestone is relatively soft on the Mohs scale of mineral hardness (around 3) which means it can be easily carved and shaped for artistic and decorative purposes.

Fossils: Many limestone deposits contain well-preserved fossils of marine organisms, making it valuable for scientific and paleontological research. (Casella *et al*., 2018)

Chemical Composition and Properties of Clay

Clay is a naturally occurring, soft, fine-grained, freely bonded rock or earthy material with a diameter of less than 0.005 mm that is mostly made up of clay particles, clay minerals also exhibit a variety of structures and properties (Bansal *et al*., 2016). Their intricate structures are made up of layers, which are two-dimensional units that may or may not have intercalated cations separating them. The crystals can be exfoliated and delaminated into single layers, and with the right chemical changes, they can be used in more advanced applications than those that are available now. (Wypych & de Freitas, 2022). Clay can incorporate with one or more clay minerals even in presence of minute quantities of quartz (SiO_2), metal oxides (Al_2O_3, MgO etc.) and organic matter (Anameje *et al*., 2023)

Chemical Composition and Properties of other Raw Materials in Cement

The other naturally occurring raw materials are silica (SiO_2), shale, and gypsum minerals (gypsum $CaSO_4.2H_2O$, anhydrite $CaSO_4$). Metallurgical slag, nepheline sludge from the alumina manufacturing sector, and sodium hydroxide production sludge—which contains $CaCO_3$, pyrite cinder, and other materials—are some examples of the industrial waste minerals used to make cements (Aragaw, 2018). Since lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron (Fe_2O_3) are the primary oxides needed to manufacture Portland cement, the raw mix needed to make cement clinker is typically made by combining a calcareous material, usually limestone, with a smaller amount of an argillaceous material, usually clay or shale. (Revuelta, 2021)

Cement Production

The procedure used to create cement can be broadly classed as dry or wet, with the difference being in the preparation of the kiln feed. The wet method, which is typically employed when the raw materials are soft, involves adding water to the raw mill while it is grinding the raw materials, resulting in a pumpable slurry (Kaplan *et al*., 2018). The dry process, which is used when raw materials are hard, involves grinding and combining them in their dry form. As a result, the state of the raw materials, whether dry or wet, has a significant impact on process selection (John & Lothenbach, 2023). In recent years, the more cost-effective dry technique has supplanted the wet process. For example, the energy usage in the dry process is roughly one-fourth that of the wet process (Adesina, 2020).

Chemical Reactions and Processes of Cement Production

The chemical reactions and physical processes involved in the production cement are as follow:

Evaporation of the physically sorbed water molecules from the raw mix (20–100 ^{O}C).

Dehydration (100–430 ^{O}C) with the production of oxides, such as silica, alumina, and hematite.
Calcination (800–1100^{O}C) with the development of calcium oxide, according to the carbonate decomposition reaction: $CaCO_3 \rightarrow CaO + CO_2$
Exothermic reactions (1100–1300 ^{O}C) with the formation of secondary silicate phases:
$2CaO + SiO_2 \rightarrow 2CaO + SiO_2$
Sintering and reactions occurring inside the melt (1300–1450 ^{O}C) with conversion of secondary silicate phases into both ternary silicates and tetracalciumaluminoferrites:
$2CaO.SiO_2 + CaO \rightarrow 3CaO.SiO_2$ $3CaO + Al_2O_3 + CaO + Fe_2O_3 \rightarrow 4CaO.Al_2O_3.Fe_2O_3$
Cooling of the system, and the crystallization of the other mineral phases (Lavagna & Nisticò, 2023). Schematic diagram of the process of cement manufacturing flow chart is shown in Fig 2 below.

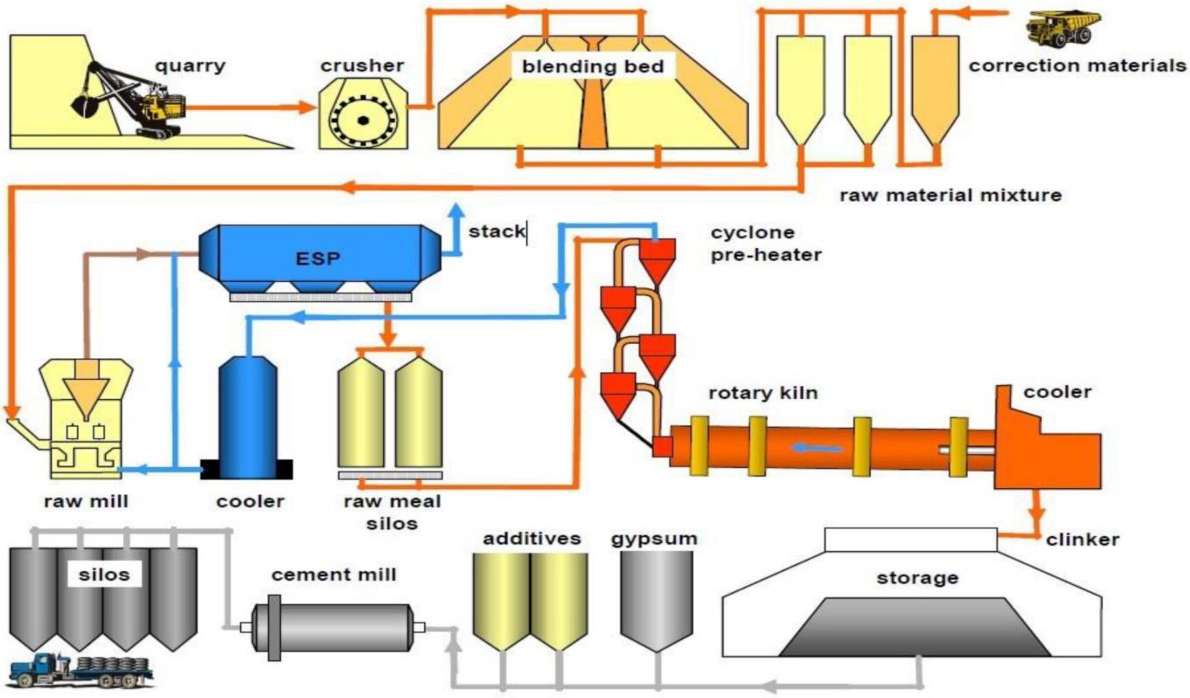

Figure 2: Schematic diagram of the process of cement manufacturing (de Queiroz *et al*., 2013) (Lavagna & Nisticò, 2023)

Cement Classification
The main types of cement worldwide can be outlined according to ASTM, EN, and ISO standards.

Portland Cement
Portland cement is one of the most commonly used construction materials globally. Known for its versatility, strength, and sustainability, it serves as a key component in concrete, mortar, stucco, and general-purpose grout (Kaplan *et al*., 2018). Its grey colour resembles Portland stone, a popular building limestone sourced from the Isle of Portland off the coast of England. The original formulation was made by heating a mixture of lime, iron, silica, and alumina in a rotating kiln, followed by grinding it into a fine powder. (Desharnais, 2019) Fig 3 below shows Portland cement fine powder.

Figure 3: Portland cement fine powder (Desharnais, 2019)

Blended Cement

Blended cement is a versatile construction material that results from the seamless combination of ordinary Portland cement (OPC) with additives like silica fumes, fly ash, limestone, and slag. This fusion enhances the properties of the cement, making it suitable for diverse applications. (Abraham *et al*., 2021). Fig 4 below shows the image of a blended cement.

Figure 4: Blended cement

Special Cement

Special cements are designed to fulfil specific functions in concrete and masonry construction. These functions may include altering the setting or hardening properties of concrete, creating unique architectural effects, improving workability, increasing water retention and plasticity in masonry, enhancing resistance to water penetration in walls or containment vessels, or reducing the cost of the cementing agent. Some of these special cements are suitable for use in extreme temperatures, whether very high or very low. Additionally, certain special cements can withstand acidic environments. (Merlo *et al*., 2021). The various types of special cement are presented below

Masonry Cement

For many years, lime mixed with sand was the standard mortar used in bricklaying. To enhance strength and speed up the hardening process, Portland cement was eventually added to the lime mixture. The plasticity and workability of masonry cement are achieved through the inclusion of limestone and an air-entraining agent. These qualities, along with its water-retention ability, improve the cement's adhesion to bricks and other building materials. (Merlo *et al*., 2020).

Oil Well Cement

In oil well drilling, oil well cement is used to fill the gap between the steel casing and the well wall, as well as to grout porous layers and prevent water or gas from entering the oil-bearing strata. This type of cement must withstand very high pressures and temperatures that can reach up to 400°F. (Abraham *et al*., 2021)

Expanding Cement

Expanding cement increases in volume as it hardens useful in repair work, unlike traditional concrete, which tends to shrink and can develop shrinkage cracks. By mixing expanding cement with regular cement in concrete, this issue can be mitigated, resulting in a material that neither shrinks nor expands. (Adjei & Elkatatny, 2021).

Sorel Cement

Sorel cement is prepared by adding strong magnesium chloride to ground calcinated magnesia finely. Within 3-4 hours, it sets to a hard mass. The advantage of sorel cement is its accelerated rate of setting, which is useful during cold weather. (Adjei & Elkatatny, 2021)

Trief Cement

Trief cement is practically the same blast furnace cement except that the blast furnace slag is ground wet and separate from cement. This cement has smaller shrinkage and smaller heat of evolution while setting than OPC. (Peng & Unluer, 2023)

High Alumina Cement

This type of cement is produced by fusing limestone and bauxite with small amounts of silicon oxide and titanium oxide at temperatures between 1500-1600°C in a rotary kiln, followed by grinding the resulting material to a fine powder, similar to the process for Portland cement. The key components of high alumina cement include monocalcium aluminate, tricalcium pentaaluminate, dicalcium silicate, and tetracalciumaluminoferrite (Peng & Unluer, 2023).

Hydration Chemistry

The chemical reaction between cement and water, referred to as the hydration of cement, plays a crucial role in determining the physical properties of concrete. The extent of hydration and the resulting microstructure of the hydrated cement directly affect these properties. Although often described as the transformation of anhydrous compounds into their corresponding hydrates, the reactions are much more complex (Pourhakkak *et al*., 2021). These reactions are exothermic, releasing enough heat to raise the temperature of the mixture to 100°C or more within a single day. The reactions of the compounds and their products can be summarized approximately as follows:

$$3CaO.SiO_2 + H_2O \rightarrow Ca(OH)_2 + \text{calcium silicate hydrate} \quad (2)$$

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2 \quad (3)$$

The hydration products can be needle-like crystals of ettringite ($6CaAl_2(SO_4)3(OH)_{12} \bullet 26H_2O$) or huge hexagonal crystals of portlandite ($Ca(OH)_2$). As hydration progresses, the deposit of hydration products on the original cement grains makes the diffusion of water to the un-hydrated nucleus more difficult, therefore lowering the rate of hydration over time. (Singh, 2020).

Chemical Reaction and Processes of Clinker Formation

The raw meal in the kiln undergoes a series of reactions as temperature increases gradually. A simplification of these reactions is the following:

Evaporation of free water (100 °C)

Decomposition of the clay minerals (500–800 °C)

Decarbonation of the calcium carbonate—calcination (900 to 1000 °C)

Reactions to form dicalcium silicate (90–1200) liquid is formed only to a minor extent

Clinkering reactions at about 1300–1450 °C to form tricalcium silicate; a melt of aluminate and ferrite is formed to act as a flux to facilitate the formation of alite by the reaction between belite and CaO and the material takes the form of nodules to constitute the clinker.

Cooling of clinker; the melt crystallizes to form the ferrite and aluminate phases; quick cooling generates a more reactive cement

In turn, the assumed chemical reactions that take place throughout the kiln are the following:

$$CaCO_3 \rightarrow CaO + CO_2 \quad (4)$$

$$CaO + 2SiO_2 \rightarrow C_2S \quad (5)$$

$$CaO + C_2S \rightarrow C_3S \quad (6)$$

$$3CaO + Al_2O_3 \rightarrow C_3A \quad (7)$$

$$4CaO + Al_2O_3 + Fe_2O_3 \rightarrow C_4AF \quad (8)$$

Cement Properties

The most important physical properties of Portland cement are setting time, compressive strength and heat of hydration. (Tsardaka *et al*., 2023)

Setting Time

The determination of initial and ultimate setting times dictates the rheological properties of cement in terms of stiffening the cement paste. The initial setting time determines when the cement paste loses its fluidity, whereas the ultimate setting time determines how long it takes for the paste to harden. (Tsardaka *et al*., 2023).

Compressive Strength

The most essential physical attribute of cement is compressive strength, which determines the quality of the final concrete product and is likely the most evident property required for structural applications (Vu *et al*., 2020). The heat of hydration is the amount of heat generated by the reaction of cement and water at a certain temperature, measured in calories per gram. The overall heat created during the hydration process will be determined by the relative quantities of cement's primary components. (Do *et al*., 2020). The ASTM C186 standard test procedure "covers the determination of the heat of hydration of a hydraulic cement by measuring the heat of solution of the dry cement and the heat of solution of a separate portion of the cement that has been partially hydrated for 7 and for 28 days, the difference between these values being the heat of hydration for the respective hydrating period." (Huang *et al*., 2018).

Pozzolanic Reactions

Pozzolanic reaction is a chemical process that occurs when pozzolanic materials (such as fly ash, silica fume, or natural pozzalans) are combined with calcium hydroxide in the presence of water, the reaction is essential in concrete as it improves the strength, durability and other properties of concrete. (Ahmed, 2019a). An overview of the mechanism involved the:

Hydration of Portland cement: Portland cement interacts with water initially to generate insoluble hydration products such calcium silicate hydrate, followed by a more soluble product called calcium hydroxide, which migrates through the pore solution. (Ahmed, 2019)

The reduction in free calcium hydroxide makes the concrete chemically more stable and prevents the penetration of hostile salts and sulphates that diffuse through the concrete (Ahmed, 2019b).

The reaction between $Ca(OH)_2$ and SiO_2, also referred to as the pozzolanic reaction is shown below (Kamau & Ahmed, 2017):

Calcium Hydroxide + Silica → Calcium Silicate Hydrate

$$3Ca(OH)_2 + 2[SiO_2] \rightarrow [3(CaO).2(SiO_2).3(H_2O)] \quad (9)$$

Because of the limited availability of $Ca(OH)_2$ in concrete, the cement substitute range utilizing pozzolans is usually between 2.5-40% (by mass) depending on the kind of pozzolan used and the application of concrete. (Khan & Dominic, 2021). As a result, most pozzolanic concrete contains significantly lower quantities of calcium hydroxide, which gives greater durability features such as sulphate resistance. (Kamau *et al*., 2018)

Supplementary Cementitious Materials (SCMS)

Supplementary cementitious materials (SCMs) are soluble siliceous, aluminosiliceous, or calcium aluminosiliceous powders that are used to partially replace clinker in cements or Portland cement in concrete mixtures. (Kupwade-Patil *et al*., 2018). The thermal energy input for fly ash manufacturing may plausibly be allocated to power production rather than the fly ash waste product. (Scrivener *et al*., 2018). The cement and concrete industries have become reliant on these materials, particularly those that are low cost and readily available from industrial waste streams. (Juenger *et al*., 2019)

Cement Admixture Interactions

Chemical Interactions between Cement and Superplasticizers

Chemical admixtures are chemicals for cementitious mix or additives for cement clinker, also known as the fourth ingredient material other than aggregate, water, and cement that are added to the cementitious mix before or during mixing to modify its properties in both the plastic and hardened stages. (Ji *et al*., 2023). Chemical Admixtures are categorized as synthetic water-soluble superplasticizers like Lignosulphonates (LS), Sulphonated Naphthalene, or Melamine Formaldehyde (NF/MF) and high performance superplasticizers like Poly Carboxylate Ether (PCE) (Ghosal & Kumar Chakraborty, 2022).

Superplasticizers (SP) are a key component of cement cementitious mix mixtures that allows the cementitious mix to flow at a low water-cement ratio while preventing segregation and bleeding, which is essential for high-performance concrete. (Zhang *et al*., 2024)

Chemical Interactions between Cement and Retarders

The term "retarder" refers to an additive that slows the concrete's curing time. Retarders are primarily composed of ligosulfonic acids and their sodium and calcium salts, hydroxycarboxylic acids and their salts, carbohydrates, particularly sugar and their derivatives, and mineral salts such as borate, phosphates, zinc salts, lead salts, and magnesium salts. (Saedi *et al*., 2021). The organic compounds such as carbohydrate molecules are frequently used with superplasticizers as sacrificial agents, increasing the dispersion of cement particles. (Guindani *et al*., 2024). Retarding admixtures have little effect on workability loss since they do not reduce the rate of water absorption or prevent all hydration reactions. (Alsadey & Said Aljenkawi, 2021).

Concrete Chemistry

Chemical Properties and Reactions of Concrete

Concrete can be defined as "a mixture of aggregate, cement, and water, which hardens" and as a "material formed by mixing cement, coarse and fine aggregate, water, with or without the incorporation of admixtures and additions. (Bustillo, 2021). Concrete is a mixture of cement, water, fine aggregate (sand), and coarse aggregate (gravel or crushed rocks), in which the cement and water harden through a chemical reaction (hydration) to bond the non-reactive aggregate. (de Brito & Kurda, 2021)

Concrete is the most popular building material in the construction business. It is utilized in all types of buildings (from residential to office blocks) as well as infrastructure projects (roads, bridges, dams, and so on), making it an important part of our society. (Nilimaa, 2023). Concrete fulfils a wide range of requirements, including its consistency, which ranges from dry to very fluid, and compressive strength, which can range from 0.5 MPa to more than 800 MPa. This broad range of values is nearly impossible to achieve with any other form of construction matter. (Verian *et al.,* 2018)

Workability

Workability is defined as "that property of freshly mixed concrete that affects the ease with which it can be mixed, placed, consolidated, and struck off" while keeping its homogeneity during these processes. (Sika, 2018). Thus, a workable concrete is one with less internal friction between particles. Characterizing workability should take into account the specific characteristics of the concrete construction to be built. (Surahyo, 2019). Consistency refers to a material's ability to maintain its shape after being moulded, or "the relative mobility or ability to flow". (W. Wang *et al*., 2021). The key parameters influencing workability are water content, aggregate size, shape, and grading, aggregate/cement ratio, admixture application, and temperature conditions. (Nithurshan & Elakneswaran, 2023). Another aspect influencing workability is the aggregate/cement ratio, as more cement results in more fluidity. This is because paste can be viewed as the "liquid phase" of the mixture. In this respect, the fineness of the cement corresponds to the loss of workability. (Gandage, 2023)

Durability

The Portland Cement Association defines durability as "the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties." As a result, concrete durability refers to the material's ability to remain usable for at least the needed period of time (working life) of the structure in which it is used. Many specialized legislation globally include criteria for a design life, which can typically vary from 50 to 100 years (Adesina & Zhang, 2024).

The standard EN 206-1 stipulates that working life is "the period of time during which the performance of the concrete in the structure will be kept at a level compatible with the fulfilment of the performance requirements of the structure, provided it is properly maintained" (Alexander & Beushausen, 2019)."

Cement Durability (Chemical Aspect of Cement Durability)

Sulphate Attack

Sodium, calcium, and magnesium compounds can be found in soil or dissolved in groundwater, and when in solution, they react with the components of cement paste. Thus, sulphate solutions react with C_3A inside the concrete, resulting in delayed ettringite formation (DEF). The generated ettringite swells and disrupts concrete. Calcium sulphate has poor solubility hence it is not a high concern. Magnesium sulphate, on the other hand, has the most severe disruptive activity since the reaction product is insoluble, causing large volume increase and perhaps disruption (Qadir *et al*., 2018). Sodium sulphate reacts with calcium hydroxide and calcium aluminate hydrate to form ettringite and gypsum. Attack occurs only when the amount of sulphate present exceeds a specified level. Sulphate attack is heavily influenced by environmental circumstances, and it is especially problematic in arid locations. Sulphates are also present in seawater, but they are less toxic than those found in groundwater. Concrete affected by sulphates usually shows whitish colouring, with damage starting at the edges and corners, followed by gradual cracking that can lead to full failure (Elahi *et al*., 2021).

Alkali-Silica Reaction

In recent decades, the alkali-silica reaction (ASR) has been identified as one of the primary concrete durability issues, resulting in expensive maintenance and reconstruction costs and economically manage the deteriorating process due to ASR in concrete structures (Figueira *et al*., 2019). A new method for minimizing ASR through a secondary role of crystalline waterproofing materials is provided by industries. (Fanijo *et al*., 2021). An aqueous solution of Multi-Crystallization Enhancer (MCE) is intermixed with water or added to the concrete mixture, at a dosage of 2% by weight of cement, then upon curing reduces the permeability under pressure by more than 99% (Al-Jabari *et al*., 2023). Alkali aggregate reactions (AAR) are a category of harmful chemical reactions that occur between soluble alkalis (from cement) and reactive mineral compounds contained within the aggregates' chemical structure. AAR include alkali silica reactions (ASR) and alkali carbonate reactions (ACR).

The ACR are associated with $CaMg(CO_3)_2$ content of the aggregates while the ASR are associated with their silica content (Saha *et al*., 2018).

Sustainability and Environmental Impact

Understanding the environmental issues of cement production has become increasingly important over the last two decades, as it is one of the most energy-intensive industrial manufacturing processes. (Mohamad *et al*., 2022)

CO_2 Emission

Energy consumption in cement manufacturing is determined by a number of parameters, including plant size and design, raw material qualities, fuel specific caloric values, clinker type, and so on. (Barbhuiya *et al*., 2024). Energy expenses account for approximately 40% of overall production costs in the manufacture of one ton of cement, with thermal energy (e.g., fuel) and electrical energy demand being the most important (Hathaway, 2020). Historically, coal was the primary solid fossil fuel used, however, a variety of other solid, liquid, or gaseous fossil fuels such as petroleum coke, lignite, and natural gas are also used (Mokhtar & Nasooti, 2020).

It is critical to remember that cement production is the world's third-largest producer of anthropogenic (man-made) CO_2, after transportation and energy generation. (Yoro & Daramola, 2020). The manufacture of cement emits greenhouse gases both directly and indirectly. CO_2 is produced at two stages during cement production, as a byproduct of fossil fuel combustion, which results in indirect

CO_2 emissions, and from the thermal decomposition of calcium carbonate, which releases CO_2 directly. Nonetheless, the impact of cement businesses is enormous because of the volume of cement production, and reducing CO_2 emissions is vital (Supriya *et al*., 2023).

Alternative fuel utilization began in the 1980s, and the primary fuels utilized are tires, animal residues, sewage sludges, motor oil, spent solvents, printing inks, paint residues, waste oil, waste wood, and solid recovered fuels extracted from industry waste streams (Stančin *et al*., 2020). Fuels derived from waste include shredded paper, plastics, textiles, and rubber. If wastes are employed in a cement plant rather than being landfilled or burned in separate sites, emissions may be lowered indirectly. (MacArthur *et al*., 2020). While some kilns have achieved 100% substitution rates, many others are unable to achieve higher rates of alternate fuel substitution due to local waste markets and permission requirements. (Zieri & Ismail, 2019). Co-processing has a direct influence on reducing CO_2 emissions since it reduces the quantity of natural raw materials required for clinker manufacture(Villagrán-Zaccardi *et al*., 2022).

Waste Reduction

To address the issue of waste, the term "green" or sustainable concrete has evolved. Sustainable concrete strives to reduce energy use, waste, and use recyclable materials. It uses some of the world's most abundant resources to create long-lasting structures with high thermal mass, lowering total environmental effect. (Gao & Ash, 2023). In response to these serious environmental issues, the building industry has begun to use alternative materials and processes. Innovations such as the use of supplementary cementitious materials (SCMs), the use of alternative fuels in cement production, and the development of new concrete mixtures are all part of a coordinated effort to reduce concrete's carbon footprint. (Clarke & Sahin-Dikmen, 2020)

Environmental and Economic Implications

The environmental and economic advantages of employing waste materials in concrete are enormous. By diverting trash from landfills and minimizing the requirement for virgin material extraction, concrete production's carbon footprint is significantly reduced while the initial cost of processing waste materials for concrete usage can be higher and environmental impact fees make a compelling case for their utilization (Jia *et al*., 2023).

Challenges and Future Directions

Despite these encouraging improvements, broad adoption of waste materials in concrete remains a hurdle. The heterogeneity in the quality of waste materials, regulatory impediments, and a lack of public understanding and acceptability are significant barriers. (Gao & Ash, 2023).

CONCLUSION

Cement remains a cornerstone of the construction industry, owing to its unique chemical composition and versatile binding properties. The detailed chemistry of cement has been examined in this work, from the hydration process to the creation of vital molecules such calcium silicate hydrates (C-S-H), which are critical to the material's strength and longevity. The building industry is confronted with a twofold dilemma as demand for sustainable construction rises: improving cement performance while reducing its carbon footprint. Future research should focus on standardizing the quality of waste materials for concrete usage, creating more efficient processing technologies, and raising public awareness through educational and demonstration program.

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