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AND THE LATEST GENERATION

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(Vol. 1)

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Revisión por pares

Cada capítulo de este libro ha sido evaluado mediante un proceso de dictaminación a cargo de académicos externos bajo la modalidad de doble par ciego. En consecuencia, la investigación presentada cuenta con el respaldo de expertos en la materia, quienes han emitido una valoración objetiva basada en criterios científicos para garantizar la solidez académica de la obra.

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Dedication

To God, the source of inspiration and wisdom, who has guided me along this path.

To my son, the light of my life and my motivation to keep moving forward.

To my wife, my companion and unconditional support, who has given me her love and encouragement every step of the way.

To my parents, who have taught me the values and the importance of perseverance and hard work.

To my siblings, who have been my support and source of inspiration in difficult times.

And to all the friends and colleagues who have contributed to the creation of this book, thank you for your collaboration, support, and friendship. Without you, this project would not have been possible.

This book is a tribute to the passion and commitment we have all shared in the pursuit of a more sustainable and responsible future. I hope it serves as a valuable tool for those seeking to build a better world for future generations.

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Introduction

This book is born from the search for a captivating topic for the reader, aiming to have an impact on the education of students in the field of construction. Concrete is one of the most versatile and durable construction materials in the world. It is used in a wide range of applications, from buildings and bridges to roads and industrial structures, which is why this organized collection of information is focused on this subject.

The material encompassed by this book was planned with the purpose of addressing important topics that enable students to understand and conceptualize concrete from its initial stages. Specific examples of topics that will capture interest from students include the use of raw materials, the origin of the materials that form cement, progressing to the manufacturing of concrete, the necessary quality controls, and the current uses and variations of concrete in the construction industry.

How do we define concrete? From a geological perspective, it is simply known as an artificial stone, whereas in architecture, its importance lies in its greatest virtue: its ability to adopt any shape. This is achieved with the help of a mold capable of shaping the concrete in the desired manner. The most characteristic advantage of concrete is that its primary component is cement, made from common raw materials such as clay and limestone.

One of the principal limitations of concrete is its low tensile strength. When concrete is subjected to tension, it stretches, leading to its first evolution, which is the combination of concrete with steel. This gives rise to reinforced concrete. A current area of study in concrete involves identifying strategic ways to assemble and reinforce it in key areas to achieve high strength and durability.

Taking this into account, the difference between concrete and cement is clear: cement is a component of concrete that, when combined with water and aggregates, serves as the binding material; therefore, cement cannot be used on its own in structural elements, whereas concrete, by integrating these components, attains the strength and durability required for construction applications.

Concrete is one of the most widely used construction materials due to its high strength, durability, versatility, and relatively low economic cost, making it essential for infrastructure and housing development; however, its extensive use entails a significant environmental cost, as cement production generates considerable CO_2 emissions, requires high energy consumption, and involves intensive extraction of natural resources, contributing to climate change, resource depletion, and ecosystem degradation, which underscores the need to move toward more sustainable construction practices.

Concrete is a major contributor to global carbon emissions, accounting for about 8–10% of total emissions. Its production process involves cement, a key ingredient that emits significant CO2 when limestone is heated to produce clinker. (Barbhuiya et al., 2025)

This book provides a comprehensive introduction to concrete. It covers the following topics:

- Concrete and its evolution over time
- Manufacturing process and chemical composition of Portland cement
- Characteristics of water, aggregates, and additives for concrete
- Mineral additions
- Concrete dosing methods
- Fresh state concrete
- Hardened state concrete
- Durability and pathology of concrete
- Special and next-generation concretes

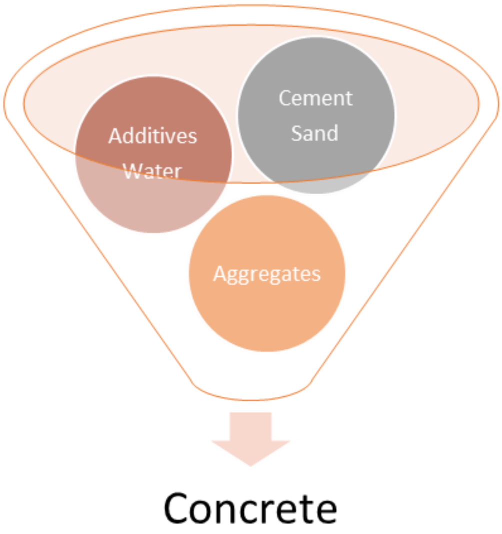
Chapter I

Concrete and Its Evolution Over Time

The construction material known as concrete is composed of cement, aggregates, and water. It is the most widely used construction material globally and is employed in a diverse range of applications, from the construction of buildings to the development of roadways.

Concrete is distinguished by its strength, durability, and versatility. It is highly resistant to compression and can bear substantial loads. Additionally, it is an exceedingly durable material, capable of withstanding the effects of weather and corrosion. Furthermore, concrete is remarkably versatile and can be used to create a wide array of shapes and structures.

Figure 1.
Mixture of Binders for Concrete



Source: Figure by authors.

Cementitious Materials in Antiquity

The earliest cements used in ancient times were made from mixtures of natural materials. These cements were relatively weak and not water-resistant. However, they marked a significant advancement in construction, enabling ancient builders to construct larger and more complex structures.

The earliest cementitious materials were used in ancient Mesopotamia, Egypt, and Greece. In Mesopotamia, the Sumerians used a mixture of clay and straw to construct bricks. In Egypt, the ancient Egyptians used a blend of lime and sand to build pyramids and other monuments. In Greece, the ancient Greeks employed a combination of lime and sand to construct temples and other edifices.

The Romans were the first to develop an advanced hydraulic cementitious systema modern cement. Roman cement was made from a mixture of lime, pozzolana (also known as pozzolanic ash), and water. Pozzolana is a volcanic material that reacts with lime to form a highly water-resistant paste. The Romans used this cement to build bridges, atriums, variously shaped vaults, aqueducts, and other monuments that still stand today.

Modern cement is made from a mixture of lime, clay, and silica. Modern cement is stronger than Roman cement and can be used to build a wide variety of structures.

Concrete is a versatile material that can be used to construct a wide range of structures, from buildings to bridges and roads. It is durable and economical, and relatively easy to produce and place.

In the 21st century, concrete remains one of the most widely used construction materials in the world. It is essential for modern construction and is likely to continue being a crucial material in the future.

Emergence of Portland Cement

Portland cement is a hydraulic binder used in the production of concrete. It is obtained by calcining a mixture of limestone and clay, which is then ground to a fine powder. Portland cement is essential for construction, used to build a wide variety of structures, from buildings to bridges and roads.

The emergence of Portland cement dates back to the 19th century. In 1824, Joseph Aspdin, an English entrepreneur (Aspdin, 1824), patented a new type of cement he named "Portland" due to its resemblance to Portland stone, a limestone found on the Isle of Portland in southern England (Sanjuán Barbudo & Chinchón Yepes, 2014).

Figure 2.
Portland Cement

Source: Rongsheng Group, 2023.

Aspdin's Portland cement was made from a mixture of limestone and clay that was calcined at temperatures above 1,400°C. The resulting product was ground to a fine powder used to make concrete.

Aspdin's Portland cement was a significant advancement in construction, being stronger and more water-resistant than the cements previously used. This enabled engineers to construct larger and more complex structures.

In the following years, improvements were made to the manufacturing process of this cement. In 1840, James Frost developed a method to produce Portland cement from a mixture of limestone and silica. This method was more efficient than Aspdin's and reduced production costs.

In the 20th century, Portland cement became the most widely used construction material in the world due to its versatility, durability, and water resistance.

Figure 3.
Rotary Kiln for Calcination

Source: Construex.

Portland Cement Today

It is used to construct a wide variety of structures, from buildings to bridges and roads (Asociación Española de Fabricantes de Cemento, 2023). Today, Portland cement is produced worldwide. The main producers of Portland cement are China, India, the United States, and Japan.

Portland cement is produced by calcining a mixture of limestone and clay. Limestone is a mineral primarily composed of calcium carbonate. Clay is a mineral primarily composed of silicates.

The production process of Portland cement can be divided into the following stages:

1. Extraction of raw materials: Limestone and clay are extracted from quarries or mines.
2. Preparation of raw materials: Limestone and clay are crushed and mixed in appropriate proportions.
3. Calcination: The mixture of limestone and clay is heated to temperatures above 1,400°C. This process removes moisture and gases from the mixture.
4. Grinding: The clinker is ground to a fine powder.
5. Addition of gypsum: Gypsum is added to the Portland cement powder to control the setting time.

Portland cement is a structurally efficient composite material characterized by high compressive strength and long-term durability under diverse environmental conditions. It is resistant to water and fire. It is used in the construction of a wide variety of structures, including:

- Buildings
- Bridges
- Roads
- Civil engineering Works
- Infrastructure projects

Portland cement is essential for modern construction. It is likely to remain an important material in the future.

Other Cements

In addition to Portland cement, other types of cement are used in construction, such as pozzolanic cement, blast furnace slag cement, high-alumina cement, white cement, and modified cement (Asociación Española de Fabricantes de Cemento, 2023). These cements differ from Portland cement in their properties and characteristics.

Some of the most common types of cement are:

- Pozzolanic Cement: This type of cement is produced by mixing Portland cement with pozzolana, a volcanic material with cementitious properties. Pozzolanic cement is more resistant to alkalinity and water action than Portland cement.
- Blast Furnace Slag Cement: It is produced by mixing blast furnace slag with Portland cement. Blast furnace slag is a byproduct of the steel industry with cementitious properties. Blast furnace slag cement is more economical than Portland cement and has higher compressive strength.
- High-Alumina Cement: Made from the calcination of bauxite, a mineral primarily composed of aluminum oxide. High-alumina cement is very resistant to heat and corrosion but is more expensive than Portland cement.

- White Cement: This cement is made from light-colored raw materials, such as white limestone and white clay. White cement has a more aesthetic appearance than Portland cement and is used in applications where appearance is important, such as in the construction of monuments and sculptures.
- Modified Cement: This type of cement consists of Portland cement with added additives to improve its properties. For example, fiber-modified cements are more resistant to tensile stress, while polymer-modified cements are more resistant to moisture.

The choice of the appropriate type of cement depends on the specific conditions of the application. For example, Portland cement is the most commonly used type in general construction, but pozzolanic cement or blast furnace slag cement may be more suitable for applications requiring greater resistance to water or alkali.

Evolution of Concrete in History

Years 7000 and 6000 B.C.

During these years, the first indications of the use of cementitious mixtures in construction were found (Asociación Española de Fabricantes de Cemento, 2023). At the archaeological site of Catal Huyuk in Turkey, remnants of structures dating back to this period were discovered. These structures were made of a mixture of lime, sand, and water.

At the archaeological site of Jericho in Palestine, remains of a wall from this period were found. This wall was made of a mixture of lime and sand.

These findings indicate that ancient civilizations already knew how to use cementitious mixtures to build structures. However, these mixtures were not as strong as modern concrete.

Figure 4.
Median Empire Ecbatana

Source: Keribark Izzet. GettyImages.

Egypt

The Early Uses of Concrete in Egypt date back to the Predynastic period, around 3100 B.C. During this period, Egyptians used a cementitious material called gypsum to bind mud bricks.

In the Dynastic period, Egyptians began using a more durable cementitious material called hydraulic lime. Hydraulic lime was obtained by calcining limestone rocks rich in alumina.

The Egyptians used concrete to build a variety of structures, such as pyramids, temples, palaces, and dams. A prime example of these structures is the Pyramids of Giza, one of the Seven Wonders of the Ancient World, made of limestone blocks bonded with hydraulic lime mortar.

Other examples of buildings constructed with concrete include:

- Egyptian temples, such as the Karnak Temple and the Luxor Temple.
- Egyptian palaces, such as the Palace of Amenhotep III at Malqata.
- Egyptian dams, such as the Aswan High Dam.

The Egyptians continued to develop concrete over the centuries. In the New Kingdom, Egyptians began using additives to improve the properties of concrete.

One of the most common additives was silica sand, which was used to increase the strength of concrete. Another common additive was volcanic ash, which was used to improve the durability of concrete.

The Egyptians were the first to use concrete on a large scale (Asociación Española de Fabricantes de Cemento, 2023). Their use of concrete allowed them to build monumental structures that have survived for centuries.

Figure 5.
Pyramids of Giza

Source: D, L. L. (2019, 20 marzo). Grupo JOBEN.

Greece

The early uses of concrete in Greece date back to the 7th century B.C. During this period, they used a cementitious material called gypsum to bind mud bricks. The Greeks used concrete to build a variety of structures, such as temples, theaters, aqueducts, and walls.

The Greeks continued to develop concrete over centuries. In the 2nd century B.C., Greek engineers developed a new type of concrete called opus caementicium, which was stronger and more durable than gypsum concrete.

Opus caementicium was made from a mixture of limestone, sand, water, and lime. Lime was obtained by calcining limestone. The Greeks used this type of concrete to build a variety of structures, such as the Roman Pantheon and the Roman Colosseum.

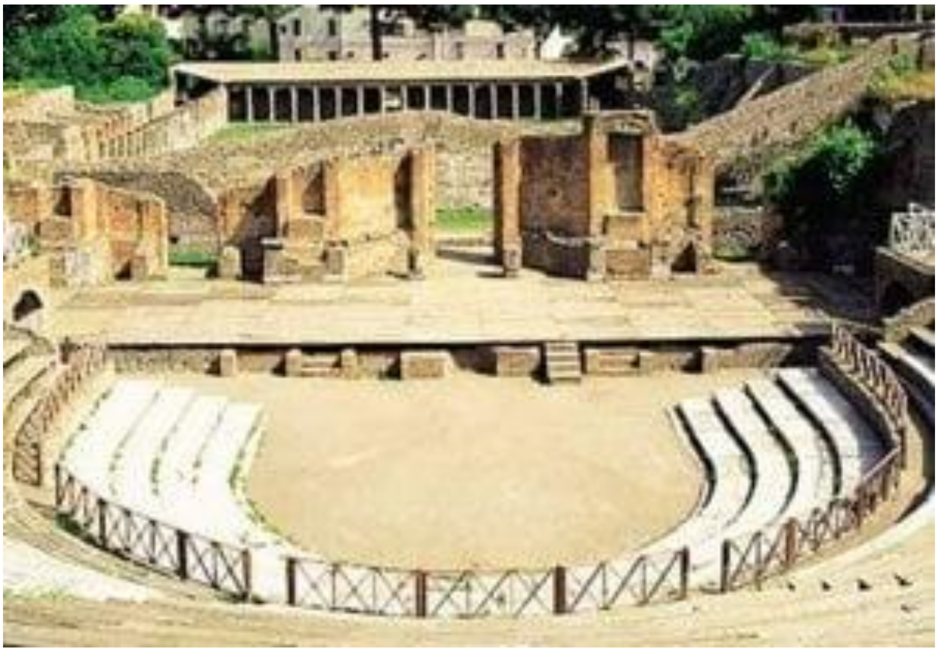
The Greeks were pioneers in the use of concrete. Their use of concrete allowed them to build monumental structures that have survived for centuries (Asociación Española de Fabricantes de Cemento, 2023). The legacy of Greek concrete remains evident in architecture worldwide.

Rome

The history of concrete in Rome dates back to the 4th century B.C., when the Etruscans began using a type of concrete made of lime, sand, and water. However, it was in the 2nd century B.C. when the Romans developed a new concrete formula that allowed them to build much larger and more resistant structures.

This formula was based on the addition of pozzolana, a volcanic ash found near Mount Vesuvius. Pozzolana has the ability to react with lime in the presence of water, forming a very resistant material.

Figure 6.
Theatre of Pompeii



Source: Ferrara Antonio, 2016.

With the incorporation of pozzolana, the Romans were able to construct structures that could not be built with Etruscan concrete. Some examples of these structures are the Colosseum, the Pantheon, and the aqueduct of Segovia.

Figure 7.
Aqueduct of Segovia

Source: World Monuments Fund.

The evolution of concrete in Rome can be divided into three main stages:

1. Etruscan Stage (4th century B.C.)

During this stage, the Etruscans used a type of concrete made of lime, sand, and water. This concrete was relatively weak and could not support large loads.

2. Early Roman Stage (2nd century B.C.)

During this stage, the Romans developed a new concrete formula incorporating pozzolana. Pozzolana gave concrete a greater strength, allowing the Romans to build much larger and more resistant structures.

3. Late Roman Stage (1st century A.D.)

During this stage, the Romans continued to develop new techniques for building with concrete. For example, they developed the use of iron to reinforce concrete, making it even more resistant.

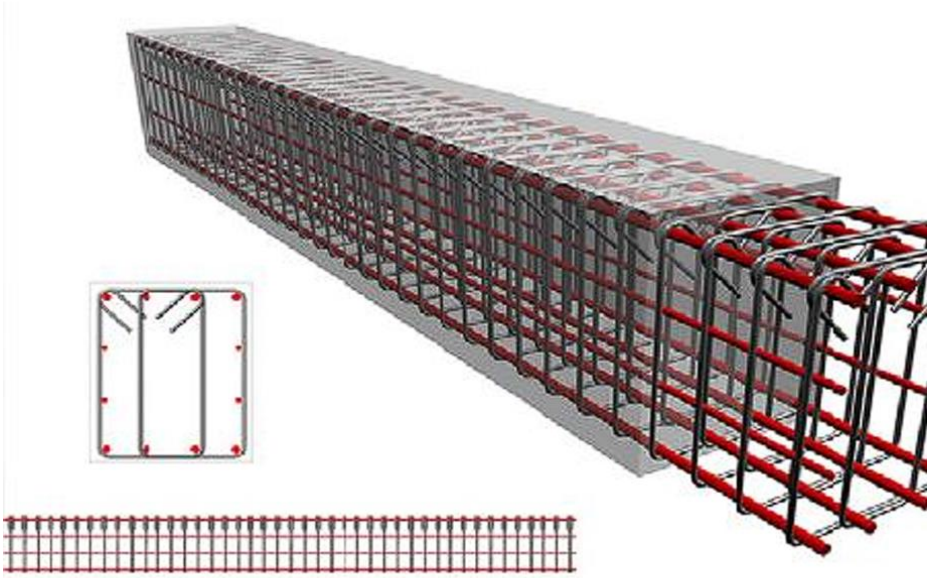
Roman concrete was a revolutionary technological advancement that allowed the Romans to build structures that could not be constructed with any other material. This material was fundamental to the development of the Roman Empire and its influence on world architecture.

1848

In 1848, British engineer William Aspdin patented a new type of cement known as Portland cement (Aspdin, 1848). Portland cement was stronger and more durable than previous cements, making it ideal for the construction of important structures.

The invention of Portland cement was an important milestone in the evolution of concrete. Portland cement allowed the construction of taller and more complex structures that were more resistant to earthquakes and other natural events.

Figure 8.
Reinforced Concrete



Source: Vargas Magaña Carlos. Construex.

1867

The year 1867 was a pivotal year in the evolution of concrete, as several technological advancements were made that enhanced its strength, durability, and versatility.

One of the most significant advancements was the development of Portland cement, a type of cement that is more resistant and durable than previous cements. Portland cement was invented by Joseph Aspdin in England in 1824, but it was not until 1867 that it was mass-produced and widely available.

Another crucial advancement was the development of steel reinforcement, used to strengthen concrete and make it more resistant to tension. Steel reinforcement was invented by François Hennebique in France in 1867.

These technological advancements made concrete more suitable for a wide range of applications, including buildings, bridges, roads, and other structures

Figure 9.
Reinforced Concrete Slab.

Source: Don Concreto, 2021.

1890

In this year, the development of the theory of reinforced concrete occurred, which is a scientific understanding of how steel and concrete interact to provide strength. The theory of reinforced concrete was developed by Eugene Freyssinet in France in 1890.

1903

One of the most significant advancements was the development of prestressed concrete, a type of concrete that is reinforced by applying tensile forces before it sets. Prestressed concrete was developed by the French engineer Eugene Freyssinet in 1903.

Another important advancement was the development of continuous mixing technology, which allowed for a more efficient and uniform production of concrete. Continuous mixing technology was developed by the American engineer Joseph Monier in 1903.

1904

In this year, the development of lightweight concrete occurred, a type of concrete produced with lightweight aggregates such as expanded clay or polystyrene foam. Lightweight concrete is lighter than conventional concrete, making it suitable for constructing structures that need to be lightweight, such as tall buildings or roofs.

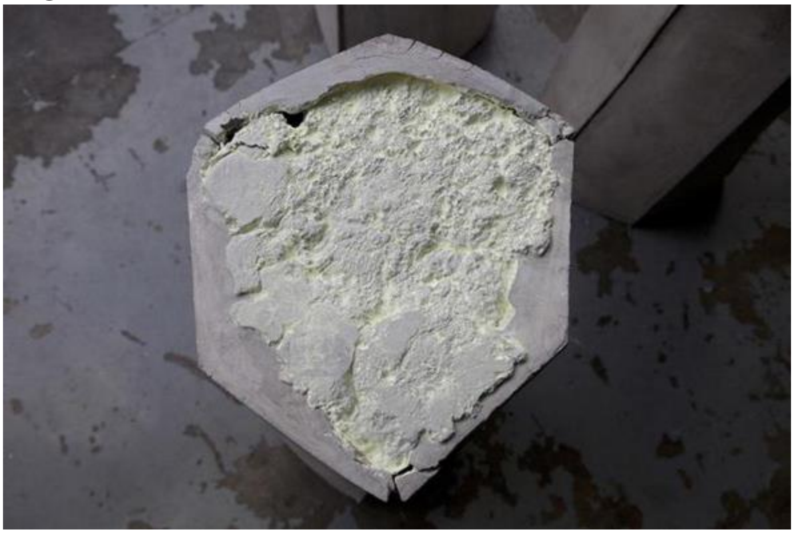
Another significant advancement was the development of prefabricated reinforced concrete, a type of reinforced concrete that is manufactured in a factory and transported to the construction site. Prefabricated reinforced concrete is faster and more efficient to construct than traditional reinforced concrete, making it more cost-effective.

1908

In this year, the development of high-strength concrete took place, a type of concrete with much higher compressive strength than normal. High-strength concrete is used in constructing structures that need to be very strong, such as tall buildings or dams.

Another significant advancement was the development of post-tensioned reinforced concrete, a type of reinforced concrete that is strengthened by applying tensile forces after it has set. Post-tensioned reinforced concrete is more resistant to tension than conventional reinforced concrete, making it suitable for constructing longer and thinner structures.

Figure 10.
High-Alumina Cement



Source: UNANSEA.

1930

In this year, precast concrete was developed, a type of concrete that is manufactured in a factory before being transported to the construction site. Precast concrete is faster and more efficient to construct than traditional concrete, making it more cost-effective.

Another significant advancement was the development of prestressed reinforced concrete, a type of reinforced concrete that is strengthened by applying tensile forces before the concrete has set. Prestressed reinforced concrete is more resistant to tension than conventional reinforced concrete, making it suitable for constructing longer and thinner structures.

Figure 11.
Permeable Concrete

Source: Betonrossi DRAINBETON.

1960

By this year, high-performance concrete was developed, a type of concrete with much higher compressive strength than conventional concrete. High-performance concrete is used in structures that need to support heavy loads, such as bridges, dams, and tall buildings.

Another significant advancement was the development of fiber-reinforced concrete, a type of concrete that is strengthened with fibers such as steel, polypropylene, or glass. Fiber-reinforced concrete is more resistant to cracking and abrasion than conventional concrete.

Figure 12.

Polymer Concrete

Source: Reforplas, 2022.

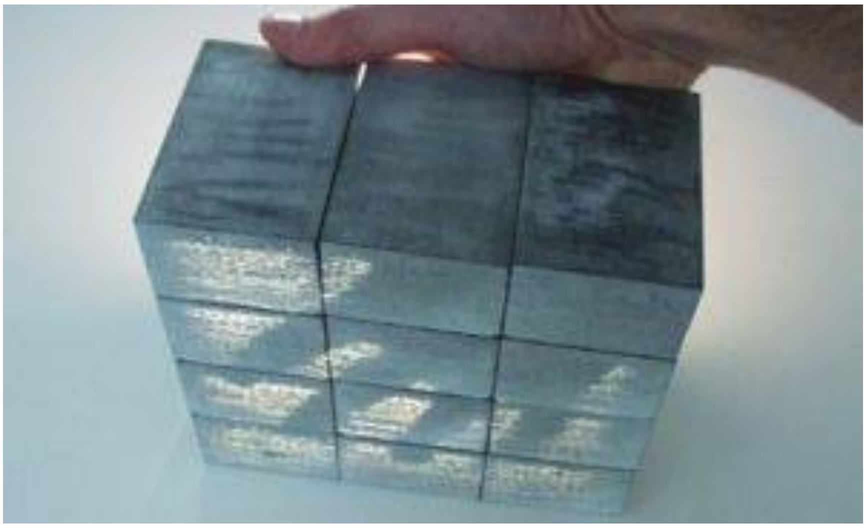
2005

In this year, recycled concrete was developed, a type of concrete manufactured with recycled aggregates such as crushed concrete, bricks, and ceramics. Recycled concrete helps reduce the amount of waste sent to landfills.

Another significant advancement was the development of self-compacting concrete, a type of concrete that does not require vibration to be placed. Self-compacting concrete is more efficient and reduces the possibility of damaging existing structures.

Figure 13.

Translucent Concrete



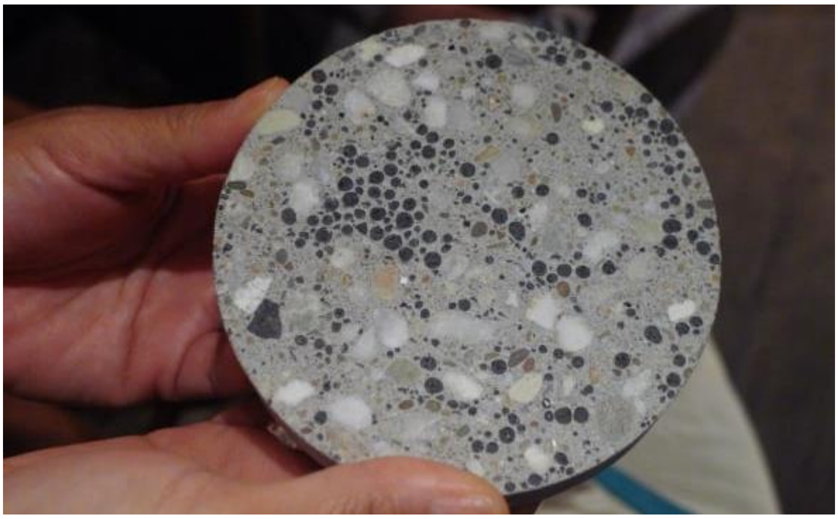
Source: PlanReforma, 2024.

2011

In this year, high-performance self-compacting concrete was developed, a type of concrete with much higher compressive strength than conventional concrete, and which does not require vibration to be placed. High-performance self-compacting concrete is more sustainable, efficient, and durable than conventional concrete.

Another significant advancement was the development of stamped concrete, a type of concrete that can be decorated with patterns or textures. Stamped concrete is more decorative and can be used to create a variety of visual effects.

Figure 14.
Bio-Concrete



Source: Buscador de Arquitectura.

2017

In this year, concrete with nanomaterials was developed, a type of concrete strengthened with nanomaterials such as carbon nanotubes or graphene. Concrete with nanomaterials is stronger, more durable, and more resistant to corrosion than conventional concrete.

Another significant advancement was the development of low-carbon concrete, a type of concrete produced using less energy and emitting fewer greenhouse gases than conventional concrete. Low-carbon concrete is more sustainable and helps reduce the environmental impact of construction.

History of Concrete Buildings

Roman Colosseum, 70 and 80 A.D.

The Roman Colosseum is a concrete building constructed between 70 and 80 A.D. It is one of the most iconic monuments of ancient Rome and is considered one of the Seven Wonders of the Modern World. It is made of a type of concrete called opus caementicium, which was made from limestone, sand, lime, and water. This type of concrete was very strong and durable, and it was used to construct a wide variety of structures in ancient Rome, such as bridges, aqueducts, and public buildings. The Colosseum is an example of the mastery of Roman engineers in the use of concrete. The structure is oval and stands 48 meters high. The facade is divided into three levels, each with 80 arches. The interior is divided into a central arena and a series of tiers.

Figure 15.
Roman Colosseum

Source: Wikiwand.

Smeaton's Tower, 1774

Smeaton's Tower was a lighthouse built in Eddystone, England, between 1759 and 1774. It was the first lighthouse constructed with concrete in the world and was a significant milestone in the history of construction. It was designed by John Smeaton, an English civil engineer. Smeaton used a mixture of limestone, sand, and lime to create a concrete strong and durable enough to withstand the harsh sea conditions. The lighthouse stood 17 meters high with a base of 15 meters in diameter.

Figure 16.
Smeaton's Tower

Source: Wikiwand. (https://www.wikiwand.com/es/articles/Estudios_cl%C3%A1sicos)

Unity Temple, 1905 and 1908

The Unity Temple is a Unitarian Universalist church in Oak Park, Illinois, and the home of the Unity Temple Unitarian Universalist Congregation. It was designed by the American architect Frank Lloyd Wright and built between 1905 and 1908.

The Unity Temple is one of the most important buildings of Frank Lloyd Wright from the early 20th century. It is considered by many architects to be the first modern building in the world.

The building is made of reinforced concrete, an innovative material at the time. Reinforced concrete is a combination of concrete and steel, which gives the material great strength and durability.

Figure 17.
Unity Temple

Source: Viñau Ena Nacho, 2017.

Fallingwater, 1935 and 1939

Fallingwater is a two-story country house built over a waterfall on Bear Run in Pennsylvania. The building was designed by the American architect Frank Lloyd Wright and constructed between 1935 and 1939.

Fallingwater is an example of organic architecture, which integrates with the natural environment. The building is made of reinforced concrete, a material that allows for creating curved and organic shapes.

Figure 18.
Fallingwater

Source: Nacho Viñau Ena, 2017. (https://decoracion.trendencias.com/varios/los-edificios-mas-celebres-construidos-por-frank-lloyd)

Panama Canal, 1914

The construction of the Panama Canal was a monumental engineering project that took over a decade and required the construction of numerous concrete buildings. The canal, which connects the Atlantic Ocean with the Pacific Ocean, was inaugurated in 1914 and is one of the most important engineering achievements in the world.

Figure 19.
Panama Canal

Source: Juan Carlos Machorro, 2020. (https://www.periodismoyambiente.com.mx/2020/08/07/1-a-50-la-competencia-que-dara-el-istmo-de-tehuantepec-al-canal-de-panama-2/)

Sydney Opera House, 1973

The Sydney Opera House is a reinforced concrete building designed by Danish architect Jørn Utzon and constructed between 1959 and 1973. It is an iconic building of Sydney and one of the most famous structures in the world.

The building is located on Sydney Harbour and is composed of a series of concrete shells that rise above the water. The shells are made of prestressed reinforced concrete, a material that allows for the creation of curved and complex shapes.

The Sydney Opera House is an architecturally and culturally significant building. It is an example of modern architecture and a symbol of the city of Sydney.

Figure 20.
Sydney Opera House

Source: Pertanto, 2023. (https://pertanto.com/arquitectura-y-diseno-dando-forma-a-vidas-transformando-comunidades/)

John F. Kennedy Museum, 1993

The John F. Kennedy Museum is a reinforced concrete building designed by architect I. M. Pei and constructed between 1989 and 1993. It is located in Columbia Point, Dorchester, Boston, Massachusetts, USA.

The building consists of a series of concrete blocks rising above a podium. The blocks are made of prestressed concrete, a material that allows for the creation of curved and complex forms.

Figure 21.
JFK Museum

Source: Dorchester, 2022. (https://www.postcard.inc/places/john-f.-kennedy-presidential-library-and-museum-boston).

Chapter II

Manufacturing Process and Chemical Composition of Portland Cement

Raw Material Extraction

The extraction of raw materials for the production of Portland cement is the first step in the manufacturing process. According to García-Molina, González-Alonso, and López-Caballero (2020), "limestone and clay are the main raw materials for the production of Portland cement" (p. 25). Limestone is a type of sedimentary rock primarily composed of calcium carbonate. Clay is a type of sedimentary rock primarily composed of aluminosilicates.

Limestone quarries can be found worldwide. The extraction of limestone is done through controlled blasting or mechanical methods. The extracted limestone is sorted by size and sent to the cement plant.

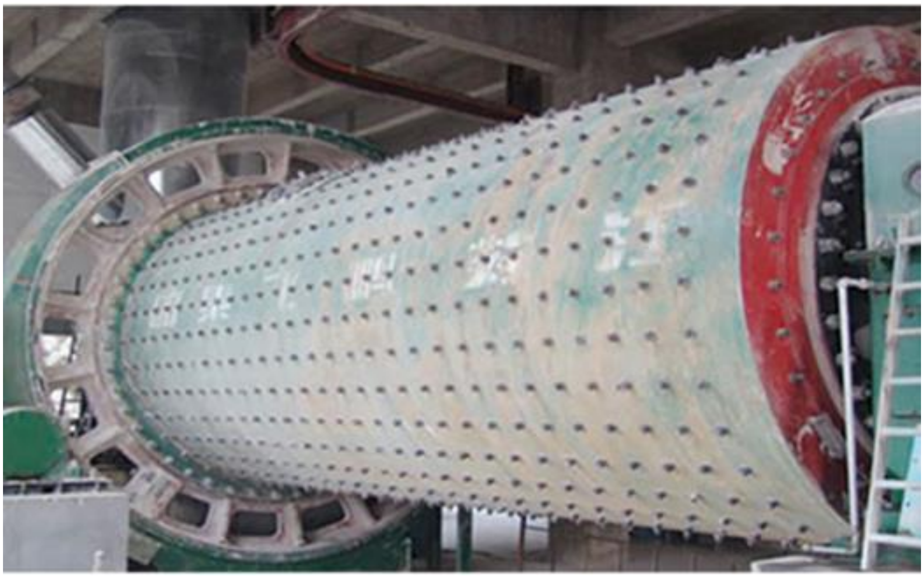
Figure 22.
Permeable concrete

Source: Cementos Torices. (https://cementostorices.com/blog/sostenibilidad/concreto-permeable-que-es-y-cuales-son-sus-aplicaciones/)

Clay quarries can also be found worldwide. The extraction of clay is carried out using mechanical methods. The extracted clay is sorted by size and sent to the cement plant. Once the raw materials are at the cement plant, they are mixed in specific proportions. The mixture is ground to a fine powder, which is then heated in a rotary kiln at temperatures up to 1,450 °C. In the kiln, the raw materials are sintered, meaning they combine to form a solid material.

The product from the kiln is known as cement clinker. The clinker is ground to a fine powder, known as Portland cement, which is a hydraulic material, meaning it hardens in the presence of water. The process of extracting raw materials for the production of Portland cement is a vital part of the cement industry. The raw materials are abundant and can be found worldwide.

Figure 23.
Raw mill



Source: ETW cloud. (https://mx.etwinternational.com/2-4-raw-material-mill-100170.html).

Raw Material Grinding

Is important to mention that the grinding raw materials is an essential step in the production of Portland cement. The raw materials, typically consisting of limestone and clay, are ground to a fine powder" (p. 27). This powder is mixed with water and heated in a rotary kiln at temperatures up to 1,450 °C. In the kiln, the raw materials are sintered, forming a solid material.

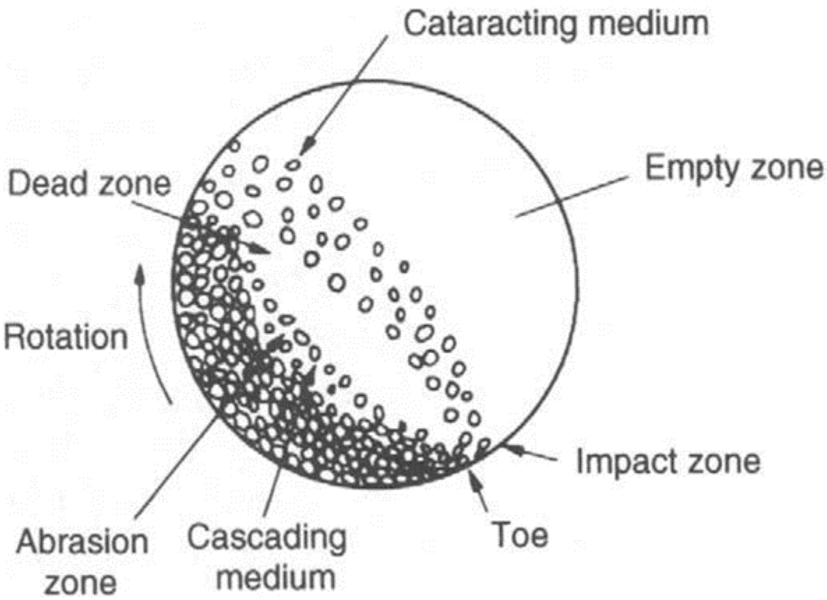
The grinding of raw materials is done in ball mills, which are large cylinders containing steel balls. The steel balls rotate at high speed, grinding the raw materials to a fine powder.

Figure 24.
Roller raw mill

Source: PSCL. (https://www.pscl.com/es/calidad-del-cemento/)

The size of the powder particles is crucial for the quality of Portland cement. The powder must be fine enough to mix uniformly with water and sinter in the kiln. If the powder is too fine, it can be challenging to mix and may cause quality issues in the cement. If the powder is too coarse, it may not sinter correctly, causing strength problems in the cement.

Figure 25.
Schematic diagram of a ball mill



Source: Gwiranai Danha, 2013. (https://www.researchgate.net/figure/Mode-of-operation-of-a-ball-mill_fig2_302901957)

Raw Material Homogenization

The homogenizing of raw materials is an important process carried out before grinding. The goal of this process is to ensure that the raw materials mix uniformly, resulting in obtaining cement with the desired properties".

The raw materials for Portland cement are typically limestone and clay, which have different chemical and physical properties. Therefore, it is crucial that they mix uniformly. Homogenizing the raw materials also helps reduce the variability of the cement, this is important to ensure product quality. The homogenization of raw materials can be carried out in various ways. A common method is using a continuous mixer, which combines the raw materials as they feed into the process. Another method for the homogenization of raw materials is using a hopper mixer, which combines the raw materials in a hopper before feeding them into the grinding process.

The homogenization process typically occurs in several stages. In the first stage, the raw materials are crushed to obtain a uniform grain size. In the second stage, the raw materials mix in a continuous or hopper mixer. In the third stage, the raw materials are stored in a silo until they are ready for grinding. This process ensures that the raw materials mix uniformly, resulting in obtaining cement with the desired properties.

Combustion of the Mix

The combustion of the mix for Portland cement is a complex process carried out in a rotary kiln". The raw material mix, typically consisting of limestone and clay, is heated to temperatures up to 1,450 °C. In the kiln, the raw materials sinter, meaning they combine to form a solid material.

The combustion process can be divided into three main stages:

- Drying: In this stage, the raw material mix is heated to a temperature of about 800 °C. The heat removes moisture from the mix, facilitating further processing.
- Pyrolysis: In this stage, the raw material mix is heated to about 1,000 °C. The heat decomposes the organic matter in the mix, releasing gases and vapors.
- Sintering: In this stage, the raw material mix is heated to up to 1,450 °C. The heat causes the raw materials to melt and combine, forming a solid material.

The product of combustion is known as "clinker," that is the primary raw material for making Portland cement.

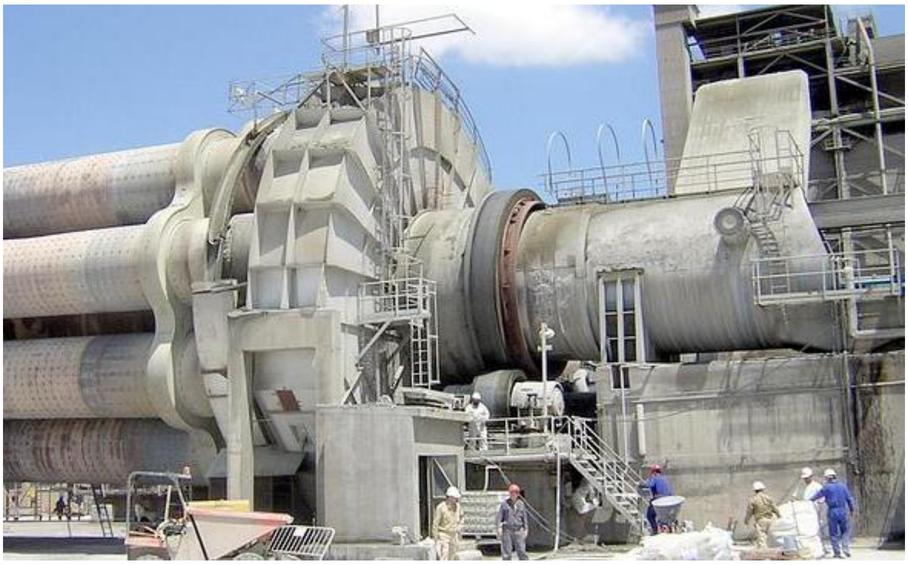
The combustion of the mix for Portland cement is a critical process which determines the properties of the final product. The temperature and duration of the process affect the chemical composition of the clinker, influencing the strength of the cement, its durability, and other properties.

Clinker Cooling

Clinker is a hard, gray substance that is the primary raw material for cement manufacturing. The cooling of clinker is carried out to solidify it and prepare it for grinding.

Figure 26.

Dry process kiln

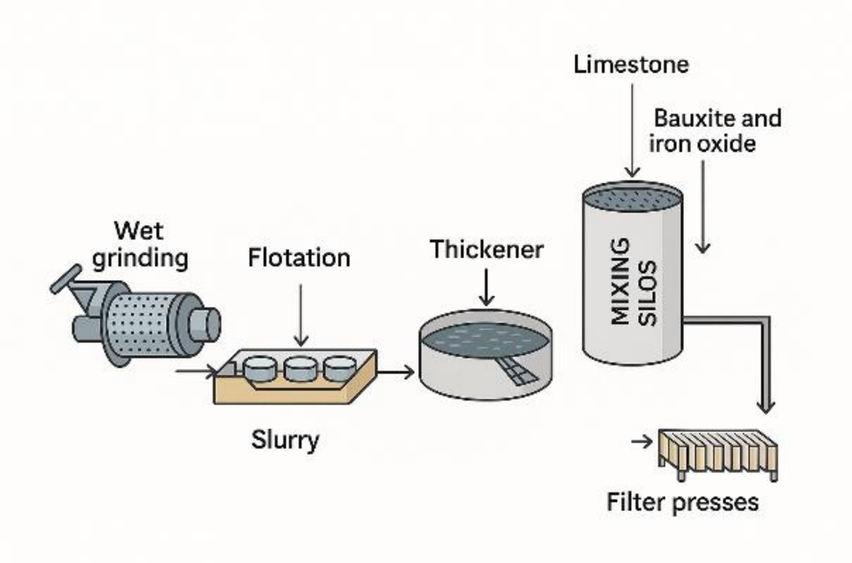


Source: Javier Prieto, 2011. (https://www.abc.es/economia/abci-cemento-201101190000_noticia.html?ref=https%3A%2F%2Fwww.abc.es%2Feconomia%2Fabci-cemento-201101190000_noticia.html)

The cooling of clinker can be done in various ways. A common method is using a grate cooler. The grate cooler is a device consisting of a series of grates through which air is blown. The cold air passes through the grates and cools the clinker.

Another method of cooling clinker is using a tube cooler. The tube cooler is a device consisting of a series of tubes through which water circulates. The cold water circulates through the tubes, cooling the clinker.

Figure 27.
Wet process



Source: José Ignacio Acosta Mora, 2017. (https://slideplayer.es/slide/11296341/)

Cooling the clinker is a delicate process. If the clinker cools too quickly, it can crack or become brittle. If the clinker cools too slowly, it can absorb moisture, making grinding difficult.

Clinker cooling is done in several stages. In the first stage, the hot clinker is discharged from the rotary kiln. In the second stage, the clinker cools to about 200 °C. In the third stage, the clinker cools to about 50 °C.

Clinker cooling is an important process that ensures the quality of Portland cement. Proper cooling of the clinker produces a solid, uniform material that is easy to grind and possesses the desired properties for cement.

The following are some factors that influence clinker cooling:

- Clinker temperature: The temperature of the clinker as it exits the rotary kiln is an important factor affecting the cooling rate.
- Cooling rate: The cooling rate is another crucial factor affecting clinker quality.
- Clinker size: The size of the clinker also influences the cooling rate.
- Air humidity: The humidity of the air can also affect the cooling rate.

Clinker Grinding

Clinker grinding is the final step in Portland cement production. Grinding the clinker reduces its size and increases its surface area.

The clinker grinding can be done in various ways. A common method is using a ball mill. A ball mill is a device consisting of a cylindrical drum that rotates at high speed. The clinker is introduced into the drum and ground between steel balls found inside.

Another method of grinding clinker is using a roller mill. A roller mill is a device consisting of two steel cylinders rotating in opposite directions. The clinker is introduced between the cylinders and ground by compression.

Figure 28.
Roller press

Source: FLSmidth S.A. de C.V. (https://www.directindustry.es/prod/flsmidth-dorr-oliver-eimco/product-62016-1488749.html)

Clinker grinding is a delicate process. If the clinker is ground too finely, it can lose its cementitious properties. If it is ground too coarsely, it may not form a homogeneous mass with water.

The particle size of cement is an important factor affecting its properties. Finer cement particles have a larger surface area, facilitating interaction with water and forming a homogeneous mass.

Grinding time is also an important factor that affects the particle size of cement. Longer grinding times produce finer particles.

Clinker grinding is a crucial process ensuring cement quality. Cement with an appropriate particle size has higher strength and durability.

Addition of Additives

Additives are substances added to Portland cement during its manufacturing or on-site to modify its properties. Additives can be used to improve workability, strength, durability, impermeability, fire resistance, abrasion resistance, volumetric stability, fluidity, segregation reduction, setting retardation, or setting acceleration.

Additives can be classified into two main types: chemical additives and mineral additives.

- Chemical Additives:

  Chemical additives are organic or inorganic substances that dissolve in water or cement. The most common chemical additives are as follows:

  - Water-reducing additives: These additives reduce the amount of water needed to obtain a cement mix with a certain workability.
  - Set-retarding additives: These additives delay the setting time of the cement.
  - Set-accelerating additives: These additives speed up the setting time of the cement.
  - Plasticizer: These additives improve the workability of the cement mix.
  - Waterproofing additives: These additives enhance the impermeability of the cement.
  - Anti-cracking additives: These additives reduce the formation of cracks in concrete.
- Mineral Additives:

  Mineral additives are inorganic substances added to cement without dissolving. The most common mineral additives are as follows:

  - Fillers: Fillers are inert materials added to cement to reduce its cost.
  - Pigments: Pigments are materials added to cement to give it color.
  - Volumetric stability additives: These additives improve the volumetric stability of concrete, enhancing its resistance to shrinkage and expansion.

The addition of additives to Portland cement mix is an increasingly common practice. Additives improve the properties of cement and adapt it to the specific needs of each application.

Figure 29.
Cement storage silos

Source: Aimix Group. (https://aimixgrupo.com.mx/silos-para-almacenar-cemento/)

Figure 30.
Cement batching plant

Source: Ais. (https://www.ais.mx/ais-servicios-detalle.php?id=2)

Figure 31.

Cement manufacturing process

Source: Marlene Gasdia-Cochrane, 2023.
(https://www.thermofisher.com/blog/mining/the-cement-manufacturing-process/)

Chemical Composition of Portland Cement

The chemical composition of Portland cement is as follows:

- Calcium oxide (CaO): Calcium oxide is the main component of Portland cement, representing around 60% of its composition. Calcium oxide is responsible for the hydraulic properties of the cement, meaning its ability to harden and gain strength in the presence of water.
- Silicon dioxide (SiO_2): Silicon dioxide represents about 21% in the composition of Portland cement. Silicon dioxide is responsible for the mechanical strength of the cement.
- Aluminum oxide (Al_2O_3): Aluminum oxide represents about 5.5% in the composition of Portland cement. Aluminum oxide is responsible for the resistance of cement to heat and wear.
- Iron oxides (Fe_2O_3): Iron oxides represent about 4.5% in of the composition of Portland cement. Iron oxides give the cement its gray color.

In addition to these main components, Portland cement may also contain other components such as magnesium oxide (MgO), sulfur trioxide (SO_3), and calcium sulfate ($CaSO_4$).

The chemical composition of Portland cement can be expressed in terms of its oxide-metric composition, which reflects the ratio of the percentage of each oxide within the cement formulation. The typical oxide-metric composition of Portland cement is as follows:

- CaO: 60-66 %

- SiO_2: 20-26 %
- Al_2O_3: 5-7 %
- Fe_2O_3: 2.5-3.5 %

Figure 32.
Vicat apparatus

Source: Mecánica Científica S.A. (https://www.mecacisa.com/es/portfolio/aparato-vicat/)

Calcium Oxide

Calcium oxide, also known as quicklime, is a chemical compound with the formula CaO. It is a white solid produced by the calcination of limestone or dolomite.

Calcium oxide is an essential component of Portland cement. It accounts for about 60% of the composition of Portland cement and is responsible for its hydraulic properties.

Calcium oxide reacts with water to form calcium hydroxide, which is a highly hygroscopic substance. This reaction generates heat, contributing to the setting of cement.

The production of calcium oxide is carried out through a process called calcination. In this process, limestone or dolomite is heated to high temperatures, between 800 and 1,200 °C. At these temperatures, the limestone or dolomite decomposes into calcium oxide and carbon dioxide.

Calcium oxide can also be obtained from the thermal decomposition of other calcium compounds, such as calcium carbonate ($CaCO_3$) or calcium hydroxide ($Ca(OH)_2$).

Silicon Dioxide

Silicon dioxide, also known as silica, is a chemical compound with the formula SiO_2. It is a colorless or white crystalline solid found in nature as quartz, sand, feldspar, and other minerals.

Silicon dioxide is an essential component of Portland cement. It accounts for about 21% of the composition of Portland cement and is responsible for its mechanical strength.

Silicon dioxide reacts with calcium oxide to form calcium silicates, which provide mechanical strength to the cement.

The production of silicon dioxide is carried out through a process called calcination. In this process, sand or other silica-rich minerals are heated to high temperatures, between 1,400 and 1,600 °C. At these temperatures, the sand or minerals decompose into silicon dioxide and other compounds.

Silicon dioxide can also be obtained from the thermal decomposition of other silicon compounds, such as sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3).

Silicon dioxide has the following properties:

- Form: Silicon dioxide appears as a crystalline solid. The crystals can have various shapes, with the most common being cubic.
- Color: Silicon dioxide is colorless or white. However, it can exhibit other colors, such as brown, black, or red, due to impurities.
- Hardness: Silicon dioxide is a hard material with a Mohs hardness of 7, compared to diamond, which has a hardness of 10.
- Melting Point: The melting point of silicon dioxide is 1,414 °C.
- Boiling Point: The boiling point of silicon dioxide is 2,230 °C.
- Solubility: Silicon dioxide is insoluble in water but soluble in hydrofluoric acid.
- Reactivity: Silicon dioxide is inert and does not react with most chemical agents.

Aluminum Oxide

Aluminum oxide, also known as alumina, is a chemical compound with the formula Al_2O_3. It is a white or colorless crystalline solid found in nature as corundum, emery, and other minerals.

Aluminum oxide is an important component of Portland cement. It accounts for about 5.5% of the composition of Portland cement and is responsible for its heat resistance and wear resistance.

Aluminum oxide has the following properties:

- Form: Aluminum oxide appears as a crystalline solid. The crystals can have various shapes, with the most common being cubic.
- Color: Aluminum oxide is white or colorless. However, it can exhibit other colors, such as brown, black, or red, due to impurities.
- Hardness: Aluminum oxide is a hard material with a Mohs hardness of 9, compared to diamond, which has a hardness of 10.
- Melting Point: The melting point of aluminum oxide is 2,072 °C.
- Boiling Point: The boiling point of aluminum oxide is 2,977 °C.
- Solubility: Aluminum oxide is insoluble in water but soluble in hydrofluoric acid.
- Reactivity: Aluminum oxide is inert and does not react with most chemical agents.

Iron Oxide

Iron oxides are chemical compounds composed of iron and oxygen. Sixteen iron oxides are known, but the most common are iron oxide(II), also known as ferrous oxide, with the formula FeO, and iron oxide(III), also known as ferric oxide, with the formula Fe_2O_3.

Iron Oxide (II)

Iron oxide(II) is a black or brown crystalline solid found in nature as hematite, magnetite, and other minerals.

Iron oxide(II) is an important component of Portland cement. It accounts for about 2% of the composition of Portland cement and is responsible for its brown color.

Iron Oxide (III)

Iron oxide (III) is a red, brown, or black crystalline solid found in nature as hematite, magnetite, and other minerals.

Iron oxide (III) is an important component of Portland cement. It accounts for about 7% of the composition of Portland cement and is responsible for its reddish-brown color.

Iron oxides possess the following general properties:

- Form: Iron oxides appear as crystalline solids. The crystals can have various shapes, with the most common being cubic and rhombohedral.
- Color: Iron oxides can exhibit different colors depending on their composition. Iron oxide (II) is black or brown, while iron oxide (III) is red, brown, or black.
- Hardness: Iron oxides are hard materials with a Mohs hardness ranging from 5 to 6, compared to diamond, which has a hardness of 10.

- Melting Point: The melting point of iron oxides ranges from 1,100 to 1,500 °C.
- Boiling Point: The boiling point of iron oxides ranges from 2,700 to 3,000 °C.
- Solubility: Iron oxides are insoluble in water but soluble in acids and bases.
- Reactivity: Iron oxides are reactive materials that react with acids and bases to form iron salts.

Magnesium Oxide

Magnesium oxide, also known as magnesia, is a chemical compound with the formula MgO. It is a white or colorless crystalline solid found in nature as periclase.

Magnesium oxide has the following properties:

- Form: Magnesium oxide appears as a crystalline solid. The crystals can have various shapes, with the most common being cubic.
- Color: Magnesium oxide is white or colorless. However, it can exhibit other colors, such as brown, black, or red, due to impurities.
- Hardness: Magnesium oxide is a hard material with a Mohs hardness of 4, compared to diamond, which has a hardness of 10.
- Melting Point: The melting point of magnesium oxide is 2,852 °C.
- Boiling Point: The boiling point of magnesium oxide is 3,600 °C.
- Solubility: Magnesium oxide is insoluble in water but soluble in acids and bases.
- Reactivity: Magnesium oxide is a reactive material that reacts with acids to form magnesium salts and with bases to form magnesium hydroxide.

Major Compounds and Their Influences on Portland Cement

According to García (2023), Portland cement is a hydraulic material that hardens upon reacting with water. It is composed of four main chemical compounds:

- Clinker: Produced by heating a mixture of limestone and clay at high temperatures. Clinker contains:
  - Limestone ($CaCO_3$): Limestone is the main component in clinker. It provides the majority of the calcium oxide (CaO) in the cement.
  - Clay (SiO_2): Clay provides most of the silica (SiO_2) in the cement.
  - Iron oxide (Fe_2O_3): Iron oxide provides most of the iron contained (Fe) in cement.
  - Al_2O_3: It is a minor component in the clinker.
- Water: It is necessary for Portland cement to harden.

- Additives: Additives are materials added to Portland cement to enhance its properties.

The main compounds of Portland cement influence its properties in the following ways:

- Clinker: The amount of clinker in the cement mix determines the strength of the concrete.
- Water: Water is necessary for Portland cement to harden. The amount of water in the cement mix determines the workability of the concrete.
- Additives: Can improve various properties of concrete, such as strength, durability, workability, and impermeability.

Tricalcium Aluminate (C_3A)

Tricalcium aluminate (C_3A) is a chemical compound with the formula $Ca_3Al_2O_6$. It is a minor component of Portland cement clinker, making up about 5-10% of the total. Tricalcium aluminate is a hydraulic compound, meaning it reacts with water to form a gel that contributes to the mechanical strength of concrete.

According to García (2023), tricalcium aluminate is important in Portland cement because it contributes to the initial strength of concrete. However, it can also cause durability problems. In the presence of sulfates, tricalcium aluminate can react to form ettringite, an expansive compound that can cause cracking and disintegration of concrete.

To reduce the risk of sulfate deterioration, Portland cement can be manufactured with a reduced tricalcium aluminate content. Additionally, additives can be added to concrete to reduce its permeability and help protect it from sulfates.

Tricalcium Silicate (C_3S)

Tricalcium silicate (C_3S) is a chemical compound with the formula Ca_3SiO_5. It is the primary component of Portland cement clinker, making up about 50-60% of the total. Tricalcium silicate is a hydraulic compound that reacts with water to form a gel responsible for the mechanical strength of concrete.

According to García (2023), tricalcium silicate is crucial in Portland cement because it contributes to both the initial and final strength of concrete. It is also responsible for forming the calcium silicate hydrate (C-S-H) gel matrix, which is the main structure providing concrete with its strength and durability.

Tricalcium silicate is highly reactive and hydrates quickly, causing concrete that contains tricalcium silicate to harden rapidly. However, this also makes the concrete susceptible to drying shrinkage and sulfate expansion.

In order to mitigate drying shrinkage, Portland cement can be manufactured with a reduced tricalcium silicate content. Additionally, additives can be added to concrete to reduce drying shrinkage.

In order to reduce the risk of sulfate expansion, Portland cement can be manufactured with a reduced tricalcium silicate content. Additives can also be added to concrete to reduce its permeability and help protect it from sulfates.

Tetracalcium Aluminoferrite (C_4AF)

Tetracalcium aluminoferrite, also known as C_4AF, is a chemical compound with the formula $Ca_4Al_2Fe_2O_{10}$. It is one of the primary components of Portland cement clinker, representing approximately 5-15% of its total composition.

Properties and functions of tetracalcium aluminoferrite:

- Low Reactivity: Compared to tricalcium aluminate (C_3A), C_4AF is significantly less reactive with water, contributing less to the initial development of concrete strength.
- Improves Workability: C_4AF acts as a flux, reducing the viscosity of the cement paste and improving its workability, facilitating the placement and compaction of concrete.
- Increases Sulfate Resistance: C_4AF is resistant to sulfate reaction, enhancing the durability of concrete in high-sulfate environments.
- Controls Ettringite Expansion: Although C_4AF does not directly participate in ettringite formation, its presence helps control the expansion of this compound, minimizing the risk of concrete cracking.
- Contributes to Final Strength: While its contribution to the initial development of strength is limited, C4AF reacts slowly with water over time, contributing to the increase in the final strength of the concrete.

Dicalcium Silicate (C_2S)

Dicalcium silicate (C_2S) is a chemical compound with the formula $2CaO{\cdot}SiO_2$. It is a hydrated calcium silicate and a typical ingredient in Portland cement clinker, characterized by a slower hydration rate compared to tricalcium silicate.

Dicalcium silicate is important in Portland cement because it contributes to the final strength of the cement. However, its effect is slower than that of tricalcium silicate, which is the main component in Portland cement and is responsible for its initial strength.

Dicalcium silicate reacts with water to form dicalcium silicate hydrate (C_2SH). Although C_2SH is less hard than the C-S-H formed by tricalcium silicate, it is more resistant to compression, contributing to the final strength of Portland cement.

The dicalcium silicate content in Portland cement varies depending on the type of cement. Type I Portland cement, the most common type, has a dicalcium silicate content of approximately 25%. Type II and III Portland cements, which are more resistant to water action, have a dicalcium silicate content of approximately 35%. Type IV Portland cements, which are more resistant to heat action, have a dicalcium silicate content of approximately 45%.

Calcium Aluminosilicate (C_2S)

C_2S is a chemical compound with the formula $2CaO \cdot SiO_2$. Calcium silicate hydrate is a compound found in Portland cement and is primarily responsible for its strength.

C_2S is an important component in Portland cement because it contributes to the final strength of the cement. However, its effect is slower than that of tricalcium silicate, which is the main component in Portland cement and is responsible for its initial strength.

C_2S reacts with water to form dicalcium silicate hydrate. Although C_2SH is less hard than the C-S-H formed by tricalcium silicate, it is more resistant to compression, contributing to the final strength of Portland cement.

The C_2S content in Portland cement varies depending on the type of cement. Type I Portland cement, the most common type, has a C_2S content of approximately 25%. Type II and III Portland cements, which are more resistant to water action, have a C_2S content of approximately 35%. Type IV Portland cements, which are more resistant to heat action, have a C_2S content of approximately 45%.

C_2S also contributes to other properties of Portland cement, such as its durability and its ability to resist freeze-thaw cycles.

Influence of C_3A

Tricalcium aluminate (C_3A) is important in Portland cement because it contributes to the initial strength of the cement. However, a high C_3A content can cause expansion and cracking problems.

C_3A reacts with water to form tricalcium aluminate hydrate (C_3AH_6), a hard and resistant substance responsible for the initial strength of Portland cement, as it forms rapidly

However, C_3A can also react with calcium sulfate in cement to form ettringite. Ettringite is an expansive substance that can cause cracking in concrete.

The C_3A content in Portland cement is regulated by standards. Type I Portland cement, the most common type, has a C_3A content of approximately 8%. Type II and III Portland cements, which are more resistant to water action, have a C_3A content of approximately 5%. Type IV Portland cements, which are more resistant to heat action, have a C_3A content of approximately 3%.

The influence of C_3A in Portland cement can be summarized in the following points:

- Provides Initial Strength: C_3A hydrates quickly to form C_3AH_6, a hard and resistant substance.
- Can Cause Expansion and Cracking: C_3A can react with calcium sulfate to form ettringite, an expansive substance that can cause cracking.
- Regulated Content: The C_3A content in Portland cement is regulated by standards to prevent expansion and cracking.

In general, C_3A is an important component of Portland cement, but its content must be controlled to avoid expansion and cracking issues.

Influence of C4AF

C4AF, or tetracalcium aluminoferrite, is a chemical compound found in Portland cement. According to Richardson (2008), it is an important component of cement as it influences its mechanical and durability properties.

C4AF contributes to the compressive strength of cement. However, it can also inhibit tensile strength. Overall, C4AF is a beneficial component for the mechanical strength of cement, but its influence can vary depending on other factors such as the chemical composition of the cement and curing conditions.

C4AF is an important component for the durability of cement. It helps protect the cement from the action of water and chemical agents. In particular, C4AF is resistant to carbonation, a chemical process that can weaken cement.

The influence of C4AF on the properties of cement can vary depending on other factors, such as the chemical composition of the cement and curing conditions:

- Chemical composition: C4AF is more abundant in cements with high alumina content. In these cements, C4AF has a more significant influence on mechanical and durability properties.
- Curing conditions: C4AF hydrates more slowly than other components of cement. Therefore, C4AF has a more significant influence on the long-term properties of cement.

Influence of C2S

C2S, or dicalcium silicate, is an important component of Portland cement. It represents approximately 20-30% of the cement content, making it the second most abundant component after C3S (Richardson, 2008).

C2S influences the properties of cement in several ways:

- Mechanical properties: C2S contributes to the compressive strength of cement. Its contribution is less than that of C3S, but it is important for the development of long-term strength.
- Durability: C2S helps protect the cement from the action of water and chemical agents. It is resistant to carbonation, a chemical process that can weaken cement.
- Setting time: C2S hydrates more slowly than C3S. This means that cement with a high C2S content sets more slowly.

The influence of C2S on the properties of cement can vary depending on other factors, such as the chemical composition of the cement and curing conditions:

- Chemical composition: C2S is more abundant in cements with high silica content. In these cements, C2S has a more significant influence on mechanical and durability properties.
- Curing conditions: C2S hydrates more slowly in dry curing conditions. Therefore, C2S has a more significant influence on the long-term properties of cement in dry curing conditions.

Influence of C-S-H

C-S-H (calcium silicate hydrate) is the principal binding phase of hydrated cement. It is a poorly crystalline calcium silicate hydrate with a layered structure related to defective tobermorite/jennite-type phases, in which calcium-oxide sheets are linked to silicate chains and interlayer water (Richardson, 2008).

C-S-H influences the properties of cement in several ways:

- Mechanical properties: C-S-H is responsible for the mechanical strength of cement. Its structure, which is similar to quartz, gives cement its compressive and tensile strength.
- Durability: C-S-H is resistant to the action of water and chemical agents. This resistance makes it important for the durability of cement.
- Setting time: C-S-H forms during the hydration of cement. The hydration process is what gives cement its strength and durability.

The influence of C-S-H on the properties of cement can vary depending on other factors, such as the chemical composition of the cement and curing conditions:

- Chemical composition: C-S-H is more abundant in cements with high silica content. In these cements, C-S-H has a more significant influence on mechanical and durability properties.

- Curing conditions: C-S-H forms more rapidly in wet curing conditions. Therefore, C-S-H has a more significant influence on the short-term properties of cement in wet curing conditions.

Sustainable Cement Manufacturing

Cement manufacturing is an energy-intensive industrial process that generates significant greenhouse gas (GHG) emissions (International Cement Association, 2023). Cement is a fundamental material for construction, so it is important to develop more sustainable manufacturing processes.

Several strategies can be adopted to reduce the environmental impact of cement manufacturing. These strategies include:

- Reducing energy consumption: Cement production is a very energy-intensive process, so it is important to reduce energy consumption at all stages of the process. This can be achieved through the use of more efficient technologies, such as cogeneration and waste heat recovery.
- Reducing GHG emissions: GHG emissions from cement manufacturing can be reduced by replacing fossil fuels with renewable energy sources, such as biomass and solar energy. Emissions can also be reduced by capturing and storing carbon (CCS).
- Reducing the use of natural resources: Cement manufacturing requires large amounts of natural resources, such as limestone, clay, and sand. The use of natural resources can be reduced by recycling waste materials, such as construction and demolition waste.

Some of the technologies and practices being developed to manufacture cement more sustainably include:

- Dry clinkerization: Clinkerization is the process in which the basic materials of cement are heated to high temperatures to form clinker, the main ingredient in cement. Dry clinkerization is a more efficient technology than wet clinkerization, as it requires less energy.
- Selective catalytic reduction (SCR): SCR is a technology used to reduce nitrogen oxide (NOx) emissions from cement plant chimneys.
- Carbon capture and storage (CCS): CCS is a technology that allows capturing CO2 from cement plant exhaust gases and storing it safely.
- Waste recycling: Construction and demolition waste can be used as substitutes for basic cement materials.

Sustainable cement manufacturing is a significant challenge, but important advances can be achieved by adopting the right technologies and practices.

CO_2 Emissions

According to the International Cement Association, cement manufacturing accounts for around 7% of global CO_2 emissions (International Cement Association, 2023). This is because the cement manufacturing process requires large amounts of energy to heat the raw materials, such as limestone and clay, to high temperatures.

Several strategies can be adopted to reduce CO_2 emissions from cement manufacturing. These strategies include:

- Reducing energy consumption: Cement production is a very energy-intensive process, so it is important to reduce energy consumption at all stages of the process. This can be achieved through the use of more efficient technologies, such as cogeneration and waste heat recovery.
- Replacing fossil fuels with renewable energy sources: GHG emissions from cement manufacturing can be reduced by replacing fossil fuels with renewable energy sources, such as biomass and solar energy.
- Capturing and storing carbon (CCS): CCS is a technology that allows capturing CO_2 from cement plant exhaust gases and storing it safely.

Sustainable cement manufacturing is a significant challenge, but important advances can be made by adopting the right technologies and practices.

Air, Water, and Soil Pollution

Portland cement manufacturing is an energy-intensive process that generates significant greenhouse gas (GHG) emissions, as well as air, water, and soil pollution (International Cement Association, 2023).

Air Pollution

Portland cement manufacturing is one of the main sources of carbon dioxide (CO_2) emissions into the atmosphere. CO_2 is a greenhouse gas that contributes to climate change. CO_2 emissions from Portland cement manufacturing occur mainly during the combustion of fossil fuels to heat the raw materials, such as limestone and clay, to high temperatures.

Other air emissions associated with Portland cement manufacturing include nitrogen oxides (NO_x), sulfur oxides (SO_x), and fine particles. NO_x contribute to the formation of smog and acid rain, while SO_x contribute to the formation of acid rain and toxic haze. Fine particles can cause respiratory and cardiovascular problems.

Water Pollution

Portland cement manufacturing can also pollute water. Wastewater from cement plants may contain contaminants such as heavy metal ions, cyanides, and organic compounds. These contaminants can pollute rivers, lakes, and aquifers.

Soil Pollution

The extraction of raw materials for Portland cement manufacturing can also pollute soil. Limestone quarries can cause erosion and landslides, while clay mines can pollute the soil with heavy metals and other contaminants.

Several measures can be taken to reduce pollution associated with Portland cement manufacturing. These measures include:

- Reducing energy consumption: Cement production is a very energy-intensive process, so it is important to reduce energy consumption at all stages of the process. This can be achieved through the use of more efficient technologies, such as cogeneration and waste heat recovery.
- Replacing fossil fuels with renewable energy sources: Portland cement production is a significant source of greenhouse gas (GHG) emissions. These emissions can be reduced by replacing fossil fuels with renewable energy.
- Carbon capture and storage (CCS): CCS is a technology that allows capturing CO2 from cement plant exhaust gases and storing it safely.
- Using alternative materials: Alternative materials to Portland cement, such as fly ash concrete, can help reduce CO2 emissions and other pollutants.

The cement industry is working to reduce pollution associated with Portland cement manufacturing. Some of the technologies and practices being developed to manufacture cement more sustainably include:

- Dry clinkerization: Clinkerization is the process in which raw materials for cement are heated to high temperatures to form clinker, the main ingredient in cement. Dry clinkerization is a more efficient technology than wet clinkerization, as it requires less energy.
- Selective catalytic reduction (SCR): SCR is a technology used to reduce nitrogen oxide (NOx) emissions from cement plant chimneys.
- Carbon capture and storage (CCS): CCS is a technology that allows capturing CO2 from cement plant exhaust gases and storing it safely.
- Recycling waste: Construction and demolition waste can be used as substitutes for raw cement materials.

Social Impact

The social impact of Portland cement is complex and encompasses a range of factors, both positive and negative (International Cement Association, 2023).

Positive Impacts.

- Employment opportunities: The cement industry is a major employer worldwide, providing direct and indirect jobs to millions of people.
- Economic development: Cement is an essential component of infrastructure, so the cement industry plays a significant role in economic development.
- Improving quality of life: Cement is used to build homes, schools, hospitals, and other buildings that contribute to improve the life quality of people.

Negative Impacts.

- Pollution: Portland cement manufacturing generates significant greenhouse gas (GHG) emissions, as well as air, water, and soil pollution.
- Social impacts: The extraction of raw materials for Portland cement manufacturing can have negative impacts on local communities, such as loss of land and water pollution.

Measures to Improve Sustainability

Some key measures to improve the sustainability of cement manufacturing include:

- Reducing energy consumption: Cement production is a very energy-intensive process, so it is important to reduce energy consumption at all stages of the process. This can be achieved through the use of more efficient technologies, such as cogeneration and waste heat recovery.
- Replacing fossil fuels with renewable energy sources: Portland cement production is a significant source of greenhouse gas (GHG) emissions. These emissions can be reduced by replacing fossil fuels with renewable energy.
- Carbon capture and storage (CCS): CCS is a technology that allows capturing CO_2 from cement plant exhaust gases and storing it safely.
- Using alternative materials: Alternative materials to Portland cement, such as fly ash concrete, can help reduce CO_2 emissions and other pollutants.
- Recycling and reusing: Recycling and reusing construction and demolition waste can help reduce the consumption of virgin materials and greenhouse gas emissions.

The cement industry is working to develop and adopt these measures to improve the sustainability of its production. These measures are important to protect the environment and ensure a sustainable future for the industry.

Use of Alternative Fuels

Cement manufacturing is an energy-intensive industrial process that generates large amounts of greenhouse gas emissions. The use of alternative fuels, such as biomass and waste, is one way to reduce these emissions and improve the sustainability of the process.

Alternative fuels, such as biomass, renewable energy, and waste, can reduce greenhouse gas emissions and improve the sustainability of cement manufacturing (International Cement Association, 2023).

- Biomass: Biomass is a renewable energy source that can be obtained from plants, animals, or waste. Biomass can be used to replace fossil fuels in cement manufacturing, reducing greenhouse gas emissions.
- Renewable energy: Renewable energy is an alternative to fossil fuels in cement manufacturing. These energies are clean and sustainable, meaning they do not produce greenhouse gas emissions.
- Waste: Waste, such as wood waste, agricultural waste, and municipal waste, can be used to replace fossil fuels in cement manufacturing. The use of waste reduces greenhouse gas emissions and helps reduce the amount of waste going to landfills.

The use of alternative fuels in cement manufacturing has several benefits, including:

- Reduction of greenhouse gas emissions: Alternative fuels reduce greenhouse gas emissions, helping to combat climate change.
- Improvement of air quality: Alternative fuels produce fewer pollutants than fossil fuels, helping to improve air quality.
- Reduction of dependence on fossil fuels: Alternative fuels reduce dependence on fossil fuels, which can help reduce energy prices and improve energy security.

The cement industry is committed to sustainability and is working to reduce its environmental impact. One way to do this is by increasing the use of alternative fuels in cement manufacturing.

Use of Alternative Raw Materials

The use of alternative raw materials in cement manufacturing is another important measure that can be taken to improve the sustainability of the process. The main raw material in cement manufacturing is limestone, which is a non-renewable resource.

Alternative raw materials, such as fly ash, blast furnace slag, and construction and demolition waste, can reduce the need for limestone and improve the sustainability of cement manufacturing (International Cement Association, 2023).

- Fly ash: Fly ash is a byproduct of coal combustion in power plants. Fly ash can be used as an additive in cement manufacturing, reducing the need for limestone.
- Blast furnace slag: Blast furnace slag is a byproduct of steel production. Blast furnace slag can be used as an additive in cement manufacturing, reducing the need for limestone.
- Construction and demolition waste (CDW): CDW is a mix of materials, such as concrete, bricks, ceramics, and wood. CDW can be used as an aggregate in cement manufacturing, reducing the need for limestone and helping to reduce the amount of waste going to landfills.

The use of alternative raw materials in cement manufacturing has several benefits, including:

- Reduction of limestone demand: The use of alternative raw materials reduces the demand for limestone, which is a non-renewable resource.
- Reduction of greenhouse gas emissions: The use of alternative raw materials can help reduce greenhouse gas emissions, as some alternative raw materials, such as fly ash and blast furnace slag, have a lower carbon content than limestone.
- Improvement of air quality: The use of alternative raw materials can help improve air quality, as some alternative raw materials, such as fly ash, have a lower content of pollutants than limestone.

Improving Energy Efficiency

Improving energy efficiency is one of the most important measures that can be taken to enhance the sustainability of cement manufacturing (International Cement Association, 2023). Cement production is an energy-intensive process, accounting for about 5% of global energy consumption.

Enhancing energy efficiency in cement manufacturing can reduce greenhouse gas emissions, improve air quality, and lower production costs.

Several measures can be taken to improve energy efficiency in cement manufacturing, including:

- Improving kiln efficiency: Kilns are the largest energy consumers in cement manufacturing. Kiln efficiency can be improved through the use of more efficient technologies, such as precalciner kilns and vertical cement kilns.
- Reducing heat loss: Heat loss can be reduced by insulating kilns and auxiliary equipment.
- Utilizing renewable energy sources: Renewable energy sources, such as biomass and solar energy, can be used to replace fossil fuels.
- Recovering waste heat: Waste heat from cement manufacturing processes can be recovered to generate electricity or heat water.

The cement industry is working to improve the energy efficiency of its processes. In 2023, the Global Cement and Concrete Association (GCCA) estimated that energy efficiency in cement manufacturing had improved by 27% since 1990.

Waste Treatment

Waste treatment is an important part of sustainable cement manufacturing (International Cement Association, 2023). Cement industry waste can be of mineral origin, such as fly ash and blast furnace slag, or of organic origin, such as construction and demolition waste.

Mineral-origin waste can be used as alternative raw materials in cement manufacturing. This helps reduce the demand for limestone, a non-renewable resource. Organic-origin waste, on the other hand, can be used to generate energy or produce sustainable building materials.

The treatment of waste in cement manufacturing has several benefits, including:

- Reducing environmental impact: Waste treatment helps reduce the environmental impact of cement manufacturing by decreasing the amount of waste sent to landfills and improving process efficiency.
- Lowering costs: Waste treatment can help reduce cement production costs by using alternative raw materials and generating energy.
- Enhancing the circular economy: Waste treatment contributes to the circular economy by utilizing resources and reducing waste.

The cement industry is working to improve waste treatment. In 2023, the Global Cement and Concrete Association (GCCA) estimated that 50% of cement industry waste was properly treated.

Water Management

Cement manufacturing is a water-intensive process, accounting for about 2% of global water consumption.

Managing water in cement manufacturing has several benefits, including:

- Reducing environmental impact: Water management helps reduce the environmental impact of cement manufacturing by lowering water use and improving wastewater quality.
- Lowering cost: Water management can help reduce cement production costs by decreasing the need for water and improving process efficiency.

The cement industry is working to improve environmental performance. In 2023, the Global Cement and Concrete Association reported that the cement industry had reduced its CO_2 emissions intensity by about 20% since 1990.

Several measures can be taken to improve water management in cement manufacturing, including:

- Water reuse and recycling: Reusing and recycling water can help reduce the amount of water used.
- Reducing wastewater contamination: Reducing wastewater contamination can help protect the environment.
- Using advanced technologies: Advanced technologies, such as advanced water treatment systems, can help improve water use efficiency and sustainability.

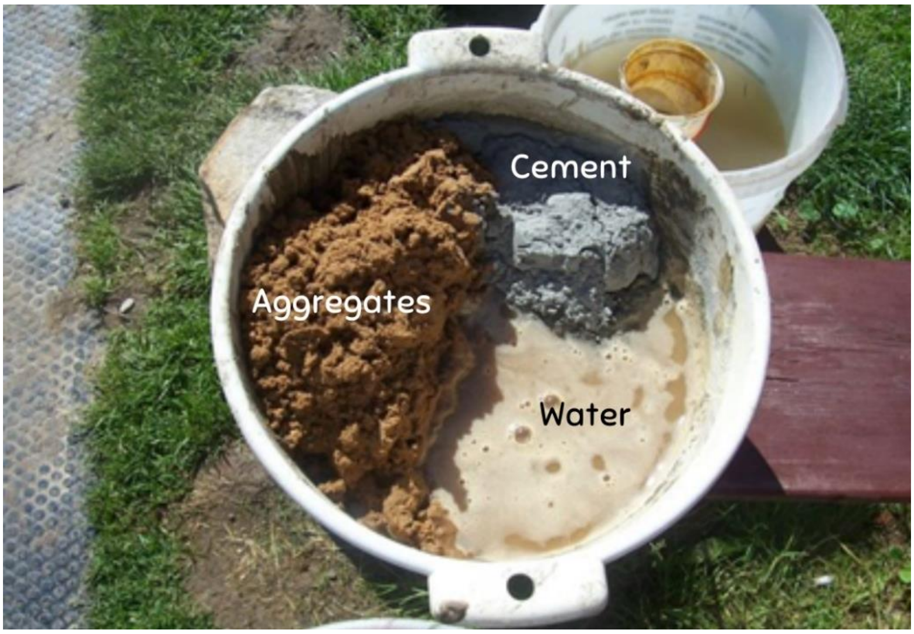
Chapter III

Components of Concrete

Concrete is a composite material made of cement, water, aggregates, and sometimes additives. The characteristics of each of these components influence the properties of the concrete, such as its strength, durability, workability, and appearance.

Figure 33.

Basic components for making concrete



Source: DecorexPro. (https://master-en.decorexpro.com/gazobeton/kak-izgotovit/)

Cements

According to González (2023), cement is a construction material used to bond solid materials like stone, sand, and gravel to form concrete. Cement is a hydraulic material, meaning it hardens when mixed with water.

There are different types of cement, each with its own specific properties and applications. The most common types of cement are:

- **Portland Cement**
  Portland cement is the most widely used type of cement in the world. It is made from a mixture of limestone, clay, and other materials heated to high temperatures to form clinker. The clinker is ground into a fine powder and mixed with water to form a paste.

- **White Portland Cement**
  White Portland cement is produced using materials with fewer impurities than gray Portland cement. It is used for applications requiring a white appearance, such as monuments or historical building restoration.

Figure 34.
Example of white Portland cement

Source: Arcus Global, 2017. (https://www.arcus-global.com/wp/el-cemento-contamina-o-reabsorbe-la-contaminacion/#prettyPhoto)

- Specialty Cements
  There are other types of specialty cements for specific applications. Examples include:
  - Pozzolanic cement
  - Blast furnace slag cement
  - Calcium aluminate cement
  - Calcium sulfate cement

Characteristics of Cements

Cements are characterized by their physical and chemical properties. Most important physical properties of cements include:

- Compressive strength: The ability of cement to withstand loads without breaking.
- Tensile strength: The ability of cement to withstand pulling forces.
- Abrasion resistance: The ability of cement to withstand wear.

Important chemical properties include:

- Sulfate resistance: The ability of cement to resist attack by sulfates, which can weaken concrete.
- Water resistance: The ability of cement to resist water penetration.

Aggregates

Aggregates are inert materials used in construction to provide strength, durability, and stability (American Concrete Institute, 2023). Aggregates are classified into two main types: natural aggregates and manufactured aggregates.

Figure 35.

Example of aggregate sizes for concrete

Source: The open University. (https://www.open.edu/openlearn/mod/oucontent/view.php?id=101227&section=_unit4.3)

Natural Aggregates

Natural aggregates are found in nature and extracted from quarries or rock deposits. The most common types of natural aggregates include:

- Sand: Granular material composed of small, rounded particles. Sand is used in the construction of concrete, mortar, and asphalt.
- Gravel: Granular material composed of larger, and more angular particles than sand. Gravel is used in concrete, mortar, and asphalt.
- Crushed Stone: Granular material composed of rock particles that have been crushed into cubes or spheres. Crushed stone is used in concrete, mortar, and asphalt.

Figure 36.
Example of natural aggregate (gravel)

Source: Slobodan B. Vrhovac. (https://mail.ipb.ac.rs/~vrhovac/sloba/science/gs.html)

Manufactured Aggregates

Manufactured aggregates are produced from recycled or processed materials. Common types of manufactured aggregates include:

- Steel Slag: A byproduct of steel production, used in concrete and asphalt manufacturing.
- Expanded Clay: Composed of clay heated to high temperatures to make it expandable, used in concrete and insulation manufacturing.
- Perlite: Composed of volcanic rock heated to high temperatures to make it expandable, used in concrete and insulation manufacturing.

Classification of Aggregates

According to the American Concrete Institute (ACI, 2022), aggregates are granular materials used in construction as components of concrete, mortar, asphalt, etc. They are essential for providing strength, durability, and economy to these mixes.

Aggregates can be classified based on different criteria, including:

- Origin: Aggregates can be natural or manufactured, obtained from rock or mineral crushing.
- Size: Aggregates are classified into fine aggregates (particle size < 5 mm) and coarse aggregates (particle size > 5 mm).
- Shape: Aggregates can be rounded, angular, or a combination of both.
- Color: White, gray, black, etc.

- Density: Aggregates are classified into light aggregates (density < 2.4 g/cm^3) and heavy aggregates (density > 2.4 g/cm^3).

Based on their origin, aggregates can be classified into:

- Natural aggregates: These are obtained from the erosion of rocks. The most common are river aggregates, quarry aggregates, and beach aggregates.
- Manufactured aggregates: These are obtained from the crushing of rocks or minerals. The most common are crushed stone aggregates, slag aggregates, and recycled aggregates.

Based on their size, aggregates can be classified into:

- Fine aggregate: These have a particle size less than 5 mm. The most common fine aggregates are sand and stone dust.
- Coarse aggregate: These have a particle size greater than 5 mm. The most common coarse aggregates are gravel, crushed stone, and cobbles.

Based on their shape, aggregates can be classified into:

- Rounded aggregates: These have a rounded shape, like those found in rivers and beaches.
- Angular aggregates: These have an angular shape, like those found in quarries.
- Mixed aggregates: These have a combination of rounded and angular shapes.

Based on their color, aggregates can be classified into:

- White aggregates: These are white in color, like those found in limestone rocks.
- Gray aggregates: These are gray in color, like those found in igneous rocks.
- Black aggregates: These are black in color, like those found in volcanic rocks.
- Colored aggregates: These have a color different from white, gray, or black.

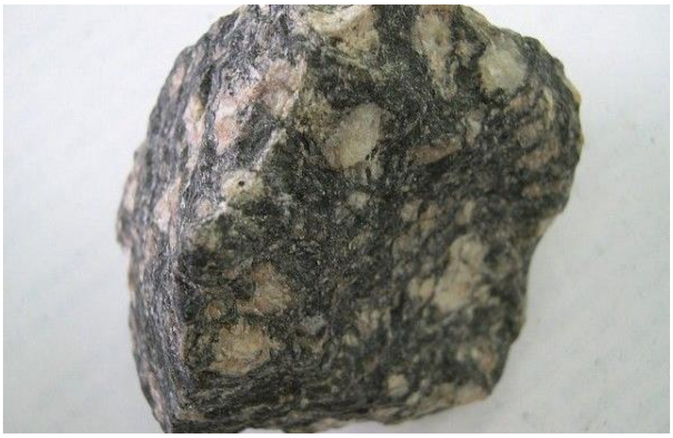
Figure 37.
Example of igneous rock

Source: Germán Portillo, 2025. (https://www.meteorologiaenred.com/tipos-de-rocas.html)

Figure 38.
Example of metamorphic rocks

Source: Maila. (https://quizlet.com/127941949/rocas-metamorficas-flash-cards/)

Figure 39.
Example of sedimentary rocks



Source: Viaje al Cosmos, 2025. (https://www.postposmo.com/tipos-de-rocas/)

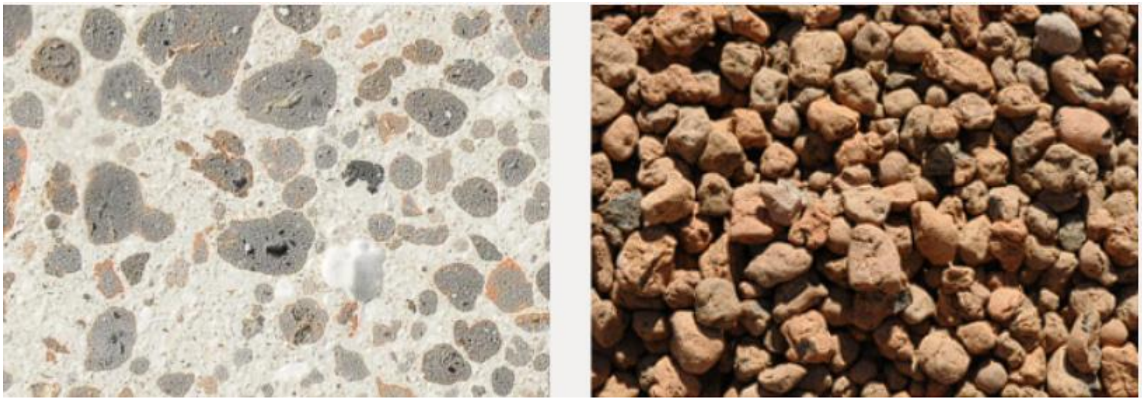
Based on their density, aggregates can be classified into:

- Lightweight aggregates: These have a density less than 2.4 g/cm³. The most common lightweight aggregates are expanded clay, expanded polystyrene, and cork.
- Heavyweight aggregates: These have a density greater than 2.4 g/cm³. The most common heavyweight aggregates are barite, magnetite, and limonite.

Based on their fragmentation mode, aggregates can be classified by their origin into:

- Natural aggregates: Formed by natural processes such as erosion, fragmentation, and weathering.
- Manufactured aggregates: Made through mechanical processes such as crushing, grinding, and cutting.

Figure 40.
Example of artificial aggregates



Source: Equihábitat. (https://baque-goni.com/materiales.html)

Based on their water absorption rate, aggregates can be classified into:

- Low Absorption (<3%):
  Aggregates such as dense, natural stone and gravel typically have low water absorption. These aggregates are preferred for durability, especially in critical environments exposed to chlorides or freeze-thaw cycles, which often have a 2-3% absorption limit.
- Normal Absorption (3-6%):
  Many natural aggregates and some manufactured aggregates fall into this category. High-quality manufactured aggregates and some well-graded natural aggregates might also be in this absorption range, with limits sometimes set around 3.5%
- High Absorption (>6%):
  These aggregates, including expanded clay, porous scoria, and recycled concrete aggregate (RCA), are characterized by their internal cellular or porous structure and can have absorption values well above 6%. Recycled aggregates, in particular, often have higher absorption and lower specific gravity compared to natural aggregate.

Classification by Origin

Aggregates are classified by their origin into natural and manufactured (ACI, 2022).

Natural Aggregates

Natural aggregates are those obtained from the erosion of rocks. The most common types are river, quarry, and beach aggregates (ACI, 2022).

River Aggregates

River aggregates are obtained from deposits of fluvial sediments. They have a rounded shape and a smooth texture. These aggregates are the most commonly used in construction because they are of good quality and relatively economical.

Quarry Aggregates

Quarry aggregates are obtained from the extraction of rocks in quarries. They can have an angular or rounded shape and a smooth or rough texture. These aggregates are used in applications where special strength is required, such as in the construction of pavements or reinforced concrete structures.

Beach Aggregates

Beach aggregates are obtained from deposits of marine sediments. They have a rounded shape and a smooth texture. These aggregates are used in applications where good abrasion resistance is required, such as in the construction of pavements or concrete exposed to the elements.

Natural aggregates have the following advantages:

- Generally more economical than manufactured aggregates.
- Easily available in many parts of the world.
- Can be of good quality.

Natural aggregates also have the following disadvantages:

- They may have variable quality.
- They may contain impurities such as clay or silt.
- They can be difficult to transport over long distances.

Classification of Natural Aggregates

Natural aggregates can be categorized by their size, shape, and color.

By Size

Natural aggregates can be classified into fine aggregates, with a particle size smaller than 5 mm, and coarse aggregates, with a particle size larger than 5 mm.

- Fine Aggregates: These are used in concrete, mortar, and other construction materials. The most common fine aggregates are sand and stone dust.
- Coarse Aggregates: These are used in concrete, pavements, and other applications where good strength is required. The most common coarse aggregates are gravel, crushed stone, and pebbles.

By Shape

Natural aggregates can be classified into rounded, angular, or mixed aggregates.

- Rounded Aggregates: These have a rounded shape, like those found in rivers and beaches.
- Angular Aggregates: These have an angular shape, like those found in quarries.
- Mixed Aggregates: These have a combination of rounded and angular shapes.

By Color

Natural aggregates can be of any color, depending on the type of rock from which they originate. The most common colors are gray, white, and black.

Properties of Natural Aggregates

The properties of natural aggregates are important for determining their suitability for a specific application. The most important properties are:

- Size: The size of the aggregate determines the strength and durability of the composite material.
- Shape: The shape of the aggregate affects the workability and strength of the composite material.
- Color: The color of the aggregate does not significantly impact the properties of the composite material.
- Density: The density of the aggregate affects the weight of the composite material.
- Strength: The strength of the aggregate determines the resistance of the composite material to compression, tension, and abrasion.
- Absorption: The absorption of the aggregate determines the amount of water the composite material absorbs.
- Durability: The durability of the aggregate determines the lifespan of the composite material.

Selecting the right natural aggregates is important to ensure that the composite material has the necessary properties for the specific application.

Manufactured Aggregates

Manufactured aggregates are those obtained from the crushing of rocks or minerals (ACI, 2022). The most common types are crushed stone, slag aggregates, and recycled aggregates.

Crushed Stone Aggregates

Crushed stone aggregates are obtained from the crushing of hard rocks, such as granite, basalt, and limestone. They have an angular shape and a rough texture. They are used in a wide range of applications, including concrete, pavement, and retaining walls.

Slag Aggregates

Slag aggregates are obtained from the smelting of metals. They have an angular shape and a rough texture. They are used in applications where fire resistance is required, such as in the construction of furnaces and chimneys.

Recycled Aggregates

Recycled aggregates are obtained from the crushing of used construction materials, such as concrete, asphalt, or bricks. They can have an angular or rounded shape and a smooth or rough texture. Recycled aggregates are used in a wide range of applications, including concrete, pavement, and fill.

Water

Water used in the production of concrete shall meet specified quality requirements to ensure that it does not adversely affect cement hydration, setting time, strength development, or durability. According to ASTM C1602/C1602M, mixing water must be free from deleterious amounts of oils, acids, alkalis, organic matter, chlorides, sulfates, and other substances that may impair the performance of concrete, with pH and ionic content maintained within prescribed limits (ASTM International, 2023). It is the most abundant component on Earth, covering approximately 71% of the surface of the planet. It is found in oceans, rivers, lakes, glaciers, and the atmosphere.

Water is essential for life. It is necessary for the growth and development of plants and animals. It is also required for digestion, circulation, and excretion. Water helps regulate body temperature and protects internal organs.

The physical properties of water are unique. It is the only liquid that expands when it freezes. It also has a high heat capacity, meaning it can absorb a lot of heat without a significant increase in temperature. This property makes water important for regulating the temperature of the Earth.

Water is a polar molecule, meaning it has a positive charge on one end and a negative charge on the other. This polarity gives water several properties, such as its ability to dissolve many substances and its ability to form hydrogen bonds.

Water is an essential molecule for life. It is necessary for the growth, development, and functioning of all living organisms.

Additives (Types of Additives and Their Main Contributions)

Additives are substances added to other materials to improve their properties or characteristics (World Health Organization, 2023). They are used in a wide range of products, including food, medicine, cosmetics, cleaning products, industrial products, and construction materials.

Additives can be classified in several ways, depending on their function, composition, or origin.

Additives can be divided into the following groups according to their function:

- Food Additives: These are added to food to improve its flavor, appearance, texture, or shelf life.
- Pharmaceutical Additives: These are added to medicines to improve their stability, bioavailability, or efficacy.
- Cosmetic Additives: These are added to cosmetics to improve their appearance, smell, or texture. Examples of cosmetic additives include preservatives, colorants, fragrances, and emulsifiers.
- Cleaning Additives: These are added to cleaning products to improve their effectiveness, safety, or appearance.
- Industrial Additives: These are added to industrial products to improve their performance, durability, or safety.
- Construction Additives: These are added to construction materials to improve their mechanical, physical, or chemical properties.

Additives can be divided into the following groups according to their composition:

- Organic Additives: These are composed of carbon, hydrogen, oxygen, nitrogen, and other elements.
- Inorganic Additives: These do not contain carbon.

Additives can be divided into the following groups according to their origin:

- Natural Additives: These are obtained from natural sources, such as plants, animals, or minerals.
- Synthetic Additives: These are obtained from chemical processes.

Type A: Plasticizer

A plasticizer is a substance added to a material to increase its flexibility (Sánchez-Martínez, 2023). Plasticizers are used in a wide range of products, including plastics, rubber, concrete, and paints.

Figure 41.

Source: InfoVias, 2015. (https://www.destinoseguro.net/nuevositio/infovias/grupo-argos-punto-de-quedarse-con-el-50-de-las-acciones-de-odisa)

Mechanism of action inside the concrete

Its mechanism of action is based on its adhesion to cement particles, reducing friction and cohesion between them, which allows for improved dispersion and fluidity of the mixture. This facilitates placement and compaction of the material, which influences the strength and durability of the final product.

Types of Plasticizers

Plasticizers can be classified into two main types:

- Organic Plasticizers: These are composed of carbon, hydrogen, oxygen, nitrogen, and other elements.
- Inorganic Plasticizers: These do not contain carbon.

Type B: Retardant

A retardant is a substance added to another material to slow down its decomposition or deterioration (García-Muñoz, 2023). Retardants are used in a wide range of products, including plastics, rubber, wood, textiles, and food.

Mechanism of action inside the concrete.

Retarding admixtures work by creating a thin film on the cement particles, making it difficult for water to reach them and thus delaying the chemical hydration reaction. This film can form by absorption or by chemical interaction with the cement components. When the film breaks or dissipates, hydration continues normally. The effectiveness of the retarder depends on factors such as the water/cement ratio, the type of cement, the ambient temperature, and the dosage of the admixture.

Types of Retardants

Retardants can be classified into two main types:

- Physical Retardants: These act by forming a physical barrier that prevents oxygen, water, or heat from entering the material.
- Chemical Retardants: These act by reacting with substances that cause the decomposition or deterioration of a material.

Type C: Accelerator

An accelerator is a substance added to a material to speed up its drying, curing, or setting process (Martínez-López, 2023). Accelerators are used in a wide range of products, including plastics, concrete, paints, and varnishes.

Figure 42.

Source: Omar Javier Silva (https://360enconcreto.com/blog/detalle/construccion-con-sistemas-industrializados/)

Mechanism of action inside the concrete

A concrete accelerating admixture works by increasing the rate of cement hydration and, therefore, accelerating the setting and hardening process. This is achieved through various chemical mechanisms, such as promoting the hydration of specific minerals, increasing the concentration of ions in the cement paste, and altering the surface of cement particles.

Types of Accelerators

Accelerators can be classified into two main types:

- Chemical Accelerators: These react with the components of the material to speed up its drying, curing, or setting process.
- Physical Accelerators: These change the environmental conditions of the material, such as temperature or humidity.

Type D: Retarding Plasticizer

A retarding plasticizer is an additive added to concrete to improve its workability and extend its setting time (López-Martínez, 2023). Retarding plasticizers work by reducing the viscosity of the concrete, making it easier to place and compact. They also delay the hydration reaction of the cement, giving the concrete more time to be placed and worked before it hardens.

Types of Retarding Plasticizers

Retarding plasticizers can be classified into two main types:

- Chemical Retarding Plasticizers: These react with the components of the concrete to reduce its viscosity and delay the hydration reaction. Examples of chemical retarding plasticizers include chloride, thiosulfate, and sulfite compounds.
- Physical Retarding Plasticizers: These change the environmental conditions of the concrete, such as temperature or humidity, to reduce its viscosity and delay the hydration reaction. Examples of physical retarding plasticizers include wet curing agents and thermal curing agents.

Type E: Accelerating Plasticizer

An accelerating plasticizer is an additive added to concrete to improve its workability and speed up its setting time (García-Martínez, 2023). Accelerating plasticizers work by reducing the viscosity of the concrete and accelerating the hydration reaction of the cement.

Types of Accelerating Plasticizers

Accelerating plasticizers can be classified into two main types:

- Chemical Accelerating Plasticizers: These react with the components of the concrete to reduce its viscosity and accelerate the hydration reaction.

Examples of chemical accelerating plasticizers include chloride, thiosulfate, and sulfite compounds.

- Physical Accelerating Plasticizers: These change the environmental conditions of the concrete, such as temperature or humidity, to reduce its viscosity and accelerate the hydration reaction. Examples of physical accelerating plasticizers include thermal curing agents and wet curing agents.

Functions of Accelerating Plasticizers

Accelerating plasticizers have the following functions:

- Improve Workability: Accelerating plasticizers reduce the viscosity of the concrete, making it easier to place and compact. This can be beneficial in a range of applications, such as precast concrete, pumped concrete, and concrete placed in cold climates.
- Accelerate Setting: Accelerating plasticizers speed up the hydration reaction of the cement, giving the concrete more time to be placed and worked before it hardens. This can be beneficial in applications where the concrete needs to harden quickly, such as in the repair of structures or in concrete exposed to adverse weather conditions.

Type F: Superplasticizer

A superplasticizer is an additive added to concrete to improve its workability and significantly reduce the amount of water needed to achieve the same consistency (Martínez-González, 2023). Superplasticizers work by altering the properties of the cement paste, making it more fluid and less viscous.

Figure 43.

Source: Archivo Asocreto. (https://360enconcreto.com/blog/detalle/generalidades-tipos-de-aditivos-para-el-concreto/)

Mechanism of action inside the concrete

Superplasticizers work by dispersing cement particles in the mix, reducing internal friction and allowing the concrete to flow more easily. This reduces the amount of water needed to achieve the same workability, which in turn improves the concrete's mechanical properties.

Types of Superplasticizers

Superplasticizers can be classified into two main types:

- High-Range Superplasticizers: These are the most common superplasticizers and provide the greatest water reduction.
- Low-Range Superplasticizers: These provide less water reduction than high-range superplasticizers.

Type G: Retarding Superplasticizer

A retarding superplasticizer is an additive added to concrete to improve its workability and delay its setting (González-Hernández, 2023). Retarding superplasticizers work by altering the properties of the cement paste, making it more fluid and less viscous, and delaying the hydration reaction of the cement.

Types of Retarding Superplasticizers

Retarding superplasticizers can be classified into two main types:

- Chemical Retarding Superplasticizers: These react with the components of the concrete to delay the hydration reaction of the cement.
- Physical Retarding Superplasticizers: These change the environmental conditions of the concrete, such as temperature or humidity, to delay the hydration reaction of the cement.

Type H: Accelerating Superplasticizer

An accelerating superplasticizer is an additive added to concrete to improve its workability and speed up its setting (Martínez-González, 2023). Accelerating superplasticizers work by altering the properties of the cement paste, making it more fluid and less viscous, and accelerating the hydration reaction of the cement.

Types of Accelerating Superplasticizers

Accelerating superplasticizers can be classified into two main types:

- Chemical Accelerating Superplasticizers: These react with the components of the concrete to accelerate the hydration reaction of the cement.
- Physical Accelerating Superplasticizers: These change the environmental conditions of the concrete, such as temperature or humidity, to accelerate the hydration reaction of the cement.

Chapter IV

Mineral Additions and Its Influence On The Sustainability

Introduction

Mineral admixtures, such as fly ash, silica fume, metakaolin, and slag, offer a sustainable alternative to traditional cement by significantly reducing CO2 (carbon dioxide) emissions from cement production while improving the mechanical and durability properties of concrete. Extensive research and experimental findings demonstrate that these admixtures enhance compressive and tensile strength, improve workability, and provide better resistance to environmental factors. By strategically substituting natural aggregates with these materials, cement production can be reduced by over 50% without compromising essential mixed qualities.

Mineral additions are materials added to concrete to technologically improve its properties. They can be of natural or artificial origin (ASTM C1602, 2023).

Mineral additions can be classified into two main groups

- Hydraulic Additions: These materials react with water to form gels that provide strength to concrete. The most common hydraulic additions are ground granulated blast furnace slag (GGBFS) and fly ash.
- Non-Hydraulic Additions: These materials do not react with water but provide additional properties to concrete, such as reducing permeability, improving workability, or reducing shrinkage. The most common non-hydraulic additions are silica fume, natural pozzolan, and artificial pozzolan.

Figure 44.
Cement with mineral additions.

Source: Laura Carolina Lopera, Juan Fernando Arango Londoño. (https://alion.com.co/wp-content/uploads/2021/04/Ma%CC%81s-de-35-tipos-de-cemento-cua%CC%81l-es-el-ido%CC%81neo-para-mi-proyecto-V3.pdf)

Mineral additions are used in concrete manufacturing to improve its properties and reduce its environmental impact. Some of the advantages of using mineral additions in concrete include:

- Improving mechanical strength: Mineral additions can increase compressive, flexural, and tensile strength of concrete.
- Reducing concrete permeability: Mineral additions can decrease concrete permeability, making it more resistant to corrosion and chemical attack.
- Enhancing workability: Mineral additions can improve concrete workability, making it easier to place and compact.
- Reducing shrinkage: Mineral additions can decrease concrete shrinkage, making it less prone to cracking.
- Reducing the environmental impact of concrete manufacturing: Mineral additions can lower energy consumption and greenhouse gas emissions in concrete production.

Mineral additions are used in a wide range of applications, including:

- Construction of structures: Mineral additions are used in building structures, bridges, roads, and other structures.
- Infrastructure construction: Mineral additions are used in civil engineering works, such as dams, canals, and tunnels.
- Pavement construction: Mineral additions are used in pavement construction, including roads, parking lots, and sidewalks.

Mineral additions are a crucial tool for enhancing concrete properties and reducing its environmental impact.

Figure 45.
Mineral additions

Source: Bayram Tunalı, 2019. (https://www.sanalsantiye.com/puzolanlar-beton-maliyetini-dusuruyor/)

Characteristics of Main Additions

Mineral additions can be classified into two main groups: hydraulic additions and non-hydraulic additions. (ASTM C1602, 2023).

Hydraulic Additions.

Hydraulic additions react with water to form gels that provide strength to concrete. The most common hydraulic additions are ground granulated blast furnace slag (GGBFS) and fly ash.

- Ground Granulated Blast Furnace Slag (GGBFS): A by-product of steel manufacturing, GGBFS is a finely ground material with relatively high silica and alumina content. GGBFS is a highly active hydraulic addition that can increase concrete compressive strength by 30% or more.
- Fly Ash: A by-product of coal combustion in power plants, fly ash is a finely ground material with relatively high silica and alumina content. Fly ash is a less active hydraulic addition than GGBFS but can still increase concrete compressive strength by 10% or more.

Non-Hydraulic Additions

Non-hydraulic additions do not react with water but contribute additional properties to concrete, such as reducing permeability, improving workability, or reducing shrinkage. The most common non-hydraulic additions are silica fume, natural pozzolan, and artificial pozzolan.

- Silica Fume: A by-product of silicon manufacturing, silica fume is an ultra-fine material with very high silica content. Silica fume is an extremely effective non-hydraulic addition for reducing concrete permeability.
- Natural Pozzolan: A volcanic material that contains silica and alumina, natural pozzolan is a non-hydraulic addition that can react with lime free from cement to form gels that provide strength to concrete.
- Artificial Pozzolan: A material manufactured from fly ash, slags, or other silica-and-alumina-rich materials, artificial pozzolan is a non-hydraulic addition that can react with lime free from cement to form gels that provide strength to concrete.

The main characteristics of mineral additions are presented below:

Table 1. *Characteristics of Main Mineral Additions*

Addition	Type	Origin	Characteristics
Ground Granulated Blast Furnace Slag (GGBFS)	Hydraulic	By-product of steel manufacturing	Finely ground material, high silica and alumina content
Fly Ash	Hydraulic	By-product of coal combustion in power plants	Finely ground material, high silica and alumina content
Silica Fume	Non-Hydraulic	By-product of silicon manufacturing	Finely ground material, high silica content
Natural Pozzolan	Non-Hydraulic	Volcanic material	High silica and alumina content
Artificial Pozzolan	Non-Hydraulic	Manufactured from fly ash, slags, or other silica-and-alumina-rich materials	High silica and alumina content

Advantages of Using Additions

Mineral additions are materials of natural or artificial origin added to cementitious mixtures to improve their properties. The advantages of using mineral additions in concrete are as follows (ASTM C1602, 2023):

- Improving concrete mechanical strength: Hydraulic additions, such as GGBFS and fly ash, can increase the compressive, flexural, and tensile strength of concrete.
- Reducing concrete permeability: Non-hydraulic additions, such as silica fume, can reduce concrete permeability, making it more resistant to corrosion and chemical attack.
- Enhancing concrete workability: Both hydraulic and non-hydraulic additions can improve concrete workability, making it easier to place and compact.
- Reducing concrete shrinkage: Both hydraulic and non-hydraulic additions can reduce concrete shrinkage, making it less prone to cracking.
- Reducing the environmental impact of concrete manufacturing: Mineral additions are often produced from industrial waste.

Fresh Concrete

Additions in fresh concrete can offer a range of advantages, including:

- Improving workability: Mineral additions can enhance concrete workability, making it easier to place and compact. This can be beneficial in applications where concrete needs to be placed in tight or hard-to-reach areas.
- Reducing shrinkage: Mineral additions can decrease concrete shrinkage, making it less prone to cracking. This can be advantageous in applications

where avoiding cracks is crucial, such as in structures under compressive loads.

- Improving corrosion resistance: Mineral additions can enhance concrete corrosion resistance, making it more durable in aggressive environments. This can be beneficial in applications where concrete is exposed to adverse weather conditions or chemicals.
- Reducing environmental impact: Mineral additions are often produced from industrial waste.

Durability

The durability of fresh concrete is a measure of its ability to maintain its physical and chemical properties throughout its service life. The service life of concrete can range from several years to decades or even centuries, depending on the environmental conditions to which it is exposed

Durability can be improved through the use of mineral additions. Mineral additions are natural or artificial materials added to cementitious mixtures to improve their properties. Mineral additions can enhance durability in several ways:

- Reducing concrete permeability: Mineral additions can decrease the number of pores in concrete, making it less susceptible to the penetration of water, gases, and chemicals.
- Improving corrosion resistance: Mineral additions can reduce the amount of chloride ions that penetrate concrete, helping protect concrete reinforcement against corrosion.
- Enhancing abrasion resistance: Mineral additions can increase the surface hardness of concrete, making it more resistant to wear.

Using mineral additions to improve the durability of fresh concrete can be beneficial in applications where concrete will be exposed to adverse environmental conditions, such as in structures exposed to weathering, pollution, or chemicals (American Society for Testing and Materials, 2023).

Pozzolans

Pozzolanic additions are natural or artificial materials added to cementitious mixtures to improve their properties (American Society for Testing and Materials, 2023). Pozzolanic additions are characterized by their ability to react with calcium hydroxide (Ca(OH)2) produced during cement hydration to form hydrated silicates, which contribute to concrete strength.

The advantages of using pozzolanic additions include:

- Strength improvement: Pozzolanic additions can enhance the compressive and flexural strength of concrete.
- Permeability reduction: Pozzolanic additions can lower concrete permeability, making it more resistant to corrosion and chemical attack.
- Durability improvement: Pozzolanic additions can enhance concrete durability, making it more resistant to degradation by environmental agents.
- Environmental impact reduction: Pozzolanic additions are often produced from industrial waste.

Properties of Pozzolans

Pozzolans are characterized by their ability to react with calcium hydroxide ($Ca(OH)_2$) produced during cement hydration to form hydrated silicates, which contribute to concrete strength.

The properties of pozzolans depend on their chemical and mineralogical composition. Pozzolans with high silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) content exhibit better pozzolanic properties.

The main properties of pozzolans are:

- Pozzolanic reaction: This chemical reaction occurs between pozzolans and calcium hydroxide to form hydrated silicates. This reaction is responsible for the improvements in concrete properties.
- Permeability reduction: Pozzolans can reduce concrete permeability, making it more resistant to corrosion and chemical attack.
- Durability improvement: Pozzolans can enhance concrete durability, making it more resistant to degradation by environmental agents.
- Environmental impact reduction: Pozzolans are often produced from industrial waste.

Classification

Pozzolans can be classified into two main categories:

- Natural Pozzolan: This is a material of natural origin found in geological deposits. Examples of natural pozzolan include volcanic ash, tuff, and shale.
- Artificial Pozzolan: This is a material produced artificially. Examples of artificial pozzolan include fly ash, ground granulated blast furnace slag, and silica fume.

Main mineral additions

Microsilica (Silica Fume)

Microsilica, also known as silica fume, is a pozzolanic material obtained as a by-product of silicon and ferrosilicon manufacturing (García, 2023). It is an extremely fine powder with an average particle diameter of 0.15 microns, approximately 100 times smaller than the average size of a cement grain.

Figure 46.

Microsilica (silica fume)

Source: Cedex materiales. (https://www.cedexmateriales.es/catalogo-de-residuos/29/humo-de-silice/111/origen.html).

Microsilica has several properties that make it a highly valuable additive for concrete. These include:

- Increasing compressive and tensile strength of concrete.
- Reducing concrete permeability, making it more resistant to corrosion and water penetration.
- Improving the adhesion of concrete to reinforcing steel.
- Reducing concrete shrinkage, making it more stable and durable.

Microsilica is used in a wide range of concrete applications, including

- Reinforced and prestressed concrete
- Structural concrete
- Pavement concrete
- Concrete for precast construction elements
- Concrete for hydraulic works

Microsilica is a sustainable material as it is obtained as a by-product of the silicon industry. Its use in concrete contributes to improving the strength and durability of this material, which can reduce the maintenance and repair costs of concrete structures.

Microsilica is a safe and efficient additive that can significantly improve concrete performance. However, it is important to use it correctly to achieve the best results.

Origin

The origin of microsilica dates back to the 1930s (García, 2023), when it was discovered that the smoke produced during silicon and ferrosilicon manufacturing had cementitious properties. In the 1940s, microsilica began to be used as an additive for concrete, and its use has since expanded to a wide range of applications

Microsilica is produced by combusting silicon and carbon in an electric furnace. The combustion process produces silica fume, which is collected and dried. The silica fume is classified according to particle size, measured in microns. Microsilica has a particle size of 0.15 microns or les

Microsilica is a sustainable material, as it is obtained as a by-product of the silicon industry. In addition its use in concrete helps to improve the strength and durability of this material, which can reduce the maintenance and repair costs of concrete structures.

Volume and Distribution

The volume and distribution of microsilica are important factors that affect concrete performance. (García, 2023)

Microsilica volume is measured as a percentage of the total volume of the cement mix. The microsilica volume typically used is in ranges between 5% and 10%.

Distribution refers to how microsilica is distributed within the concrete mix. Microsilica must be uniformly distributed to have an optimal effect on concrete performance.

Proper volume and distribution can help improve the following concrete properties:

- Strength: Microsilica reacts with cement lime to form new compounds, increasing concrete compressive and tensile strength.
- Permeability: Microsilica fills the pores in concrete, making it more resistant to water penetration and other corrosive agents.
- Adhesion: Microsilica improves the bond between concrete and reinforcing steel, reducing the risk of corrosion.
- Shrinkage: Microsilica reduces concrete shrinkage, making it more stable and durable.

Microsilica volume is usually specified in the concrete mix design. The recommended volume depends on the specific properties to be improved.

In general, a higher microsilica volume leads to greater improvements in concrete properties. However, an excessively high microsilica volume can negatively impact concrete workability.

Microsilica distribution can be improved by properly mixing the concrete. Microsilica should be well-mixed with cement and aggregates to ensure even distribution. It can also be improved by using a dispersion additive. Dispersion additives help distribute microsilica in the concrete mix, improving workability and mix uniformity.

Chemical Properties

The chemical properties of microsilica are as follows (García, 2023):

- Composition: Microsilica is composed primarily of silicon dioxide (SiO_2), with a content between 90% and 98%. It may also contain small amounts of other elements, such as aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and magnesium oxide (MgO).
- Reactivity: Microsilica is a pozzolanic material, meaning it can react with cement lime to form new compounds, such as calcium silicate hydrate (C-S-H). This reaction is exothermic, meaning it releases heat.
- Compatibility: Microsilica is compatible with most construction materials, including cement, steel, concrete, and mortar.

The chemical composition of microsilica is responsible for its pozzolanic properties. Silicon dioxide, the principal component of microsilica, is essential for its reaction with the lime present in cement.

Reactivity is an important property that determines concrete performance. More reactive microsilica will produce concrete with greater strength and durability.

Microsilica compatibility is important to ensure concrete uniformity and durability. Microsilica should be compatible with other construction materials used in concrete.

Microsilica reacts with cement lime to form new compounds, such as calcium silicate hydrate (C-S-H). This reaction is exothermic, meaning it releases heat.

The chemical reaction between microsilica and cement lime can be represented as follows:

$$SiO_2 + Ca(OH)_2 \rightarrow C\text{-}S\text{-}H + H_2O$$

In this reaction, silicon dioxide (SiO_2) reacts with lime ($Ca(OH)_2$) to form calcium silicate hydrate (C-S-H) and water (H_2O).

Calcium silicate hydrate is a hard and durable material that provides microsilica with its pozzolanic properties.

Fly Ash

Fly ash is a by-product of pulverized coal combustion (García, 2023, p. 10). It is produced in coal-fired power plants, where coal is burned in a furnace at very high temperatures. Fly ash forms when the volatile material in the coal vaporizes and then condenses into a solid form.

Figure 47.
Fly ash

Source: Ripuka. (https://ripuka.com.mx/es/venta/refractaria-y-ceramica/)

Fly ash is a fine powder, ranging in color from gray to brown. Its particle size is approximately 0.1 to 0.2 microns, which is about 100 times smaller than the average size of a cement grain. Fly ash is used as an additive in concrete. It has several properties that enhance concrete performance, including:

- Strength: Fly ash reacts with cement lime to form compounds that increase concrete strength.
- Permeability: Fly ash fills the pores in concrete, making it more resistant to water penetration and other corrosive agents.
- Durability: Fly ash improves concrete durability, making it more resistant to degradation over time and climate.

Fly ash is a sustainable material that can be used to reduce the amount of waste sent to landfills.

Chemical Properties.

The chemical properties of fly ash are as follows:

- Composition: Fly ash is primarily composed of silicates, aluminates, and iron oxides. It may also contain small amounts of other elements, such as calcium oxide, magnesium oxide, and sulfur oxide. The percentage of differents compouns is according next values: SiO_2 (15%-60%), Al_2O_3 (3.68%-35%), Fe_2O_3 (4%-40%), CaO (1%-40%) and MgO (0%-10%), the above information is expressed in ranges, due to the final chemical composition of fly ash depends of the class of Fly Ash that will be used.
- Reactivity: Fly ash is a pozzolanic material, meaning it can react with cement lime to form new compounds, such as calcium silicate hydrate (C-S-H). This reaction is exothermic, meaning it releases heat.
- Compatibility: Fly ash is compatible with most construction materials, including cement, steel, concrete, and mortar.

The reaction between fly ash and cement lime can be represented as follows:

$$SiO_2 + Ca(OH)_2 \rightarrow C\text{-}S\text{-}H + H_2O$$

In this reaction, the silicon dioxide (SiO_2) in fly ash reacts with the lime ($Ca(OH)_2$) in cement to form calcium silicate hydrate (C-S-H) and water (H_2O).

Calcium silicate hydrate is a hard and durable material that provides fly ash with its pozzolanic properties.

Hydraulic Activity

The hydraulic activity of fly ash measures its ability to react with cement lime to form new compounds, such as hydrated silica (C-S-H) (García, 2023, p. 20). This reaction is exothermic, meaning it releases heat.

The hydraulic activity of fly ash is measured using a standard test known as the pozzolanic activity test. This test involves mixing fly ash with lime and water, and then measuring the strength of the resulting material.

Fly ash with high hydraulic activity reacts more quickly with cement lime and forms more C-S-H. This results in concrete with greater strength and durability.

The hydraulic activity of fly ash depends on several factors, including:

- Chemical composition: Fly ash with a higher content of silica and alumina has higher hydraulic activity.
- Particle size: Fly ash with smaller particle size has higher hydraulic activity.
- Purity: Purity plays a role; purer fly ash has higher hydraulic activity.

Fly ash with low hydraulic activity can be improved through a process called activation. Activation involves treating the fly ash with a chemical agent, such as sodium chloride or sodium sulfate.

The hydraulic activity of fly ash is an important factor to consider when selecting fly ash for use in concrete. Fly ash with high hydraulic activity provides concrete with greater strength and durability.

Volcanic Ash

Volcanic ash can be used in concrete to increase strength, durability, and sustainability by replacing a portion of the cement, a process pioneered by the ancient Romans. As a natural pozzolan, pulverized volcanic ash reacts with water to form cement-like compounds, enhancing the concrete's long-term compressive strength and resistance. This use offers a low-carbon alternative to Portland cement, providing a sustainable way to build stronger structures and reduce the environmental impact of construction (García, 2023).

Figure 48.
Volcanic ash

Source: Lado B, 2012. (https://www.ladobe.com.mx/2012/04/la-ceniza-volcanica-enriquece-la-tierra-puede-usarse-para-composta/).

Chemical composition

Volcanic ash used in concrete is a natural pozzolan, a material primarily composed of silica (SiO_2) and alumina (Al_2O_3), often with minor amounts of iron oxide (Fe_2O_3), magnesium oxide (MgO), and alkalis (Na_2O, K_2O, CaO). Its usefulness in concrete stems from its amorphous, cementitious properties, which allow it to react with calcium hydroxide to form durable calcium silicate hydrates, similar to Portland cement, enhancing the concrete's strength and durability. The percentage of differents compouns is around next values: SiO_2 (77.80%), TiO_2 (0.18%), Al_2O_3 (12.95%), FeO (0.67 %), MgO (0.36 %), CaO (0.88%), NaO (3.34%), K_2O (3.98%).

Reactivity of volcanic ash in the concrete

Volcanic ash can be a reactive pozzolanic material used in concrete, but its reactivity varies, often requiring modification like grinding to increase surface area, activating it with lime or alkaline activators, or using it with other pozzolans like fly ash to achieve desirable strength and durability. Research indicates that finer grinding can improve reactivity and mechanical properties up to a certain replacement level, while high temperatures can also enhance the pozzolanic reaction of low-calcium materials like volcanic ash.

Chemical Reactions During the Hydration Process

The hydration process of volcanic ash is a chemical reaction that occurs when volcanic ash is mixed with water. This reaction produces new compounds, such as hydrated silica (C-S-H), these compounds provide volcanic ash with its cementitious properties.

The chemical reactions that occur during the hydration process of volcanic ash are as follows:

- Reaction of volcanic ash with water: Volcanic ash is an aluminosilicate material that contains calcium oxide (CaO). When volcanic ash is mixed with water, the CaO reacts with water to form calcium hydroxide ($Ca(OH)_2$) (García, 2023).
- Reaction of calcium hydroxide with silica: Calcium hydroxide is an alkaline material that reacts with silica to form hydrated silica (C-S-H). C-S-H is a hard and resistant material that gives volcanic ash its cementitious properties.
- Reaction of volcanic ash with hydrated calcium aluminate: Hydrated calcium aluminate (C_3A) is a compound found in Portland cement. When volcanic ash is mixed with Portland cement, hydrated calcium aluminate reacts with volcanic ash to form new compounds, such as calcium monocarboaluminate (C_3AH_6). C_3AH_6 is a hard and resistant material that provides concrete with strength.

The hydration process of volcanic ash is a slow process that can last several days or even weeks. The hydration rate depends on several factors, such as temperature, humidity, and the composition of volcanic ash.

Volcanic ash is a sustainable material that can be used as a partial substitute for Portland cement in concrete. Volcanic ash can help reduce the cost and environmental impact of concrete.

Metakaolin

Metakaolin is a pozzolanic material produced by calcining kaolin at temperatures between 500 and 700 °C (García, 2023). Kaolin is a clay mineral composed mainly of kaolinite, a hydrated aluminosilicate. During the calcination process, kaolinite loses its water of hydration and transforms into metakaolin, an amorphous aluminosilicate.

Figure 49.

Metakaolin (MK)

Source: Solid waste (https://www.solidwaste.ru/enterprise/460/kuzbasskaya_associaciya_pererabotchikov_othodov/market/530/merteli_ogneupornye_alyumosilikatnye_msh-28.html).

Metakaolin has several properties that make it suitable for use in concrete, including (García, 2023, p. 20):

- Improved strength: It reacts with water and lime to form new compounds, such as hydrated silica (C-S-H). C-S-H is a hard and resistant material that provides concrete with strength.
- Improved durability: It fills the pores of concrete, making it more resistant to water penetration and other corrosive agents.
- Improved impermeability: It reduces the amount of water that can penetrate concrete, making it more resistant to freeze-thaw cycles.
- Improved workability: It enhances concrete workability, making it easier to place and compact.

Metakaolin is a thermally activated aluminosilicate material that can be used as a partial substitute for Portland cement in concrete. Metakaolin has cementitious properties similar to Portland cement. It hydrates in the presence of water to form cementitious compounds that provide concrete with strength and durability.

In general, concrete using metakaolin is a versatile material with a range of properties that make it suitable for various applications.

Chemical composition

Metakaolin's chemical composition is primarily silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), typically ranging from 50-55% SiO_2 and 40-45% Al_2O_3, respectively. It also contains trace amounts of other oxides like iron oxide (Fe_2O_3), titanium dioxide (TiO_2), and alkaline oxides (Na_2O, K_2O, CaO, MgO). The specific composition can vary depending on the source kaolin clay and the calcination process used in its production.

Reactivity of metakaolin in the concrete

Metakaolin is a highly reactive supplementary cementitious material (SCM) that enhances concrete performance through several mechanisms: the pozzolanic reaction with calcium hydroxide (CH) to form stable, durable compounds, and a filler effect that densifies the concrete microstructure. This dual action leads to improved mechanical properties like compressive strength, enhanced durability by reducing porosity and improving transport properties, and can help mitigate alkali-silica reaction.

Percentage of replacement in the concrete

The optimum metakaolin percentage for replacement in concrete ranges from 5% to 15% by weight of cement, with 10-15% often cited as the ideal range to significantly improve compressive strength and other properties. While some studies show benefits up to 15%, higher replacement levels can decrease strength due to decreased workability and delayed pozzolanic reaction.

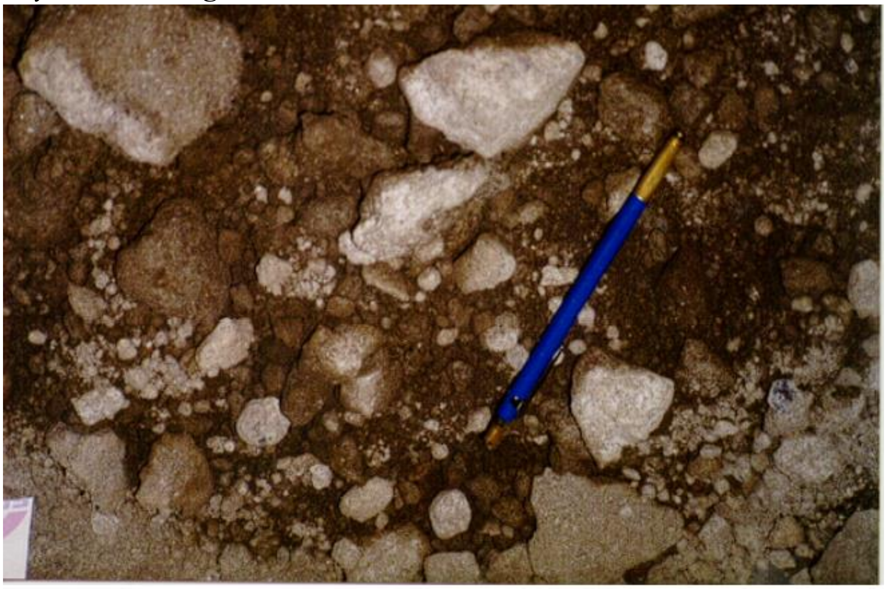
Ground Granulated Blast Furnace Slag (GGBFS)

Ground granulated blast furnace slag is a byproduct of iron and steel production. It is a cementitious material obtained by rapidly cooling molten slag from a blast furnace in water or steam. The resulting product is a glassy granular material that is dried and ground into a fine powder.

Figure 50.
Granulated slag

Source: Víctor Yepes Piqueras. (https://victoryepes.blogs.upv.es/tag/escoria/)

Figure 51.
Crystallized slag



Source: CEDEX, 2011. (https://www.cedexmateriales.es/catalogo-de-residuos/39/escorias-de-horno-alto/259/origen.html)

GGBFS has several properties that make it suitable for use in concrete. It is a pozzolanic material, meaning it reacts with water to form hydraulic compounds. This allows GGBFS to partially replace Portland cement in concrete, reducing the cost and environmental impact of concrete.

GGBFS also has properties that improve concrete performance. It can increase the early strength of concrete, reduce concrete permeability, and improve its resistance to fire (Smith, 2023).

GGBFS is an eco-friendly alternative to Portland cement. It is a sustainable material that can help reduce greenhouse gas emissions and air pollution.

Origin

The origin of GGBFS dates back to ancient times. The earliest traces of blast furnace slag have been found in China, India, and the Middle East, dating back over 3,000 years. However, it was not until the 19th century that GGBFS began to be used in concrete.

In 1875, British engineer Isaac Johnson patented the first use of ground granulated blast furnace slag in concrete. Johnson discovered that GGBFS could partially replace Portland cement in concrete, reducing costs and improving concrete performance.

Since then, the use of GGBFS in concrete has grown considerably. Today, GGBFS is used in a wide range of concrete applications, including roads, bridges, buildings, dams, and other engineering structures.

Properties

GGBFS has several properties that make it suitable for use in concrete. These properties include:

Pozzolanic reaction: GGBFS reacts with water to form hydraulic compounds. This allows GGBFS to partially replace Portland cement in concrete, reducing the cost and environmental impact of concrete.

- Early strength: GGBFS can increase the early strength of concrete, reducing curing time.
- Reduced permeability: GGBFS can reduce concrete permeability, improving resistance to corrosion and chemical attack.
- Fire resistance: GGBFS can improve fire resistance of concrete.

Pozzolanic Reaction

GGBFS is a pozzolanic material, meaning it reacts with water to form hydraulic compounds. These hydraulic compounds are similar to Portland cement, providing concrete with strength and durability.

The pozzolanic reaction of GGBFS occurs when calcium silicate in GGBFS reacts with water to form hydrated calcium silicate. Hydrated calcium silicate is a strong and durable material that can help improve concrete performance.

Early Strength

GBFS can increase the early strength of concrete. This is because GGBFS reacts with water more quickly than Portland cement.

Early strength is important for applications where concrete needs to reach a specific strength within a short period. For example, GGBFS can be used in the construction of structures that need to be put into service quickly.

Reduced Permeability

GGBFS can reduce concrete permeability. This occurs because GGBFS can fill concrete pores.

Permeability is the ability of a material to allow water and other fluids to pass through it. Reducing concrete permeability can improve resistance to corrosion and chemical attack.

Fire Resistance

GGBFS can improve the fire resistance of concrete. This is because GGBFS is a refractory material.

Fire resistance is the ability of a material to withstand heat and fire. Improving the fire resistance of concrete can be important for applications where concrete may be exposed to fire.

Chemical Properties

GGBFS, or Ground Granulated Basic Fluid Slag, is a byproduct of steel manufacturing. It is produced by pouring molten metal into water to cool and solidify it quickly. GGBFS has a basic chemical composition, with a CaO (Calcium oxide) content of approximately 60-70% and an MgO (Magnesium oxide) content of approximately 20-30%. It also contains smaller amounts of other oxides, such as SiO2 (Silicon dioxide), Al2O3 (Aluminum oxide), and Fe2O3 (Iron oxide).

The main chemical properties of GGBFS are:

- Basicity: GGBFS is a basic material with a pH of approximately 12. This makes it compatible with Portland cements, which are slightly acidic (López, 2023, p. 23).
- Reactivity: GGBFS is a reactive material that reacts with water to form calcium silicates and aluminates. This reaction releases heat, helping to accelerate concrete curing
- Fluidity: GGBFS has high fluidity, making it ideal for self-compacting concretes.

The chemical properties of GGBFS provide several advantages over other cementitious materials, such as Portland cement. GGBFS is more sustainable as it is a byproduct of the steel industry. It is also more energy-efficient, requiring less energy to produce than Portland cement. Additionally, GGBFS improves concrete properties, such as strength, durability, and fire resistance.

Nano-additives

Nanotechnology is a field of science concerned with the manipulation of matter on a nanometric scale, specifically from 1 to 100 nanometers. Nanomaterials are materials that have one or more dimensions within this scale.

Nano-additives are nanomaterials that are incorporated into other materials to enhance their properties. In the context of concrete, nano-additives are used to improve strength, durability, and other attributes.

The most common nano-additives used in concrete are:

- Nanosilica: Composed of nanometric-sized silica particles, nanosilica enhances compressive strength, tensile strength, abrasion resistance, and durability of concrete.
- Nanolime: Composed of nanometric-sized lime particles, nanolime improves compressive strength, tensile strength, fire resistance, and durability of concrete. Nanolime, specifically calcium hydroxide nanoparticles dispersed in a solvent, is used in concrete and other building materials as a consolidation agent to improve strength and durability. It works by penetrating the material and reacting with carbon dioxide to form calcium carbonate, strengthening the structure
- Nanoalumina: Composed of nanometric-sized alumina particles, nanoalumina enhances compressive strength, tensile strength, abrasion resistance, and durability of concrete. Nanoalumina acts as both a dispersion agent for cement particles and a nano-filler, leading to a denser, more durable concrete with improved mechanical properties. Specifically, it can enhance compressive strength, flexural strength, and tensile strength, while also improving resistance to chemical attacks like sulphate attack.

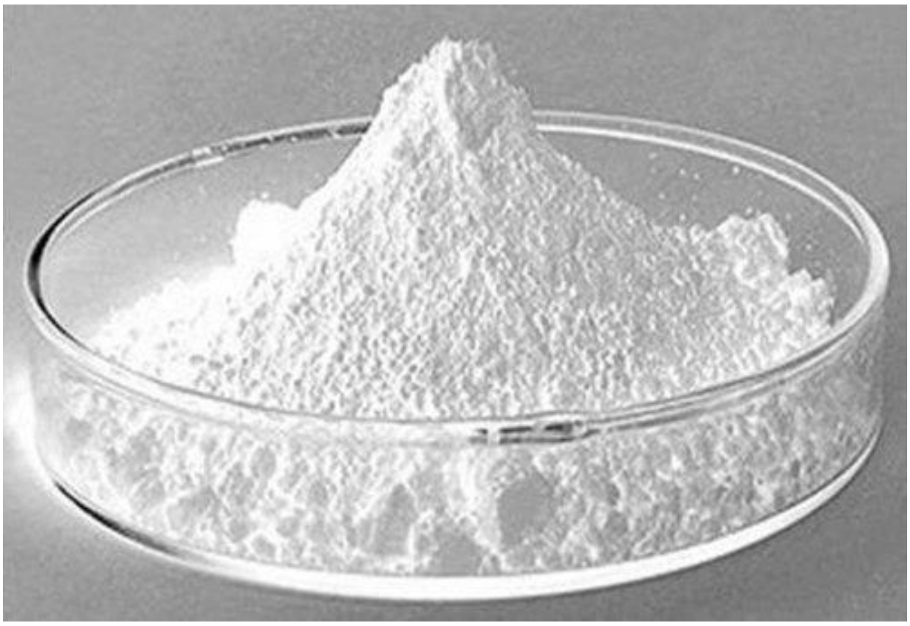
Nano-additives can be added to concrete in the form of powder, liquid, or suspension. The method of addition depends on the type of nano-additive and the specific properties of the concrete to be improved.

Although nano-additives are a relatively new technology still under development, they have shown great efficacy in enhancing concrete properties.

Nanosilica

Nanosilica is a form of silica with particle sizes ranging from 1 to 100 nanometers (nm). This inorganic material is naturally found in sand, granite, and other minerals. Nanosilica can be industrially produced from silica through processes such as thermal decomposition and hydrolysis (López, 2023, p. 2).

Figure 52.
Nanosilica



Source: Boubyan International Company. (https://www.chemicals.boubyaninternational.com/zinc-oxide.html)

Nanosilica boasts several properties that make it valuable for a variety of applications. It is a strong and durable material with a high absorption capacity. Additionally, nanosilica is an excellent conductor of heat and electricity.

Applications of nanosilica include:

- Construction Materials: Used to enhance mechanical, thermal, and durability properties of construction materials such as concrete, steel, and plastic.

- Cosmetic Products: Serves as a filler and opacifying agent in cosmetics like creams and powders.
- Pharmaceuticals: Functions as an excipient in pharmaceutical products like tablets and capsules.
- Electronics: Utilized in manufacturing electronic components such as transistors and capacitors.

Nanosilica is safe and non-toxic but should be handled carefully as it can irritate the skin and eyes.

The unique properties of nanosilica arise from its small particle size. Nanoparticles of silica possess a large specific surface area, meaning there is a lot of available surface area relative to volume. This large specific surface area is responsible for many of the unique properties of nanosilica, such as:

- Strength: Can enhance material strength by filling pores and increasing density.
- Durability: Improves material durability by making them more resistant to wear and corrosion.
- Thermal Properties: Enhances thermal properties by increasing thermal conductivity.

Optical Properties: Enhances optical properties by making materials more reflective or transparent.

Characteristics

Nanosilica is an inorganic material naturally found in sand, granite, and other minerals. It can be industrially produced through processes such as thermal decomposition and hydrolysis.

The unique characteristics of nanosilica are attributed to its small particle size. Nanoparticles of silica have a large specific surface area, resulting in a wide available surface in relation with volume. This gives rise to a number of distinctive properties such as:

- Strength.
  It can improve the strength of materials by filling pores and increasing density. Pores are empty spaces found in materials. When nanosilica is added to a material, the nanoparticles fill these pores, making the material denser. Density is a measure of the amount of mass per unit volume. A denser material is stronger.

- Durability.
  It can improve the durability of materials by making them more resistant to wear and corrosion. Wear is the process of material loss through

abrasion. Corrosion is the process of deterioration of a material due to the chemical action of an environment. Nanosilica can improve the durability of materials by making them more resistant to these processes.

- Thermal.
  It can improve the thermal properties of materials by increasing thermal conductivity. Thermal conductivity is a measure of the ability of a material to transfer heat. A material with a higher thermal conductivity is a better heat conductor. Nanosilica can increase the thermal conductivity of materials by providing a more direct path for heat to flow through the material.

- Optics.
  It can improve the optical properties of materials by making them more reflective or transparent. Reflectance is the measure of the amount of light that is reflected from a surface. Transparency is the measure of the amount of light that passes through a surface. Nanosilica can improve the optical properties of materials by changing the way light interacts with the surface of a material.

Geometric Characteristics of Nanosilica (nano-SiO2)

The geometric characteristics of nanosilica (nano-SiO2) pertain to its size, shape, and distribution. These characteristics have a significant impact on the properties of the material, such as strength, durability, and optical attributes (López, 2023).

- Size.
  The size of silica nanoparticles is an important factor that determines their properties. Silica nanoparticles with a size of 1 to 100 nanometers (nm) are considered nanosilica. At this size, nanoparticles have a large specific surface area, meaning there is a lot of available surface area relative to volume. This large specific surface area is responsible for many of the unique properties of nanosilica.

- Shape.
  The shape of silica nanoparticles can also affect their properties. Silica nanoparticles can be spherical, cubic, hexagonal or other shapes. The shape of nanoparticles can affect their ability to interact with other materials and substances.

- Distribution.
  The distribution of silica nanoparticles in a material can also affect its properties. Silica nanoparticles can be uniformly distributed, dispersed or

agglomerated. The distribution of nanoparticles can affect their ability to improve material properties.

Typical geometric features of nanosilica include:

- Size: 1 to 100 nm.
- Shape: Spherical, cubic, hexagonal.
- Distribution: Uniform, dispersed, agglomerated.

Chemical Composition of Nanosilica (nano-SiO2)

The chemical composition of nanosilica (nano-SiO2) is SiO2, which means that it is mainly composed of silicon (Si) and oxygen (O) (López, 2023). Silicon is a chemical element found on the periodic table with atomic number 14. Oxygen is a chemical element found on the periodic table with atomic number 8.

Nanosilica can be produced from sand, quartz or crystallized silica. Sand is a natural material that is mainly composed of silicon and oxygen. Quartz is a mineral that is mainly composed of silicon and oxygen. Crystallized silica is a material that is mainly composed of silicon and oxygen.

The production process involves the breakdown of silicon and oxygen into nanometer-sized particles. This can be done by various methods such as thermal decomposition, hydrolysis and solvolysis. The chemical composition is important because it determines its properties. Silicon is a strong and resistant chemical element, while Oxygen is light and volatile. The combination of these two elements gives rise to a series of unique properties, such as strength, durability and thermal conductivity.

The typical chemical composition of nanosilica is:

- Silicon (Si): 99.9%
- Oxygen (O): 0.1%

This composition is typical for nanosilica produced from sand, quartz, or crystallized silica.

Dosage of Concrete with Nanosilica

The dosage of concrete with nanosilica is a careful process to ensure desired properties are achieved. The amount of nanosilica to be added depends on several factors, such as the type of concrete, desired properties, and application conditions.

Some factors to consider when dosing concrete with nanosilica are the following:

- Type of Concrete: The type of concrete to be manufactured will determine the amount of nanosilica to be added.
- Desired Properties: They influence the amount of nanosilica added in the concrete.

- Application Conditions: These conditions can also affect the dosage of nanosilica.

Preparation of Cement Mix with Nanosilica

The preparation of cement mix with nanosilica is a straightforward process that can be done manually or automatically (López, 2023). The manual method consists of adding the nanosilica to the dry cement and then adding water. The automatic method consists of adding nanosilica to wet cement.

Manual Method:

- Place the cement in a bucket.
- Add nanosilica to the cement and mix well.
- Add sand and gravel and mix well.
- Add water and mix until a uniform mass is formed.

Automatic Method:

- Add cement and nanosilica to a mixer.
- Add sand and gravel and mix well.
- Add water and mix until a uniform mass is formed.

Chapter V

Concrete Mix Design Methods

Introduction

Concrete mix design is the process of determining the appropriate proportions of concrete components, such as cement, aggregates, and water, to achieve a mix that meets the requirements for strength, durability, and consistency in construction structures. (Pérez, 2023)

There are various methods for concrete mix design, including the volume method, weight method, and design method.

The factors to consider in concrete mix design are as follows:

- Compressive Strength: Compressive strength is the most important property of concrete. The mix design must ensure that the mix achieves the required strength.
- Durability: Concrete must be durable to withstand the effects of climate, chemical exposure, and other environmental factors. The mix design must take into account durability requirements.
- Workability: Concrete must be workable enough to be placed and compacted correctly. The mix design must ensure that the mix has the required workability.
- Cost: The cost of concrete is an important factor to consider. The mix design should optimize the cost of the mix without compromising strength, durability, or workability.

Considerations for a correct Mix Design Procedure

Strength Requirements (F´C)

Strength requirements (f´c) refer to the mechanical characteristics that concrete must meet to withstand the loads to which it will be exposed. (American Concrete Institute, 2023)

Compressive strength is the most important mechanical property of concrete. It is defined as the ability of concrete to withstand an axial load without collapsing. Compressive strength is measured in megapascals (MPa) or kilograms per square centimeter (kg/cm^2).

Strength requirements are established to ensure that the concrete can withstand service loads without damage. Strength requirements are also used to determine the proportions of concrete components.

Strength requirements may vary depending on the type of construction and exposure conditions. Strength requirements can be classified into two types:

- Design requirements: These requirements are based on engineering calculations that consider the loads applied to the concrete.

- Specification requirements: These requirements are established in construction standards or design documents.
- Strength requirements can be determined in several ways, including:
- Engineering calculations: These calculations are used to determine the required concrete strength to withstand service loads.
- Laboratory tests: These tests are used to measure concrete strength.
- Estimates: These estimates are based on experience and knowledge of concrete.

Strength requirements significantly impact the cost and quality of concrete. Higher strength requirements need to use more expensive materials and more complex manufacturing processes.

Experience in Mix Design

Mix design is the process of determining the proportions of the components in a mixture to achieve the desired properties. It is applied in a wide range of industries, including construction, food, chemicals, and pharmaceuticals. (Rodríguez, 2023, p. 2)

In construction, mix design is used to determine the proportions of concrete, mortar, and other construction materials. Desired concrete properties include compressive strength, flexural strength, durability, and workability.

The concrete mix design process begins with gathering information about the job site conditions. This includes specifying compressive strength, flexural strength, slump, and durability. The type of aggregates and cement available must also be considered.

Once the information is gathered, different methods can be used to design the mix. A common method is trial and error, where different proportions of the components are mixed and then the concrete properties are tested.

Another common method is using a computer mix design program. These programs use mathematical formulas to determine the amount of each component needed to achieve the desired properties.

Mix design is a complex task that requires a deep understanding of construction materials and concrete properties. However, with experience and practice, the ability to design concrete mixes that meet job requirements can be developed.

Environmental Characteristics and Structure Dimensions (w/c for Durability)

Environmental Characteristics

The environmental characteristics where the structure will be built are important factors to consider when determining the water-cement (W/C) ratio to ensure concrete durability. Environmental factors that can affect concrete durability include:

- Climatic conditions: Exposure to moisture, rain, ice, and snow can accelerate the corrosion of reinforcing steel.
- Water quality: Mixing water containing chlorides, sulfates, or other aggressive agents can accelerate reinforcing steel corrosion.
- Industrial atmosphere: Exposure to acidic, corrosive gases, or pollutants can accelerate reinforcing steel corrosion.

Structure Dimensions

The structure dimensions are also important factors to consider when determining the W/C ratio to ensure concrete durability. Larger structures exposed to adverse environmental conditions require a lower W/C ratio to ensure durability.

In general, a W/C ratio of 0.50 or less is recommended to ensure concrete durability under adverse environmental conditions (Martínez-Martínez et al., 2019). For structures exposed to moderate environmental conditions, a W/C ratio of 0.55 to 0.60 can be used.

Characteristics of Materials

Material characteristics are properties that determine how a material behaves under external stimuli, such as light, heat, forces, etc. (Callister & Rethwisch, 2014). These characteristics can be physical, mechanical, chemical, electrical, or thermal.

Physical Characteristics

Physical characteristics are the most easily measured and observed. Some of the most important physical characteristics include:

- Density: The ratio of the mass of a material to its volume.
- Color: A property perceived by the human eye.
- Hardness: The ability of a material to resist deformation without breaking. Deformation is a change in shape that can be permanent or temporary.
- Brittleness: The tendency of a material to fracture when subjected to a force or load. Brittle materials cannot deform and break easily when force is applied.

- Elasticity: The ability of a material to stretch or compress under force and return to its original shape when the force is removed.
- Plasticity: The ability of a material to change shape permanently when a force is applied.
- Thermal conductivity: The ability of a material to conduct heat.
- Electrical conductivity: The ability of a material to conduct electricity.

Mechanical Characteristics

Mechanical characteristics describe the behavior of a material under force or deformation. Some of the most important mechanical characteristics include:

- Tensile strength: The measure of force a material can withstand before breaking when stretched.
- Compressive strength: The measure of force a material can withstand before breaking when compressed.
- Impact resistance: The ability of a material to withstand sudden loads without breaking.
- Flexural strength: The measure of force a material can withstand before breaking when bent.
- Wear resistance: The ability of a material to remain in good condition when rubbed against another material.

Chemical Characteristics

Chemical characteristics determine the ability of a material to react with other materials or substances. Some of the most important chemical characteristics include:

- Reactivity: The ability of a material to react with other materials or substances.
- Corrosion: The deterioration of a material caused by chemical reaction with other materials or substances.
- Oxidation: A type of corrosion that occurs when a material reacts with oxygen.
- Hydrolysis: A type of corrosion that occurs when a material reacts with water.
- Erosion: The deterioration of a material caused by wear due to external agents such as water, wind, or chemicals.

Electrical Characteristics

Electrical characteristics describe how materials react to electricity. Some of the most important electrical characteristics include:

- Electrical Conductivity: The ability of a material to conduct electricity.
- Electrical Resistance: The opposition of a material to the flow of electricity.
- Polarization: The separation of electrical charges in a material.
- Dielectricity: The ability of a material to store electrical energy.

Thermal Characteristics

Thermal characteristics describe how materials react to heat and electricity. Some of the most important thermal characteristics include:

- Thermal conductivity: The ability of a material to conduct heat.
- Specific heat: The amount of heat required to raise the temperature of one gram of a material by one degree Celsius.
- Melting Point: The temperature at which a material changes from solid to liquid.
- Boiling Point: The temperature at which a material changes from liquid to gas.

Material characteristics are important for determining suitability for a specific application. For example, materials with high thermal conductivity are suitable for applications that require heat dissipation, and materials with high corrosion resistance are suitable for applications exposed to aggressive environments.

Initial Mix Design

The concrete mix design procedure is a way to determine the proportions of materials to be used in a concrete mixture. The method is based on the relationship between concrete compressive strength and the water-cement ratio.

The concrete mix design process begins with selecting the desired compressive strength. Once the desired strength is known, the following equation can be used to determine the initial water-cement ratio:

Water-cement ratio = 0,25 + 0,025 * f'c

Mix Design Methods

Volume Method

The volume method is the simplest and oldest method for concrete mix design. In this method, the components are measured by volume, such as liters or cubic meters.

The volume method is suitable for simple, low-strength concrete mixes. However, it is not very precise and can be difficult to control.

Weight Method

The weight method is more accurate than the volume method. In this method, the components are measured by weight, such as kilograms or tons.

The weight method is suitable for complex and high-strength concrete mixes. It is the most commonly used method today.

Design Method

The design method is more sophisticated than the volume and weight methods.

This method uses formulas and tables to determine the proportions of concrete components.

The design method is suitable for special concrete mixes, such as high-strength concrete, impermeable concrete, or highly durable concrete.

Basic Data and Mix Design Procedure

Basic Data

The basic data for concrete mix design are as follows:

- Strength Requirements: Compressive strength is the most important property of concrete.
- Durability Requirements: Concrete must be durable to withstand the effects of climate, chemical exposure, and other environmental factors.
- Workability Requirements: Concrete must be workable enough to be placed and compacted correctly.
- Economic Requirements: The cost of concrete is an important factor to consider. Economic requirements are established based on the project budget.

Mix Design Procedure

The concrete mix design procedure can be divided into the following steps:

1. Selection of materials: Select the materials to be used in the concrete mix. Typical materials include cement, aggregates, and water.
2. Determination of proportions: Determine the proportions of materials to be used in the concrete mix.
3. Mix testing: Prepare and test various concrete mixes to determine the optimal combination of proportions.
4. Mix approval: The approved mix is used for construction.

Mix Design Methods

Various methods of concrete mix design include:

- Volume Method: In this method, the components are measured by volume, such as liters or cubic meters.
- Weight Method: In this method, the components are measured by weight, such as kilograms or tons.
- Design Method: In this method, formulas and tables are used to determine the proportions of concrete components.

The appropriate mix design method depends on the characteristics of the concrete mix and the project requirements.

ACI Method (American Concrete Institute)

The ACI method is a concrete mix design method that uses formulas and tables to determine the proportions of concrete components (American Concrete Institute, 2023).

The ACI method is the most accurate mix design method and is used for a wide range of applications, from low-strength concrete to high-strength concrete.

The ACI method consists of the following steps:

1. Selection of materials: Select the materials to be used in the concrete mix. Typical materials include cement, aggregates, and water.
2. Determine concrete strength requirements.
3. Determination of maximum aggregate size: Determine the maximum aggregate size. The maximum aggregate size is selected based on the strength, durability, and workability of the concrete.
4. Determination of slump: Determine the concrete slump. Slump is a measure of concrete workability.

5. Determination of Proportions: Use formulas and tables to determine the proportions of concrete components. Proportions are determined based on strength requirements, maximum aggregate size, and slump. Like:

The water–cement ratio (w/c) is defined as:

Cement (kg/m^3)= Water (kg/m^3)

Water–cement ratio

The absolute volume method for concrete mix design:

Vc+Vw+Vca+Vfa+Vair=1.00

Where:

Vc = volume of cement

Vw = volume of water

Vca = volume of coarse aggregate

Vfa = volume of fine aggregate

$Vair$ = volume of entrapped or entrained air

This equation is used in the absolute volume method to convert the mass of each concrete constituent into its corresponding volume, assuming water has a unit density of 1000 kg/m^3:

V= P

γ×1000

Where:

V = absolute volume of the material (m^3)

P= mass of the material (kg)

γ = specific gravity of the material (dimensionless)

The ACI method is a precise and reliable mix design method. However, it requires adequate knowledge of the materials and factors affecting concrete quality.

Füller Method

This concrete mix design method uses a formula to calculate the compressive strength of concrete based on the gradation curve of the aggregates.

It was developed by the German engineer Friedrich Füller in 1928. The method is simple and easy to use and is widely used in practice.

This method is based on the following steps:

1. Determination of Required Compressive Strength
   The first step in designing a concrete structure is to determine the amount of force it must withstand. This amount is known as compressive strength. Compressive strength can be found in structural design standards or building codes.
2. Determination of the Ideal Gradation Curve
   The ideal gradation curve is a graphical representation of the amount of each aggregate size found in a concrete mix. The ideal curve has a specific shape based on the properties of the cement, water, and aggregates.
3. Determination of Fine and Coarse Aggregate Proportions
   The amount of fine and coarse aggregate to be used in a concrete mix can be determined by comparing the gradation curve of the actual aggregates with the ideal gradation curve.
   The Füller method uses the following formula to determine the proportions of fine and coarse aggregate:

   $$\text{Fine Aggregate Percentage} = 1 - (D/d)^2$$

   Where:

   - Fine Aggregate Percentage: percentage of fine aggregate in the concrete mix
   - D: Maximum size of the coarse aggregate
   - d: Mesh size of 0.25 mm
4. Determination of Cement Quantity
   The quantity of cement can be determined using the following formula:
   Cement Quantity = Required Compressive Strength / (0.28 * Water/Cement Ratio)
   Where:
   - Required Compressive Strength: Required compressive strength for the specific application
   - Water/Cement Ratio: Water/cement ratio of the concrete mix
5. Determination of Water Quantity
   The quantity of water can be determined using the following formula:
   Water Quantity = Cement Quantity * Water/Cement Ratio

Bolomey Method

This concrete mix design method uses a formula to calculate the compressive strength of concrete based on the amount of cement, water, fine aggregate, and coarse aggregate in the mix.

It was developed by the French engineer Eugène Bolomey in 1909. The method is simple and easy to use and is widely used in practice.

It is based on the following steps:

1. Determination of Required Compressive Strength
   The first stage of the designing process is to determine the required compressive strength for the specific application. Compressive strength can be determined from structural design standards or building code recommendations.
2. Determination of the Water/Cement Ratio
   The amount of water in a concrete mix affects its properties in several ways. A low water/cement ratio, meaning there is less water in the mix, produces stronger and more durable concrete. However, it can also make the concrete more difficult to work with. A high water/cement ratio, meaning there is more water in the mix, produces more workable concrete. However, it can also make the concrete less strong and durable. The water/cement ratio also affects the cost of concrete. A low water/cement ratio requires less cement, which is one of the most expensive components of concrete.
   The Bolomey method recommends the following water/cement ratios for general-purpose concrete:
   - Normal strength concrete: 0.45 to 0.55
   - High strength concrete: 0.35 to 0.45
3. Determination of Cement Quantity
   The quantity of cement can be determined using the following formula:
   Cement Quantity = Required Compressive Strength / (0.28 * Water/Cement Ratio)
4. Determination of Global Aggregate Quantity
   The quantity of global aggregate can be determined using the following formula:
   Global Aggregate Quantity = Total Volume of the Mix - Volume of Water
5. Determination of Fine and Coarse Aggregate Proportions
   The proportions of fine and coarse aggregate can be determined using the following formula:
   Fine Aggregate Percentage = $(1 - 0.2 * \text{Water/Cement Ratio})^2$
   Where:
   - Fine Aggregate Percentage: Percentage of fine aggregate in the concrete mix
   - Water/Cement Ratio: Water/cement ratio of the concrete mix

Faury Method

The Faury method is a concrete mix design method that is based on the relationship between the compressive strength of concrete and the gradation curve of the aggregates.

It was developed by the French engineer Henri Faury in 1956. The method is simple and easy to use and is widely used in practice.

The Faury method is based on the following steps:

1. Determination of Required Compressive Strength
   The first stage of the designing process is to determine the required compressive strength for the specific application. Compressive strength can be determined from structural design standards or building code recommendations.
2. Determination of the Ideal Gradation Curve
   The ideal gradation curve is a curve that represents the ideal distribution of aggregate sizes in a concrete mix. The ideal gradation curve can be determined from the properties of cement, water, and aggregates.
3. Determination of Fine and Coarse Aggregate Proportions
   The proportions of fine and coarse aggregate can be determined from the gradation curve of the actual aggregates and the ideal gradation curve.
   The Faury method uses the following formula to determine the proportions of fine and coarse aggregate:
   Fine Aggregate Percentage = $1 - [(D/d)^2 / (D'/d)^2]$
   Where:
   - Fine Aggregate Percentage: Percentage of fine aggregate in the concrete mix
   - D: Maximum size of the coarse aggregate
   - d: Mesh size of 0.25 mm
   - D': Maximum size of the fine aggregate
4. Determination of Cement Quantity
   The quantity of cement can be determined using the following formula:
   Cement Quantity = Required Compressive Strength / (0.28 * Water/Cement Ratio)
   Where:
   - Required Compressive Strength: Required compressive strength for the specific application
   - Water/Cement Ratio: Water/cement ratio of the concrete mix
5. Determination of Water Quantity
   The quantity of water can be determined using the following formula:
   Water Quantity = Cement Quantity * Water/Cement Ratio

De La Peña Method

This concrete mix design method uses a formula to calculate the compressive strength of concrete based on the water/cement ratio.

The De La Peña method was developed by the Spanish engineer Carlos de la Peña in 1955. This method is simple and easy to use, which is why it is widely used in practice.

The De La Peña method is based on the following steps:

1. Determination of Required Compressive Strength
   The first step in the designing process is to establish the required compressive strength for the specific application. This strength can be calculated from structural design standards or building code recommendations.
2. Determination of the Water/Cement Ratio
   The ratio between the amount of water and the amount of cement in a concrete mix is a key factor determining its properties. A low water/cement ratio produces stronger and more durable concrete but is also more difficult to work with. A high water/cement ratio produces more workable concrete but is less strong and durable.
   The De La Peña method recommends the following water/cement ratios for general-purpose concrete:
   - Normal strength concrete: 0.45 to 0.55
   - High strength concrete: 0.35 to 0.45
3. Determination of Cement Quantity
   The quantity of cement can be determined using the following formula:
   Cement Quantity = Required Compressive Strength / (0.28 * Water/Cement Ratio)
4. Determination of Global Aggregate Quantity
   The quantity of global aggregate can be determined using the following formula:
   Global Aggregate Quantity = Total Volume of the Mix - Volume of Water
5. Determination of Fine and Coarse Aggregate Proportions
   The proportions of fine and coarse aggregate can be determined using the following formula:
   Cement content (kg/m^3)= Mixing water content (kg/m^3)
   Water–cement ratio (w/c)
   Where:
   - Cement content = mass of cement per unit volume of concrete (kg/m^3)
   - Mixing water content = mass of water required to achieve the specified slump and workability (kg/m^3)
   - Water–cement ratio (w/c) = selected based on the required compressive strength and durability requirements

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THE MANUFACTURING OF CEMENT IS THE ACHILLES' HEEL OF CONCRETE WHEN IT COMES TO SUSTAINABILITY AND ITS CARBON FOOTPRINT. EVERY DAY, EFFORTS ARE MADE TO DEVELOP CEMENT MANUFACTURING PROCESSES THAT PRODUCE A LOWER CARBON FOOTPRINT BECAUSE THIS IS THE STAGE WHERE CEMENT, AND THEREFORE CONCRETE, HAS A SIGNIFICANT ENVIRONMENTAL IMPACT. A LARGE AMOUNT OF POLLUTANTS ARE GENERATED IN CEMENT PRODUCTION, AS LIMESTONE AND CLAY MUST BE CALCINED AT HIGH TEMPERATURES, A PROCESS THAT RESULTS IN SIGNIFICANT POLLUTION. MAJOR CEMENT COMPANIES RELEASE VAST AMOUNTS OF CARBON DIOXIDE INTO THE ATMOSPHERE, CONTRIBUTING TO A LARGE CARBON FOOTPRINT. IT IS CRUCIAL TO UNDERSTAND THE MANUFACTURING PROCESS BECAUSE DAILY EFFORTS ARE MADE TO CREATE A MORE EFFICIENT, LESS POLLUTING PROCESS. THIS RESULTS IN A MORE SUSTAINABLE AND ENVIRONMENTALLY FRIENDLY MATERIAL.

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