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AND THE LATEST GENERATION

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EDITORIAL SINERGY

Sustainable Concrete and the Latest Generation

(Vol. 2)

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Peer Review

Each chapter of this book has been evaluated through a double-blind peer review process by external academics. Consequently, the research presented is supported by experts in the field, who have issued an objective assessment based on scientific criteria to ensure the academic soundness of the work.

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.

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 perspectiveIn geography, 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.

What is the weak point of concrete? 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

Fresh state concrete

Introduction

According to Fernández and Pérez (2022), fresh concrete is the mixture of cement, aggregates, water, and additives that is in a plastic and moldable state and can be transported, placed, and compacted without crumbling or drying out.

The fresh state of concrete is crucial because it is during this time that the concrete can be manipulated to achieve the desired shape. The properties of fresh concrete, such as workability, slump, and cohesion, influence how easily the concrete can be placed and compacted.

The properties of fresh concrete can be controlled through the selection of materials and the mix design. Cement provides strength and durability, aggregates provide strength and volume, water provides workability, and additives can enhance the properties of fresh or hardened concrete.

Fresh concrete is a complex material that undergoes physical and chemical changes. Concrete begins to harden as soon as it is mixed, and the hardening process accelerates with heat. Hardened concrete is a strong and durable material used in a wide range of applications, from the construction of buildings and roadways to the manufacture of precast products.

Fresh concrete

Fresh concrete is the mixture of cement, aggregates, water, and additives used for building structures. In this state, concrete is plastic and moldable, allowing it to be placed in form and compacted to achieve a solid structure (García, 2023, p. 1).

The properties of fresh concrete are important to ensure that the concrete can be properly placed and compacted. These properties include:

- Workability: The ability of concrete to be mixed, transported, placed, and compacted without segregation. Workability can be measured through tests such as the slump test or the flow test.
- Segregation: The separation of concrete components, which can lead to a decrease in the strength and durability of the concrete. Segregation can be reduced by using uniformly sized aggregates and adding additives.
- Flow: The ability of concrete to flow under its own weight. Flow is important to allow concrete to fill voids and be completely compacted.
- Viscosity: The resistance of concrete to flow. Viscosity is important to prevent concrete from slumping before it can be placed and compacted.
- Adhesion: The ability of concrete to adhere to surfaces. Adhesion is important to ensure that concrete bonds to reinforcement and other elements of the structure.

Fresh concrete must be handled and placed according to the recommendations of the manufacturer. Concrete should be placed in a single pass, without interruptions, to avoid segregation. Concrete should be compacted to remove air bubbles and ensure uniform distribution of components.

Fresh concrete cures as the cement hydrates. Curing is the process of providing moisture to the concrete so that the cement can fully react and develop its strength. Concrete should be cured for at least seven days to reach its final strength.

Quality control of properties of fresh concrete

Quality control of fresh concrete is an important process to ensure that the concrete meets design requirements and customer expectations. Quality control of fresh concrete focuses on evaluating the physical properties of the concrete, such as slump, unit weight, air content, temperature, and workability. The physical properties of fresh concrete are important to ensure that the concrete can be properly placed and compacted and that it achieves the desired strength and durability.

Quality control tests for fresh concrete are a series of tests conducted to evaluate the physical properties of concrete before it hardens. These tests are important to ensure that the concrete meets design requirements and customer expectations.

Quality control tests for fresh concrete can be conducted using various methods, including:

- Field Tests: Field tests are conducted at the construction site. Common field tests include the slump test, unit weight test, and air content test.
- Laboratory Tests: Laboratory tests are conducted in a lab. Common laboratory tests include compressive strength, tensile strength, and durability tests.

The physical properties of fresh concrete that are commonly controlled include:

Workability (ASTM C143, Standard Test Method for Slump of Hydraulic-Cement Concrete).

Workability is an important property of fresh concrete that determines how easily it can be placed and compacted. Concrete with good workability is easy to pump, pour, and compact, resulting in a more uniform and higher-quality structure.

Workability can be measured through tests such as the slump test or the flow test. The slump test measures the amount of settlement that occurs when concrete is placed in a slump cone. The flow test measures the distance that concrete can flow under its own weight.

Concrete slump test is one acceptance criteria are set by project specifications and typically require the slump to be within ±25 mm (or ±1 inch) of the specified slump, though this tolerance can vary. Acceptance also depends on the absence of segregation or collapse, and consistency between batches. Specifications may also define separate slump tolerances for "not to exceed" (maximum) requirements, particularly for easier mixes.

The ideal concrete slump range varies by project type; low slump (25–75 mm) is suitable for pavements and roads, medium slump (50–100 mm) for foundations and footings, and high slump (100–175 mm) for densely reinforced columns and walls where high workability is needed. The slump test measures concrete consistency, indicating workability and potential mix defects.

Segregation

Segregation is the separation of concrete components, which can lead to decreased strength and durability. Concrete components can separate by size, weight, or density. Segregation can be reduced by using uniformly sized aggregates and adding additives. Uniformly sized aggregates are less likely to separate than unevenly sized aggregates. Additives such as plasticizers and superplasticizers can improve the workability of concrete and reduce segregation. While there isn't one universal "segregation standard," proper concrete handling, mixing, and placement techniques outlined in general construction standards (such as ASTM standards for handling and placement) are used to prevent segregation.

Flow (ASTM C1611: Standard Test Method for Slump Flow of Self-Consolidating Concrete)

Flow is the ability of concrete to flow under its own weight. Concrete with good flow can fill voids and compact completely.

Flow can be measured through tests such as the flow test, which measures the distance concrete can flow under its own weight.

Viscosity

Viscosity is the resistance of concrete to flow. Concrete with high viscosity is more resistant to flow than concrete with low viscosity. Viscosity is important to prevent concrete from slumping before it can be placed and compacted. There is no single universal standard for the "viscosity of concrete," but rather established industry practices and standards, primarily from organizations like ASTM International, for measuring the rheological properties that determine flow behavior, such as the slump test for workability and specialized rheometers for quantifying plastic viscosity and yield stress.

Adhesion

Adhesion is the ability of concrete to bond to surfaces. Adhesion is important to ensure that concrete adheres to reinforcement and other elements of the structure.

Adhesion can be improved by using additives such as bonding agents. Concrete adhesion is evaluated using various ASTM International (ASTM) standards, such as ASTM C1583 for the bond strength of concrete repair materials, ASTM C1857 for evaluating the bond strength of repair and overlay mortars, ASTM D7234 for pull-off adhesion strength of coatings on concrete, and ASTM D3359 for a visual X-cut or cross-cut test of coatings. Additionally, ASTM C1059 outlines specifications for latex agents used in bonding fresh to hardened concrete.

Temperature

The temperature of fresh concrete should be between 10 and 32 °C to ensure good workability and strength. The ASTM C1064 standard is used to test and measure the temperature of freshly mixed concrete, while the ACI 201.2R Guide to Durable Concrete and ACI 301 Specifications for Concrete Construction provide guidelines for temperature control.

Air content

Air content is a measure of the amount of air trapped in the concrete. A higher air content indicates a lighter concrete, while a lower air content indicates a heavier concrete. The standard for measuring air content in fresh concrete is primarily defined by ASTM C231 (Pressure Method) and ASTM C173 (Volumetric Method), with AASHTO T196 also specifying the volumetric method. These ASTM standards outline the required procedures for testing, but the specific target air content percentage, often ranging from 5% to 8% for air-entrained concrete, depends on the project's specifications and its intended use, particularly for freeze-thaw resistance

Vibration

During the mixing, transport, and placement of concrete, air bubbles can form in the concrete mass. These air bubbles can weaken the concrete and make it more susceptible to cracking. Vibration helps eliminate air bubbles, improving the quality of the concrete. Vibration helps ensure that the concrete is evenly distributed within the formwork. This is important to ensure that the concrete structure is uniform and strong.

Vibration helps eliminate free water from the concrete, increasing its strength and durability. Vibration also helps improve the bond between the concrete and the formwork and reinforcement. The vibration time is important to ensure that the concrete is properly compacted. The recommended vibration time depends on the type of concrete, the depth of the layer, and the placement method.

Concrete vibration standards are detailed in documents like the American Concrete Institute's (ACI) ACI 309R, which provides guidelines for consolidating fresh concrete to ensure its strength and durability by removing air voids. Key standards from ASTM International include C1170/C1170M for determining the consistency of roller-compacted concrete and C1176/C1176M for making roller-compacted concrete specimens using a vibrating table.

Concrete manufacturing process

On-site concrete manufacturing

Mixing

"Mixing is an important stage in the on-site concrete manufacturing process. The goal of mixing is to ensure that the materials are evenly distributed and that the concrete has the correct consistency" (García, 2023, p. 3).

Mixing can be done manually or with a concrete mixer. Manual mixing involves loading the materials into a container and mixing them with shovels or rakes. Mechanical mixing involves loading the materials into a concrete mixer and mixing them with a rotating drum.

Manual mixing is a slow and laborious process, mainly used for small quantities of concrete or DIY (Do It Yourself) projects.

Mechanical mixing is a fast and efficient process used for large quantities of concrete or commercial projects.

Figure 1.
Mixing methods

Note. Adapted from Mahajan Bhushan (2023).

Equipment used for mechanical mixing

The equipment used for mechanical mixing of concrete can be classified into two main categories: stationary concrete mixers and mobile concrete mixers.

- Stationary concrete mixers: These mixers are located in a fixed position and are used to mix large quantities of concrete. Types of stationary concrete mixers include:
    - Drum mixers: The most common type of concrete mixer, featuring a rotating drum that mixes the materials together.
    - Paddle mixers: This type of mixer uses paddles that stir the materials to mix them.
    - Twin-shaft mixers: These mixers have two shafts that rotate in opposite directions to mix the materials.
- Mobile concrete mixers: These mixers can be transported to the site and are used to mix smaller quantities of concrete. Types of mobile concrete mixers include:
    - Rotary drum concrete mixers: Similar to a stationary rotary drum mixer but smaller and easier to transport.
    - Paddle concrete mixers: Similar to a stationary paddle mixer but smaller and easier to transport.
    - Hydraulic-driven concrete mixers: These mixers use a hydraulic system to rotate the mixing drum.

Mechanical mixing equipment is used to ensure that concrete materials are evenly mixed and that the concrete has the correct consistency. The selection of the appropriate mixing equipment depends on the quantity of concrete to be mixed and the job location.

Figure 2.

Types of mixers. Hopper mixer (left), drum mixer (right)

Note. Adapted from PNGKey

Mixer loading procedure

Add coarse aggregate:

Coarse aggregate is the largest material in the mix, such as sand or gravel. It should be added first to allow space for even mixing with the other materials.

Add water:

The amount of water to be added depends on the amount of cement and fine aggregate used. Generally, enough water should be added to give the mix a consistency similar to bread dough.

Mix:

The mix should be mixed for at least 5 minutes, or until it is uniform. This will help ensure that all materials are well distributed and that the mix is strong and durable.

Turn off and close the mixer:

Once the mix is ready, the mixer should be turned off and the drum door closed. This will help prevent the mix from drying out or becoming contaminated.

Mixing time

Mixing time is the time it takes to mix all the ingredients in a concrete mix to achieve a uniform mixture. Mixing time is important to ensure that all ingredients are well distributed and that the mix has the appropriate strength and durability.

The recommended mixing time for concrete varies depending on the type of concrete, the proportion of ingredients, and the type of mixer used. In general, concrete should be mixed for at least 5 minutes, or until the mix is uniform.

Recommended mixing times for the most common types of concrete are as follows:

- Normal strength concrete: 5-7 minutes
- High-strength concrete: 7-10 minutes
- Pumped concrete: 10-12 minutes

If the mixing time is too short, the mix may not be uniform and may have lower strength and durability. If the mixing time is too long, the mix may lose workability and be difficult to place.

Ready-mix concrete manufacturing

Ready-mix concrete

Concrete manufacturing in plants is the process of producing ready-mix concrete, a type of concrete that is produced in a concrete plant and delivered directly to the construction site, ready to be placed.

Ready-mix concrete is a versatile product that can be used for various applications, including the construction of buildings, roads, bridges, and other structures. Ready-mix concrete has several advantages over site-mixed concrete, including consistency, precision, and convenience.

Advantages of ready-mix concrete

Consistency

Ready-mix concrete is produced in a concrete plant where the quality of the ingredients and the mixing process can be carefully controlled. This results in a more uniform concrete mix than site-mixed concrete.

Precision

Ready-mix concrete can be precisely dosed, allowing the contractor to specify the strength, workability, and other properties of the concrete. This is important to ensure that the concrete meets the requirements of the project.

Convenience

Ready-mix concrete is delivered to the construction site in mixer trucks, eliminating the need for the contractor to mix their own concrete. This can save time and labor.

In addition to the advantages mentioned above, ready-mix concrete also offers the following benefits:

- Increased durability: Ready-mix concrete can be made with high-quality ingredients, which can improve its durability.
- Less waste: Ready-mix concrete can be precisely dosed, which can help reduce waste.
- Reduced safety risks: Ready-mix concrete is delivered in mixer trucks, which can help reduce the safety risks associated with on-site concrete mixing.

Concrete transportation

Concrete transportation is the process of transporting concrete from the concrete plant to the construction site. Concrete is a material that hardens over time, so it is important that it is transported and placed quickly to ensure that it achieves the required strength and durability.

Types and conditions of transportation

There are several methods for transporting concrete, including:

- Mixer Trucks: Mixer trucks are the most common method for transporting concrete. These trucks have a rotating drum that mixes the concrete ingredients during transport. This helps ensure that the concrete is evenly distributed and does not dry out.
- Concrete Pumps: Concrete pumps are used to transport concrete to great heights or distances. These pumps have a long pipe that extends from the concrete plant to the construction site. The concrete is pumped through the pipe and placed in its final location.
- Buckets: Buckets are used to transport concrete over short distances. These are machines with a bucket that is filled with concrete. The concrete is then discharged from the bucket at the construction site.

Pumping

Concrete pumping is a process of transporting concrete through a tube or hose using a concrete pump. The concrete is pumped through the pump, which creates pressure to push the concrete through the tube. Concrete pumping standards are set by organizations like ASME (ASME B30.27), ISO (ISO 21573-2), and regional bodies like the American Concrete Institute (ACI PRC-304.2R-17), which cover equipment safety, mix design requirements for pumpability, safe operational procedures, and worker training to prevent accidents and ensure quality placement of concrete. Key standards focus on proper concrete mix design with enough mortar, appropriate pipe diameter relative to aggregate size, the use of personal protective equipment (PPE), and the safe handling of the pumping equipment itself.

Concrete pumping is used to transport concrete to great heights or distances or to place concrete in hard-to-reach locations. It can also be used to place concrete in adverse weather conditions, such as cold or rain.

There are two main types of concrete pumps: piston pumps and screw pumps.

- Piston Pumps: Piston pumps use a piston to pump the concrete through the pump. These are the most common type of pump for concrete pumping.
- Screw Pumps: Screw pumps use a screw mechanism to pump the concrete through the pump. These pumps are more suitable for pumping concrete over long distances or heights.

Concrete placement

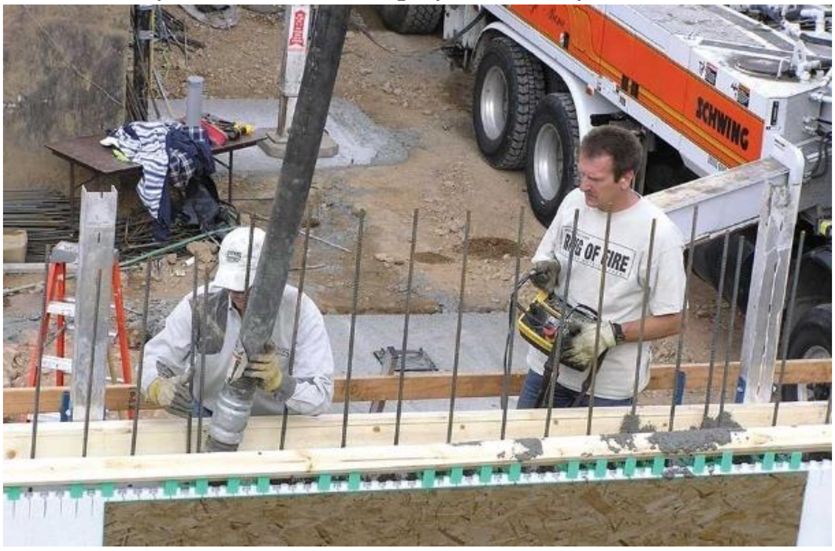
Concrete placement is the process of placing concrete in its final location. It is a crucial process that must be done correctly to ensure that the concrete cures properly and reaches its final strength and durability.

Placing concrete at the top of a narrow form

Placing concrete at the top of a narrow form can be challenging, as the concrete may fall and cause injuries. To prevent this, it is important to follow these steps:

- Prepare the placement surface: The surface should be clean, level, and free of contaminants.
- Use a suitable work platform: The platform should be strong enough to support the weight of the concrete and the workers.
- Pour the concrete in layers: Do not pour all the concrete at once, as this may cause the concrete to spill.
- Consolidate the concrete: Use a vibrator to remove air bubbles and ensure even distribution.
- Cure the concrete properly: The concrete should be cured for at least 28 days to reach its final strength and durability.

Figure 3.
Placement of concrete at the top of a narrow form.



Note. Adapted from ICF Builder (2006).

Consistency of concrete in deep and narrow forms

The consistency of concrete is an important factor when placing it in deep and narrow forms. Concrete that is too wet may be difficult to place and compact, while concrete that is too dry may be difficult to flow and may cause cold joints.

Generally, it is recommended to use concrete with a slump of 5 to 10 cm for deep and narrow forms. This will help ensure that the concrete is fluid enough to flow easily but firm enough to be properly compacted.

Placing concrete through openings

Placing concrete through openings can be challenging, as the concrete may be difficult to pour and compact.

There are two main methods for placing concrete through openings:

- Manual placement: The concrete is poured and consolidated by hand.
- Pumping: The concrete is pumped through a tube or hose to its final location.

Placing concrete in columns and walls using a pump

Placing concrete in columns and walls using a pump is an efficient and safe method for placing large amounts of concrete. The concrete is pumped through a hose or tube from a concrete mixer to the final location.

Placing in slabs

There are two main methods for placing concrete in slabs:

- Manual placement: The concrete is poured and consolidated by hand.
- Pumping: The concrete is pumped through a tube or hose to its final location.

Manual placement is the simplest and most economical method, but it can be difficult and slow for large quantities of concrete. Pumping is the most efficient method for large quantities of concrete but can be more expensive.

Figure 4.

Placement in slabs

Note. Adapted from Ungvar.

Placing concrete on steep slopes

Placing concrete on steep slopes can be difficult, as the concrete may slide or segregate. Several factors must be considered to ensure successful placement, including:

- Slope design: The slope should be designed to facilitate concrete placement. Gentle slopes are easier to place than steep slopes.
- Type of concrete: The concrete used should be suitable for the application. For steep slopes, a concrete with a slump of 5 to 10 cm is recommended.
- Placement method: The placement method should be chosen based on the slope and the size of the project. For steep slopes, pumping is recommended.
- Safety precautions: Safety precautions should be taken to avoid injuries.

Placing concrete on gentle slopes

Placing concrete on gentle slopes is a relatively straightforward process that can be done with basic labor and equipment. However, it is important to follow certain steps to ensure successful placement:

- Prepare the placement surface.
- Set the formwork.
- Place the reinforcement.
- Place the concrete.
- Consolidate the concrete.
- Cure the concrete.

Concrete curing

Concrete curing is the process of keeping concrete moist during setting and hardening (García-Hernández & López-López, 2023, p. 127). Setting is the process by which concrete changes from a fluid to a solid state, and hardening is the process by which concrete continues to gain strength and durability over time.

The recommended curing period for concrete varies depending on the type of concrete and climatic conditions. Generally, concrete should be cured for at least seven days.

Proper curing is essential to ensure that concrete reaches its full potential.

Water curing

Concrete curing is the process of maintaining concrete moisture during the initial hours or days after placement. According to "Concrete Curing" (2023), water curing is important to ensure that concrete reaches its maximum strength.

Figure 5.

Early curing by water spraying

Note. Adapted from Martínez, G. (2019).

According to Gómez (2023), water curing is the most common and economical method of curing concrete. It works by keeping the surface of the concrete moist to prevent it from drying too quickly. Water helps the cement hydrate properly, which is essential for concrete strength development.

Water curing can be performed in several ways:

- Spraying: The most common method. A hose or sprayer is used to spray water on the surface of the concrete.

- Membranes: Waterproof membranes are applied to the surface of the concrete to prevent it from drying.
- Covers: Covers are placed over the surface of the concrete to prevent it from drying.

The frequency with which concrete should be sprayed depends on climatic conditions. In hot and dry climates, concrete needs to be sprayed more frequently.

Sealing materials

Sealing materials for concrete include acrylics, polyurethanes, epoxies, and polyaspartics. These fall into two categories: penetrating sealers, which soak into the pores to protect from the inside, and topical sealers (or film-forming sealers), which create a protective coating on the surface. The choice depends on factors like desired appearance, durability, and the specific type of protection needed against stains, water, salt, and UV rays.

Liquid compounds for forming curing membranes

According to Gómez, Martínez, and Pérez (2023), liquid compounds for forming curing membranes are products used to create an impermeable barrier on the surface of fresh concrete. This barrier helps retain the moisture of concrete, which is essential for proper curing.

They are available in a variety of types, each with its own advantages and disadvantages. The most common types of liquid compounds for forming curing membranes include:

- Acrylic Curing Membranes: Acrylic curing membranes are a good option for applications requiring a durable impermeable barrier. They are resistant to UV rays, chemicals, and water.
- Polyurethane Curing Membranes: Polyurethane curing membranes are a good option for applications requiring a flexible impermeable barrier. They are resistant to UV rays, chemicals, and water.
- Epoxy Curing Membranes: Epoxy curing membranes are a good option for applications requiring a highly waterproof and chemical-resistant barrier. They are highly impermeable and resistant to UV rays.

Liquid compounds for forming curing membranes are generally applied with a roller or brush. They should be applied evenly over the entire surface of the fresh concrete, avoiding unused areas. Liquid compounds for forming curing membranes are an important part of the concrete curing process. They help protect fresh concrete from evaporation and elements, ensuring that it reaches its maximum strength.

Steam curing

Steam curing is a method of curing concrete that involves exposing fresh concrete to steam at controlled temperature and humidity. This method accelerates the strength gain of concrete, allowing it to be used sooner. Steam curing is performed in a curing chamber. The chamber is equipped with a steam generator that provides steam at a controlled temperature and humidity. Fresh concrete is placed in the chamber and exposed to the steam for a specified period of time.

Chapter II

Hardened state concrete

Introduction

Hardened concrete is a composite material formed by cement hydration products binding aggregates within a solid matrix. Cement is a hydraulic material that reacts with water to form a paste that hardens over time. Aggregates are inert materials that provide strength and volume to the concrete. Admixtures are substances added to the concrete to enhance its properties, such as workability, strength, or durability.

Once the concrete has been placed and cured, it acquires a solid and durable structure. This structure is due to the formation of a network of cement crystals that interlock with the aggregates. The mechanical performance of hardened concrete is governed primarily by the water–cement ratio, degree of hydration, microstructural densification, and aggregate–paste interaction.

It is important to be aware that the properties of hardened concrete change continuously with time and ambient conditions and that these properties are intimately connected with the role which water plays at the molecular level in the multiphase material. Additionally, durability depends on the pore structure and transport mechanisms through the permeable hardened cement paste which will themselves change with time. Concrete mixtures are proportioned to meet specific structural and durability requirements of the structure of which it is a part and hence there are no standard requirements for every concrete.

Mechanical properties of concrete

According to Martínez (2023), the mechanical properties of concrete determine its ability to withstand loads and forces. The most important mechanical properties of concrete include (p. 1):

- Compressive strength: Compressive strength is the measure of the force that concrete can withstand before breaking under an axial load. It is the most important mechanical property of concrete because it determines its capacity to bear the loads it will be subjected to in service.
- Flexural strength: Flexural strength is the ability of concrete to withstand loads that attempt to bend it. This property is crucial for structures such as beams and columns designed to bear bending loads.
- Tensile strength: This property refers to the ability of concrete to withstand stretching forces. Tensile strength is the weakest mechanical property of concrete because concrete is a brittle material, meaning it breaks easily under tensile stresses.
- Modulus of elasticity: This is the ratio of stress to strain in concrete. The modulus of elasticity is important for determining the stiffness of concrete.

- Impact resistance: The ability to withstand sudden and sharp forces without damage. This property is important for structures exposed to impacts, such as pavements, curbs, and roads.

Table 1. *Comparative Table of Mechanical Properties of Concrete.*

Mechanical Property	Typical Value Range	Test Method	Source
Compressive strength	21 – 80 MPa	ASTM C39	ACI / PCA
Tensile strength (splitting)	2 – 5 MPa	ASTM C496	ACI 318
Flexural strength (modulus of rupture)	3 – 7 MPa	ASTM C78	PCA
Shear strength (plain concrete)	2 – 8 MPa	Structural evaluation	ACI 318
Modulus of elasticity	20 – 40 GPa	ASTM C469	ACI 318
Impact resistance	Variable depending on mix design	Various dynamic tests	PCA

The mechanical properties of concrete are affected by various factors, including:

- Concrete composition: The strength of concrete increases with the cement content, but so does its permeability. The use of high-quality stone aggregates also improves concrete strength.
- Water/cement ratio: The strength of concrete is inversely proportional to the water/cement ratio.
- Curing of concrete: Proper curing enhances the strength of concrete.

Microstructure of Concrete

The microstructure of concrete refers to its internal structure at the microscopic scale and is primarily governed by mix composition, water–cement (w/c) ratio, and curing conditions. It comprises three fundamental phases.

Cementitious Phase

Formed by the hydration of cement, this phase provides the primary mechanical strength. It consists mainly of:

- Calcium silicate hydrate (C–S–H), the principal binding phase.
- Calcium aluminate hydrates (C–A–H).
- Other crystalline products such as portlandite.

A dense and well-developed hydrated matrix significantly enhances strength and durability.

Pore Structure

Concrete is inherently porous. Its pore system includes:

- Gel pores (very fine pores within C–S–H).
- Capillary pores (larger voids formed by excess mixing water).
- Entrapped or entrained air voids.

The connectivity, size distribution, and total porosity determine permeability and durability.

Aggregate Phase and Interfacial Transition Zone (ITZ)

Aggregates provide dimensional stability and wear resistance. Between the aggregates and the cement paste lies the ITZ, typically more porous and weaker than the bulk paste. A strong ITZ improves mechanical performance and reduces crack propagation.

A refined microstructure—low porosity, dense paste, and strong ITZ—results in improved strength, reduced permeability, and enhanced long-term durability.

Mechanical Properties

The mechanical performance of concrete is closely linked to its microstructure.

Compressive strength

Compressive strength is the primary design parameter in structural concrete. It represents the material's ability to resist axial compressive loads and is expressed in megapascals (MPa).

According to ASTM C39, compressive strength is determined by testing cylindrical specimens under axial loading. Typical strength classes range from approximately 21 MPa to 80 MPa or higher.

Factors influencing compressive strength:

- Cement content and quality.
- Water/cement ratio (strength decreases as w/c increases).
- Aggregate quality and grading.
- Curing conditions.
- Temperature exposure.

A lower w/c ratio and proper curing produce a denser microstructure and higher strength.

Tensile strength

Concrete exhibits low tensile capacity compared to compressive strength. Tensile strength governs cracking behavior and serviceability.

Direct tensile testing is uncommon due to practical difficulties; instead, indirect methods are used. ASTM C1583 evaluates surface tensile bond strength, particularly for overlays and repairs.

Tensile strength is typically 8–15% of compressive strength and is strongly influenced by porosity and ITZ quality.

Flexural strength

Flexural strength reflects the capacity of concrete to resist bending stresses. It is determined through beam testing:

- ASTM C78 (third-point loading).
- ASTM C293 (center-point loading).

Both methods determine the Modulus of Rupture (MOR). Flexural performance depends on tensile strength, elastic modulus, microstructural integrity, and crack resistance.

Shear strength

Shear strength describes the resistance to sliding failure along internal planes. Although less frequently tested directly in plain concrete, it depends on:

- Tensile capacity.
- Aggregate interlock.
- Microstructural cohesion.
- Quality of the ITZ.

Improved density and reduced pore connectivity enhance shear resistance.

Elastic modulus

The modulus of elasticity (E) represents stiffness and is determined according to ASTM C469/C469M, which measures strain under compressive loading up to 40% of the ultimate strength.

Typical ranges:

- Hardened cement paste: 10–30 GPa.
- Aggregates: 45–85 GPa.
- Normal-weight concrete: 30–50 GPa.

The modulus decreases at higher stress levels due to microcracking within the matrix and ITZ.

Table 2. *Typical Ranges of the Modulus of Elasticity of Concrete*

Concrete Type	Compressive Strength (MPa)	Typical Modulus of Elasticity (GPa)	Description
Low-strength concrete	21 – 28 MPa	20 – 25 GPa	Used in pavements, sidewalks, and non-structural elements.
Normal-strength concrete	28 – 40 MPa	25 – 30 GPa	Commonly used in structural elements such as beams, slabs, and columns.
Medium-high strength concrete	40 – 60 MPa	30 – 35 GPa	Used in bridges and heavily loaded structural components.
High-strength concrete	60 – 80 MPa	35 – 45 GPa	Used in high-rise buildings and specialized infrastructure.
High-performance concrete	>80 MPa	40 – 50 GPa	Designed for advanced structural applications with improved durability and microstructure.

Physical and Durability-Related Properties

Porosity

Porosity is the ratio of void volume to total volume, expressed as a percentage. It significantly affects strength, permeability, and durability.

Testing methods include:

- Water absorption (e.g., ASTM C1585).
- Mercury Intrusion Porosimetry (MIP) (ASTM D4404).

Lower porosity results in:

- Higher compressive and tensile strength.
- Lower permeability.
- Improved resistance to chemical attack and freeze–thaw cycles.

Density

Density is the mass per unit volume (kg/m³). Typical values:

- Normal-weight concrete: 2300–2500 kg/m³.
- Heavyweight concrete: up to 3000 kg/m³.
- Lightweight concrete: as low as 1000 kg/m³.

Testing standards include:

- ASTM C642 (density, absorption, voids).
- ASTM C1040 (in-place nuclear density testing).

Higher density generally correlates with improved mechanical strength but increases structural dead load.

Table 3. *Typical Classification of Concrete Compressive Strength (21–80 MPa)*

Strength Class	Compressive Strength (MPa)	Typical Applications	Structural Characteristics
Low-Strength Concrete	21 – 28 MPa	Sidewalks, pavements, residential slabs	Adequate for non-critical structural elements
Normal Structural Concrete	28 – 40 MPa	Residential and commercial buildings, beams, columns	Most widely used strength range in structural construction
Medium-High Strength Concrete	40 – 60 MPa	Bridges, parking structures, heavy-load elements	Improved durability and structural capacity
High-Strength Concrete	60 – 80 MPa	High-rise buildings, prestressed structures, special infrastructure	High load-bearing capacity and reduced structural dimensions

Permeability

Permeability describes the capacity of concrete to allow fluid penetration, directly affecting durability.

Common evaluation methods:

- Rapid Chloride Permeability Test (RCPT) – ASTM C1202.
- Air permeability methods described in ACI 228.2R.

Permeability depends on:

- Water/cement ratio.
- Aggregate quality.
- Degree of curing.
- Pore connectivity.

Lower permeability enhances resistance to corrosion, sulfate attack, and chemical deterioration.

Thermal properties

Concrete exhibits moderate thermal performance influenced by density and porosity.

Thermal conductivity

Thermal conductivity measures heat transfer capacity and is expressed in W/(m·K). Normal-weight concrete typically ranges between 1.0 and 2.0 W/(m·K).

Lower conductivity is achieved through:

- Reduced density.
- Lightweight or cellular aggregates.
- Improved pore structure control.

Lightweight and cellular concretes provide significantly better insulation.

Specific Heat Capacity

Concrete has relatively high specific heat capacity, enabling it to store thermal energy effectively. This thermal mass effect contributes to:

- Energy efficiency in buildings.
- Improved thermal comfort.
- Temperature stabilization.

The performance of concrete is fundamentally controlled by its microstructure. The water/cement ratio, aggregate characteristics, and curing conditions govern pore structure, ITZ quality, and hydration development. These, in turn, determine mechanical strength, stiffness, permeability, durability, density, and thermal behavior.

Optimizing microstructural parameters leads to concrete with:

- Higher compressive and tensile strength.
- Improved durability and reduced permeability.
- Enhanced thermal efficiency.
- Better long-term structural performance.

A holistic understanding of these interconnected properties is essential for advanced mix design, durability engineering, and sustainable construction practice.

Chapter III

Durability and pathology of concrete

Introduction

Concrete is a widely used structural material in construction due to its strength, durability, and relative cost-effectiveness. However, concrete can also be affected by various factors that can cause its deterioration (Hernández, 2023, p. 2).

The durability of concrete is defined as its ability to withstand the effects of the environment and usage throughout its service life. The pathology of concrete refers to the study of the defects and damages that can affect concrete, along with their causes and consequences.

Durability and pathology of concrete

Durability of concrete

The durability of concrete is defined as its ability to resist the effects of the environment and usage throughout its service life. Concrete durability is influenced by a number of factors, including:

- Materials used: The quality of materials used in concrete production, such as cement, aggregate, and water, has a significant impact on its durability.
- Design and construction: Proper design and construction of concrete are also crucial to ensure its durability.
- Environmental conditions: Concrete can be affected by various environmental factors, such as exposure to water, chemicals, extreme temperatures, and radiation (Hernández, 2023, p. 2).

Figure 6.

Example of concrete damage

Note. Adapted from Acosta Amaya C. (2019).

Pathology of concrete

The pathology of concrete is the study of the defects and damages that can affect concrete, along with their causes and consequences.

The defects and damages of concrete can be classified according to their origin into:

- Mechanical defects: Caused by external forces acting on the concrete. These can include:
  - Cracks: Cracks are openings in the concrete that can be caused by various factors, such as shrinkage, thermal expansion, or load.
  - Spalling: Spalling is the separation of fragments of concrete from the surface. It can be caused by the impact of objects, load shocks, or freeze-thaw cycles.
  - Particle loss: Particle loss refers to the removal of particles from the concrete surface. It can be caused by abrasion, erosion, or corrosion.
- Chemical defects: Caused by the reaction of concrete with chemical substances. These can include:
  - Corrosion: Corrosion is the degradation of reinforcing steel due to the action of acids or alkalis.
  - Chemical attack: Chemical attack refers to the degradation of concrete by chemical substances, such as acids or alkalis.
  - Alkali-aggregate reaction: The alkali-aggregate reaction is a chemical reaction between the alkalis in cement and the aggregates, which can cause expansion and cracking in concrete.
- Electrochemical defects: Caused by the action of electricity. These can include:
  - Galvanic current: Galvanic current is the electric current that flows between two different materials in contact. It can cause the corrosion of reinforcing steel in concrete.
  - Electrolysis current: Electrolysis current is the electric current that flows through water. It can cause the corrosion of reinforcing steel in concrete and the formation of deposits on the concrete surface.
- Biological defects: Caused by the action of living organisms. These can include:
  - Fungi and bacteria: Fungi and bacteria can grow in concrete and cause its deterioration.
  - Insects: Insects, such as termites and ants, can damage concrete.

Concrete durability: concepts and sustainability

The durability of concrete is defined as its ability to withstand the effects of the environment and usage throughout its service life. It is an important consideration in the design and construction of concrete structures, as it affects their safety, functionality, and maintenance costs (Hernández, 2023, p. 2).

Concrete durability is influenced by a number of factors, including:

- Materials used: The quality of the materials used in concrete production, such as cement, aggregate, and water, significantly impacts its durability.
- Design and construction: Proper design and construction of concrete are also important to ensure its durability.
- Environmental conditions: Concrete can be affected by various environmental factors, such as exposure to water, chemicals, extreme temperatures, and radiation.

Concepts of Concrete Durability

Concrete durability can be classified into two main categories:

- Intrinsic durability: This is the inherent durability of concrete, which is based on the composition and properties of the materials used.
- Extrinsic durability: This is the durability that can be enhanced through proper design and construction.

The intrinsic durability of concrete can be improved by using high-quality materials and controlling the production processes. For example, using sulfate-resistant cement can help protect concrete from corrosion in sulfate-rich environments.

The extrinsic durability of concrete can be improved through proper design and construction. For example, designing an adequate drainage system can help protect concrete from water exposure.

Sustainability of Concrete

The durability of concrete is important for the sustainability of this material. Durable concrete requires less maintenance and repairs, which can reduce costs and environmental impact.

The durability of concrete can also contribute to the reduction of greenhouse gas emissions. For example, concrete with a longer service life may require less new concrete, which can reduce the amount of energy needed for production.

Management of Concrete Durability

The management of concrete durability is an ongoing process that begins with selecting the right materials. Designers and builders must consider the environmental conditions to which the concrete will be exposed to ensure its durability.

Proper maintenance is also important to maintain the durability of concrete. Concrete structures should be inspected regularly for signs of deterioration and repaired as necessary.

What is concrete durability?

Concrete durability is defined as its ability to resist the effects of the environment and usage throughout its service life. It is an important consideration in the design and construction of concrete structures, as it affects their safety, functionality, and maintenance costs.

Concrete durability is influenced by a number of factors, including:

- Materials used: The quality of the materials used in concrete production, such as cement, aggregate, and water, significantly impacts its durability.
- Design and construction: Proper design and construction of concrete are also important to ensure its durability.
- Environmental conditions: Concrete can be affected by various environmental factors, such as exposure to water, chemicals, extreme temperatures, and radiation.

Durability in projects

“Durability is an important consideration in any project, whether it is construction, engineering, or technology. It refers to the ability of a product, system, or structure to withstand the effects of time, use, and the environment” (Sánchez, 2023, p. 2).

In the context of projects, durability is important for several reasons. First, it can help ensure the safety of users. For example, a durable bridge is less likely to collapse, protecting the people who use it. Second, durability can help reduce maintenance costs. A durable product requires fewer repairs and replacements, which can save money in the long run. Third, durability can contribute to sustainability. A durable product can last longer, reducing the need to produce new products, which can lessen the environmental impact.

There are several things that can be done to ensure durability in projects. These include:

- Using high-quality materials: When choosing materials for a project, it is important to select those that are suitable for the environment in which they will be used.

- Designing the project with durability in mind: When designing a project, it is important to consider the factors that may affect its durability.
- Building the project correctly: The construction of a project is a crucial part of ensuring its durability. It is important that the project is built correctly, in accordance with standards and building codes.

Causes of durability failures

Hernández (2023, p. 10) states that the causes of durability failures can be classified into two main categories:

- Internal factors: These are factors related to the materials and construction of the concrete.
- External factors: These are factors related to the environment in which the concrete is located.

Internal Factors

Internal factors that can cause durability failures in concrete include:

- Quality of materials: The quality of materials used in concrete production, such as cement, aggregate, and water, significantly impacts its durability.
- Design and construction: Proper design and construction of concrete are also important to ensure its durability.

External Factors

External factors that can cause durability failures in concrete include:

- Environmental conditions: Concrete can be affected by various environmental factors, such as exposure to water, chemicals, extreme temperatures, and radiation.
- Use and maintenance: Improper use and maintenance of concrete can accelerate its deterioration.

Agents affecting concrete durability

"The agents affecting concrete durability can be classified into two main categories: internal factors and external factors" (Hernández, 2023, p. 10).

"Durability and sustainability are two closely related concepts" (Hernández, 2023, p. 15). Durability refers to the ability of a material or structure to resist deterioration and wear over time. Sustainability refers to the ability of a material or structure to meet current needs without compromising the ability of future generations to meet their own needs.

Durability is important for sustainability because durable materials and structures require less maintenance and replacement, which reduces environmental impact. For example, a well-designed and constructed concrete building can last for hundreds of years, reducing the amount of resources needed to construct new buildings over time.

There are several factors that can affect the durability of a material or structure, including:

- Materials used: High-quality, well-specified materials are more durable than low-quality materials.
- Design: Proper design can help protect a material or structure from environmental factors that may cause deterioration.
- Construction: Proper construction is essential to ensure the durability of a material or structure.
- Maintenance: Regular maintenance can help extend the service life of a material or structure.

There are several things that can be done to promote durability and sustainability in construction, including:

- Using high-quality, well-specified materials.
- Designing projects with durability in mind.
- Constructing projects correctly.
- Conducting regular inspections and maintenance.

Durability in reinforced concrete structures

"Durability in reinforced concrete structures is the ability of these structures to resist deterioration and wear over time" (Hernández, 2023, p. 18). Durability is important to ensure the safety and functionality of reinforced concrete structures.

Figure 7.

Example of a reinforced concrete building.

Note. Adapted from Reporte Indigo (2017).

Why strive for durability?

There are many reasons to strive for durability. In general terms, durability refers to the ability of something to resist deterioration and wear over time. When something is durable, it is less likely to need replacement or repair, which can save money and resources (Hernández, 2023, p. 16).

In the context of construction, durability is particularly important. Construction structures are exposed to various factors that can cause deterioration, such as weather, chemicals, and use. Durable structures are safer and more efficient and can last many years without needing major repairs.

Below are some specific reasons to strive for durability in construction:

- Safety: Durable structures are safer for occupants and users. They are less likely to collapse or fail, which can prevent injuries or fatalities.
- Efficiency: Durable structures are more energy-efficient. They can help reduce heating and cooling costs, which can save money and reduce greenhouse gas emissions.
- Waste reduction: Durable structures require less maintenance and replacement, which can reduce the amount of waste sent to landfills.
- Improved quality of life: Durable structures can improve the quality of life for people. They can provide a safe and comfortable environment for living, working, and recreation.

Exposure conditions

"Exposure conditions are the environmental factors to which a reinforced concrete structure will be subjected. These factors can affect the durability of the concrete, so it is important to consider them in the design, construction, and maintenance of structures" (Hernández, 2023, p. 21).

Exposure conditions can be classified into two main categories:

- Natural environmental factors: These factors include climate, water, soil, chemicals, and radiation.
- Human environmental factors: These factors include the use, maintenance, and repair of the structure.

Natural environmental factors

Natural environmental factors can have a significant impact on the durability of concrete. The following factors are the most important:

- Climate: Climate can affect the durability of concrete in several ways. Extreme temperatures, both high and low, can cause cracking and expansion. Humidity can lead to the corrosion of reinforcing steel, efflorescence, and carbonation. Ultraviolet radiation can cause surface degradation.

- Water: Water is an important factor affecting the durability of concrete. Exposure to water can lead to the corrosion of reinforcing steel, efflorescence, and carbonation.
- Soil: Soil can contain chemical agents that can attack concrete. Sulfates, for example, can cause the alkali-aggregate reaction.
- Chemicals: Chemicals can cause various problems in concrete. Acids, for example, can lead to the corrosion of reinforcing steel.
- Radiation: Radiation, such as ultraviolet radiation, can cause surface degradation.

Human Environmental Factors

Human environmental factors can also affect the durability of concrete. The following factors are the most important:

- Use: The use of the structure can affect its durability. For example, a structure subjected to heavy loads or vibrations may be more susceptible to deterioration.
- Maintenance: Proper maintenance is essential to ensure the durability of concrete. Regular maintenance can help detect and repair problems before they become severe.
- Repair: Improper repair can damage concrete and reduce its durability. It is important to use appropriate repair techniques to ensure the structure remains safe and durable.

Harmful agents for concrete

"Harmful agents for concrete are those that can cause deterioration, reducing its strength, durability, and aesthetics. These agents can be of natural or human origin and can act directly or indirectly." (Hernández, 2023, p. 24).

Harmful agents of natural origin

Harmful agents of natural origin are those found in the environment, such as climate, water, soil, and chemicals.

- Climate: Climate can affect concrete in various ways. Extreme temperatures, both high and low, can cause cracking and expansion. Humidity can lead to the corrosion of reinforcing steel, efflorescence, and carbonation. Ultraviolet radiation can cause surface degradation.

- Water: Water is a significant factor that affects the durability of concrete. Exposure to water can lead to the corrosion of reinforcing steel, efflorescence, and carbonation.
- Soil: Soil may contain chemical agents that can attack concrete. Sulfates, for example, can cause an alkali-aggregate reaction.
- Chemicals: Chemicals can cause various problems in concrete. Acids, for instance, can cause the corrosion of reinforcing steel.

Harmful agents of human origin

Harmful agents of human origin are those caused by human activity, such as the use, maintenance, and repair of structures.

- Use: The use of the structure can affect its durability. For example, a structure subjected to heavy loads or vibrations may be more susceptible to deterioration.
- Maintenance: Proper maintenance is essential to ensure the durability of concrete. Regular maintenance can help detect and repair problems before they become severe.
- Repair: Incorrect repair can damage concrete and reduce its durability. It is important to use the proper repair techniques to ensure that the structure is safe and durable.

Aggressiveness level

The aggressiveness level is an important factor to consider in the design, construction, and maintenance of reinforced concrete structures. The aggressiveness level determines the durability requirements of the concrete, as well as the necessary protective measures to ensure the lifespan of the structure (Hernández, 2023, p. 29).

There are several scales of aggressiveness used to classify environments according to their level of aggressiveness. One of the most commonly used scales is the aggressiveness scale of the International Cement Association. This scale classifies environments into four categories, from the most benign (A1) to the most aggressive (A4):

- A1: Dry or wet environments with low salt content.
- A2: Wet environments with moderate salt content.
- A3: Wet environments with high salt content.
- A4: Wet environments with very high salt content.

Aggressive agents

"Aggressive agents are those that can cause deterioration to concrete, reducing its strength, durability, and aesthetics. These agents can be of natural or human origin and can act directly or indirectly." (Hernández, 2023, p. 24).

Aggressive agents can cause various effects on concrete, including:

- Cracking: Cracking can be caused by various factors, such as thermal expansion, drying shrinkage, corrosion of reinforcing steel, and alkali-aggregate reaction.
- Efflorescence: Efflorescence is a white deposit that forms on the surface of concrete. It is caused by the accumulation of salts on the surface of the concrete.
- Carbonation: Carbonation is a chemical process in which carbon dioxide from the air reacts with the cement in concrete. This reduces the alkalinity of the concrete, which can lead to the corrosion of reinforcing steel.
- Alkali-aggregate reaction: The alkali-aggregate reaction is a chemical reaction that occurs between the alkalis in the cement and the constituents of the aggregate. This can cause expansion and cracking of the concrete.
- Corrosion of reinforcing steel: The corrosion of reinforcing steel is a chemical process in which the steel oxidizes. This reduces the cross-sectional area of the steel and can cause a loss of concrete strength.
- Damage from chemicals: Chemicals can cause various damages to concrete, including the corrosion of reinforcing steel, erosion, and surface degradation.

Chloride attack on concrete

Chloride attack on concrete is a chemical process that causes the corrosion of reinforcing steel, which can weaken or even destroy the concrete structure. "Chlorides are ions found in seawater, deicing salts, and other chemicals. When chlorides come into contact with concrete, they can penetrate the pores of the material and react with the reinforcing steel" (García-Ruiz, González-Martínez, and García-Gutiérrez, 2022, p. 2).

Chloride attack occurs in two stages:

- Penetration of chlorides: Chlorides can penetrate concrete through its pores. The penetration rate depends on several factors, such as the porosity of the concrete, the concentration of chlorides in the contact water, and the temperature.
- Corrosion of reinforcing steel: Chlorides react with the reinforcing steel, forming a layer of iron oxide. This layer is porous and allows water and oxygen to continue reacting with the steel, leading to its corrosion (García-Ruiz, González-Martínez, and García-Gutiérrez, 2022, p. 3).

The effects of chloride attack on concrete can be severe. The corrosion of reinforcing steel can weaken or even destroy the concrete structure. Signs of chloride attack include:

- Efflorescence: Efflorescence is a white or reddish layer that forms on the surface of concrete. It is caused by the accumulation of corrosion products.
- Oxidation of reinforcing steel: The oxidation of reinforcing steel can cause the material to turn brown or red.
- Cracking: Cracking can be a sign of weakening concrete.

The process and its agents

Chloride attack on concrete is a corrosion process that occurs when chloride ions present in the environment penetrate the concrete and react with the reinforcing steel. This process can be divided into the following stages:

- Penetration of chlorides: Chlorides can penetrate concrete by diffusion, migration, or through the penetration of water contaminated with chlorides. Diffusion is the most common process and occurs by the movement of chloride ions through the porous structure of the concrete. Migration is a faster process than diffusion and occurs when chlorides are carried by water circulating through the concrete. The penetration of water contaminated with chlorides is a more direct process and can occur through contact of concrete with seawater or with contaminated groundwater.
- Reaction of chlorides with reinforcing steel: Once chloride ions penetrate the concrete, they react with the reinforcing steel, forming a layer of iron chloride. This layer is initially passive, meaning it protects the steel from corrosion. However, if the concentration of chlorides is too high, the iron chloride layer becomes active and begins to corrode the steel.
- Corrosion of reinforcing steel: The corrosion of reinforcing steel is an electrochemical process that occurs when the steel oxidizes. Oxidation is a chemical reaction that produces iron oxide, a material much less resistant than steel. The corrosion of reinforcing steel causes a loss of cross-sectional area of the steel, which weakens the concrete structure.

Agents of chloride attack

The main agents that contribute to chloride attack on concrete are:

- The concentration of chlorides: The concentration of chlorides is the most important factor affecting the rate of chloride attack. The higher the concentration of chlorides, the faster the corrosion process.

- The thickness of the concrete cover: The thickness of the concrete cover is the distance that separates the reinforcing steel from the surface of the concrete. A thicker concrete cover provides greater protection to the reinforcing steel against corrosion.
- The porosity of the concrete: The porosity of the concrete is the amount of void spaces it contains. Higher porosity of the concrete facilitates the penetration of chlorides.
- The presence of cracks: The presence of cracks in the concrete allows chlorides to penetrate without having to pass through the porous structure of the concrete.

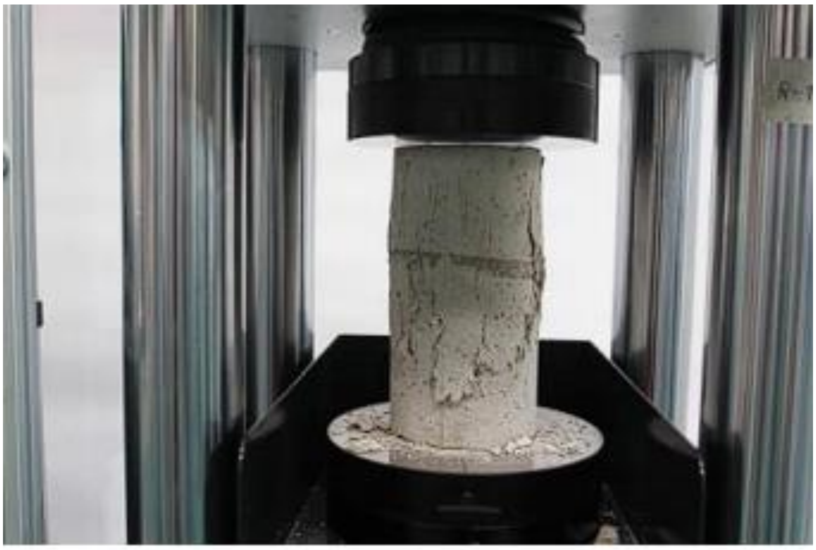
Effects on concrete

The corrosion of reinforcing steel in concrete produces several negative effects on the concrete, which can be summarized as follows:

- Reduction in tensile strength of concrete: The corrosion of reinforcing steel produces a loss of cross-sectional area of the steel, which reduces the tensile strength of the concrete.
- Reduction in compressive strength of concrete: The corrosion of reinforcing steel can cause the formation of cracks in the concrete, which reduces the compressive strength of the concrete.
- Reduction in the durability of concrete: The corrosion of reinforcing steel can cause the disintegration of the concrete, reducing its durability.

Figure 8.

Compression strength test.



Note. Adapted from Murciano et al. (s. f.)

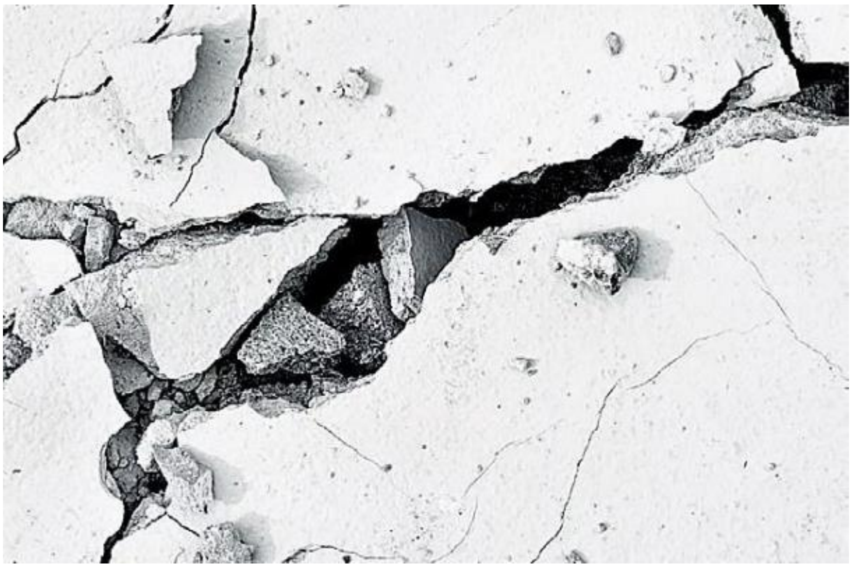
The effects of corrosion of reinforcing steel in concrete can be evaluated through a series of tests, such as the following:

- Tensile test: This test measures the tensile strength of the concrete.
- Compression test: This test measures the compressive strength of the concrete.
- Ultrasonic test: This test measures the speed of sound waves propagation in the concrete.

Incidence of cracking

The corrosion of reinforcing steel in concrete can cause the formation of cracks in the concrete. These cracks can be superficial or deep, and can affect the structural integrity of the structure.

Figure 9.
Cracking



Source: TK Vineeth, (2023).

The formation of cracks due to corrosion of reinforcing steel occurs through two main mechanisms:

- Increase in internal pressure: The corrosion of reinforcing steel produces corrosion products that occupy a larger volume than the original steel. This increase in volume causes an increase in internal pressure in the concrete, which can lead to the formation of cracks.

- Reduction in the bond between steel and concrete: The corrosion of reinforcing steel can weaken the bond between steel and concrete. This can lead to the formation of tensile cracks in the concrete.

The factors that influence the incidence of cracking due to corrosion of reinforcing steel are as follows:

- Concentration of chlorides: The higher the concentration of chlorides, the faster the corrosion process and the greater the incidence of cracking.
- Thickness of the concrete cover: A thinner concrete cover provides less protection to the reinforcing steel, which increases the incidence of cracking.
- Porosity of the concrete: The higher the porosity of the concrete, the easier it is for chlorides to penetrate, increasing the incidence of cracking.
- Presence of cracks: The presence of cracks in the concrete facilitates the penetration of chlorides and increases the incidence of cracking.

Concrete durability

The durability of concrete is its ability to withstand the conditions to which it will be exposed during its service life.

Concrete durability is an important factor to consider in the design and construction of concrete structures. Concrete structures exposed to adverse environmental conditions, such as moisture, freeze-thaw cycles, and chemical agents, must have high durability to avoid premature deterioration.

The factors that influence concrete durability are as follows:

- Concrete composition: The composition of concrete, including the type of cement, aggregates, and additives, has a significant impact on its durability.
- Manufacturing process: The process of manufacturing concrete, including batching, mixing, and placement, can also affect its durability.
- Exposure conditions: The exposure conditions to which the concrete will be subjected will also influence its durability.

There are several measures that can be taken to improve the durability of concrete, such as:

- Using high-alkalinity-resistant cement: High-alkalinity-resistant cement is more resistant to the corrosion of reinforcing steel.
- Using high-quality aggregates: High-quality aggregates are more resistant to degradation by chemical agents.
- Adding chemical additives: Chemical additives can help improve concrete durability in various ways, such as reducing concrete porosity, inhibiting

the corrosion of reinforcing steel, or protecting concrete from chemical agents.

- Using a waterproof coating: A waterproof coating can help protect concrete from moisture and chemical agents.
- Keeping the concrete dry: Concrete that is kept dry is more resistant to degradation.

The environment

The environment can have a significant impact on the durability of concrete. Environmental factors that can affect concrete durability include:

- Temperature: Concrete is more susceptible to degradation at extreme temperatures, such as high summer temperatures or low winter temperatures.
- Humidity: Humidity can lead to the corrosion of reinforcing steel, which is the primary factor limiting concrete durability.
- Pollution: Pollutants, such as chlorides, sulfates, and acids, can cause concrete degradation.
- Freeze-thaw cycles: Freeze-thaw cycles can cause cracks in the concrete, which can facilitate the penetration of contaminants.

Exposure to these environmental factors can result in reduced strength, ductility, and impermeability of the concrete. This can lead to structural problems, such as cracking, spalling, and collapse.

Chloride potential in the air

The chloride potential in the air is a measure of the amount of salt in the air. The salt can come from various sources, such as the ocean, industries, traffic, and agriculture.

The amount of salt in the air is measured in parts per million (ppm). One ppm is a unit of concentration equivalent to one part of salt in one million parts of air. For example, a chloride potential of 100 ppm means that there are 100 parts of chlorides in one million parts of air.

The chloride potential in the air can affect the durability of concrete. Chlorides can penetrate the concrete and react with the reinforcing steel, causing its corrosion. Corrosion of the reinforcing steel can weaken the concrete structure and lead to cracking, spalling, and collapse.

The chloride potential in the air can vary by location. Coastal areas usually have a higher chloride potential than inland areas. Areas near industries that use chlorides, such as water treatment plants and chemical manufacturing plants, may also have a higher chloride potential.

Control procedures

These are the mechanisms, standards, and procedures established to ensure the durability of concrete and prevent the appearance of pathologies.

Concrete durability is its ability to resist the effects of environmental and usage agents during its service life. Concrete pathology is the set of alterations that occur in concrete as a result of the action of environmental and usage agents.

Control procedures for durability and pathology of concrete can be classified into two main types:

- Preventive procedures: These procedures are designed to prevent the occurrence of pathologies. For example, proper design and construction procedures can help ensure that the concrete has good durability.
- Corrective procedures: These procedures are designed to detect and repair pathologies that have already occurred. For example, periodic inspections can help identify pathologies in time for them to be repaired.

Durability and pathology control procedures should be designed with consideration of the environmental and usage factors to which the concrete structure will be exposed. For instance, a concrete structure exposed to aggressive environments, such as coastal or industrial areas, will require stricter control procedures than a concrete structure exposed to less aggressive environments.

Durability and pathology control procedures should be reviewed and updated periodically to ensure they remain effective. This is important because the environmental and usage factors to which a concrete structure is exposed may change over time.

During concrete manufacturing

According to García (2023), "the manufacturing of concrete is a process that involves the combination of four basic materials: cement, water, coarse aggregates, and fine aggregates" (p. 2). These materials are mixed in a specific proportion to create a homogeneous mixture that can be molded and cured to form a solid structure.

During the manufacturing of concrete, the following steps are carried out:

1. Preparation of materials.
   The first step is to prepare the basic materials. Cement is produced in a cement factory from raw materials such as limestone, clay, and gypsum. Coarse aggregates, such as crushed stone, are extracted from quarries. Fine aggregates, such as sand, can be extracted from quarries or from rivers and streams.

2. Batching of materials.
   Once the materials are prepared, they are batched in the correct proportion. The proportion of cement, water, coarse aggregates, and fine aggregates determines the properties of the concrete, such as its strength, durability, and workability.

3. Mixing.
   The materials are mixed in a concrete mixer until a homogeneous mixture is formed. The mixing time is important to ensure that the materials are evenly mixed.

4. Transport
   The concrete is transported from the concrete plant to the construction site in mixer trucks. Mixer trucks have a rotating drum that helps keep the concrete mixed during transport.

5. Placement.
   The concrete is placed at the construction site and molded into the desired shape. Concrete can be placed in various ways, such as by gravity, pumping, or vibration.

6. Curing
   The concrete must be cured for a specified period to reach its maximum strength. Curing can be done by spraying the concrete with water or using plastic sheets.
   During concrete manufacturing, several factors must be controlled to ensure that the final product meets the specified requirements. These factors include:
   - The quality of the materials
   - The accuracy of batching
   - The efficiency of mixing
   - The temperature of the concrete
   - The transport time
   - The placement of the concrete
   - The curing of the concrete

Controlling these factors is important to ensure that the concrete is safe, durable, and meets design requirements.

In the case of pre-mixed concrete manufacturing, the process is similar but is carried out in a concrete plant. Pre-mixed concrete plants are equipped with equipment for preparing, batching, mixing, transporting, and delivering concrete.

During pouring

During pouring, there are several factors that can affect the durability and pathology of concrete:

- The temperature of concrete: Concrete should be poured at an appropriate temperature to ensure strength and durability. The temperature of concrete should be between 10 and 32 °C (50 and 90 degrees Fahrenheit). If the temperature of the concrete is too low, curing will slow down and the concrete may be more susceptible to cracking. If the temperature is too high, the concrete may lose water too quickly and may be less resistant.
- The placement of concrete: Concrete placement must be careful to avoid segregation, void formation, and air entrapment. Segregation is the separation of concrete components, which can reduce strength and durability. Voids are empty spaces in the concrete, which can reduce strength and durability. Air entrapment is the presence of air bubbles in the concrete, which can reduce strength and durability.
- Curing of concrete: Curing is the process of providing moisture to the concrete to ensure proper curing. Proper curing is essential for ensuring the strength and durability of the concrete. Concrete should be cured for at least seven days.

After pouring

After pouring, several factors can affect the durability and pathology of concrete. These factors include:

- Curing: Curing is the process of providing moisture to the concrete to ensure proper curing. Proper curing is essential for ensuring the strength and durability of the concrete. Concrete should be cured for at least seven days.
- Protection: Concrete should be protected from environmental damage, such as rain, wind, and sun. Proper protection can help extend the service life of the concrete.
- Maintenance: Concrete should be properly maintained to ensure its durability. Maintenance can include tasks such as cleaning, sealing, and reinforcing.

Damaged structures

According to the American Concrete Institute (ACI), "damaged structures due to concrete durability and pathology are a common problem worldwide" (ACI, 2019, p. 6). Damage can range from minor surface defects to complete structural failures.

Some of the most common types of structural damage from concrete durability and pathology include:

- Cracking: Cracking is one of the most common forms of concrete deterioration. Cracking can occur for various reasons, including thermal stresses, shrinkage stresses, and load stresses.
- Corrosion of reinforcing steel: Reinforcing steel is an important component of reinforced concrete structures. Reinforcing steel can corrode if exposed to water and oxygen. Corrosion of reinforcing steel can lead to a loss of structural strength.
- Chemical attack: Concrete can be attacked by various chemicals, such as acids and alkalis. Chemical attack can cause a loss of concrete strength and durability.

Damage from concrete durability and pathology can have several negative consequences, including:

- Reduction in structural strength: Damage can weaken the structure, increasing the risk of failure.
- Aesthetic damage: Damage can make the structure appear unattractive.
- Repair costs: Damage can require costly repairs.

Sea water attack

According to the American Concrete Institute (ACI), "sea water is a highly aggressive environment for concrete" (ACI, 2019, p. 10). Sea water contains a large amount of chlorides, which are the main agents responsible for attacking concrete. Chlorides can penetrate concrete by diffusion or through cracks. Once chlorides have penetrated the concrete, they can cause corrosion of reinforcing steel, which can lead to a loss of strength and structural failure.

Figure 10.

Effects of sea water on concrete

Source: Flores May N., (2020).

The main effects of sea water attack on concrete are:

- Corrosion of reinforcing steel: Chlorides are corrosive to steel and can lead to a loss of steel strength. Corroded reinforcing steel can expand and cause the concrete to crack, leading to a loss of structural strength.
- Chemical attack: Chlorides can also directly attack the concrete, causing a loss of strength and durability.
- Efflorescence: Chlorides can react with concrete components to form salts. These salts can accumulate on the surface of the concrete, forming a white layer known as efflorescence. Efflorescence can be a sign of sea water attack, but it is not always the case.

Acid attacks

According to the American Concrete Institute (ACI), "acid attacks are a type of durability damage that can affect concrete" (ACI, 2019, p. 12). Acids can penetrate concrete by diffusion or through cracks, causing a loss of strength and durability.

Figure 11. *Concrete damage from acids*

Note. Adapted from Martínez, R. (2018).

The main types of acids that can attack concrete are:

- Mineral acids: Mineral acids are the most common and are found in various chemicals, such as sulfuric, hydrochloric, and nitric acids.
- Organic acids: Organic acids are found in various natural products, such as citric, phosphoric, and acetic acids.

The main effects of acid attacks on concrete are:

- Dissolution of cement hydration products: Acids dissolve the hydration products of cement, which can lead to a loss of concrete strength and durability.
- Corrosion of reinforcing steel: Acids can corrode reinforcing steel, leading to a loss of structural strength.
- Efflorescence: Acids can react with concrete components to form salts. These salts can accumulate on the surface of the concrete, forming a white layer known as efflorescence.

Factors that can increase the risk of acid attack on concrete include:

- Acid concentration: Higher acid concentration increases the risk of acid attack.
- Duration of exposure: Concrete exposed to acids for a prolonged period is at greater risk of acid attack.
- Presence of cracks in concrete: Cracks provide a route for acids to penetrate.

Carbonation attack

Carbonation attack is a type of durability damage that can affect concrete. Carbonation is a chemical process that occurs when carbon dioxide from the air reacts with the hydration products of cement. This process lowers the pH of the concrete, which leads to the corrosion of the reinforcing steel.

Figure 12.

Damage to concrete from carbonation

Note. Adapted from Jaramillo (2025).

The main factors that can increase the risk of carbonation attack in concrete are:

- Carbon dioxide content in the air: Higher levels of carbon dioxide in the air increase the risk of carbonation attack.
- Prolonged exposure to air: Concrete exposed to air for extended periods is at a greater risk of carbonation attack.
- Presence of cracks in the concrete: Cracks provide a pathway for carbon dioxide to penetrate.

The main effects of carbonation attack on concrete are:

- Corrosion of reinforcing steel: The corrosion of reinforcing steel is the most significant effect of carbonation attack. Corroded reinforcing steel can lead to a loss of strength and structural failure.
- Reduction in concrete strength: The reduction in concrete strength is another major effect of carbonation attack. Decreased strength can result in a loss of structural stability.

How to stop carbonation in concrete

Carbonation is a chemical process that occurs when carbon dioxide from the air reacts with the hydration products of cement, reducing the pH of the concrete and causing reinforcing steel to corrode.

Carbonation is a slow process but can be very detrimental to concrete. The corrosion of reinforcing steel can lead to a loss of strength and structural failure.

According to the American Concrete Institute (ACI), "there is no way to completely stop carbonation, but measures can be taken to slow its progress" (ACI, 2019, p. 15). These measures include:

- Using high-quality materials: High-quality materials, such as low-permeability cement, can help reduce the rate of carbonation.
- Following proper construction practices: Proper construction practices, such as correct compaction of concrete, can help reduce the permeability of concrete and thus slow down carbonation.
- Applying surface treatments: Surface treatments, such as sealers, can help protect concrete from carbon dioxide.

Factors affecting carbonation

Factors that can affect the carbonation of concrete include:

- Carbon dioxide content in the air: Higher carbon dioxide content in the air increases the rate of carbonation. Carbon dioxide levels can vary based on geographical location, time of day, and weather conditions.
- Prolonged exposure to air: Concrete exposed to air for a long period is at greater risk of carbonation.
- Presence of cracks in the concrete: Cracks provide a route for carbon dioxide to penetrate.
- Concrete moisture content: Wet concrete is less susceptible to carbonation compared to dry concrete.
- Type of cement used: Low-permeability cement is more resistant to carbonation than high-permeability cement.
- Water/cement ratio: A lower water/cement ratio produces denser and less porous concrete, making it more resistant to carbonation.
- Characteristics of aggregates used: Aggregates with a rough surface can provide greater resistance to carbonation compared to those with a smooth surface.
- Concrete curing conditions: Proper curing helps reduce concrete permeability and thus slows carbonation.

The relative importance of these factors can vary depending on the specific exposure conditions of the concrete. For example, carbon dioxide content in the air is a more significant factor in structures exposed to urban environments than in those exposed to rural environments.

Carbonation is a slow process but can be very damaging to concrete. The corrosion of reinforcing steel can lead to loss of strength and structural failure.

What should be done to repair and protect structures from carbonation?

According to the American Concrete Institute (ACI), the repair and protection of structures from carbonation depend on the extent of the damage suffered by the structure. In mild cases, applying a surface treatment, such as a sealer or impregnant, may be sufficient to protect the concrete from carbon dioxide penetration (ACI, 2019, p. 16).

In more severe cases, structural repair may be necessary, such as replacing damaged concrete or applying an additional protective layer.

The main measures for repairing and protecting structures from carbonation include; surface treatments can help protect concrete from carbon dioxide penetration. The most common treatments are:

- Sealers: Sealers form a physical barrier that prevents carbon dioxide from penetrating the concrete.
- Impregnants: Impregnants penetrate the surface of the concrete and form a chemical barrier that protects against corrosion.

Surface treatments are suitable for structures that have not suffered severe damage from carbonation.

Structural repairs may be necessary for structures that have experienced significant damage from carbonation. The most common repairs are:

- Replacement of damaged concrete: Damaged concrete is removed and replaced with new concrete.
- Application of an additional protective layer: An additional layer of protection is applied over the existing concrete to protect it from carbon dioxide penetration.

Attack by biological agents

According to Rodríguez-Núñez et al. (2022), "biological agents such as viruses, bacteria, fungi, and toxins can attack concrete and cause damage that can affect its durability and pathology" (p. 15).

Biological agents can attack concrete in several ways:

- Embedding: Biological agents can embed themselves on the surface of concrete and form a layer that can hinder the adherence of other materials.
- Corrosion: Biological agents can corrode concrete, leading to cracking and spalling.
- Degradation: Biological agents can degrade the mechanical properties of concrete, causing it to weaken and collapse.

The types of biological agents that most commonly affect concrete include:

- Fungi: Fungi are the most common biological agents affecting concrete. They can cause various types of damage, such as cracking, spalling, and degradation.
- Bacteria: Bacteria can also damage concrete but are less common than fungi.
- Algae: Algae can cause staining and discoloration of concrete.
- Viruses: Viruses are less common than other biological agents but can cause severe damage to concrete.

Factors that can increase the risk of biological attack on concrete include:

- Exposure to water: Water is necessary for the development of biological agents. Concrete exposed to moisture, such as in humid environments or near water, is at greater risk of biological attack.
- Contamination: Contamination of concrete with organic matter, such as animal or plant waste, can increase the risk of biological attack.
- Temperature conditions: Warm and humid temperatures are ideal for the growth of biological agents.

Concrete cracking

Volume variations and fissures

Concrete cracking is a common phenomenon that can occur for various reasons. “The most common causes of concrete cracking are volume variations and fissures.” (Hernández, 2023, p. 24)

Volume variations

Hernández (2023) notes that concrete expands and contracts as it cures and dries. These volume variations can cause cracking if not properly controlled. (p. 24-25)

Volume variations can be caused by several factors, including:

- Temperature changes: Concrete expands when heated and contracts when cooled.

- Humidity changes: Concrete expands when it absorbs water and contracts when it loses water.
- Curing conditions: Inadequate curing can cause premature concrete shrinkage.

Fissures

Fissures are cracks that form in concrete. They can be caused by several factors, including:

- Excessive Loads: Excessive loads can cause concrete to break.
- Construction Defects: Construction defects, such as lack of reinforcement or use of low-quality materials, can cause concrete cracking.
- Environmental Attacks: Environmental attacks, such as reinforcement steel corrosion or chemical exposure, can cause concrete cracking.

Cracking after concrete hardening

Concrete cracking can occur at any stage of its life, from placement to demolition. However, "cracking after concrete hardening is the most common type of cracking" (Hernández, 2023, p. 25).

Cracking in hardened concrete

Hernández (2023) notes that cracking after concrete hardening can be due to various factors, including:

- Temperature Variations: Concrete expands when heated and contracts when cooled. If these temperature variations are too large, they can cause cracking.
- Humidity Variations: Concrete expands when it absorbs water and contracts when it loses water. If these humidity variations are too large, they can cause cracking.
- Excessive Loads: If the loads applied to the concrete are too large, they can cause it to break.
- Construction Defects: Construction defects, such as lack of reinforcement or use of low-quality materials, can cause concrete cracking.
- Environmental Attacks: Environmental attacks, such as reinforcement steel corrosion or chemical exposure, can cause concrete cracking.

Durability requirements

According to the American Concrete Institute (ACI) (2019), durability requirements for concrete are "the properties that concrete must meet to withstand the effects of the environment and use throughout its service life" (p. 1). These requirements are specified in construction standards and codes.

The main durability requirements for concrete include:

- Resistance to Carbonation: Carbonation is a chemical process that occurs when carbon dioxide from the atmosphere reacts with the cement in concrete. Carbonation can reduce concrete strength and increase its permeability.
- Resistance to Corrosion: Corrosion is a chemical process that occurs when the reinforcing steel in concrete oxidizes. Corrosion can cause cracking and spalling of concrete.
- Resistance to Freeze-Thaw Cycles: Freeze-thaw cycles can cause cracking and spalling of concrete.
- Abrasion Resistance: Abrasion is wear caused by friction. Abrasion can cause surface wear of concrete.
- Resistance to Chemical Agents: Chemical agents, such as acids and alkalis, can attack concrete and cause its deterioration.

Durability requirements for concrete can be met through the use of high-quality materials, proper mix design, correct execution of work, and adequate maintenance of concrete.

Prevention: A weapon against pathology

According to the American Concrete Institute (ACI) (2019), "prevention is the best weapon against concrete pathology" (p. 2). By taking measures to prevent damage to concrete, it is possible to ensure that concrete structures last a long time and fulfill their intended function.

The main factors that can cause damage to concrete include:

- Water: Water is essential for concrete construction but can also cause damage if not properly controlled. Exposure to water can lead to carbonation of concrete, reducing its strength and increasing its permeability. It can also cause corrosion of reinforcing steel, leading to cracking and spalling of concrete.
- Chemical Agents: Chemical agents, such as acids and alkalis, can attack concrete and cause its deterioration.
- Freeze-Thaw Cycles: Freeze-thaw cycles can cause cracking and spalling of concrete.

- Abrasion: Abrasion, such as that caused by traffic, can cause surface wear of concrete.

Prevent to avoid regret

Concrete pathology is the study of defects that can arise in concrete during its service life. These defects can cause damage to concrete structures, leading to costly repairs or even replacement of the structure.

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Chapter IV

Special and next-generation concretes

Introduction.

Special and next-generation concretes are types of concrete that are characterized by their enhanced properties. These properties can include superior compressive strength, improved tensile strength, greater durability, or lower permeability.

Special and next-generation concretes are used in a wide range of applications where specific properties are required. For example, high-strength concretes are used in the construction of high-load structures such as bridges and tall buildings. High-durability concretes are used in applications exposed to adverse environmental conditions, such as coastal areas and arid zones.

Types of concrete

There are many different types of concrete and concrete building materials, some of which can be used for the same purpose. It depends on the goal you wish to achieve. You can choose the appropriate form for your concrete work to accomplish the task.

Recycled aggregate concretes

Recycled aggregate concretes are a type of concrete that uses recycled aggregates, such as construction and demolition waste (CDW). CDW are materials generated during the construction and demolition of buildings, bridges, roads, and other structures.

The compressive strength of recycled aggregate concretes can be improved by using high-strength cements and additives. The permeability of recycled aggregate concretes can be reduced by using high-quality recycled aggregates and additives. The tendency for cracking in recycled aggregate concretes can be reduced by using appropriate design and construction techniques.

Recycled aggregate concretes are increasingly used in construction. They are used in a wide range of applications, such as the construction of buildings, bridges, roads, and pavements.

Recycled aggregate

Recycled aggregate is a granular material obtained from the crushing of construction and demolition waste (CDW). CDW are materials generated during the construction and demolition of buildings, bridges, roads, and other structures.

Figure 13.

Natural Aggregates (Left), Recycled Aggregates (Right). (Castaño, 2009)

Note. Adapted from Sharma J., Singla S., (2014).

The compressive strength of recycled aggregates can be improved by using high-strength cements and additives. The permeability of recycled aggregates can be reduced by using high-quality recycled aggregates and additives. The tendency for cracking in recycled aggregates can be reduced by using appropriate design and construction techniques.

Recycled aggregates are increasingly used in construction. In Mexico, the NMX-C-414-ONNCCE-2014 standard establishes the requirements for the manufacture and use of recycled aggregates in construction.

Properties and classification of recycled aggregates for concrete

- Gradation
  The gradation of recycled aggregates is an important factor that affects the properties of concrete. Gradation is defined as the distribution of particle sizes within an aggregate.
  The gradation of recycled aggregates must meet the requirements specified in the standards for concrete aggregates. In Mexico, the NMX-C-414-ONNCCE-2014 standard establishes the requirements for the gradation of recycled aggregates for concrete.
  The gradation of recycled aggregates can be improved through selection and classification processes. Selection is used to separate particles of different sizes, while classification is used to sort particles according to their size.

Jiménez Torrez (2023) points out that proper gradation of recycled aggregates helps ensure that the concrete has the desired properties, such as strength, durability, and workability.

- Shape and surface textura
  Jiménez Torrez (2023) also notes that the shape and surface texture of recycled aggregates are factors that affect the properties of concrete.
  The shape of recycled aggregates is usually irregular, with sharp edges. This irregular shape improves concrete adhesion and reduces permeability. The surface texture of recycled aggregates is generally rough. This rough texture also improves concrete adhesion and reduces permeability.
  The shape and surface texture of recycled aggregates can be improved through appropriate crushing processes and they are important for the following reasons:
  - They improve concrete adhesion: Concrete adhesion is the ability of concrete to adhere to other materials, such as steel reinforcements. The irregular shape and rough texture of recycled aggregates increase the surface roughness of the concrete, which improves adhesion.
  - They reduce permeability: Permeability is the ability of a material to allow liquids or gases to pass through it. The irregular shape and rough texture of recycled aggregates reduce the permeability of concrete, making it more resistant to corrosion and damage from external agents.

- Adhered mortar
  Adhered mortar is a composite material used to bond two concrete surfaces together. Adhered mortar is composed of a mixture of cement, sand, and water.
  Recycled aggregates for adhered mortar concrete are used to replace part of the natural sand in the mortar mix. Recycled aggregates for adhered mortar concrete can improve the properties of the mortar, such as compressive strength, adhesion, and impermeability.

- Density
  The properties of recycled aggregates for concrete differ from those of natural aggregates. Generally, they have lower density, higher water absorption, and lower mechanical strength.
  The density of recycled aggregates for concrete is measured in kilograms per cubic meter (kg/m^3). According to García and Gutiérrez (2019), typical

values range between 2.1 and 2.6 kg/m³, which is lower than the density of natural aggregates, usually between 2.5 and 2.9 kg/m³.

- Water absorption

  Water absorption is an important property of recycled aggregates for concrete. It is defined as the amount of water that an aggregate absorbs when submerged in water for a specified period. The water absorption of recycled aggregates is typically higher than that of natural aggregates, which can affect the properties of concrete.

  The water absorption of recycled aggregates is measured using the ASTM C127 standard test. In this test, the aggregates are weighed before and after being submerged in water for 24 hours. The difference in weight is the amount of water absorbed.

  Typical water absorption values for recycled aggregates range from 4% to 15%. Recycled aggregates with water absorption greater than 15% are generally considered unsuitable for the manufacture of structural concrete. The water absorption of recycled aggregates can affect the properties of concrete in several ways.

- Abrasion resistance

  Abrasion resistance is another important property of recycled aggregates for concrete. It is defined as the ability of an aggregate to resist wear from friction or impact. The abrasion resistance of recycled aggregates is typically lower than that of natural aggregates, which can affect the durability of concrete.

  The abrasion resistance of recycled aggregates is measured using the ASTM C131 standard test. In this test, the aggregates are placed in a rotating drum containing steel balls. The drum rotates at a specified speed for a specified period. The percentage of mass lost from the aggregates is a measure of their abrasion resistance.

  Typical abrasion resistance values for recycled aggregates range between 40% and 80% of natural aggregates. Recycled aggregates with abrasion resistance lower than 40% are generally considered unsuitable for applications where durability is a significant factor.

  The abrasion resistance of recycled aggregates can be influenced by various factors, such as the type of concrete, aggregate size, and cement content. Concrete engineers should consider the abrasion resistance of recycled aggregates when selecting materials and designing mixes.

- Contaminants and impurities
  Recycled aggregates for concrete can contain contaminants and impurities that can affect their properties (García & Gutiérrez, 2019). These contaminants may include:
  - Foreign materials: Such as wood, metal, glass, or plastic pieces.
  - Dust: Which can reduce concrete strength.
  - Salts: Which can cause corrosion of reinforcing steel.
  - Oils and greases: Which can reduce the adhesion between concrete and reinforcing steel.

Contaminants and impurities can reduce the properties of concrete, such as strength, durability, and workability. Therefore, it is important that recycled aggregates are properly cleaned and sorted before use in concrete.

Clean and sorted recycled aggregates can be used to produce high-quality concrete. However, it is important to consider the potential effects of contaminants and impurities when selecting and designing concrete mixes.

International classification

The international classification of recycled aggregate concretes is based on two main criteria:

The type of recycled aggregate used:

- Concrete with recycled concrete aggregate: This type of concrete uses recycled concrete aggregates obtained from crushing previously used concrete.
- Concrete with recycled aggregate from other materials: This type of concrete uses recycled aggregates from other materials, such as natural aggregates, artificial aggregates, or industrial waste.

The percentage of replacement:

- Concrete with partial recycled aggregate: This type of concrete uses a proportion of recycled aggregates between 0% and 60% of the total aggregates.
- Concrete with total recycled aggregate: This type of concrete uses a proportion of recycled aggregates of 60% or more of the total aggregates.

In addition to these two main criteria, other criteria can also be used to classify recycled aggregate concretes, such as the type of application, mechanical properties, or durability.

The international classification of recycled aggregate concretes is important to ensure the quality and safety of this type of material.

Effects of coarse aggregate replacement on compressive strength

In general, replacing coarse aggregate with recycled aggregate reduces the compressive strength of concrete (García & Gutiérrez, 2019). This decrease is due to several factors, such as:

- The surface of recycled aggregate is rougher than that of natural aggregate, creating more friction between the aggregates and the cement paste. This reduces the cohesion of the concrete and, therefore, its strength.
- Recycled aggregate may contain contaminants, such as dust, salts, or metals, which can weaken the concrete.
- Recycled aggregate may have a lower density than natural aggregate, reducing the mass of the concrete and, therefore, its strength.

The magnitude of the decrease in compressive strength depends on several factors, such as:

- The type of recycled aggregate used: Recycled crushed concrete aggregates generally have a more negative impact on compressive strength than recycled aggregates from other materials, such as natural aggregates or industrial waste.
- The percentage of recycled aggregate replacement: The impact on compressive strength is greater as the replacement percentage increases.
- The quality of the recycled aggregate: The impact on compressive strength is lower if the recycled aggregate is clean and properly sorted.

In general, it is recommended to limit the percentage of recycled aggregate replacement in concrete to a maximum of 60%. However, this percentage may vary depending on the specific application of the concrete.

In some cases, it is possible to compensate for the decrease in compressive strength by using a higher cement content or a plasticizing additive.

Wood concrete, rice husk or wheat concrete

Wood concrete is a type of concrete that uses crushed wood as coarse aggregate. Crushed wood is obtained from wood residues, such as sawdust, shavings, or recycled wood.

Wood concrete has several advantages over traditional concrete (García & Gutiérrez, 2019), such as:

- Better thermal and acoustic insulation: Wood is a good thermal and acoustic insulator, so wood concrete can help reduce heating and cooling costs in buildings.

- Greater corrosion resistance: Wood is resistant to corrosion, making wood concrete a good option for applications in humid or corrosive environments.
- Reduced environmental impact: Using crushed wood as coarse aggregate helps reduce the amount of wood waste sent to landfills.

However, wood concrete also has some disadvantages, such as:

- Higher cost: Crushed wood is more expensive than natural aggregates, so wood concrete is usually more expensive than traditional concrete.
- Lower compressive strength: Wood is less resistant to compression than natural aggregates, so wood concrete usually has lower compressive strength than traditional concrete.

Rice husk or wheat husk concrete is a type of concrete that uses rice husk or wheat husk as coarse aggregate. Rice husk and wheat husk are residues from the food industry that can be used as substitutes for natural aggregates.

Rice husk or wheat husk concrete has several advantages over traditional concrete, such as:

- Reduced environmental impact: Using rice husk or wheat husk as coarse aggregate helps reduce the amount of food industry waste sent to landfills.
- Better thermal insulation: Rice husk and wheat husk are good thermal insulators, so rice husk or wheat husk concrete can help reduce heating and cooling costs in buildings.
- Greater corrosion resistance: Rice husk and wheat husk are resistant to corrosion, making rice husk or wheat husk concrete a good option for applications in humid or corrosive environments.

However, rice husk or wheat husk concrete also has some disadvantages, such as:

- Higher cost: Rice husk and wheat husk are more expensive than natural aggregates, so rice husk or wheat husk concrete is usually more expensive than traditional concrete.
- Lower compressive strength: Rice husk and wheat husk are less resistant to compression than natural aggregates, so rice husk or wheat husk concrete usually has lower compressive strength than traditional concrete.

High-strength concretes

High-strength concretes are a type of concrete that has a compressive strength greater than 50 MPa (megapascals). This strength is significantly higher than that of traditional concrete, which typically has a compressive strength of 20-30 MPa.

Material requirements for achieving high strength

The material requirements for achieving high-strength concrete are as follows (García & Gutiérrez, 2019):

Cement

Cement is the main component of concrete and is responsible for its strength. High-strength cements have a higher content of tricalcium silicate (C3S), which is the component of cement that reacts more quickly and produces more hydraulic calcium compounds. High-strength cements also have a lower content of dicalcium silicate (C2S), which is a component of cement that reacts more slowly and produces less strong hydraulic calcium compounds.

Aggregates

Aggregates are the inert components of concrete and provide the structure and volume of concrete. High-strength aggregates have a compressive strength greater than 100 MPa. Common high-strength aggregates include granite, basalt, and blast furnace slag.

Water

Water is necessary for cement to react and form hydraulic calcium compounds. However, excessive water can reduce the strength of concrete. Therefore, it is important to use the correct amount of water to achieve high strength.

Additives

Additives are chemicals added to concrete to improve its properties. Additives used to increase concrete strength include:

- Superplasticizing additives: These additives reduce the amount of water needed to produce concrete, which increases its strength.
- Compressive strength additives: These additives react with cement to form compounds that improve the strength of concrete.

Manufacturing process

The manufacturing process of concrete is also important for achieving high strength. Concrete must be mixed adequately to ensure that all components are well-distributed. Additionally, concrete must be properly placed and compacted to remove air bubbles.

Mixing procedures

The mixing procedures for high-strength concrete are characterized by the following aspects (García & Gutiérrez, 2019):

- Use of a high-speed mixer: High-speed mixers allow materials to be mixed more uniformly and efficiently, which is important for achieving high strength.
- Pre-mixing of cement and water: Pre-mixing cement and water helps initiate the chemical reaction between the two components, which also contributes to higher strength.
- Addition of additives: Additives can improve concrete properties, such as its strength, workability, and durability.
- Continuous mixing: Continuous mixing helps ensure that all materials are well-mixed.

The specific procedures for mixing high-strength concrete may vary depending on the materials and conditions of the application. However, in general, the procedures usually follow these steps:

- Preparation of materials: Materials must be clean and dry. Aggregates should be free of dust, dirt, and other contaminants.
- Mixing of cement and water: Cement and water are mixed in an appropriate ratio for a specified period.
- Addition of aggregates: Aggregates are gradually added to the mixer and mixed until a uniform mix is obtained.
- Addition of additives: Additives are added to the mixer and mixed until fully integrated.
- Continuous mixing: The concrete is continuously mixed for a specified period.

After mixing, concrete must be properly placed and compacted to remove air bubbles. The concrete must also be adequately cured to reach its maximum strength.

Use and application of high-strength concretes

High-strength concretes are used in a wide range of applications, from high-rise buildings to bridges and industrial structures. Some of the most common applications include:

- High-rise buildings: High-strength concretes are used in high-rise buildings to reduce the weight of the structure and, therefore, construction costs.
- Bridges: High-strength concretes are used in bridges to support heavy loads, such as vehicle and pedestrian traffic.
- Industrial structures: High-strength concretes are used in industrial structures to support heavy loads, such as the weight of machinery and equipment.

Self-compacting concretes

Self-compacting concrete (SCC) is a type of concrete that has the property of filling the formwork without the need for mechanical compaction. This is achieved through the use of a combination of materials and additives that give the concrete high fluidity and flow capacity.

SCC has several advantages over conventional concrete. It is easier to place, which can reduce construction time and cost. It is also less likely to segregate, meaning it provides better reinforcement distribution and higher strength.

SCC is used in a variety of applications, including:

- Reinforced concrete structures, such as buildings, bridges, and dams.
- Precast elements, such as beams, columns, and panels.
- Mass concrete works, such as retaining walls and pavements.

In Mexico, SCC is increasingly being used in construction projects. This is due to its advantages in terms of ease of placement, strength, and durability.

SCC is a relatively new technology but has quickly gained popularity worldwide. It is a viable option for a variety of construction applications and offers several advantages over conventional concrete.

Characteristics

The characteristics of self-compacting concrete (SCC) are what allow it to fill the formwork without the need for mechanical compaction. These characteristics are achieved through the use of a combination of materials and additives that give the concrete high fluidity and flow capacity.

The main characteristics of SCC are:

- Fluidity: SCC has significantly higher fluidity than conventional concrete. This is measured using the slump flow test, where concrete is poured into a slump cone and then the distance the concrete spreads is measured. SCC should have a slump flow of at least 200 mm.

- Flow capacity: SCC has a higher flow capacity than conventional concrete, meaning it can flow through complex and narrow forms without the need for vibration.
- Segregation resistance: SCC is less likely to segregate than conventional concrete, meaning the components of the concrete, such as cement, coarse aggregate, and fine aggregate, remain evenly mixed.
- Strength: SCC can have similar or superior strength to conventional concrete. This is because self-compacting concrete is placed more uniformly, providing better reinforcement distribution.
- Durability: According to Calderón and Martínez (2021, p. 18), SCC has higher abrasion and corrosion resistance than conventional concrete, making it more suitable for applications in hostile environments.

In addition to these characteristics, SCC also has several additional properties that make it attractive for a variety of construction applications.

How is SCC achieved?

Self-compacting concrete (SCC) is achieved through the use of a combination of materials and additives that give the concrete high fluidity and flow capacity. The basic materials used in SCC are the same as those used in conventional concrete: Portland cement, coarse and fine aggregates, water, and air. However, the additives used in SCC differ from those used in conventional concrete.

The additives used in SCC are divided into two main categories:

- Water-reducing additives: These additives reduce the amount of water needed to produce a concrete mix with adequate fluidity and flow capacity.
- Rheology-modifying additives: These additives modify the rheology of the concrete, meaning its mechanical behavior. Rheology-modifying additives can improve the flow capacity of the concrete, reduce segregation, and improve crack resistance.

The combination of additives used in SCC depends on the specific properties desired. Generally, SCC is classified into three main types:

- High-performance SCC (HSC): This type of SCC has very high fluidity and flow capacity. It is used in applications requiring a high level of performance, such as the construction of complex or high-strength structures.
- Standard performance SCC (SSC): This type of SCC has intermediate fluidity and flow capacity. It is used in a variety of applications, such as the construction of reinforced concrete structures and prefabrication.

- Low-performance SCC (LSC): This type of SCC has low fluidity and flow capacity. It is used in applications requiring easy placement, such as the construction of pavements and retaining walls.

The production of self-compacting concrete requires careful selection of materials and additives, as well as strict control of the mix. Self-compacting concrete can be produced in a concrete plant or on the construction site.

The placement of self-compacting concrete can be done manually or with specialized equipment. The concrete is placed in the form and allowed to flow by its own weight. Mechanical compaction is not required.

Advantages

Self-compacting concrete offers a series of advantages over conventional concrete, including:

- Ease of placement: Self-compacting concrete can be placed in complex and narrow forms without the need for vibration. This reduces construction time and cost and also improves worker safety.
- Reduced segregation: Self-compacting concrete is less likely to segregate than conventional concrete. This means it provides better reinforcement distribution and greater strength.
- Better finish: Self-compacting concrete produces a more uniform and smooth finish than conventional concrete. This can reduce the need for subsequent repairs.
- Greater durability: Self-compacting concrete has higher abrasion and corrosion resistance than conventional concrete. This makes it more suitable for applications in hostile environments.

Lightweight concretes

Lightweight concretes are those with a density less than 1900 kg/m^3. They are characterized by having a lower bulk density than conventional concrete, which gives them several advantages, such as:

- Lower weight: This can reduce transportation and construction costs.
- Better thermal insulation: This can help reduce energy costs.
- Better impact absorption: This can reduce the risk of injury.
- Better fire resistance: This can help protect people and property in the event of a fire.

Structural lightweight concrete

Structural lightweight concrete is a type of concrete with a density of less than 2000 kg/m³ that meets the strength and durability requirements for structures. It is characterized by having a lower bulk density than conventional concrete.

Structural lightweight concretes can be classified into two main types:

- Cellular concretes: These concretes are produced by forming air bubbles in the mix. Air bubbles can be formed using foaming agents or expansive additives.
- Lightweight concretes: These concretes are produced using lightweight aggregates, such as expanded clay, vermiculite, or perlite.

Structural lightweight concretes must meet the durability requirements specified in the ACI 318-23 standard. These requirements are based on abrasion resistance and corrosion resistance.

Non-structural lightweight concrete

Non-structural lightweight concrete is a type of concrete with a density of less than 2000 kg/m³ that does not meet the strength and durability requirements for structures. It is characterized by having a lower bulk density than conventional concrete.

Non-structural lightweight concretes do not have specified strength requirements. However, it is important that the concrete has sufficient strength to support the loads and stresses to which it will be exposed.

Non-structural lightweight concrete can be produced using a variety of materials and techniques. The most common foaming agents are liquid air and hydrogen peroxide. The most common lightweight aggregates are expanded clay, vermiculite, and perlite.

Non-structural lightweight concrete can be applied in several ways. It can be placed wet, like conventional concrete, or it can be prefabricated into panels or blocks.

Non-structural lightweight concrete is a sustainable option for construction. It has a lower environmental impact than conventional concrete, as it requires fewer materials and energy for its production.

Self-curing concretes

Self-curing concretes are a type of concrete that has the ability to cure itself without the need for additional water. This is achieved by incorporating self-curing additives into the concrete mix.

Self-curing additives work by creating a protective film on the surface of the concrete. This film helps retain the moisture and nutrients necessary for the curing of the concrete. It also helps protect the concrete from damage caused by weather and exposure to the elements.

Properties

The properties of self-curing concretes are similar to those of conventional concretes, but with some additional advantages.

Strength

Self-curing concretes usually have higher strength than conventional concretes. This is because the protective film helps prevent the formation of micro cracks in the concrete.

Durability

Self-curing concretes are more durable than conventional concretes. This is because the protective film helps protect the concrete from damage caused by weather and exposure to the elements.

Less maintenance

Self-curing concretes require less maintenance than conventional concretes. This is because the protective film helps protect the concrete from damage caused by natural wear and tear.

Other properties

Self-curing concretes may also have other improved properties, such as:

- Better impermeability
- Better corrosion resistance
- Better fire resistance
- Self-healing mechanisms

Self-curing concretes work by generating a protective film on the surface of the concrete. This film can be formed by a variety of mechanisms, such as:

- Chemical reaction: The film can be formed by a chemical reaction between the components of the concrete, such as cement and water.
- Biological reaction: The film can be formed by the action of microorganisms, such as bacteria.

- Physical reaction: The film can be formed by the expansion of a material, such as foam.

Applications

Self-curing concretes are used in a variety of applications, such as:

- Construction of structures: Self-curing concretes are used to build structures that require high strength and durability.
- Rehabilitation of structures: Self-curing concretes are used to rehabilitate structures that are damaged or deteriorated.
- Protection of structures: Self-curing concretes are used to protect structures from damage caused by weather and exposure to the elements.

Advantages

- Greater strength: Self-curing concretes usually have greater strength than conventional concrete. This is because the protective film helps prevent the formation of micro cracks in the concrete.
- Better durability: Self-curing concretes are more durable than conventional concrete. This is because the protective film helps protect the concrete from damage caused by weather and exposure to the elements.
- Less maintenance: Self-curing concretes require less maintenance than conventional concrete. This is because the protective film helps protect the concrete from damage caused by natural wear and tear.
- Better impermeability: The protective film helps prevent water from penetrating the concrete, which can improve its impermeability.
- Better corrosion resistance: The protective film can help protect the concrete from corrosion, which can extend its lifespan.
- Better fire resistance: The protective film can help protect the concrete from fire, which can reduce the risk of structural damage.

Geopolymer concretes

Geopolymer concretes are a type of concrete that uses geopolymers as the main binder instead of Portland cement. Geopolymers are inorganic cementitious materials formed by the reaction of aluminosilicates with alkalis.

The chemical reaction between aluminosilicates and alkalis produces a three-dimensional network of polymers that confer strength and durability to the concrete. Geopolymers can be made from a variety of materials, such as fly ash, steel slag, ceramic waste, and other industrial waste.

Components

The basic components of polymer concretes are:

- Polymers: Polymers are the main components of polymer concretes. Polymers provide the strength and durability of the concrete. The most common polymers used in polymer concretes are:
  - Resins: Resins are liquid polymers that harden when cured. The most common resins used in polymer concretes are epoxy resin, polyester resin, and vinyl ester resin.
  - Powder polymers: Powder polymers are mixed with Portland cement to form a binder. The most common powder polymers used in polymer concretes are aluminum silicate, calcium aluminate, and calcium silicate.
  - Fibers: Polymer fibers are added to concrete to improve its tensile strength and fracture resistance. The most common polymer fibers used in polymer concretes are glass fibers, carbon fibers, and polypropylene fibers.
- Aggregates: Aggregates are the inert materials added to concrete to provide volume and strength. The most common aggregates used in polymer concretes are sand and coarse aggregate.
- Water: Water is needed to hydrate the polymers and Portland cement.

Properties

Polymer concretes offer a series of properties that distinguish them from conventional concrete. These properties include:

- Greater strength: Polymer concretes usually have greater strength than conventional concrete. This is because polymers form a stronger three-dimensional network than the gel network formed by Portland cement.
- Better durability: Polymer concretes are more durable than conventional concrete. This is because polymers are more resistant to corrosion and damage caused by weather.
- Lower permeability: Polymer concretes are more impermeable than conventional concrete. This is because polymers form a barrier that prevents water penetration.
- Better fire resistance: Polymer concretes are more fire-resistant than conventional concrete. This is because polymers form a barrier that slows the spread of fire.
- Wear resistance: Polymer concretes are more wear-resistant than conventional concrete. This is because polymers form a harder and more resistant surface.

- Flexibility: Polymer concretes are more flexible than conventional concrete. This is because polymers have greater elasticity than Portland cement.

The specific properties of polymer concretes depend on the type of polymer used and the proportions of the components. Resin concretes typically have superior strength and durability compared to powder polymer concretes. Polymer fiber concretes offer improved tensile strength and fracture resistance.

Cyclopean concrete

According to Worland and Williams (2015), cyclopean concrete is a type of concrete characterized by its high compressive strength. It consists of a mixture of cement, sand, water, and large stones, which can be concrete, granite, or basalt.

Figure 14.
Cyclopean concrete

Note. Adapted from Gracia Ledesma, (2025).

Precast concrete

According to the American Concrete Association (2020), precast concrete is a type of concrete that is manufactured in a factory and transported to the construction site in the form of prefabricated components. These components are assembled on site to form the final structure.

Figure 15.

Precast concrete

Note. Adapted from Artedinamico (s. f.)

Permeable concrete

According to the American Concrete Association (2020), permeable concrete is a type of concrete that allows water to pass through its mass. This type of concrete is used for various applications, including:

- Drainage: Permeable concrete can be used to drain surfaces, such as roads, parking lots, and sidewalks.
- Filtration: Permeable concrete can be used to filter wastewater and stormwater.
- Bioretention: Permeable concrete can be used to retain water and promote vegetation growth.

Figure 16.

Permeable concrete

Note. Adapted from Cementos Torices (2024).

Fiber-reinforced concrete

Fiber-reinforced concrete (FRC) is a type of concrete that incorporates fibers into its matrix. The fibers can be made of different materials, such as steel, glass, polymers, or natural materials.

The fibers are incorporated into the concrete to improve its mechanical properties, such as tensile strength, impact resistance, and ductility. They can also improve the workability of the concrete and reduce shrinkage.

FRC is used in a wide range of applications, such as construction of structures, pavements, coatings, and precast products.

- Types of fibers.
  The most common types of fibers used in FRC are:
  - Steel: Steel fibers are the most commonly used in FRC. They are strong and provide good tensile and impact resistance.
  - Glass: Glass fibers are lightweight and provide good impact resistance.
  - Polymers: Polymer fibers are flexible and provide good ductility.
  - Natural: Natural fibers, such as hemp, sugarcane, and bamboo, are sustainable and provide good tensile strength.

Figure 17. *Metallic fibers for concrete reinforcement*

Note. Adapted from 360° en Concreto (2025).

- Properties and applicable tests for fibers.
  The percentage of fiber incorporated into FRC varies depending on the application. Generally, fiber percentages of up to 2% are used.

Fibers can be incorporated into concrete in several ways, including:

- Manual incorporation: Fibers are added to the concrete manually during mixing.
- Automatic incorporation: Fibers are incorporated into the concrete automatically using special equipment.

Fibers enhance the mechanical properties of concrete, such as tensile strength, impact resistance, and ductility.

The impact resistance of FRC is higher than that of concrete without fibers. This is because the fibers absorb the energy of the impact.

The ductility of FRC is higher than that of concrete without fibers. This is because the fibers allow the concrete to deform more before breaking.

Tests applied to fibers are used to determine their physical and mechanical properties. These tests are essential for the design and manufacture of textile products, composites, and other materials that contain fibers.

Tests applied to fibers can be classified into two main categories: characterization tests and performance tests.

Characterization Tests

Characterization tests are used to determine the basic properties of fibers, such as their strength, modulus of elasticity, density, and other characteristics. These tests are performed before the fibers are used in product manufacturing.

Some of the most common characterization tests applied to fibers are:

- Tensile test: This test is used to determine the tensile strength and modulus of elasticity of fibers.
- Compression test: This test is used to determine the compressive strength of fibers.
- Bending test: This test is used to determine the bending strength of fibers.
- Elongation test: This test is used to determine the elongation of fibers before breaking.
- Density test: This test is used to determine the density of fibers.

Performance Tests

Performance tests are used to determine how fibers behave in specific applications. These tests are performed after the fibers have been used in product manufacturing.

Some of the most common performance tests applied to fibers are:

- Abrasion test: This test is used to determine the abrasion resistance of fibers.
- Impact resistance test: This test is used to determine the impact resistance of fibers.
- Wet tensile strength test: This test is used to determine the tensile strength of fibers in wet conditions.
- Flame resistance test: This test is used to determine the flame resistance of fibers.

Chapter V

A dialogue with the authors

Figure 18. *Interview with the authors*

Note. Adapted from authors.

Interview by Fidel Lerma

Interviewer: Could you talk about the process of bringing a book about concrete to the public? In this case, what will this book accomplish? What are the contents that will be covered in this upcoming book?

Engineer: Yes, well, we spent a lot of time looking at interesting topics that would have an impact on the education of engineering students. Without a doubt, concrete, which is the most widely used material in construction worldwide, turned out to be the topic we wanted to focus on in this document, a well-organized and structured compendium of information. This is how the idea of creating a book that addresses important topics emerged, allowing students to understand and gain a comprehensive view of concrete, starting from its raw materials and the origin of materials that make up cement, moving on to the production of concrete, understanding all the quality controls, its current usage, and the various applications of concrete in the construction industry.

Interviewer: Indeed, in summary, could you mention some history about concrete?

Engineer: Yes, touching on the most important points, concrete is known to have been patented in 1824 by an Englishman named Joseph Aspdin. He was a bricklayer who started experimenting with materials, which led to the first formation of what we now know as concrete. How do we define concrete? In geography, 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, and the raw materials for making Portland cement are found everywhere, such as clays and limestone. Once Portland cement is made, we can create various types of cement and concrete as needed.

Interviewer: In this upcoming book, the first chapter discusses concrete and its evolution. How has this material evolved over time, as explored in this book?

Engineer: The evolution of concrete has gone hand in hand with several factors. Initially, concrete has always been known as a material with a high capacity for compression. When you compress concrete, it performs excellently. The weak point of concrete is when it is subjected to tension or stretching. This led to the first major evolution, which was combining concrete with steel, resulting in reinforced concrete. Many experts in the field began identifying strategic ways to reinforce concrete in certain areas because steel is much more expensive than concrete. They decided to create reinforced concrete structures without overloading them with steel to avoid high construction costs, placing steel only in areas with significant tension. This is how reinforced concrete came into being.

What other developments have occurred? How have we continued to evolve? For instance, there are concretes with special characteristics, such as high-density concretes for dams. They realized that conventional concrete was not suitable because they needed a heavy concrete to resist the force of water. So, they developed high-density concretes by using heavier aggregates. There are also ultra-lightweight concretes, where lighter aggregates are used to achieve a concrete that is both strong and lightweight. Additionally, translucent concretes have been developed with advanced technologies, allowing light to pass through, making the concrete translucent rather than transparent. Durability has also been a focus, as there was a need to create very strong but also durable concretes. It is often said that major changes and inventions arise from necessity, such as during world wars when there was a demand for quick construction. This led to the use of prefabrication and quick-setting concretes with high early strength. The need of humanity for more specific construction characteristics has driven the evolution of concrete, along with advances in mechanical properties and theory that have made concrete more versatile.

Interviewer: In chapter two, the book also discusses the manufacturing process and chemical composition of Portland cement. What does the book say about this process?

Engineer: The manufacturing of cement is considered the Achilles' heel of concrete, especially in terms of sustainability and carbon footprint. Every day, efforts are made to develop cement manufacturing processes that generate less carbon footprint because that is the problematic aspect of cement and, by extension, concrete. The process of making cement involves calcining limestone and clay at high temperatures, which generates a lot of pollution. Major cement manufacturers emit large amounts of carbon dioxide, creating a significant carbon footprint. Understanding the manufacturing process is crucial because every day, there is a push to make this process more efficient and less polluting, making cement a more sustainable and environmentally friendly material. Knowing the chemical composition of cement is essential. As the saying goes, if we control the micro, we can manage the macro. If we understand the chemical composition of cement and its compounds, we can produce concretes tailored to our needs.

Interviewer: Is Portland cement the strongest and most durable cement?

Engineer: It is the conventional, the basic type. It is called Portland cement because it resembles a type of stone with a similar color. The Portland cement we know is grayish, a powdery grayish material that resembles Portland stone, which is why it is called Portland cement.

Interviewer: Earlier, you mentioned the characteristics and additives for concrete. What does the book teach us about the characteristics of water and its aggregates?

Engineer: The components that make up fresh concrete vary widely around the world. The water we have here in Mazatlán has a different composition than the water in southern Mexico, Europe, or China. It is important to manage and care for the water because it often contains aggressive agents, and we might inadvertently introduce these agents into the concrete. Therefore, it is necessary to pay attention to it. As for aggregates, we are fortunate in Sinaloa to have excellent aggregates due to the many rivers that carry high-quality gravel and sand from the mountains. However, in southern Mexico, such as in Yucatán, the materials are often porous, so they do not have good aggregates. They have to use crushed aggregates, which requires additional processing. In the United States, for example, they have plenty of aggregates, but they also face issues with aggregate reactivity, which can lead to problems with concrete durability. So, it is important to understand the nature of the aggregates, their geometry, and chemical composition. If there are problems, we need to know what treatments to apply. Additives have revolutionized concrete in recent years, allowing for greater fluidity over longer periods, enabling concrete pours over long distances without premature setting. Additives also ensure that concrete achieves its required strength in shorter times, such as 3-day or 7-day strengths. Additives are what have changed concrete technology and are considered state-of-the-art today.

Interviewer: Perfect. The fourth chapter discusses mineral additions. Could you tell us something about this?

Engineer: Yes, mineral additions have a significant impact on sustainability. The majority of these mineral additions are byproducts of primary industrial processes. For instance, silica fume is a byproduct of a silicon production process, fly ash comes from another industrial process, and blast furnace slag is also a waste material. What has happened recently is that these materials, which used to be dumped in landfills and contaminated large areas of land, have been studied and found to have pozzolanic activity. They are capable of replacing a percentage of cement, which is great. If you reduce the amount of cement per cubic meter by incorporating a waste material, you are making the concrete much more sustainable. There are other additions, such as metakaolin, which is not a byproduct but requires a process like calcination to produce. Many other natural additions, such as rice husk and volcanic ash, have also emerged. These additions aim to replace a portion of the cement, creating concrete with the same mechanical and durable properties as the original but with less cement, thereby reducing the carbon footprint.

Interviewer: Speaking of the history of volcanic ash, let's go back in time to Pompeii, where a city was petrified due to a volcanic eruption. The dried volcanic ash preserved the city, and these are the types of additives used in concrete. What can you tell us about this?

Engineer: Yes, some of these additives have been used, and volcanic ash is also used in other industries. The cosmetics industry, for example, uses volcanic materials for their mineral content. In construction, volcanic ash is being explored as well. We worked for a time in Colima, Mexico, where the Colima volcano is very active, constantly emitting volcanic ash. This has become a problem because the rivers are filled with so much ash that they cannot hold much water. When it rains, the rivers overflow immediately, flooding towns and cities. So, there is a need to dredge the rivers, but what they remove is volcanic ash. It is then when people start asking, "Who needs it? Who wants it?" in order to avoid the cost of transporting it away.

Interviewer: Yes, of course.

Engineer: And they are considering concessions and other arrangements.

Interviewer: Perfect. Could you also explain chapter five, which discusses concrete mix design methods? What does this entail?

Engineer: Yes, there are several theories for designing concrete mixes, but none of them are absolute. Those of us who have worked in a laboratory know that concrete can behave differently from day to day. Today, you might get one result, and tomorrow, you might get another due to changes in moisture content in the sand and gravel. Concrete is a very iterative process, requiring knowledge of the materials and understanding their moisture content. However, it is important to have a framework to guide you, and these are the concrete mix design methods. ACI (American Concrete Institute) provides a mix design method. ACI is a private association that conducts extensive research and disseminates a lot of information internationally. They have established mix design methods for achieving specific concrete strengths, self-compacting concrete, and other characteristics. In Europe, particularly in Spain, there is the Abrams method, developed by a Spanish engineer, which outlines another mix design methodology. Ultimately, a method consists of a series of steps that help you achieve concrete with specific characteristics. While these methods are not final, they do guide you toward your goal more efficiently.

Interviewer: And chapter six discusses fresh concrete. What can you tell us about concrete in this state?

Engineer: Yes, fresh concrete is essential for those of us in construction. It is crucial to handle and control it properly because fresh concrete can complicate a pour or the production of a structural element due to environmental factors. If you have fluid, workable fresh concrete, but it is drying out quickly due to high temperatures, you need to know how to respond. Additives have greatly contributed to maintaining the workability of fresh concrete over time.

Interviewer: Yes, of course.

Engineer: There are many additives added to concrete to regulate viscosity and workability, and these have greatly improved fresh concrete handling for constructors.

Interviewer: Yes, it is the way to manage concrete because, once it is hardened, as discussed in chapter seven, it becomes a big problem.

Engineer: Exactly.

Interviewer: Yes, chapter seven deals with hardened concrete. What could you tell us about this?

Engineer: Yes, once concrete hardens, there are standards and parameters that are important to monitor, such as temperature and slump. We need to ensure that fresh concrete is within these standards. Just because it is fresh and flows easily, it does not mean it is well-made. It needs to meet workability requirements, have the correct slump, and not lose moisture due to bleeding. Once you have evaluated the fresh concrete, you then evaluate it in its hardened state, which is more about the mechanical properties and load-bearing capacity of structures. Hardened concrete continues to evolve, even at early ages.

Interviewer: Yes, indeed.

Engineer: All tests are conducted at 28 days because it is said that by then, concrete has developed beyond 80% of its strength. However, many internal processes are still taking place, with the cement continuing to hydrate. We do not see it, but internally, the cement grains are still hydrating. That is why curing processes are essential, where water is applied to the concrete during the first seven to fourteen days. The concrete still contains a lot of unhydrated cement. When you provide water, it is not to reach the cement directly, but to prevent the internal water from escaping. When we cure, we do not add more water, as that would disrupt the water-cement ratio. Instead, we create a film of water that prevents the internal water from evaporating. If we do not apply water, the internal water escapes. This is what we aim for during the curing of hardened concrete over those 28 days; it needs to be cared for and evaluated to ensure it possesses the desired properties. This is a process in daily construction practice known as quality control.

Interviewer: For those of us who are not in the engineering field, when we see concrete being poured in a house or on a street, and we are told not to step on it for 28 days, well, I did not understand that until now.

Engineer: Exactly.

Interviewer: It's good that something positive comes out of this. So, how can we tell if a concrete is good or of high quality? How can we know that?

Engineer: Look, everything is relative. Clearly, concrete for a sidewalk, where pedestrians will walk, if you evaluate it by compressive strength, you might say it is poor-quality concrete. But for its intended use, it is appropriate concrete, as it was meant for a sidewalk where pedestrians, bicycles, and skateboards will be. It is suitable concrete. If we are talking about high-strength concrete for a bridge, we are looking for high mechanical performance, concretes with compressive strengths of 400 kg per cm^2, 500 kg per cm^2. That is good and appropriate concrete for that project. Now, let's add its mechanical performance, and if it is concrete with high sulfate resistance, given that sulfates are an aggressive agent, then it is even more appropriate. We often use the term "tropicalized" for the environment. The material needs to be adapted because having concrete in Mazatlán, where there is a high presence of salts and chlorides, is different from having concrete in Durango, where it is less likely to encounter such conditions. Therefore, concrete must be adapted to the region where it will be used, with the right characteristics.

Interviewer: Yes, that is what I was going to ask. Here in Mazatlán, in the malecón area, the sidewalk is always deteriorating due to the type of concrete used. So, I was wondering what quality concrete could be used, but as concrete is constantly evolving, I imagine they are now using better quality materials.

Engineer: Yes, and there are several factors at play. When you are in construction, many processes are intertwined. There is the design process, the manufacturing process, and the maintenance process. If one of these three fails, your structure will have problems. You can have an excellent structural and architectural design, but if it is poorly constructed, the design will not evolve properly. You can design well, you can construct well, but if it is not maintained, the structure will not perform well. These stages must be accompanied and each stage must have a responsible party ensuring it is done correctly. Sometimes, the construction process is not adequate, and even if you have the best concrete, if the construction process is poor, the outcome will not be successful.

Interviewer: And what about the durability and pathology of concrete?

Engineer: Yes, those topics have been in vogue for the last twenty years. For a long time, concrete was designed to be strong; we wanted concretes with high compressive strengths, high f'c values, and concretes with 500 kilograms per square centimeter. We would think, what could happen to a concrete with 500 kilograms per square centimeter? But then we started noticing that after 5 or 10 years, the 500-strength concrete was failing. Why? Because issues of pathology and durability started to emerge. You had a strong concrete, but it was weak in terms of chloride resistance. Chlorides would penetrate through the porous network, reach the steel reinforcement, and cause it to oxidize. When steel oxidizes, its volume increases by 400%, and this expansion cracks the concrete. This is where durability and pathology come in. Today, methods like those from ACEI require you to design for both strength and durability.

Interviewer: ACEI?

Engineer: ACEI requires you to design with both strength and durability in mind. You cannot just design for strength because, as a Spanish doctor used to say, today's constructions are the mortgage of future repairs. You cannot build more because you are constantly going back to maintain what you built five years ago.

Interviewer: Exactly.

Engineer: Look at the Mazatlán-Durango highway. Even now, there is always a section under repair. And how old is that project? Not very old, yet money is constantly being spent on maintenance, money that could be used for new projects. But perhaps something went wrong during the construction process or the initial design.

Interviewer: Speaking of roads, I have not traveled all over the country, but I have traveled on many roads in Mexico, and I have noticed that asphalt is being used less and concrete more. Is this due to durability?

Engineer: Totally.

Interviewer: Or is it simply the better option?

Engineer: Durability, absolutely. But there is a trade-off. Concrete is much more durable, but it is a less flexible material, which means that tire wear is greater. So, there is the issue that frequent users might have—unlike someone who only drives occasionally—of noticing that tires wear out faster on concrete roads. You can immediately tell when you switch from an asphalt road to a concrete one because the friction noise inside the car is much louder than on an asphalt road. On an asphalt road, you hardly hear anything. But concrete offers durability, so you get a road that lasts a long time with little maintenance required. What happens with poorly made asphalt roads during rain? The asphalt washes away, leading to potholes, but a conventional concrete road, made with cement, is much more resilient and does not require or demand as much maintenance and attention.

Interviewer: At least here in Sinaloa, I think the highways, especially the maxipista, should be 100% made of concrete because they are always patching and repairing that poor road. Lastly, in chapter nine, you talk about special and next-generation concretes.

Engineer: Yes, we have touched on some of that in our conversation. Concretes with very specific characteristics have emerged. Another example that comes to mind is permeable concrete. In many areas, when environmentalists look at engineers, they see us as the world's main enemy—and while I do not fully agree, I do think we share some of the blame, along with architects. We have built so much without considering the environmental impact. The flooding in cities is heavily influenced by our construction activities. We keep building and covering natural ground that used to absorb water. Now, this water no longer seeps into the ground because we have developed and built ten hectares of housing with great fanfare. But all the water that used to infiltrate the soil now falls on rooftops, runs into street drains, and ends up in lined channels where it never touches the earth—until it is dumped into the main waterways.

Interviewer: What happens in the channel? Was part of it lined, and that is what caused this issue?

Engineer: Exactly. It is not that the process is inherently flawed, but it needs to be managed carefully. For example, a special concrete like permeable concrete allows water to pass through while still being walkable. It is usually placed in pedestrian areas, so if it rains, you are not walking through mud, but water can still flow through it. Permeable concrete is made with only coarse aggregate and a very strong slurry—a mix of cement and water—that binds the stones together. But since there is no sand, it does not clog up. You can pour water on permeable concrete, and it will pass through, recharging the groundwater. If you had used conventional concrete, that would not have happened. There are many other special concretes emerging to meet specific needs. This is where concrete technology significantly contributes, as the international scientific community constantly asks, “What’s next? Where are we headed now? What does the latest research say?” You explore many avenues, and special next-generation concretes are developed with all these characteristics in mind.

Interviewer: At the last CASSAC (College of Architects of Southern Sinaloa A.C.) congress I attended, the architects talked about the durability and lifespan of materials. Since they travel to different cities and build in various places, they talked about the quality and durability of concretes. What you have just explained to me was covered in that congress and it was very interesting.

Well, finally, who else is involved in this book besides you?

Engineer: We are working with experienced professionals, and we are diversifying to bring in different perspectives to make the content even richer. Dr. Víctor Manuel Martínez García supported us, Dr. Yennifer Díaz, Dr. Eloy Valdez Camacho provided guidance and helped shape the document, and Dr. Manuel Iván Tostado Ramírez facilitated much of the process. This is an important project that requires many people to come together to make it happen. Our goal is to create an accessible document where students can learn about concrete without needing to be experts. Often, the books we have consulted start with complex topics right from page one, and many students, not all, but many, get overwhelmed and abandon the book. So, we aim to make the information easy to digest but still very enriching for them, so that when they enter the workforce, they will remember there is a resource that can help them make decisions. It will be easy to understand, and if the answers are not in the book, there will be guidance on where to find complementary information.

Interviewer: So, this is not a very technical book?

Engineer: There are certain areas that do get technical because it is essential to cover topics like dosage methods and provide technical information. But it is not a scientific document filled with complex scientific terms that might overwhelm the reader. As I mentioned, that can be challenging for students. If a graduate student wants to research concrete and cement, there are specialized books on cement that they can consult, which will be more chemically focused. For example, in the world of cement, the leading researchers are not civil engineers but chemists. Yes, globally, cement researchers are chemists because cement is chemistry. That is what they say: “Cement is chemistry; everything about cement is pure chemistry.” As civil engineers, when we hear about chemistry, and the same goes for architects, it can be a bit daunting. When I was in graduate school, I told the professor, “Just give me the basics of chemistry. What do these two elements produce when combined? What is it used for?” In the technical field, that is what you need to know. You cannot be completely ignorant of the chemistry involved, but you have to understand it. If you want to pursue a graduate-level career, there will be documents you will need to consult, but for this book, we aim to provide information that is nutritious for students in the concrete field, helping them make decisions and giving them a global understanding of what concrete is. Many people think concrete is just water, cement, sand, and gravel mixed together, but there is a whole world behind it.

Interviewer: Thank you very much.

Engineer: You're welcome.

Afterword

The intention of this book is to provide easily accessible information so that students can learn about concrete without needing to be experts. Often, books introduce dense topics right from the first page, and students nowadays can quickly become overwhelmed and set aside the material. This is the primary reason why we aim to make the information easy to digest, but still very enriching, so that in the future, they will know where to turn in the professional field.

There are certain areas that do get technical because it is essential to cover topics like dosage methods. However, it is not a scientific document filled with complex terminology that might make the reader feel overwhelmed.

Cement is chemistry; everything that happens with cement is pure and simple chemistry, so one cannot be ignorant of this fact. This book provides enriching information for students in the concrete field, helping them make decisions and giving them a global understanding of what concrete is.

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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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