Chapter 1

Introduction to Concrete

1.1 CONCRETE DEFINITION AND HISTORICAL DEVELOPMENT

Concrete is a man-made construction material resembling natural stone, its name originating from the Latin word "concretus," meaning "to grow together." It comprises coarse granular components, known as aggregate or filler, enmeshed within a solid matrix, typically cement or binder, which fills the gaps between the aggregate particles, creating cohesion. In essence, concrete can be defined as a composite substance primarily constituted of a binding agent wherein aggregate particles or fragments are incorporated. The simplest definition of concrete can be written as:

$$\text{Concrete} = \text{Filler} + \text{Binder}$$

Different types of concrete are classified based on the binder used in their composition. For example, concrete made with nonhydraulic cement is referred to as nonhydraulic cement concrete, while that made with hydraulic cement is called hydraulic cement concrete. When asphalt is used as the binder, it is termed asphalt concrete, and when polymer serves as the binder, it becomes polymer concrete. Both nonhydraulic and hydraulic cement require water for mixing and reaction, but they vary in their ability to gain strength in water, with nonhydraulic cement lacking this capacity.

Nonhydraulic cement concretes have a rich historical background, dating back to approximately 6500 BC when they were utilized by the Syrians. This technology spread across regions such as Egypt, the Middle East, Crete, Cyprus, and ancient Greece, with the Romans notably refining its use. The primary ingredients of early nonhydraulic cement concrete included gravel, coarse sand, hot lime, and water, with occasional additions like animal blood. The Romans extensively employed concrete in road construction, erecting an impressive 5300 miles of roads using this material. They also experimented with various admixtures such as pozzolana, animal fat, milk, blood, and horsehair to improve concrete properties and reduce shrinkage. Additionally, historical evidence suggests that Assyrians and Babylonians utilized clay as a bonding material, while lime was obtained by calcining limestone through a specific chemical reaction:

$$CaCO_3 \xrightarrow{1000°C} CaO + CO_2$$

When CaO is mixed with water, it can react with water to form:

$$CaO + H_2O \xrightarrow{\text{ambient temperature}} Ca(OH)_2$$

and is then further reacted with CO_2 to form limestone again:

$$Ca(OH)_2 + CO_2 + H_2O \xrightarrow{\text{ambient temperature}} CaCO_3 + 2H_2O$$

The Egyptians used gypsum mortar in construction, and the half-water gypsum was obtained by calcining two-water gypsum with a reaction of:

$$2CaSO_4 \cdot 2H_2O \xrightarrow{107-130°C} 2CaSO_4 \cdot \tfrac{1}{2}H_2O + 3H_2O$$

When mixed with water, half-water gypsum could turn into two-water gypsum and gain strength:

$$2CaSO_4 \cdot \tfrac{1}{2}H_2O + 3H_2O \xrightarrow{\text{ambient temperature}} 2CaSO_4 \cdot H_2O$$

The Egyptians opted for gypsum over lime due to its ability to be calcined at lower temperatures. Around 3000 BC, gypsum mortar was utilized in constructing the Pyramid of Cheops, although the pyramid was plundered long before archaeologists could study its building materials. Figure 1.1 shows a pyramid in Giza. Chinese engineers in the Qin dynasty (220 BC) employed lime mortar in constructing the Great Wall, as depicted in Fig. 1.2.

Fig. 1.1: Pyramid built with gypsum mortar, Giza, Egypt

Hydraulic lime, a development by the Greeks and Romans, was derived from limestone containing clayey impurities. The Greeks utilized volcanic ash from Santorini, while the Romans sourced volcanic ash from the Bay of Naples to create hydraulic lime by mixing it with lime. This hydraulic lime mortar proved resistant to water, hence its widespread use in hydraulic structures from the first century BC to the second century AD. However, the quality of cementitious materials declined during the Middle Ages due to a loss of expertise in lime burning and a lack of siliceous impurities, leading to a scarcity of high-quality mortars.

Fig. 1.2: The Great Wall built in the Qin dynasty

In 1756, John Smeaton undertook the reconstruction of the Eddystone Lighthouse off the coast of Cornwall, England. Recognizing the importance of siliceous impurities in water resistance, Smeaton conducted extensive experiments with various limes and pozzolans. He discovered that limestone with a high clay content produced superior hydraulic lime for mortar. Smeaton ultimately used a mortar composed of hydraulic lime mixed with imported pozzolan from Italy. This mixture, combined with coarse aggregate and powdered brick, closely resembled the proportions of modern concrete. The reconstructed Eddystone Lighthouse stood for 126 years until it was replaced with a modern structure.

Following Smeaton's pioneering work, the development of hydraulic cement progressed rapidly. In 1796, James Parker of England patented a natural hydraulic cement produced by calcining nodules of impure limestone containing clay. Meanwhile, Vicat of France developed artificial hydraulic lime by calcining synthetic blends of limestone and clay. Joseph Aspdin of England patented Portland cement in 1824, naming it after the limestone quarried in Portland, southern England, due to its similar color post-hydration. However, Aspdin's claimed temperature in his invention wasn't sufficient to create true Portland cement. It was Isaac Johnson who achieved this milestone in 1845 by burning the raw materials to the necessary clinkering temperature. Consequently, the use of Portland cement spread rapidly throughout Europe and North America, primarily in concrete production.

Germany conducted the first systematic testing of concrete in 1836, measuring its tensile and compressive strength. Aggregates, including sand, crushed stone, clay, gravel, slag, and shale, are integral components of concrete. The term "first generation of concrete" typically refers to plain concrete comprising Portland cement and aggregates. The advent of reinforced concrete marked the second generation, pioneered by François Coignet in France. Coignet began experimenting with iron-reinforced concrete in 1852 and, in 1853, constructed the world's first iron-reinforced concrete structure: a four-story house in St. Denis, near his family's cement plant. This house, designed by local architect Theodore Lachez, served as a promotional endeavor for Coignet's cement business.

At the 1855 Paris Exposition, Coignet showcased his reinforced concrete technique, confidently predicting its eventual displacement of stone as a primary construction material. He proceeded to patent a method employing iron tirants for reinforced concrete in 1856, followed by the publication of his techniques in 1861.

Further advancements in reinforced concrete were made by Hennebique towards the end of the 19th century. It was recognized that performance could be enhanced by placing bars under tension, thereby keeping the concrete under compression. While early attempts at tension reinforcement showed promise by reducing cracking, these cracks tended to reopen after a few months, as documented in Leonhardt (1964). The first reinforced concrete bridge was erected in 1889 in San Francisco's Golden Gate Park.

To address cracking issues in reinforced concrete, prestressed concrete emerged, with engineer P.H. Jackson patenting the concept as early as 1886 in San Francisco. Prestressing involves applying stress to a structural member before it bears the service load. Prestressed concrete was hailed as the third generation of concrete. This stress is typically induced by stretching reinforcing steel within the member. Prestressing methods are categorized as pretensioning or post-tensioning based on the sequence of concrete casting. Pretensioning involves stretching the reinforcing steel before concrete casting, with prestress achieved through the bond between the stretched steel and hardened concrete. In contrast, post-tensioning involves stretching the steel after casting and attaining sufficient strength. In post-tensioning, steel tendons are inserted into preformed holes in the concrete specimen, and prestress is applied through end anchorage. Figure 1.3 illustrates the sequence of the pretensioning technique for prestressed concrete.

Following World War II, prestressed concrete gained widespread acceptance in Europe, partly driven by steel shortages. North America's inaugural prestressed concrete structure, the Walnut Lane Memorial Bridge in Philadelphia, Pennsylvania, was completed in 1951. Today, the advancement of prestressed concrete technology has facilitated the construction of long-span bridges, tall buildings, and marine structures. The Barrios de Lura Bridge in Spain currently holds the record as the world's longest-span prestressed concrete cable-stayed bridge, boasting a main span of 440 meters. Additionally, the Shibanpo Yangtze Bridge stands as the world's longest prestressed concrete girder bridge, featuring a main span of 330 meters. Notably, in Canada, the prestressed Toronto CN Tower stands at a towering height of 553 meters.

In concrete design, the compressive strength at 28 days is a primary consideration. This choice is based on several factors, including concrete's principal function of bearing compression loads and the relatively straightforward measurement of compressive strength. Moreover, it is believed that other concrete properties correlate with its

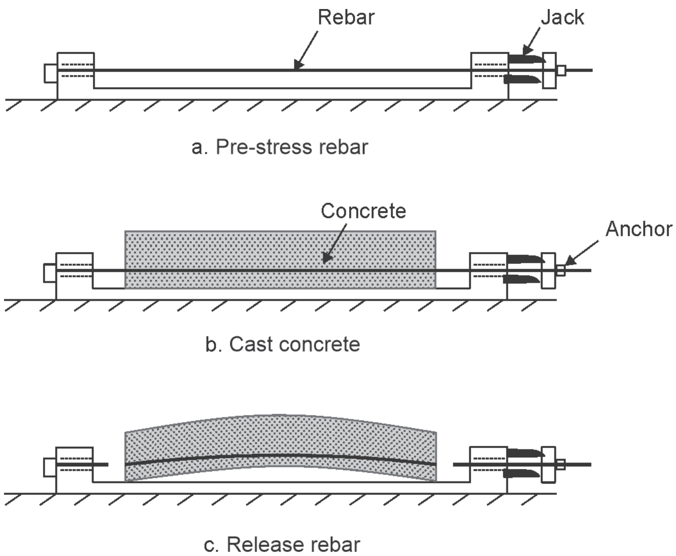

Fig. 1.3: Pretensioning sequence for prestressed concrete

compressive strength. Efforts to enhance compressive strength date back to 1918 when Duff Adams discovered its inverse relationship with the water-to-cement (w/c) ratio. Despite this, progress in achieving high compressive strength was slow until the 1960s, with concrete exceeding 30MPa considered high-strength.

Since the 1960s, advancements in high-strength concrete have accelerated, driven primarily by the invention of water-reducing admixtures and the incorporation of mineral additives like silica fume, fly ash, and slag. Water-reducing admixtures enhance workability under low w/c ratios, while mineral additives densify the concrete's microstructure, improving its properties. Notable milestones include the production of 52MPa concrete for the 52-story Mid-Continental Plaza in Chicago in 1972 and 62MPa concrete for Water Tower Place, a 74-story building, also in Chicago. By the 1980s, the industry achieved a remarkable 95MPa concrete for the 225 West Wacker Drive building project. The pinnacle was reached with Union Plaza in Seattle, Washington, boasting a compressive strength of 130MPa in its construction.

Since the 1980s, contemporary concrete production has typically involved the inclusion of fly ash, slag, or silica fume, along with various chemical admixtures. Consequently, the hydration mechanism, hydration products, and microstructure characteristics of such concrete differ significantly from those produced without these additives. Additionally, their mechanical properties diverge from traditional concrete, leading to their classification as contemporary concretes.

Two notable innovations in contemporary concrete are self-compacting concrete (SCC) and ultra-high-performance concrete (UHPC). SCC, a type of high-performance concrete (HPC), emerged as a concept in the 1980s, aiming to meet specialized performance and uniformity requirements that conventional materials and practices couldn't consistently achieve. These requirements include improved placement and compaction without segregation, enhanced long-term mechanical properties, early-age strength, toughness, volume stability, and durability in harsh environments.

SCC, developed by Professor Okamura and his research group in Japan in the late 1980s, addresses challenges posed by heavily reinforced concrete structures, particularly in earthquake-prone regions like Japan. Conventional concrete struggled to flow effectively around densely packed rebars, resulting in poor-quality casts and compromised durability. To overcome this, Okamura's team engineered concrete with exceptionally high flowability, facilitated by the invention of high-range water reducers or plasticizers. Initially dubbed "high-performance concrete," the term was later refined to SCC for clarity, as HPC encompasses broader meanings. Durability stands as a primary focus of HPC, recognizing that many concrete structures fail to meet service requirements not due to inadequate strength but insufficient durability. Hence, there arose a critical need for high-performance concrete capable of extending concrete service life.

In the 1990s, a ground-breaking type of "concrete" boasting compressive strength exceeding 200MPa emerged in France. Initially, termed reactive powder concrete due to its significant silica fume content, it later became known as ultra-high-strength (performance) concrete (UHSC) owing to its exceptional compressive strength. Researchers Richard and Cheyrezy introduced this material in 1995. Ultra-high-strength concrete has achieved compressive strengths of up to 800MPa with thermal treatment. However, its inherent brittleness necessitates the incorporation of fibers. By integrating fine steel fibers, UHSC can attain flexural strength of up to 50MPa. The first practical application of UHSC was witnessed in Sherbrooke, Canada, where a footbridge was constructed in 1998.

1.2 CONCRETE AS A STRUCTURAL MATERIAL

In this book, the term concrete usually refers to Portland cement concrete, if not otherwise specified. For this kind of concrete, the compositions can be listed as follows:

Portland cement + Water (and admixtures) → Cement paste +
Fine aggregate → Mortar + Coarse aggregate → Concrete

It is worth noting that admixtures have become indispensable in modern concrete practices, being incorporated into nearly all concrete mixes. Admixtures, defined as materials added to concrete batches just before or during mixing, offer various benefits. Chemical admixtures, for instance, can alter the setting and hardening properties of cement paste by influencing hydration rates. Water-reducing admixtures enhance the workability of fresh concrete by lowering water surface tension. Air-entraining admixtures enhance concrete durability, while mineral admixtures like pozzolans can mitigate thermal cracking.

Concrete stands as the most prevalent construction material globally, owing to two primary factors. Firstly, its versatility allows for its application in a myriad of structures such as dams, pavements, building frames, and bridges, surpassing other construction materials. Secondly, concrete's usage surpasses that of any other material by a considerable margin, with global production exceeding that of steel by a factor of 10 in tonnage and over 30 in volume.

In concrete structures, two main structural materials are commonly employed: concrete and steel. A structural material not only supports its own weight but also bears the load from other components.

Steel undergoes precise manufacturing under controlled conditions in sophisticated facilities. The properties of each steel type are meticulously determined in laboratories and documented in manufacturer certificates. Consequently, for a steel structure, designers need only specify compliant steel, while constructors must ensure correct usage and proper connections between steel members.

Contrastingly, concrete production is less refined, resulting in variable quality. While cement quality is assured by manufacturers akin to steel, concrete quality lacks such assurance due to numerous factors like aggregates, mixing techniques, and the expertise of personnel involved in production, placement, and consolidation.

Attaining concrete of specified quality from a ready-mix supplier is feasible, but even in this scenario, only the raw materials are procured for a construction project. The quality of a cast concrete structure is significantly influenced by transportation, placement, and especially compaction. Unlike steel, where choices are relatively limited, the array of concrete mixes is virtually endless, demanding a thorough understanding of concrete properties and behavior for proper selection. Consequently, the designer and specifier's expertise determines potential concrete qualities, while the supplier and contractor's proficiency ensures actual quality in the finished structure. This underscores the importance of their familiarity with concrete properties, production, and placement.

Within a concrete structural element, concrete primarily bears compressive and shear stresses, while steel handles tension stresses. Additionally, concrete typically contributes stiffness to structures, aiding in their stability.

1.3 CHARACTERISTICS OF CONCRETE

1.3.1 Advantages of Concrete

(a) **Cost-effectiveness:** Concrete stands as the most economical and abundantly available material worldwide. Its production costs are comparatively low when contrasted with other engineered construction materials. Water, aggregate, and cement, the three primary components of concrete, are readily accessible and inexpensive globally. This allows for concrete to be manufactured at minimal expenses for local markets across the globe, mitigating transport costs and associated carbon emissions associated with alternative materials.

(b) **Ambient temperature strength development:** Cement, as a low-temperature bonded inorganic material, undergoes its reaction at room temperature, enabling concrete to achieve strength without necessitating high-temperature curing procedures.

(c) **Ability to be cast:** Fresh concrete possesses fluid-like properties, facilitating its pouring into various moulds to create diverse shapes and sizes directly on-site or within precast facilities.

(d) **Energy efficiency:** Concrete production consumes less energy compared to steel. The energy requirement for plain concrete production ranges from 450 to 750 kWh/ton, while reinforced concrete production consumes 800 to 3200 kWh/ton. In contrast, structural steel demands 8000 kWh/ton or more for manufacturing.

(e) **Superior water resistance:** Unlike wood and steel, concrete can cure underwater and withstand water action without significant deterioration. This feature makes it an ideal material for water-related structures like pipelines and dams. For instance, the Central Arizona Project utilizes concrete pipelines for water transportation. Contrary to common belief, water itself is not detrimental to concrete; rather, chemicals dissolved in water, such as chlorides, sulfates, and carbon dioxide, lead to concrete deterioration.

(f) **High-temperature resilience:** Concrete has a slow heat conduction rate and can retain substantial heat from its surroundings. Moreover, the primary hydrate responsible for binding aggregates in concrete, calcium silicate hydrate (C–S–H), remains partially hydrated until temperatures reach 910°C. Consequently, concrete exhibits superior resistance to high temperatures compared to wood and steel, withstanding fire for 2 to 6 hours, allowing ample time for rescue operations. Hence, concrete is frequently used to provide protective layers for steel structures.

(g) **Waste utilization capability:** With industrial development, the generation of by-products and waste has escalated, posing environmental challenges. To address this issue, many industrial wastes can be repurposed as substitutes for cement or aggregate in concrete production, such as fly ash, slag (GGBFS), waste glass, and ground vehicle tires. Incorporating industrial waste in concrete production not only aids environmental preservation but also enhances concrete structure performance. Given the significant global concrete production, there exists potential to utilize a substantial portion of industrial waste worldwide, provided suitable techniques for waste integration are available.

(h) **Compatibility with reinforcing steel:** Concrete exhibits a coefficient of thermal expansion similar to steel, providing excellent protection to steel due to the presence of calcium hydroxide (CH) and other alkalis under normal conditions. Concrete serves as a physical barrier against aggressive agents while offering chemical protection in a highly alkaline environment (pH approximately 13.5), effectively passivating black steel.

(i) **Reduced maintenance requirements:** Under typical conditions, concrete structures do not necessitate coating or painting for weatherproofing, unlike steel or wooden structures, which require protective layers. Furthermore, coatings and paints on steel or wooden structures need periodic replacement, resulting in higher maintenance costs compared to concrete structures.

1.3.2 Limitations

(a) **Quasi-brittle failure mode:** Material failure modes are typically categorized as brittle, quasi-brittle, or ductile, as shown in Fig. 1.4 . Brittle materials, exemplified by glass, fracture abruptly upon reaching their tensile strength. Quasi-brittle

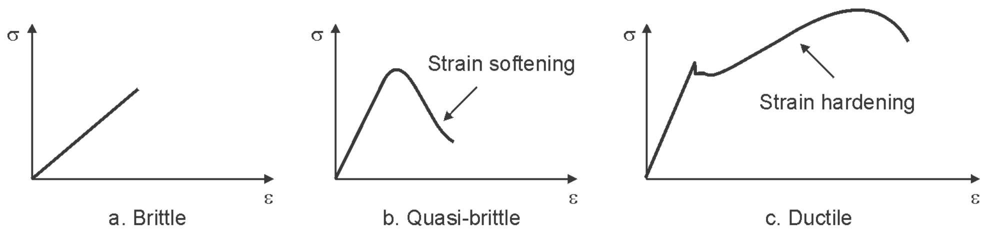

Fig. 1.4: Three failure modes of materials

materials exhibit strain-softening behavior, characterized by a lack of significant deformation before failure. Concrete falls into the category of quasi-brittle materials due to its low fracture toughness. To enhance its structural performance, concrete is often reinforced with steel bars, forming reinforced concrete, which offers improved stability.

(b) **Low tensile strength:** Concrete demonstrates significant discrepancy between its compression and tension strengths, with its tensile strength typically only about one-tenth of its compressive strength for normal-strength concrete. This ratio is even lower for high-strength concrete. To address this limitation, techniques such as fiber-reinforced concrete and polymer concrete have been developed to augment concrete's tensile strength.

(c) **Low toughness (ductility):** Toughness, denoting a material's capacity to absorb energy, is evaluated by the area under a load-displacement curve. Concrete exhibits notably low toughness compared to steel, typically ranging from 1/50 to 1/100 of steel's toughness, as shown in Fig. 1.5. Incorporating fibers into concrete is an effective method to enhance its toughness.

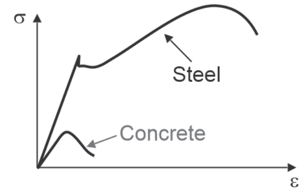

Fig. 1.5: Stress-strain curves of steel and concrete

(d) **Low specific strength (strength/density ratio):** Concrete generally has a specific strength lower than 20, whereas steel boasts a value of about 40. Increasing concrete's specific strength can be achieved by either reducing its density or enhancing its strength. Consequently, lightweight concrete and high-strength concrete have been developed to address this issue.

(e) **Requirement for formwork:** Fresh concrete, in its liquid state, necessitates formwork to maintain its shape and support its weight until it sets. Formwork construction, typically using steel or wood, is labor-intensive and time-consuming, contributing to its costliness, as shown in Fig. 1.6. To streamline this process, methods such as precast concrete, extrusion, and 3D printing have been introduced to enhance efficiency.

(f) **Lengthy curing time:** Concrete's strength development is typically assessed based on its 28-day compression strength, requiring a month for full strength development at ambient temperature. Measures such as steam curing or microwave curing have been introduced to expedite the curing period.

(g) **Management of cracks:** Despite reinforcement, concrete structures often develop cracks, particularly on the tension side due to concrete's low tensile strength. To address this issue, prestressed concrete has been developed, representing a third-generation concrete solution. Many reinforced concrete structures exhibit existing cracks on their tension sides while under service load.

1.4 TYPES OF CONCRETE

1.4.1 Classification in Accordance with Unit Weight

According to the unit weight of concrete, it can be categorized into four types, as outlined in Table 1.1. Ultra-lightweight concrete is suitable only for non-structural

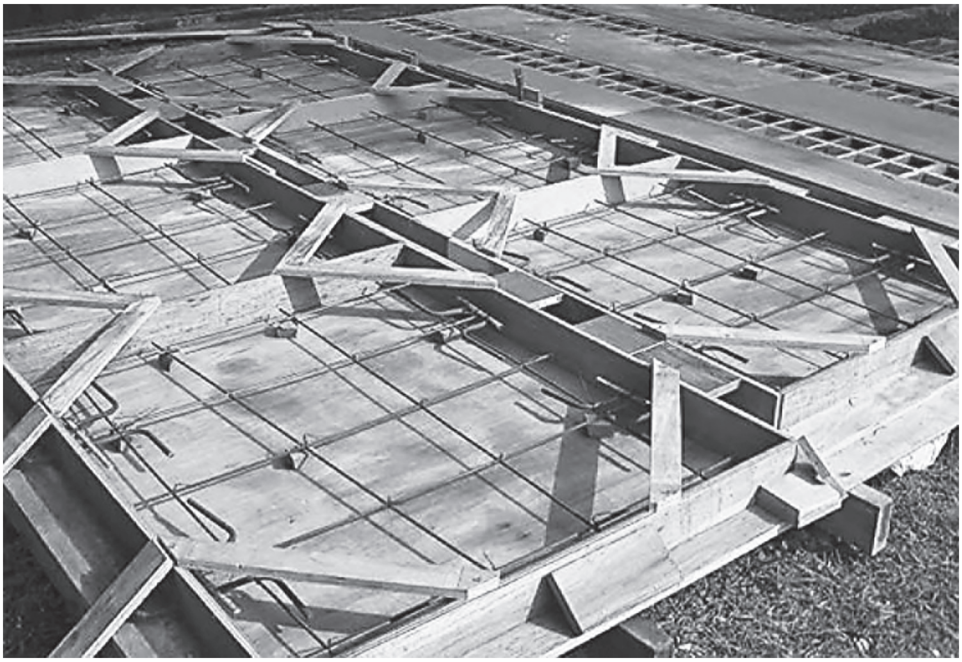

Fig. 1.6: Formwork for concrete casting

components. Lightweight concrete can be employed for both structural and non-structural elements, contingent upon its specified composition. Normal weight concrete is widely used in infrastructure and building construction. Heavyweight concrete finds application in specialized structures such as laboratories, hospital examination rooms, and nuclear plants, where protection against radiation is imperative for public health.

Table 1.1: Classification of concrete in accordance with unit weight

Classification	*Unit weight (kg/m^3)*
Ultra-lightweight concrete	<1200
Lightweight concrete	1200 < UW < 1800
Normal weight concrete	≈ 2400
Heavyweight concrete	>3200

The primary factor influencing the unit weight of concrete is the aggregate used. The distinctions in unit weight correspond to different types of aggregates utilized: ultra-lightweight aggregates for ultra-lightweight concrete, lightweight aggregates for lightweight concrete, normal weight aggregates for normal weight concrete, and heavyweight aggregates for heavyweight concrete.

1.4.2 Classification in Accordance with Compressive Strength

In accordance with its compressive strength, concrete can be categorized into four classes, as outlined in Table 1.2. Low-strength concrete finds application in mass concrete structures, road subgrades, and partitions. Moderate-strength concrete stands as the most commonly utilized type in building construction, bridges, and similar infrastructure. High-strength concrete is suitable for constructing tall building columns, bridge towers, and shear walls. Ultra-high-strength concrete, although not extensively employed in structural projects, has been utilized in select footbridges and specific structural elements such as girders.

Table 1.2: Concrete classified in accordance to compressive strength

Classification	*Compressive strength (MPa)*
Low-strength concrete	< 20
Moderate-strength concrete	20~50
High-strength concrete	50~150
Ultra-high-strength concrete	> 150

1.4.3 Classification in Accordance with Additives

Concrete can be categorized into various types based on additives other than cement, aggregate, and water. Table 1.3 presents four examples of such classifications. Fiber-reinforced concrete (FRC) incorporates various fibers like steel, glass, polymers, and carbon to enhance toughness, tensile properties, shrinkage control, and decorative aspects. Macro-defect-free (MDF) is a cement-based composite enriched with a water-soluble polymer, manufactured via a twin-roll mixing process to boost tensile and flexural properties. DSP concrete, densified with small particles, integrates a significant amount of silica fume, offering excellent abrasion resistance, primarily used in manufacturing machine tools and industrial molds. Polymer incorporation into concrete is facilitated through three methods: utilizing the polymer as a binder, impregnating normal Portland cement concrete members with the polymer, or employing the polymer as an admixture in normal Portland concrete.

Table 1.3: Concrete classifications in accordance to additives

Classification	*Additives*
MDF	Polymers
Fiber reinforced concrete	Different fibers
DSP concrete	Large amount silica fume
Polymer concrete	Polymers

1.4.4 Classification in Accordance with Construction Methods

Within the realm of concrete construction methods, aside from traditional casting, there exist specialized approaches yielding concretes with distinct properties, necessitating tailored designs. Notable methods include 3D printable concrete, sprayable concrete (also known as shotcrete), and roller-compacting concrete.

3D concrete printing (3DCP) (Fig. 1.7) is a recent technological advancement, employing a layer-by-layer deposition technique guided by computer-aided design. This method offers several advantages over conventional casting, including reduced

Fig. 1.7: 3D printing technology

waste (due to formwork-free construction), decreased labor requirements, and heightened construction efficiency. Moreover, it enables the fabrication of structures with intricate geometries through customized designs and automated printing, thereby lowering construction costs. Successful formulation of 3D printable concrete demands a multi-level material design, addressing mixture composition, rheology, printing process intricacies, and composite structure requirements. Achieving optimal pumpability for delivery and buildability for deposition is crucial, emphasizing meticulous tailoring of fresh concrete's flow characteristics, with rheological properties being of paramount importance.

Spray concrete technology, also known as shotcrete, employs the pneumatic projection of sprayable concrete through a hose onto a substrate at high velocity to construct desired structures. This method is commonly utilized for vertical and overhead surfaces, where conventional casting is impractical, as well as for reinforcing caves or tunnels and repairing defective structures. Compared to castable concrete, sprayable concrete exhibits enhanced cohesion to resist pressure-induced bleeding during pumping and improved adhesion to ensure strong bonding with the substrate. Furthermore, it must demonstrate good pumpability for efficient material delivery.

Roller-compacting concrete represents another conventional method primarily employed in road pavement construction. This approach offers superior resistance to abrasion compared to castable concrete. Fresh roller-compacting concrete exhibits high stiffness and low flowability, necessitating compaction by road rollers to ensure uniform distribution and leveling to the desired height.

1.4.5 Classification in Accordance with Non-structural Functionality

Concrete, primarily known for its structural capabilities, is traditionally engineered to optimize mechanical properties like compressive and flexural strength, and elastic modulus. However, with advancements in concrete technology, there has been a shift towards developing new types of concrete, such as high-strength and ultra-high-strength varieties. Moreover, the emergence of multi-functional concretes highlights the importance of non-structural functionalities in certain scenarios.

(a) **Decoration function:** Transforming plain concrete structures into visually appealing decorative elements has gained significance due to their ubiquitous presence in daily environments. Specialized concretes designed for decorative purposes include architectural, colored, polished, stained, and stamped variants.

(b) **Abrasion-resistant function:** Resistance to abrasion is critical in various applications like dams, water channels, floors, and pavements. Specific binder selections (e.g. high calcium aluminate ferrite phase), stronger aggregates, and meticulous mix proportioning ensure enhanced abrasion resistance.

(c) **Shielding function:** Ensuring protection from microwaves, radiation, acoustic noises, and heat is crucial for maintaining a safe living environment. Concrete structures endowed with shielding capabilities are engineered through unique designs involving density, pore structures, and compositions.

The advent of nanotechnology has facilitated innovative approaches in realizing multi-functionalities in concrete structures. Leveraging nanomaterials like nanoTiO_2, nanoSiO_2, nano$CaCO_3$, nanoclay, carbon nanotubes, and graphene has led to the development of novel functionalities such as photocatalysis, self-cleaning properties, rheology modification, and improved heat conduction. These innovations aim to enhance specific features and overall performance of traditional concrete.

1.5 FACTORS INFLUENCING CONCRETE PROPERTIES

1.5.1 w/c Ratio (or w/b or w/p Ratio)

In determining the properties of concrete, a critical factor is the water/cement (w/c) ratio. In modern concrete practices, this ratio is often substituted with the water/binder (w/b) or water/powder (w/p) ratio, acknowledging that Portland cement isn't the sole binding material. The w/c or w/b ratio significantly impacts concrete properties such as compressive strength, permeability, and diffusivity. Generally, a lower w/c ratio results in stronger and more durable concrete. This relationship between w/c and concrete compressive strength has been recognized since the early 1900s, leading to Abrams's law.

1.5.2 Cement Content

When water is introduced to a concrete mix, it combines with cement to form cement paste, which serves three primary functions: binding, coating, and lubricating. Cement paste binds individual aggregates, reinforcing bars, and fibers together, creating a cohesive material. Additionally, it coats the surfaces of aggregates and fibers during the fresh stage of concrete, while the remaining paste acts as a lubricant, facilitating the movement of aggregates or fibers. Cement content plays a pivotal role in concrete workability during the fresh stage, heat release rate during rapid hydration, and volume stability in the hardened stage. Typically, cement content ranges from 160 to 200 kg/m^3 in mass concrete, less than 400 kg/m^3 in normal strength concrete, and between 400 and 600 kg/m^3 in high-strength concrete.

1.5.3 Aggregate

(a) **Maximum aggregate size:** The largest coarse aggregate size significantly affects the cement paste requirement in concrete. With larger aggregate sizes, there is less total surface area requiring cement paste coating. Consequently, concrete with larger maximum aggregate sizes, when using the same amount of cement, retains more cement paste as a lubricant, enhancing fluidity compared to concrete with smaller maximum aggregate sizes. For normal-strength concrete, at equivalent water/cement ratios and cement content, larger maximum sizes improve workability; conversely, at consistent workability, larger maximum sizes yield higher strength. However, larger aggregate sizes may introduce non-homogeneity and affect concrete transport and mechanical properties. Generally, the maximum aggregate size should be the largest economically viable size compatible with structural dimensions, ensuring it doesn't exceed specified proportions relative to form dimensions, slab depth, or reinforcing bar spacing.

(b) **Aggregate grading:** Aggregate grading, defining the size distribution of aggregates, primarily impacts particle packing. Optimal grading reduces voids in concrete, hence decreasing cement content. Given aggregate costs are typically one-tenth that of cement, well-defined grading not only enhances compressive strength and reduces permeability but also proves more cost-effective.

(c) **Aggregate shape and texture:** Shape and texture influence concrete workability, bonding, and compressive strength. Angular, rough-surfaced aggregates enhance bond and mechanical properties but reduce workability, while spherical, smooth-surfaced aggregates offer higher workability at the expense of bond strength and mechanical properties.

(d) **Sand/Coarse aggregate ratio:** The ratio impacts concrete packing and fresh-stage workability. Increasing sand to coarse aggregate ratio enhances cohesiveness but diminishes consistency, being a proven measure for improving concrete cohesiveness.

(e) **Aggregate/Cement ratio:** This ratio affects concrete cost, workability, mechanical properties, and volume stability. Increasing the ratio decreases concrete cost but lowers consistency due to reduced cement paste lubrication. While higher ratios yield greater stiffness and compressive strength with proper compaction, they also enhance dimensional stability by reducing shrinkage and creep.

1.5.4 Admixtures

Chemical and mineral admixtures play crucial roles in modern concrete technology, offering essential means to modify or enhance concrete properties, both when fresh and hardened. For instance, air-entraining agents, water reducers, and fly ash can influence concrete workability, while silica fume is known to enhance concrete strength.

1.5.5 Mixing Procedures

Mixing procedures encompass the arrangement of adding raw materials into a mixer and the duration required for each step. These procedures have a direct impact on the workability of fresh concrete and indirectly affect certain mature concrete properties.

Currently, ready-mixed concrete (RMC) is gaining popularity and can be produced through three methods:

(a) **Central mixing:** Concrete is thoroughly mixed in a stationary mixer before being discharged into transporting equipment such as a truck agitator, a truck mixer operating at agitation speed, or a no-agitating truck.

(b) **Shrink mixing:** Concrete undergoes partial mixing in a stationary mixer and completes mixing in a concrete truck mixer during transportation to the work site.

(c) **Truck mixing:** Concrete is entirely mixed in a concrete truck mixer. Mixing constituents are batched at a plant, loaded into the transporting truck, and mixed as the truck travels to the work site.

The duration of mixing depends on mixer power, slump requirements, and properties of raw materials, typically ranging from 30 seconds to several minutes.

A specialized mixing procedure can achieve excellent workability with proper coating on coarse aggregates to prevent alkali-aggregate reaction:

- **Step 1:** Coarse aggregate + 50% water + 50% cement: Mix for 30 seconds to 1 minute.
- **Step 2:** Add 50% cement + 25% water + superplasticizer + fine aggregate: Mix for 2 minutes.
- **Step 3:** Add 25% water: Mix for 3 minutes.

1.5.6 Curing

Curing refers to the practices implemented immediately after the casting of fresh concrete. The primary objective of curing is to maintain favorable moisture levels within an appropriate temperature range during the rapid hydration process of concrete. This stage is pivotal for the development of concrete strength and for regulating early volume changes. Proper care during curing is essential, akin to nurturing a newborn. Diligent curing ensures that concrete undergoes proper hydration, resulting in a sound microstructure, adequate strength, and dimensional stability. Conversely, negligent curing often leads to inadequate hydration, resulting in microstructural defects, insufficient strength, and unstable dimensions. One common consequence of improper curing is plastic shrinkage, which can cause early-age cracking, providing pathways for harmful agents to penetrate the concrete and compromise its durability. Despite its simplicity, curing is frequently overlooked on construction sites.

Various methods can aid in curing:

(a) Moistening the subgrade and forms.

(b) Sprinkling water on aggregates.

(c) Installing windbreaks and sunshades.

(d) Cooling aggregates and mixing water.
(e) Employing fog spray.
(f) Using covers.
(g) Implementing high-temperature (70–80°C) steam curing.
(h) Utilizing shrinkage-compensating admixtures.

Recently, a novel technique known as internal curing has emerged, leveraging saturated porous aggregates to create a reservoir within concrete, supplying water internally for curing purposes.