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Dr. Mert Yücel YARDIMCI
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Chapter 1

INTRODUCTION TO CONCRETE
Concrete

The most widely used material in the world.

Used in infrastructure and buildings...
Historical Development

- Concrete is a manmade building material that looks like stone.

- The word “concrete” is derived from the Latin *concretus*, meaning “to grow together.”

Concrete is a composite material

- Cement paste
- Aggregates
- Aggregate - cement transition zone
Transition zone?
Depending on what kind of binder is used, concrete can be named in different ways.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Concrete Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-hydraulic binder</td>
<td>Non-hydraulic cement concrete</td>
</tr>
<tr>
<td>Hydraulic cement</td>
<td>Hydraulic cement concrete</td>
</tr>
<tr>
<td>Asphalt</td>
<td>Asphalt concrete</td>
</tr>
<tr>
<td>Polymer</td>
<td>Polymer concrete</td>
</tr>
</tbody>
</table>

Both nonhydraulic and hydraulic cement need water to mix in and react. **They differ here in the ability to gain strength in water.** Nonhydraulic cement cannot gain strength in water, while hydraulic cement does.
Historical Development

Non-hydraulic cement concretes are the oldest used in human history.

6500 BC, nonhydraulic cement concretes were used by the Syrians, Egypt, Middle East, Crete, Cyprus, and ancient Greece.

The nonhydraulic cements used at that time were gypsum and lime (Romans).
Romans used pozzalana, animal fat, milk, and blood as admixtures for building concrete.

To reduce shrinkage, they were known to have used horsehair.

Assyrians and Babylonians used clay as the bonding material.
Lime was obtained by calcining limestone with a reaction of

\[
\text{CaCO}_3 \xrightarrow{1000^\circ C} \text{CaO} + \text{CO}_2
\]

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

\[
\text{CaO} + \text{H}_2\text{O} \xrightarrow{\text{ambient temperature}} \text{Ca(OH)}_2
\]

and is then further reacted with CO2 to form limestone again:

\[
\text{Ca(OH)}_2 + \text{CO}_2 + \text{H}_2\text{O} \xrightarrow{\text{ambient temperature}} \text{CaCO}_3 + 2\text{H}_2\text{O}
\]
Historical Development - Gypsum

The Egyptians used gypsum mortar in construction, and the gypsum was obtained by calcining impure gypsum with a reaction of

\[
2\text{CaSO}_4 \cdot \text{H}_2\text{O} \xrightarrow{107-130^\circ\text{C}} 2\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + 3\text{H}_2\text{O}
\]

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

\[
2\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + 3\text{H}_2\text{O} \xrightarrow{\text{ambient temperature}} 2\text{CaSO}_4 \cdot 2\text{H}_2\text{O}
\]

The Egyptians used gypsum instead of lime because it could be calcined at much lower temperatures.
Historical Development

Figure 1-1  Pyramid built with gypsum mortar in Gaza, Egypt

Figure 1-2  The Great Wall, built in the Qin dynasty

Lime mortar
Historical Development

- A hydraulic lime was developed by the Greeks and Romans using limestone containing argillaceous (clayey) impurities.

- The Greeks even used volcanic ash from the island of Santorin, while the Romans utilized volcanic ash from the Bay of Naples to mix with lime to produce hydraulic lime.

- It was found that mortar made of such hydraulic lime could resist water.

- Thus, hydraulic lime mortars were used extensively for hydraulic structures from second half of the first century BC to the second century AD. However, the quality of cementing materials declined throughout the Middle Ages. The art of burning lime was almost lost and siliceous impurities were not added. High-quality mortars disappeared for a long period.
Historical Development
-The birth of modern cement-

In 1756, John Smeaton was commissioned to rebuild the Eddystone Light house off the coast of Cornwall, England.

Smeaton conducted extensive experiments with different limes and pozzolans, and found that limestone with a high proportion of clayey materials produced the best hydraulic lime for mortar to be used in water.

Eventually, Smeaton used a mortar prepared from a hydraulic lime mixed with pozzolan imported from Italy.

He made concrete by mixing coarse aggregate (pebbles) and powdered brick and mixed it with cement, very close to the proportions of modern concrete.

The rebuilt Eddystone Lighthouse lasted for 126 years until it was replaced with a modern structure.
The term ‘Portland cement’ was first applied by Joseph Aspdin in his British Patent No. 5022 (1824), which describes a process for making artificial stone by mixing lime with clay in the form of a slurry and calcining (heating to drive off carbon dioxide and water) the dried lumps of material in a shaft kiln.

The calcined material (clinker) was ground to produce cement. The term ‘Portland’ was used because of the similarity of the hardened product to that of Portland stone from Dorset and also because this stone had an excellent reputation for performance.

Joseph Aspdin was not the first to produce a calcium silicate cement but his patent gave him the priority for the use of the term ‘Portland cement’
Historical Development

*The birth of modern cement*

- **2000-**
  - Multistage combustion – emission control
  - New horizontal cement mill technology
  - High-pressure roll press for cement pregrinding
  - Automatic kiln control using expert systems

- **1980**
  - High-efficiency separator introduced for cement grinding
  - Precalcer process developed

- **1960**
  - X-ray fluorescence (XRF) rapid chemical analysis
  - Suspension preheater process introduced

- **1940**
  - Lepol (module) process introduced
  - Introduction of pneumatic blending silos for raw meal

- **1920**
  - First electrostatic precipitator installed in cement works

- **1900**
  - Paper sacks introduced for cement

- **1880**
  - British (BS 12) and ASTM (C9) standards published
  - Rotary kilns introduced
  - Tube grinding mills for cement

- **1860**
  - Method for carbonate of lime developed
  - J. Grant introduced tensile strength test for cement

- **1840**
  - W. Aspdin bottle kiln plant at Northfleet

- **1820**
  - Patent for Portland Cement granted to J. Aspdin

Landmarks in Portland cement production.
The cements produced in the first half of the nineteenth century did not have the same compound composition as modern Portland cements as the temperature achieved was not high enough for the main constituent mineral of modern cements, tricalcium silicate (C₃S), to be formed. The only silicate present was the less reactive dicalcium silicate (C₂S).

It was the introduction of the rotary kiln at the end of the nineteenth century that enabled a homogeneous product to be manufactured, which had experienced a consistently high enough temperature to ensure C₃S formation.
Isaac Johnson who first burned the raw materials to the clinkering temperature in 1845 to produce modern Portland cement.

After that, the application of Portland cement spread quickly throughout Europe and North America.
### World Production and Capacity:

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>United States (includes Puerto Rico)</td>
<td>77,400</td>
<td>83,300</td>
<td>104,300</td>
<td>104,300</td>
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<tr>
<td>Brazil</td>
<td>70,000</td>
<td>72,000</td>
<td>60,000</td>
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<tr>
<td>China</td>
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<td>1,900,000</td>
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<tr>
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<td>31,300</td>
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<tr>
<td>India</td>
<td>280,000</td>
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<tr>
<td>Indonesia</td>
<td>56,000</td>
<td>60,000</td>
<td>51,000</td>
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<tr>
<td>Iran</td>
<td>72,000</td>
<td>75,000</td>
<td>80,000</td>
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<tr>
<td>Italy</td>
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<td>22,000</td>
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<td>46,000</td>
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<tr>
<td>Japan</td>
<td>57,400</td>
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<td>Korea, Republic of</td>
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<td>47,700</td>
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<td>Mexico</td>
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<td>35,000</td>
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<tr>
<td>Pakistan</td>
<td>31,000</td>
<td>32,000</td>
<td>43,400</td>
<td>44,000</td>
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<tr>
<td>Russia</td>
<td>66,400</td>
<td>69,000</td>
<td>80,000</td>
<td>80,000</td>
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<tr>
<td>Saudi Arabia</td>
<td>57,000</td>
<td>63,000</td>
<td>55,000</td>
<td>55,000</td>
</tr>
<tr>
<td>Thailand</td>
<td>42,000</td>
<td>42,000</td>
<td>50,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Turkey</td>
<td>71,300</td>
<td>75,000</td>
<td>68,500</td>
<td>69,000</td>
</tr>
<tr>
<td>Vietnam</td>
<td>58,000</td>
<td>60,000</td>
<td>80,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Other countries (rounded)</td>
<td>536,000</td>
<td>525,000</td>
<td>348,000</td>
<td>349,000</td>
</tr>
<tr>
<td><strong>World total (rounded)</strong></td>
<td><strong>4,080,000</strong></td>
<td><strong>4,180,000</strong></td>
<td><strong>3,470,000</strong></td>
<td><strong>3,570,000</strong></td>
</tr>
</tbody>
</table>

(Millions tons)

Historical Development

The main application of Portland cement is to make concrete.

Plain concrete made of Portland cement and aggregate is usually called the first generation of concrete. The second generation of concrete refers to steel bar-reinforced concrete.

Francois Coignet was a pioneer in the development of reinforced concrete. Coignet started experimenting with iron-reinforced concrete in 1852 and was the first builder ever to use this technique as a building material.
As a structural material, the compressive strength at an age of 28 days is the main design index for concrete.

Reasons for choosing compressive strength as the representative index.

• Concrete is used in a structure mainly to resist the compression force.
• The measurement of compressive strength is relatively easier.
• It is thought that other properties of concrete can be related to its compressive strength through the microstructure.

As early as 1918, Duff Adams found that the compressive strength of a concrete was inversely proportional to the water-to-cement ratio. Hence, a high compressive strength could be achieved by reducing the \( w/c \) ratio.
Relationship between the Water/Cement Ratio and Strength

Compressive Strength

Water / Cement Ratio

Vibration
Hand compaction
Fully compacted concrete
Insufficiently compacted concrete
To keep a concrete workable, there is a minimum requirement on the amount of water; hence, the $w/c$ ratio reduction is limited, unless other measures are provided to improve concrete’s workability. For this reason, progress in achieving high compressive strength was very slow before the 1960s.

At that time, concrete with a compressive strength of 30 Mpa was regarded as high-strength concrete.

Two main reasons of further development in strength

• Invention of water-reducing admixtures
• The incorporation of mineral admixtures, such as silica fume, fly ash, and slag.
**Water-reducing admixture** is a chemical admixture that can help concrete keep good workability under a very low w/c ratio.

**Mineral admixtures** are mineral particles that can react with a hydration product in concrete, calcium hydroxide, to make concrete microstructure denser.
In 1972, the first 52-MPa concrete was produced in Chicago for the 52-story Mid-Continental Plaza.

<table>
<thead>
<tr>
<th>In 1972, a 62-MPa concrete was produced, also in Chicago, for Water Tower Place, a 74-story concrete building, the tallest in the world at that time.</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the 1980s, the industry was able to produce a 95-Mpa concrete to supply to the 225 West Whacker Drive building project in Chicago,</td>
</tr>
</tbody>
</table>
The highest compressive strength of 130 MPa was realized in a 220-m-high, 58-story building, the Union Plaza constructed in Seattle, Washington.

Concrete produced after the 1980s usually contains a sufficient amount of fly ash, slag, or silica fume as well as many different chemical admixtures, so its hydration mechanism, hydration products, and other microstructure characteristics are very different from the concrete produced without these admixtures.
Compressive strength of concrete started to increase by utilizing very fine mineral admixtures providing more compact microstructure in concrete.
Two innovative developments in contemporary concrete:

- **Self Compacting Concrete (SCC)**
- **Ultra-High-Performance Concrete (UHPC)**
Due to low flowability, conventional concrete could hardly flow past the heavy reinforced rebars, leaving poor-quality cast concrete and leading to poor durability.

Sometimes, the reinforcing steel was exposed to air immediately after demolding.

To solve the problem, Professor Okamura (Japan) and his students conducted research to develop a concrete with high flowability. With the help of the invention of the high-range water reducer or plasticizer, such a concrete was finally developed. They were so excited that they called this concrete “high-performance concrete” at the beginning. It was corrected later on to SCC, as HPC covers broader meanings.
Self-Compacting concrete (SCC) is a typical example of high-performance concrete that can fill in formwork in a compacted manner without the need of mechanical vibration.

SCC

Vibrating Concrete
In the 1990s, a new “concrete” with a compressive concrete strength higher than 200 MPa was developed in France.

Due to the large amount of silica fume incorporated in such a material, it was initially called reactive powder concrete and later on changed to ultra-high-strength (performance) concrete (UHSC), due to its extremely high compressive strength. The ultra-high-strength concrete has reached a compressive strength of 800 Mpa with heating treatment.

However, it is very brittle, hence, incorporating fibers into UHSC is necessary. After incorporating fine steel fibers, flexural strength of 50 MPa can be reached.
RPC Products

İSTON İstanbul Concrete Elements and Ready Mixed Concrete Facroties Corporation

Compressive strength (MPa)
Flexural strength (MPa)
Fracture energy (Joule/m²)
Compressive strength vs. water to cement ratio relationship on concrete's evolution

Thanks to the superplasticizers & usage of very fine mineral admixtures (silica fume)

Taşdemir, M.A. ve Bayramov, F., “Yüksek Performanslı Çimento Esaslı Kompozitlerin Mekanik Davranışı”, İTÜ dergisi/d mühendislik; Ekim, Cilt 1, Sayı 2, s. 125-144. 2002. (In Turkish)
General Characteristics of Concrete

Portland cement

+ water (& admixtures) → cement paste
+ fine aggregate → mortar
+ coarse aggregate → concrete
Advantages of Concrete

• Economical
• Hardens in ambient temperature (no need high temp.)
• Ability to be cast
• Energy efficient (Compared to structural steel)
• Resistance to water
• High-temperature resistant
• Ability to consume waste materials
• Ability to work with structural steel
• Less maintenance need
Economical

Concrete is the most inexpensive and the most readily available material in the world.
The cost of production of concrete is low compared with other engineered construction materials.
The three major components in concrete are water, aggregate, and cement. Compared with steels, plastics, and polymers, these components are the most inexpensive, and are available in every corner of the world. This enables concrete to be produced worldwide at very low cost for local markets, thus avoiding the transport expenses necessary for most other materials.
Because cement is a low-temperature bonded inorganic material and its reaction occurs at room temperature, concrete can gain its strength at ambient temperature. No high temperature is needed.
Ability to be cast

Fresh concrete is flowable like a liquid and hence can be poured into various formworks to form different desired shapes and sizes right on a construction site. Hence, concrete can be cast into many different configurations.
Energy efficient

Compared with steel, the energy consumption of concrete production is low. The energy required to produce plain concrete is only 450–750 kWh/ton and that of reinforced concrete is 800–3200 kWh/ton, while structural steel requires 8000 kWh/ton or more to make.
High-temperature resistance

Concrete conducts heat slowly and is able to store considerable quantities of heat from the environment. Moreover, the main hydrate that provides binding to aggregates in concrete, calcium silicate hydrate (C–S–H), will not be completely dehydrated until 910°C. Thus, concrete can withstand high temperatures (like fire) much better than wood and steel. Even in a fire, a concrete structure can withstand heat for 2–6 hours, leaving sufficient time for people to be rescued. That is why concrete is frequently used to build up protective layers for a steel structure.
Ability to consume waste materials

With the development of industry, more and more by-products or waste has been generated, causing a serious environmental pollution problem. To solve the problem, people have to find a way to consume such wastes.

It has been found that many industrial wastes can be recycled as a substitute (replacement) for cement or aggregate, such as fly ash, slag (GGBFS = ground granulated blast-furnaces slag), waste glass, and ground vehicle tires in concrete.

Production of concrete with the incorporation of industrial waste not only provides an effective way to protect our environment, but also leads to better performance of a concrete structure. Due to the large amount of concrete produced annually, it is possible to completely consume most of industry waste in the world, provided that suitable techniques for individual waste incorporation are available.
Ability to work with structural steel

Concrete has a similar value to steel for the coefficient of thermal expansion (steel $1.2 \times 10^{-5}$; concrete $1.0–1.5 \times 10^{-5}$).

Concrete produces a good protection to steel due to existence of CH and other alkalis (this is for normal conditions). Therefore, while steel bars provide the necessary tensile strength, concrete provides a perfect environment for the steel, acting as a physical barrier to the ingress of aggressive species and giving chemical protection in a highly alkaline environment (pH value is about 13.5).
Limitations of concrete

• Quasi-brittle failure mode
• Low tensile strength
• Low toughness (ductility)
• Low strength/density ratio
• Formwork is needed
• Long curing time
• Working with cracks
Concrete is a quasi-brittle material with low fracture toughness!

Brittle and quasi-brittle materials fail suddenly without giving a large deformation as a warning sign. Ductile failure type should be applied when you do a structural design!
Low tensile strength

Concrete has different values in compression and tension strength.

Its tension strength is only about $1/10$ of its compressive strength for normal-strength concrete, or lower for high-strength concrete. To improve the tensile strength of concrete, fiber-reinforced concrete and polymer concrete have been developed.
Low toughness (ductility)

Toughness is usually defined as the ability of a material to consume energy. Toughness can be evaluated by the area of a load–displacement curve. Compared to steel, concrete has very low toughness, with a value only about 1/50 to 1/100 of that of steel. Adding fibers is a good way to improve the toughness of concrete.
Low strength/density ratio

*Low specific strength (strength/density ratio)*: For normal-strength concrete, the specific strength is less than 20, while for steel it is about 40.

There are two ways to increase concrete specific strength: one is to reduce its density and the other is to increase its strength. Hence, lightweight concrete and high-strength concrete have been developed.
Formwork is needed

Fresh concrete is in a liquid state and needs formwork to hold its shape and to support its weight. Formwork can be made of steel or wood. The formwork is expensive because it is labor intensive and time-consuming.
To improve efficiency of formworks, precast techniques, climbing mold and tunnel formwork systems have been developed.

[Image: Precast concrete]

https://www.youtube.com/watch?v=EB8noJ4_AJl (Climbing mold)

[Image: Tunnel formwork]

https://www.youtube.com/watch?v=5vD62cZN4LE  Tunnel formwork
Long curing time

Curing is defined as the measures for taking care of fresh concrete right after casting. The main principle of curing is to keep favorable moist conditions under a suitable temperature range during the fast hydration process for concrete.

Careful curing will ensure that the concrete is hydrated properly, with good microstructure, proper strength, and good volume stability. The design index for concrete strength is the 28-day compressive strength. Hence, full strength development needs a month at ambient temperature. To reduce the curing period for obtaining the target strength in a shorter time the accelerated curing methods (i.e. steam curing) could be applied.
Working with cracks

The tension side of reinforced concrete members has a concrete cover to protect the steel bars. Due to the low tensile strength, the concrete cover cracks. To solve the crack problem, **prestressed concrete** is developed, and it is also realized as a third-generation concrete.

Most reinforced concrete structures have existing cracks on their tension sides while carrying the service load.
TYPES OF CONCRETE

Classification can be made in accordance with:

- Unit weight
- Compressive strength
- Additives
In accordance with unit weight

<table>
<thead>
<tr>
<th>Classification</th>
<th>Unit Weight (Kg/m³)</th>
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<tbody>
<tr>
<td>Ultra-lightweight concrete</td>
<td>&lt;1200</td>
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<tr>
<td>Lightweight concrete</td>
<td>1200 &lt; UW &lt; 1800</td>
</tr>
<tr>
<td>Normal-weight concrete</td>
<td>~2400</td>
</tr>
<tr>
<td>Heavyweight concrete</td>
<td>&gt;3200</td>
</tr>
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</table>
In accordance with compressive strength

<table>
<thead>
<tr>
<th>Classification</th>
<th>Compressive Strength (MPa)</th>
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<tr>
<td>Low-strength concrete</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Moderate-strength concrete</td>
<td>20–50</td>
</tr>
<tr>
<td>High-strength concrete</td>
<td>50–150</td>
</tr>
<tr>
<td>Ultra-high-strength concrete</td>
<td>&gt;150</td>
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In accordance with additives

<table>
<thead>
<tr>
<th>Classification</th>
<th>Additives</th>
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<tbody>
<tr>
<td>MDF</td>
<td>Polymers</td>
</tr>
<tr>
<td>Fiber-reinforced concrete</td>
<td>Different fibers</td>
</tr>
<tr>
<td>DSP concrete</td>
<td>Large amount silica fume</td>
</tr>
<tr>
<td>Polymer concrete</td>
<td>Polymers</td>
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</table>

MDF: Macro-defect free
DSP: Densified with small particles
FACTORS INFLUENCING CONCRETE PROPERTIES

- $w/c$ ratio (or $w/b$ or $w/p$ ratio)
- Degree of compaction
- Cement content
- Aggregate properties
- Admixtures
- Curing
**w/c ratio (or w/b or w/p ratio)**

One property of concrete is the water/cement ratio. In contemporary concrete, w/c is frequently replaced with w/b (water/binder) or w/p (water/powder), since Portland cement is not the only binding material in such a concrete.

The w/c or w/b ratio is one of the most important factors influencing concrete properties, such as **compressive strength**, **permeability**, and **diffusivity**.

A lower w/c ratio will lead to a stronger and more durable concrete.
w/c ratio (or w/b or w/p ratio)

The influence of w/c on the concrete compressive strength has been known since the early 1900s (Abrams, 1927), leading to Abrams’s law

\[ f_c = \frac{A}{B^{1.5(w/c)}} \]

where \( f_c \) is the compressive strength, \( A \) is an empirical constant (usually 97 MPa), and \( B \) is a constant that depends mostly on the cement properties (usually 4). It can be seen from the formula that the higher the w/c ratio, the lower the compressive strength.
Figure 14.2  Relationship between the Water/Cement Ratio and Strength
Cement content

When water is added a concrete mix, cement paste will be formed.

Cement paste has three functions in concrete:

• **binding,**
• **coating,**
• **lubricating.**

Cement paste provides binding to individual aggregates, reinforcing bars, and fibers and glues them together to form a unique material.

Cement paste also coats the surface of the aggregates and fibers during the fresh stage of concrete.
Cement content

The rest of the paste after coating can make the movement of the aggregates or fibers easier, rather like a lubrication agent.

The cement content influences
• Concrete workability in the fresh stage
• Heat release rate in the fast hydration stage
• Volume stabilities in the hardened stage.

The range of the amount of cement content in mass concrete is 160–200 kg/m³, in normal strength concrete it is less than 400 kg/m³, in high strength concrete it is 400–600 kg/m³.
Aggregate

- Maximum aggregate size
- Aggregate grading
- Aggregate shape and texture
- Sand/coarse aggregate ratio
- Aggregate/cement ratio
Maximum aggregate size

The maximum coarse aggregate size mainly influences the cement paste requirement in the concrete.

*For the same volume of aggregate, the ones with a large aggregate size will lead to a small total surface area and a lower amount of cement paste coating.*

If the same amount of cement is used, *concrete with a larger maximum aggregate size will have more cement paste left as a lubricant and the fluidity of concrete can be enhanced, as compared to concrete with a smaller maximum aggregate size.*
Maximum aggregate size

For normal-strength concrete, at the same w/c ratio and with the same cement content, the larger the maximum sizes, the better the workability; at the same workability, the larger the maximum sizes, the higher the strength.

A larger aggregate size has some drawbacks.

- First, a larger aggregate size may make the concrete appear nonhomogeneous.
- Second, a larger aggregate size may lead to a large interface that can influence the concrete transport properties and the mechanical properties.
Maximum aggregate size

Generally, the maximum size of coarse aggregate should be the largest that is economically available and consistent with the dimensions of the structure.

In choosing the maximum aggregate size, the structural member size and spacing of reinforcing steel in a member have to be taken into consideration.

The maximum size of aggregate shouldn’t exceed (TS 500)

- one-fifth (1/5) of the narrowest dimension in the sizes of the forms,
- one-third (1/3) of the depth of slabs,
- three-quarters (3/4) of the minimum clear spacing between reinforcing bars.
- Concrete cover thickness.
Aggregate grading

Aggregate grading refers to the size distribution of the aggregate.

The grading mainly influences the space filling or particle packing.

Well-defined grading with an ideal size distribution of aggregate will decrease the voids in the concrete and hence the cement content.
Aggregate grading

Examples of grading regions for continuously graded aggregates (CEB-FIB MC-90)

A continuously graded aggregate includes all particle sizes from the finest to the largest.

An aggregate grading falling into Zone 1 tends to a harsh mixture which is difficult to work and liable to bleed. Aggregates in Zone 5 may require large amounts of water and in consequence high cement contents for a given water / cement ratio to achieve a given strength.
A gap-graded aggregate is the one in which one or intermediate grading groups are missing.

For the gap-graded aggregates, the aggregates having a grading curve falling into the region between the curves U and C is assumed to be appropriate.
Aggregate grading

The effect of sand grading on compressive strength.
Aggregate shape and texture

The aggregate shape and texture can influence the workability, bonding with cement paste, and compressive strength of concrete.

At the same w/c ratio and with the same cement content, aggregates with angular shape and rough surface texture result in lower workability, but lead to a better bond and better mechanical properties.

aggregates with spherical shape and smooth surface texture result in higher workability, but lead to a lower bond and lower mechanical properties.
Concrete with gravel aggregates

Round shape and smooth surface

Concrete with crushed stone aggregates

Angular shape and rough surface
Sand (fine)/coarse aggregate ratio

The fine/coarse aggregate ratio influences the packing of concrete.

It also influences the workability of concrete in the fresh stage.

Increase of the sand to coarse aggregate ratio can lead to an increase of cohesiveness, but reduces the consistency.

Increase of the sand/coarse aggregate ratio also increases the specific surface area of aggregate phase to be covered with cement paste. If there is no enough cement paste, after a certain limit, an increase in sand to coarse aggregate ratio can lead to have lower compressive strength.
Aggregate/cement ratio

The aggregate/cement ratio has an effect on the

- concrete cost,
- workability,
- mechanical properties,
- volume stability.

Due to the price difference between the aggregate and cement, increasing the aggregate/cement ratio will decrease the cost of concrete.

An increase of the aggregate to cement ratio results in a lower consistency because of less cement paste for lubrication.

Increase of the aggregate/cement ratio can lead to a high stiffness and compressive strength if proper compaction can be guaranteed.

Increasing the aggregate/cement ratio will definitely improve concrete’s dimension stability due to reduction of shrinkage and creep.