LECTURE 1. INTRODUCTION TO CONCRETE TECHNOLOGY

Prepared by:
D.Sc. Fahim Al-Neshawy,

Reviewed by:
Prof. Jouni Punkki

Aalto University School of Engineering
Department of Civil Engineering
A: P.O.Box 12100, FIN-00076 Aalto, Finland
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1.1 Definitions

**Definition of Concrete**

Concrete is a mixture of **cement** (9 – 15%), **water** (15 – 16%), **fine aggregate** (sand, 25 – 30%), **coarse aggregate** (gravel or crushed rocks, 30 – 45%), **air** (2 – 6%) and **chemical admixtures** in which the cement and water have hardened by a chemical reaction – hydration – to bind the nearly (non-reacting) aggregate.

![Concrete ingredients](image)

*Figure 1-1. Basic ingredients of concrete*

**Definition of Cement**

Portland cements are hydraulic cements, meaning they react and harden chemically with the addition of water. Cement contains limestone, clay, rock and iron ore blended and heated to 1200 to 1500 C°. The resulting product "clinker" is then ground to the consistency of powder. Gypsum is added to control setting time.

**Definition of Fine Aggregate**

Normally called sand, this component can be natural sand or crushed stone, and represents particles smaller than 4.0 mm. Generally accounts for 30%-35% of the mixture.

**Definition of Coarse Aggregate**

May be either gravel or crushed stone. Makes up 40%-45% of the mixture, comprised of particles greater than 4mm.
Definition of Chemical Admixtures

Materials added to alter the properties of concrete including:

- **Air entraining admixtures**: add microscopic air bubbles to the concrete, enhancing its resistance to freeze/thaw cycles and makes the concrete easier to finish.
- **Set accelerators**: speed the set-time of the mixture, enabling finishing operations to begin sooner, useful during cold weather pours.
- **Set retarders**: have the opposite effect, slowing the set and enabling delivery to distant sites and finishing during hot weather.
- **Water reducers**: are used to reduce the amount of water required to produce a given slump. They also provide a ball bearing effect, making the concrete easier to finish, and produce better cement hydration. By reducing the amount of water required, cement amounts can be reduced because concrete strength is directly related to the water/cement ratio.

Definition of Mineral Admixtures

Mineral admixtures include fly ash, hydrated lime, silica fume and ground blast furnace slag. Many of these materials have cement-like properties, increasing the strength and density of the finished concrete. They generally improve the workability, density and long-term strength of concrete, at the expense of set time and early strengths.

Definitions of Workability of Concrete

ACI (American Concrete Institute) defines the workability of concrete as ‘the property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished. A concrete is said to be workable if:

- It can be handled without segregation
- It can be placed without loss of homogeneity
- It can be compacted with specified effort
- It can be finished easily

1.2 European standards for concrete

The concrete standards are being implemented across Europe to create harmonization between all European countries and remove trade barriers between members. This harmonization will create and promote opportunities to increase free trade throughout the European Community.
1.3 Main uses of concrete [1]

Concrete is the second most widely used substance after water and over six milliard tons of concrete is produced each year. Concrete is specific to different applications like new construction, repair, rehabilitation and retrofitting. Concrete building components in different sizes and shapes include wall panels, doorsills, beams, pillars and more. Post-tensioned slabs are a preferred method for industrial, commercial and residential floor slab construction. It makes sense to classify the uses of concrete on the basis of where and how it is produced, together with its method of application, since these have different requirements and properties.

1.3.1 Concrete cast in situ and precast concrete (ordinary concrete)

Cast-in-site concrete is an unhardened state, like ready-mix, and is placed in molds. Ready mixed concrete is proportioned and mixed off the project site. It finds application in foundations and slabs-on-ground, walls, beams, columns, floors, roofs, bridges, pavements, and other infrastructure. Ready Mixed concrete is durable and hard wearing and is used for variety of applications owing to its crack-resistance and durability. Situ concrete is cast in place, on site. Precast concrete finds application in concrete curtain walls, exterior cladding and structural walls, as it monolithic and can be easily used

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for two-way structural systems. It is also adjustable to post tensioning and easily adapts to any building shape.

Figure 1-3. The 605 metres high, the Burj Khalifa skyscraper in Dubai will be the world’s tallest building. Burj Khalifa's construction used 330,000 m³ of concrete. [2]

1.3.2 Special concretes

A special concrete is a concrete made with special ingredients or by a special process may be ideally suited to some special needs. Special concretes are used in modern times, for increased strength and construction of skyscraper or special structures. The special concretes include (among other things):

- Concrete for traffic areas
- Self-compacting concrete (scc)
- Frost and freeze/thaw resistant concrete
- High strength concrete
- Slip formed concrete
- Waterproof concrete
- Fair-faced concrete
- Mass concrete
- Fiber reinforced concrete
- Heavyweight concrete
- Underwater concrete
- Lightweight concrete
- Rolled concrete
- Coloured concrete
- Semi-dry concrete for precast manufacture of concrete products
- Concrete with enhanced fire resistance
- Tunnel segment concrete
- Monolithic concrete
- Granolithic concrete

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2 https://en.wikipedia.org/wiki/Burj_Khalifa
The difference between the ordinary and special concrete is shown in Table 1.

Table 1. Difference between the ordinary and special concrete.

<table>
<thead>
<tr>
<th>Ordinary Concrete</th>
<th>Special Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary concrete is used for normal works like building, bridges, road etc.</td>
<td>This type of concrete is used for special type of structures like nuclear reactor, buildings with acoustic treatment, air conditioned buildings etc.</td>
</tr>
<tr>
<td>Ingredients of ordinary concrete are cement, sand, aggregate and water.</td>
<td>In case of light weight aggregate concrete, light weight aggregates are used. In polymer concrete, polymer binder is used instead of water.</td>
</tr>
<tr>
<td>Construction is carried out by conventional method.</td>
<td>Concreting is done by special techniques</td>
</tr>
<tr>
<td>Properties of Concrete like density, strength etc. are of normal range.</td>
<td>Properties of concrete like density strength are of higher range. For example, density of light weight concrete is about 500 to 2000 kg/m³ and that of heavy weight concrete is about 3000 to 5000 kg/m³</td>
</tr>
<tr>
<td>It is economical</td>
<td>It is costly</td>
</tr>
</tbody>
</table>

1.4 History of Concrete [3]

The history of cement and concrete spans over 5,000 years, from the time of the Egyptian Pyramids to present day decorative concrete developments. Concrete has been used for many amazing things throughout history, including architecture, infrastructure and more.

3000 BC - Egyptian Pyramids

The Egyptians were using early forms of concrete over 5000 years ago to build pyramids. They mixed mud and straw to form bricks and used gypsum and lime to make mortars.

300 BC - 476 AD - Roman Architecture

The ancient Romans used a material that is remarkably close to modern cement to build many of their architectural marvels, such as the Colosseum, and the Pantheon. The Romans also used animal products in their cement as an early form of admixtures.

1824 - Portland Cement Invented

*Joseph Aspdin* of England is credited with the invention of modern portland cement. He named his cement portland, after a rock quarry that produced very strong stone.

1836 - Cement Testing

The first test of tensile and compressive strength took place in Germany.

1850 Concrete road

1850 - The first concrete roads appeared in Austria.
1865 - in England
1891 - in Bellefontaine, Ohio US

1854 First reinforced concrete

William B. Wilkinson, an English plasterer, erected a small reinforced concrete two-story servant's cottage. He reinforced the concrete floor and roof with iron bars and wire rope. This is credited as the first reinforced concrete building.
1889 Alvord Lake Bridge

The first concrete reinforced bridge was built in San Francisco. Alvord Lake Bridge still exists today, over two hundred years after it was built!

1901 Column clamp - Concrete form

Arthur Henry Symons designed a column clamp to be used with job-built concrete forms

1902 Rotary kiln – for cement production

Thomas Edison was a pioneer in the further development of the rotary kiln, which allows for continuous production cement

1913-Ready Mix concrete

The first load of ready mix was delivered in Baltimore, Maryland. The first patent for a concrete pump was filed. This made concrete transportation easy and allowed on site mixing.

1915 Colored concrete

Lynn Mason Scofield founded L.M. Scofield, the first company to produce color for concrete. Their products included color hardeners, colorwax integral color, sealers, and chemical stains.

1928 Pre-stressed concrete

1928 - Eugene Freyssinet - French civil engineer - successfully develops pre-stressed concrete and built two air hangars with parabolic curved shape at Orly Airport - Paris.
1930-Air Entraining Agents

Air entraining agents were used for the first time in cement to resist against damage from freezing and thawing.

1970's-Fiber Reinforcement

Fiber reinforcement was introduced as a way to strengthen concrete.

1980's Self-compacting concrete


1980's Superplasticizers and Silica fume

Superplasticizers were introduced as admixtures. and silica fume was introduced as a pozzolanic additive. The "highest strength" concrete was used in building the Union Plaza constructed in Seattle, Washington.

1999 Polished concrete

The first installation of a polished concrete floor in the US was a 40,000-square-foot warehouse floor for the Bellagio in Las Vegas. The popularity of polished concrete has soared in just the few short years it has been around, it is now being used in retail locations and even residential homes.
1.5 Compressive strength classes - Concrete families [4]

According to SFS-EN 206:2014, concrete is classified with respect to its characteristic compressive strength at 28 days of 150 mm diameter by 300 mm cylinders (f_{ck,cyl}) or the characteristic compressive strength at 28 days of 150 mm cubes (f_{ck,cube}), tested in accordance with EN 12390-3 may be used for classification.

Table 2. Compressive strength classes for normal-weight and heavy-weight concrete

<table>
<thead>
<tr>
<th>Compressive strength class</th>
<th>Minimum characteristic cylinder strength. $f_{ck,cyl}$ [N/mm$^2$]</th>
<th>Minimum characteristic 150 mm cube strength. $f_{ck,cube}$ [N/mm$^2$]</th>
<th>$^{[5]}$ Minimum characteristic 100 mm cube strength. $f_{ck,cube}$ [N/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8/10</td>
<td>8</td>
<td>10</td>
<td>15.6</td>
</tr>
<tr>
<td>C12/15</td>
<td>12</td>
<td>15</td>
<td>20.6</td>
</tr>
<tr>
<td>C16/20</td>
<td>16</td>
<td>20</td>
<td>25.8</td>
</tr>
<tr>
<td>C20/25</td>
<td>20</td>
<td>25</td>
<td>30.9</td>
</tr>
<tr>
<td>C25/30</td>
<td>25</td>
<td>30</td>
<td>38.1</td>
</tr>
<tr>
<td>C30/37</td>
<td>30</td>
<td>37</td>
<td>46.4</td>
</tr>
<tr>
<td>C35/45</td>
<td>35</td>
<td>45</td>
<td>51.5</td>
</tr>
<tr>
<td>C40/50</td>
<td>40</td>
<td>50</td>
<td>56.6</td>
</tr>
<tr>
<td>C45/55</td>
<td>45</td>
<td>55</td>
<td>61.8</td>
</tr>
<tr>
<td>C50/60</td>
<td>50</td>
<td>60</td>
<td>69</td>
</tr>
<tr>
<td>C55/67</td>
<td>55</td>
<td>67</td>
<td>77.2</td>
</tr>
<tr>
<td>C60/75</td>
<td>60</td>
<td>75</td>
<td>87.6</td>
</tr>
<tr>
<td>C70/85</td>
<td>70</td>
<td>85</td>
<td>97.8</td>
</tr>
<tr>
<td>C80/95</td>
<td>80</td>
<td>95</td>
<td>105</td>
</tr>
<tr>
<td>C90/105</td>
<td>90</td>
<td>105</td>
<td>108.2</td>
</tr>
<tr>
<td>C100/115</td>
<td>100</td>
<td>115</td>
<td></td>
</tr>
</tbody>
</table>

1.6 Advantages and limitations of concrete

Concrete is an artificial stone-like material used for various structural purposes. Basic advantages and limitations of concrete are as follows.

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Betoninormit 2016 – BY 65, Suomen Betoniyhdistys ry]
Some advantages of concrete are given below in brief:

- Concrete is economical when ingredients are readily available in most of the places.
- Concrete’s long life and relatively low maintenance requirements increase its economic benefits.
- Concrete is not as likely to rot, corrode, or decay as other building materials.
- Concrete has the ability to be molded or cast into almost any desired shape and casting of concrete and can be manufactured to desired strength.
- Building of the molds (framework) and casting can occur on the work-site, which reduces cost.
- Concrete is a non-combustible material, which makes it fire-safe and able to withstand high temperatures (Cracking starts at 550°C, popouts over chert or quartz aggregate particles at 600 °C and spalling at 800 °C) \[^6\].
- Concrete is resistant to wind, water, rodents, and insects. Hence, concrete is often used for storm shelters.
- Maintenance cost of concrete is almost negligible.
- As a sound proofing material lightweight concrete could be used.

Limitations of concrete:

- Compared to other binding materials, the tensile strength of concrete is relatively low.
- Concrete is less ductile.
- The weight of compared is high compared to its strength (low strength-to-weight ratio).
- Concrete may contain soluble salts. Soluble salts cause efflorescence.
- Concrete is susceptible to cracking.

### 1.7 Review of the concrete mix design methods

The objective in designing concrete mixtures is to determine the most economical and practical combination of readily available materials to produce a concrete that will satisfy the performance requirements under particular conditions of use. Quantities of materials for the production of required quantity of concrete of given mix proportions can be calculated by absolute volume method. This method is based on the principle that the volume of fully compacted concrete is equal to the absolute volume of all the materials of concrete, i.e. cement, sand, coarse aggregates and water. The formula for calculation of materials for required volume of concrete is given by:

\[^6\] Evaluating fire damage to concrete structures. Online at:
http://www.buildsmartercolorado.org/documents/Evaluating%20Fire%20Damage%20to%20Concrete%20Structures_tcm45-343618.pdf
\[ V_{\text{con}} = \frac{Q_{\text{cem}}}{S_{\text{cem}}} + \frac{Q_{\text{FA}}}{S_{\text{FA}}} + \frac{Q_{\text{CA}}}{S_{\text{CA}}} + Q_w + V_{\text{Air}} \]

Where:
- \( V_{\text{con}} \) = Absolute volume of fully compacted fresh concrete, \([\text{m}^3]\)
- \( Q_{\text{cem}} \) = Mass of cement, \([\text{kg}]\)
- \( Q_w \) = Mass of water, \([\text{kg}]\)
- \( Q_{\text{FA}} \) = Mass of fine aggregates, \([\text{kg}]\)
- \( Q_{\text{CA}} \) = Mass of coarse aggregates, \([\text{kg}]\)
- \( S_{\text{cem}}, S_{\text{FA}} \text{ and } S_{\text{CA}} \) are the specific gravities of cement, fine aggregates, and coarse aggregates respectively
- \( V_{\text{Air}} \) = the volume of the air content

This method of calculation for quantities of materials for concrete takes into account the mix proportions from design mix for structural strength and durability requirement.

This section covers mix design fundamentals common to the Finnish - Nykänen and BRE (Building Research Establishment, UK) mix design methods.

1.7.1 Concrete mix design procedure (Nykänen method)

Nykänen method (7):
- Developed by professor Arvo Nykänen (1912 – 1990)
- 1st version of the proportion method was developed in 1945 and the publications about the method during the years 1947 and 1948
- The new version of the methods established in 1955 because of the changes in the code of practices and the development of concrete technology

Specified concrete properties

A properly proportioned concrete mix should possess the following qualities:

i. Acceptable workability of the freshly mixed concrete

ii. Durability, strength, and uniform appearance of the hardened concrete \(\rightarrow\) result from the structural design process

iii. Economy.

The requirement (input) for the Nykänen method are:

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- The 28 days compressive strength of the concrete (nominal strength)
- The slump of the fresh concrete mass (workability), shown in Table 3.
- The 28 days compressive strength of the cement used
- The air-content of concrete (generally assumed 2% for normal concrete)
- The grading and the moisture content of the aggregates
- The amount of absorbing water in the aggregates (generally estimated to be 0.4 %)
- Any other information about the concrete structure

Table 3. The permissible slump for various types of concrete in relation to their use

<table>
<thead>
<tr>
<th>Concrete structures</th>
<th>Consistency (Slump), [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>Reinforced foundation walls and footings</td>
<td>125</td>
</tr>
<tr>
<td>Plain footings, caissons and substructure walls</td>
<td>100</td>
</tr>
<tr>
<td>Slabs, beams, thin reinforced walls and building columns</td>
<td>150</td>
</tr>
<tr>
<td>Pavements and floor laid on ground</td>
<td>75</td>
</tr>
<tr>
<td>Heavy mass construction</td>
<td>75</td>
</tr>
</tbody>
</table>

Example - Procedure for concrete mix design

Proportion a concrete mix with a 28 day **compressive strength of 35 MPa** and a **slump of 90 mm**, made with ordinary Portland cement with **cement strength of 49.5 MPa**. Grading of the aggregate is presented in Figure 1-7. All aggregates are dry, absorbing 0.8 %, not crushed

**Step 1. Calculating the proportioning strength:**

The proportion strength is calculated using the following equation:

\[ K_s = k_t \times K \times k_{cem} = 1.2 \times 35 \times \frac{42.5}{49.5} = 36 \text{ MPa} \]

Where:

- \( K_s \) is proportion strength for the concrete mix
- \( k_t \) is the target strength factor, \( k_t = 1.2 \)
- \( K \) is the nominal strength of the concrete (28d compressive strength)
- \( k_{cem} \) is the cement strength factor
  \((k_{cem} = (42.5/N))\), where \( N \) is the 28d cement strength in MPa, according to Nykänen proportioning formula

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Step 2. Choice of the aggregates and calculating of the grading factor (H)

Selecting the maximum coarse aggregate size: The maximum size of coarse aggregate that can be used in a mix depends on the size, shape, and reinforcing of a concrete member.

Maximum aggregate size ($D_{\text{max}}$) should not be larger than:

i) $\frac{1}{5}$ the minimum dimension of structural members such as beams columns, frames etc. ($b/5$)

ii) $\frac{1}{3}$ the thickness of a concrete slab ($h/3$)

iii) $\frac{3}{4}$ the clearance between reinforcement bars ($3S/4$)

iv) $\frac{3}{4}$ the concrete cover depth ($3C/4$) → the clearance between reinforcing steel and the concreting forms (molds).

These restrictions limit maximum aggregate size to 32 mm, except in mass applications. In many countries, the largest available sizes vary 16 mm to 32 mm\(^9\).

For the laboratory concrete mix design, the maximum aggregate size is the sieve size that passes 95% of the combined aggregate.

Specify the guideline passing values for sieve #0,125 mm and sieve #4 mm aggregates from the mix design form based on (1) the proportion strength $K_s$ and (2) the maximum aggregate (see Figure 1-7).

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\(^9\) ACI 211.1: Maximum Aggregate Size For Concrete Mix Design. Online at: [http://www.ce.memphis.edu/1112/notes/project_2/beam/ACI_mix_design.pdf](http://www.ce.memphis.edu/1112/notes/project_2/beam/ACI_mix_design.pdf)
Figure 1-5. Selecting of the guideline passing values for #0,125 mm and #4 mm aggregates.

Based on the values from Figure 1-5, we generate groups of equations (based on the number of aggregate fractions) in order to solve the %-values for the aggregates. In this example, we consider only three fractions, shown in Figure 1-7, to be solved using iteration method in Excel for example:

Combined \( \rightarrow a + b + c \approx 100\% \)

\(< \ #0.125 \ mm \rightarrow a \cdot 12 + b \cdot 3 + c \cdot 0 \approx 4\% \)

\(< \ #4 \ mm \rightarrow a \cdot 100 + b \cdot 30 + c \cdot 5 \approx 37\% \)

Figure 1-6. Example of the fractions values calculation adapted from BY 201 “Betonitekniikan oppikirja”. 1) Assume suitable values for \(a, b\) and \(c\). 2) Iterate the calculation until you fulfill the fraction equations.
After a few iteration steps for the first and second equation, we got the following values: (a = 27%, b = 25% and c = 48%).

Notice that you can’t find the exact values for a, b and c, but make them close enough.

The steps for the choice of the aggregates as follow (example using Excel sheet is shown in Figure 1-7):

1) Using the aggregate grading available
2) Calculate the passing percentages for each aggregate fraction based on (i) the cumulative passing through 0.125 and 4 mm and (ii) fitting the aggregate limits curve
3) Calculate the granulometric value of the grading factor (H) using:

\[ H = \sum_{\text{sand}} \left( \frac{\text{Fraction portion} \times 100}{\%} \right) \times \sum_{0.125}^{64} \text{Sieve passing value} \%
\]

![Figure 1-7. Example of aggregate combination procedure and calculating the grading factor (H).](image)

**Step 3. Specifying the amounts of water, cement and aggregates**

Using the mix design form shown in Figure 1-8 to specify the amounts of water, cement and aggregates is following the next procedure:

**Mix design Exercise**

- Ks = 36 MPa
- Slump = 90 mm
- No crushed aggregates (0%)
- Air content 2% (20 dm³ of air in m³ concrete)
- The grading factor, H = 412
Figure 1-8. Concrete mix design - Specifying the amounts of water, cement and aggregates

1) Using the grading factor (H) value, point (1)
2) Move vertically to the value of the concrete slump (input – workability), point (2)
3) Move horizontally (consider the amount of crushed aggregates, which was 0% in the example case) to point (3)
4) Move parallel with the same slope as the proportional strength Ks line until the meet the Ks value, point (4)
5) Move horizontally (consider the air content, which was 2% in the example case) to point (5).
   **Notice:** if the air content is more than 2%, 1st you move horizontally, then parallel to the air content lines to point (5)
6) Connect point (5) with point (6), which is the value of the proportional strength Ks using straight line
7) Point (7) is the amount of water + air (dm³/m³-concrete). Because you know already the air content (A), you be able to calculate the amount of water (W)
8) Point (8) is the amount of aggregates (kg/m³) or (dm³/m³).
   **Remember to take into account the effective amount of water (effective amount of water = total water – absorbed water) when calculating the final aggregate mix.
9) Point (9) is the amount of cement (kg/m³) or (dm³/m³)
Water + Air = 188 dm³/m³ → point (7)
Air = 20 dm³
Water = 188 – 20 = 168 dm³ = 168 kg/m³ - concrete (density of water 1 kg/dm³)
Aggregates = 1860 kg/m³ - concrete → point (8)
Cement = 310 kg/m³ - concrete → point (9)
All aggregates are dry (i.e moisture content 0%), absorbed water 0.8 %, not crushed

**Step 4. Adjustments for aggregate moisture and final proportion**

**Aggregate weights:**
Aggregate volumes are calculated based on oven dry unit weights, but aggregate is typically batched based on actual weight. Therefore, any moisture in the aggregate will increase its weight and stockpiled aggregates almost always contain some moisture. Without correcting for this, the batched aggregate volumes will be incorrect.

**Amount of mixing water:**
If the batched aggregate is anything but saturated surface dry it will absorb water (if oven dry or air dry) or give up water (if wet) to the cement paste. This causes a net change in the amount of water available in the mix and must be compensated for by adjusting the amount of mixing water added. Example of the aggregates and mixing water adjustments is shown in Table 4.

**Table 4. Concrete mix proportion with adjustment.**

<table>
<thead>
<tr>
<th>Concrete ingredient</th>
<th>Amount (kg/m³)</th>
<th>Aggregate fraction</th>
<th>Fraction portion (%)</th>
<th>Mix (kg/m³)</th>
<th>Water content of aggregates</th>
<th>Adjusted mix (kg/m³)</th>
<th>BATCH m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>310</td>
<td></td>
<td></td>
<td>310</td>
<td></td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>Aggregates</td>
<td>1860</td>
<td>Sand</td>
<td>27</td>
<td>502</td>
<td>0</td>
<td>0.8</td>
<td>-4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gravel</td>
<td>25</td>
<td>465</td>
<td>0</td>
<td>0.8</td>
<td>-3.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rough gravel</td>
<td>48</td>
<td>893</td>
<td>0</td>
<td>0.8</td>
<td>-7.1</td>
</tr>
<tr>
<td>Water</td>
<td>168</td>
<td></td>
<td></td>
<td>168</td>
<td></td>
<td></td>
<td>183</td>
</tr>
<tr>
<td>Air content (4)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

(1) Free water = (total moisture content - absorbed water) (%)
(2) Free water (kg/m³) = (Free water (%) * amount of aggregate fraction (kg/m³)) / 100
(3) Adjusted aggregate fraction value = value of aggregate fraction (kg/m³) + Free water (kg/m³)

Adjusted water value = Water content (kg/m³) - total amount of free water (kg/m³)
(4) The target volume of air in the concrete mix (dm³/m³)
1.7.2 Concrete mix design procedure (Building Research Establishment (BRE)-method)

**BRE mix design method:**

- “Design of Normal Concrete Mixes” was published by the Building Research Establishment Ltd., United Kingdom in 1997. (Formerly by Department of Environment, DOE).
- DOE is the method published by the Department of Environment in the year 1988.
- Compressive strength is, in general, related to durability. The greater the strength the more durable the concrete. To satisfy the required compressive strength, a value for water/cement (w/c) ratio is estimated for an appropriate test age (generally 28 days) and cement type.
- Tables in the BRE mix design handbook are consulted relating aggregate:cement (a/c) ratio, workability and water:cement (w/c) ratio for the different aggregate particle shapes and maximum size.
- From these tables the a/c ratio can be selected. A desired level of workability is chosen. The ratio of sand to coarse aggregate is chosen to produce a satisfactory plastic concrete. Generally there is a minimum amount of sand necessary to fill the voids between the coarse aggregate particles. Increasing the percentage of sand makes for a less harsh and more easily placed mix.

**Example - Procedure for concrete mix design**

Proportion a concrete mix with a 28 day **compressive strength of 35 MPa** and a **slump of 90 mm**, made with ordinary Portland cement with **cement strength of 42,5 MPa**. Grading of the aggregate is presented in Figure 1-7. All aggregates are dry, absorbing 0.8 %, not crushed.

**Step-1: Target mean strength**

- It is generally accepted that the variation in concrete strengths or a particular mix follows the normal distribution as shown Figure 1-9.
- In the figure, for example if the mean strength of the mix is 40 N/mm². That is, we can expect half of the test results will be higher than 40 N/mm² and half will be lower.
- In practice, we specify the quality of concrete not as a minimum strength, and not as a mean strength, but as a characteristic strength below which a specified percentage of the test results, often called defectives, may be expected to fall. Characteristic strength may be defined as to have any proportion of defectives. (Structural Use of Concrete adopt the 5% defective level in the UK)

---

As a result, it is necessary to design a mix to have a target mean strength greater than the specified characteristic strength by an amount termed the margin.

Target mean strength ($f_m$) = Characteristic strength ($f_k$) + Margin

Margin = $k$ (constant) * $s$ (standard deviation)

$$f_m = f_k + k \times s$$

Figure 1-9. Normal distribution of concrete strength (Source: Building Research Establishment)

Figure 1-10. Relationship between standard deviation and characteristic strength.

- Constant $k$ is derived from the mathematics of the normal distribution.

<table>
<thead>
<tr>
<th>Defective</th>
<th>1.0%</th>
<th>2.5%</th>
<th>5.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant ($k$)</td>
<td>2.33</td>
<td>1.96</td>
<td>1.64</td>
</tr>
</tbody>
</table>

- The standard deviation ($s$) is obtained from the graph in Figure 1-10. It is recommended to use the maximum value of standard deviation if compressive strength test samples are less than 20 samples.

$$f_m = 35 + 1.64 \times 8 = 48 \text{ MPa}$$
**Step-2: Determining the Water/ Cement Ratio**

Table 5. Example of the approximate compressive strength (N/mm²) of concrete mixes made with a free-water contents ratio of 0.5.

<table>
<thead>
<tr>
<th>Cement strength class</th>
<th>Type of coarse aggregate</th>
<th>Compressive strengths (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Age (days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>42.5</td>
<td>Uncrushed</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Crushed</td>
<td>27</td>
</tr>
<tr>
<td>52.5</td>
<td>Uncrushed</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Crushed</td>
<td>34</td>
</tr>
</tbody>
</table>

- Based on cement compressive strength, Table 1 is used to obtain the **compressive strength**, at the specified age that corresponds to a free water/cement ratio of 0.5. In the example above the approximate compressive strength is 42 MPa at 28 days for uncrushed aggregates and cement strength class of 42.5 MPa.

**Figure 1-11. Example of determining the Water/ Cement Ratio from the relationship between compressive strength and water/ cement ratio graph.**
plot the approximate compressive strength for 0.5 W/C in the relationship between compressive strength and water/cement ratio graph (point 1), then a curve is drawn from (point 1) and parallel to the printed curves
- draw a horizontal line from the target mean strength (point 2) till the drawn dotted curve (point 3)
- Draw a vertical line from (point 3) to determine the concrete mix W/C ratio (point 4). W/C = \[ W/C \approx 0.48 \]

**Step-3: Determination of the Free-Water Content**

- The free-water content can be determined from Table 6 depending upon the type and maximum size of the aggregate to give a concrete of the specified slump or Vebe time.
  \[ \text{Water content} = (175+(40-32) \times (195-175)/(40-20)) = 183 \text{ kg/m}^3 \]

*Table 6. Example of determination of the approximate free-water contents required to give various levels of workability.*

**Step-4: Determination of Cement Content**

- The cement content can be determined from equation below:

  \[
  \text{Cement Content} = \frac{\text{Free Water Content}}{\text{water-Cement Ratio}}
  \]

  \[ \text{Cement content} = 183/0.48 = 380 \text{ kg/m}^3 \]
The resulting value should be checked against any maximum or minimum value that may be specified. If the calculated cement content below a specified minimum, this minimum value must be adopted and a modified free-water/cement ratio calculated.

If the design method indicates a cement content that is higher than a specified maximum then it is probable that the specification cannot be met simultaneously on strength and workability requirements with the selected materials. Consideration should then be given to changing the type or strength class, or both, of cement, the type and maximum size of aggregate or the level of workability of the concrete, or to the use of a water-reducing admixture.

Step 5: Determining the Total Aggregate Content

Density of fully compacted concrete can be estimated from Figure 1-12. This value depends upon the free-water content and the relative density of the combined aggregate in the saturated surface-dry condition. If no information is available regarding the relative density of the aggregate, an approximation can be made by assuming a value of 2.6 for un-crushed aggregate and 2.7 for crushed aggregate.

\[ \text{wet density of concrete} = 2380 \text{ kg/m}^3 \]

The total aggregate content can be calculated using the equation below:

\[ \text{Total Aggregate Content} = D - C - W \]

Total Aggregate Content = 2380 – 380 – 183 \approx 1820 \text{ kg/m}^3

where:

- \( D \) = The wet density of concrete (in kg/m\(^3\))
- \( C \) = The cement content (in kg/m\(^3\))
- \( W \) = The free-water content (in kg/m\(^3\))

Note: Weight of aggregate is rounded into the nearest 5 kg
**Step 6: Determining of the fine and coarse aggregate contents**

- Current step demonstrate how to find out total fine aggregate (materials smaller than 5 mm, i.e. the sand or fine aggregate content). The Figure 1-13 shows recommended values for the proportion of fine aggregate depending on the maximum size of aggregate, the workability level, the grading of the fine aggregate (defined by the percentage passing a 600 μm sieve) and the free-water/ cement ratio. The best proportion of fines to use in a given concrete mix design will depend on the shape of the particular aggregate, the grading and the usage of the concrete.

- Determination of fine and coarse aggregate can be made using the proportion of fine aggregate obtained from Figure 4 and the total aggregate content derived from Step-5

\[
\text{Fine Aggregate Content} = \text{Total Aggregate Content} \times \text{Proportion of Fines}
\]

\[
\text{Fine Aggregate Content} = 1820 \times 26\% \approx 475 \text{ kg/m}^3
\]

*Figure 1-13. Example of determination of the recommended proportions of fine aggregate according to percentage passing 600 μm sieve*
Coarse Aggregate Content = Total Aggregate Content – Fine Aggregate
→ Coarse Aggregate Content = 1820 – 475 = 1345 kg/m³

The coarse aggregate content itself can be subdivided if single sized 10, 20 and 40 mm materials are to be combined.

**Step 7. Adjustments for aggregate moisture and final proportion**

**Aggregate weights:**
Aggregate volumes are calculated based on oven dry unit weights, but aggregate is typically batched based on actual weight. Therefore, any moisture in the aggregate will increase its weight and stockpiled aggregates almost always contain some moisture. Without correcting for this, the batched aggregate volumes will be incorrect.

**Amount of mixing water:**
If the batched aggregate is anything but saturated surface dry it will absorb water (if oven dry or air dry) or give up water (if wet) to the cement paste. This causes a net change in the amount of water available in the mix and must be compensated for by adjusting the amount of mixing water added. Example of the aggregates and mixing water adjustments is shown in Table 4.

**Table 7. Example of a concrete mix proportion with the adjustment of water content of aggregates.**

<table>
<thead>
<tr>
<th>Concrete ingredient</th>
<th>Amount (kg/m³)</th>
<th>Aggregate fraction</th>
<th>Fraction portion (%)</th>
<th>Mix (kg/m³)</th>
<th>Water content of aggregates</th>
<th>Adjusted mix (kg/m³)</th>
<th>BATCH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>380</td>
<td></td>
<td></td>
<td>380</td>
<td></td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>Aggregates</td>
<td>1820</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregates</td>
<td></td>
<td>26</td>
<td></td>
<td>475</td>
<td>0</td>
<td>0.8</td>
<td>-3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>471</td>
</tr>
<tr>
<td>Coarse aggregates</td>
<td></td>
<td>14</td>
<td></td>
<td>255</td>
<td>0</td>
<td>0.8</td>
<td>-2.0</td>
</tr>
<tr>
<td>(10 mm)(4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>253</td>
</tr>
<tr>
<td>Coarse aggregates</td>
<td></td>
<td>20</td>
<td></td>
<td>365</td>
<td>0</td>
<td>0.8</td>
<td>-2.9</td>
</tr>
<tr>
<td>(20 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>362</td>
</tr>
<tr>
<td>Coarse aggregates</td>
<td></td>
<td>40</td>
<td></td>
<td>730</td>
<td>0</td>
<td>0.8</td>
<td>-5.8</td>
</tr>
<tr>
<td>(40 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>724</td>
</tr>
<tr>
<td>Water</td>
<td>183</td>
<td></td>
<td></td>
<td>183</td>
<td></td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>Air content(4)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Free water = (total moisture content - absorbed water) (%)
(2) Free water (kg/m³) = (Free water (%) * amount of aggregate fraction (kg/m³)) / 100
(3) Adjusted aggregate fraction value = value of aggregate fraction (kg/m³) + Free water (kg/m³)
Adjusted water value = Water content (kg/m³) - total amount of free water (kg/m³)
(4) The target volume of air in the concrete mix (dm³/m³)
<table>
<thead>
<tr>
<th>Stage</th>
<th>Item</th>
<th>Reference or calculation</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>Characteristic strength</td>
<td>Specified N/mm² at days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proportion defective</td>
<td>%</td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td>Standard deviation</td>
<td>Fig 3</td>
</tr>
<tr>
<td>1.3</td>
<td></td>
<td>Margin</td>
<td>C1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specified N/mm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>or</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specified N/mm²</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td></td>
<td>Target mean strength</td>
<td>C2</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>Cement strength class</td>
<td>Specified 42.5/52.5</td>
</tr>
<tr>
<td>1.6</td>
<td></td>
<td>Aggregate type: coarse</td>
<td>Crushed/uncrushed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aggregate type: fine</td>
<td>Crushed/uncrushed</td>
</tr>
<tr>
<td>1.7</td>
<td></td>
<td>Free-water/cement ratio</td>
<td>Table 2, Fig 4</td>
</tr>
<tr>
<td>1.8</td>
<td></td>
<td>Maximum free-water/</td>
<td>Specified Use the lower value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cement ratio</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>Slump or Vebe time</td>
<td>Specified Slump mm or Vebe time mm</td>
</tr>
<tr>
<td>2.2</td>
<td></td>
<td>Maximum aggregate size</td>
<td>Specified kg/m³</td>
</tr>
<tr>
<td>2.3</td>
<td></td>
<td>Free-water content</td>
<td>Table 3</td>
</tr>
<tr>
<td>3</td>
<td>3.1</td>
<td>Cement content</td>
<td>C3</td>
</tr>
<tr>
<td>3.2</td>
<td></td>
<td>Maximum cement content</td>
<td>Specified kg/m³</td>
</tr>
<tr>
<td>3.3</td>
<td></td>
<td>Minimum cement content</td>
<td>Specified kg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Use 3.1 if ≤ 3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Use 3.3 if &gt; 3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modified free-water/cement ratio</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4.1</td>
<td>Relative density of aggregate (SSD)</td>
<td>known/assumed</td>
</tr>
<tr>
<td>4.2</td>
<td></td>
<td>Concrete density</td>
<td>Fig 5</td>
</tr>
<tr>
<td>4.3</td>
<td></td>
<td>Total aggregate content</td>
<td>C4</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>Grading of fine aggregate</td>
<td>Percentage passing 600 µm sieve</td>
</tr>
<tr>
<td>5.2</td>
<td></td>
<td>Proportion of fine aggregate</td>
<td>C5</td>
</tr>
<tr>
<td>5.3</td>
<td></td>
<td>Fine aggregate content</td>
<td>C5</td>
</tr>
<tr>
<td>5.4</td>
<td></td>
<td>Coarse aggregate content</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Cement (kg)</th>
<th>Water (kg or litres)</th>
<th>Fine aggregate (kg)</th>
<th>Coarse aggregate (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>per m³ (to nearest 5 kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>per trial mix of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the unit N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton, Pa = pascal.)
The internationally known term "relative density" used here is synonymous with "specific gravity" and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface dry condition.
1.8 References

http://www.buildsmartercolorado.org/documents/Evaluating%20Fire%20Damage%20to%20Concrete%20Structures_tcm45-343618.pdf

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