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Introduction to concrete design

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1. Aim of the task

The purpose of the exercise is to become familiar with the basic definitions, test methods and design of ordinary and lightweight concrete according to PN-EN 206.

2. Theoretical background

2.1. Definitions

Concrete – a material resulting from mixing cement, coarse and fine aggregate, water and any possible admixtures and additives, which obtains its properties as a result of cement hydration.

Concrete mix – completely mixed concrete components that are able to be compacted using the chosen method.

Hardened concrete - concrete that is solid and has reached a certain level of strength.

Concrete produced at the construction site – concrete produced at the construction site by the contractor for his own use.

Commodity concrete – concrete delivered as a concrete mix by a person or entity who is not a contractor.

Precast concrete product – a concrete product formed and maturing at a location other than its final location.

Ordinary concrete – concrete with a dry density greater than 2000 kg/m^3 but not exceeding 2600 kg/m^3.

Lightweight concrete – concrete with a dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3. This concrete is produced using only or partly lightweight aggregate.

Heavy concrete – concrete with a dry density greater than 2600 kg/m^3.

High-strength concrete – concrete with a compressive strength class greater than C50/60 for ordinary and heavy concrete and concrete with a higher compressive strength class than LC50 /55 for lightweight concrete.

Designed concrete – concrete whose required properties and additional features are given to the manufacturer, who are responsible for delivering concrete in accordance with the required properties and additional features.

Formula concrete – concrete whose composition and components to be used are given to the manufacturer responsible for supplying concrete with such a specific composition.

Cubic meter of concrete – the amount of concrete mix that, when compacted in accordance with the procedure given in EN 12350-6, occupies a volume of one cubic meter.

Admixture – a component added during the mixing process of a concrete mix in small amounts in relation to the weight of cement to modify the properties of the concrete mix or hardened concrete**.**

Additive – a fine-grained component used for concrete to improve certain properties or obtain special properties; usually added in quantities above 5% of cement; the additive can significantly modify the properties of both concrete mix and hardened concrete.

Aggregate – granular material used in construction; aggregate can be natural, artificial or recycled.

Cement – finely ground inorganic material, which – when mixed with water – gives a cement paste, setting and hardening as a result of hydration reactions and processes, and after hardening remains strong and durable, also under water.

Water/cement ratio – ratio of the effective water content to the mass content of cement in the concrete mix..

Characteristic strength – the value of strength below which may be 5% of the population of all possible strength determinations for a given volume of concrete.

2.2.Introduction do concrete mix design

Concrete is a composite material, i.e. a material composed of two or more components (phases) that differ in properties, the combination of which gives a material with better and/or new properties, while the properties of composites are never the sum or average of the properties of its components. Concrete consists of at least three phases – hardened cement paste, aggregate grains and air in the form of pores, scratches or delamination, etc.

Concrete is classified in terms of apparent density in the dry state as:

- heavy concrete – of density in dry state > 2600 kg/m^3,
- ordinary concrete – of density in dry state ≥ 2000 kg/m^3 i ≤ 2600 kg/m^3,
- lightweight concrete – of density in dry state ≥ 800 kg/m^3 i < 2000 kg/m^3.

Concrete can be produced on the construction site (obtained from a mixture made at the construction site), outside the construction site (ready-mixed concrete made from a mixture produced in a concrete plant) or produced in a factory of precast concrete elements (molded and maturing products at a location other than their place of usage).

Designing concrete consists in determining the appropriate type and quantity of components per 1 m^3 of concrete mix ensuring the achievement of the assumed properties of the concrete mix and concrete, which will ensure the ability to maintain material durability under given operating conditions. To this end, one of the available concrete mix design methods should be used - e.g. the three equation method, paste method, etc. Most concrete design methods are experimental and computational methods in which the formulation of the recipe involves the following stages:

2.2.1. Preliminary assumptions: concrete use

The first design stage requires making assumptions concerning:

- **Intended use of concrete** - associated with the use of concrete (monolithic construction, massive construction, prefabricated product, etc.).

2.2.2. Preliminary assumptions: exposure class

- **Exposure class** – classification related to environmental impact conditions for the designed concrete in the structure. Environmental conditions can be chemical or physical effects and can affect concrete or reinforcement or other metal components within it. These actions are not included as a load in the structural design. Each exposure class is marked with a letter and number symbol in which the letters indicate the type of environmental impact, and the number indicates the degree of impact (Table 1).

  For each exposure class, the requirements for the composition and properties of concrete are given, including:
  - the maximum value of the water/cement ratio (w / c),
  - the minimum cement content (by mass),
  - the minimum class of concrete compressive strength.

Meeting the requirements given for each exposure class is synonymous ensuring durability of concrete exploited in a specific environment. It is necessary, however, to correctly select the exposure class, correct arrangement, and concentration and concrete care, design and implementation of appropriate reinforcement cover, as well as proper maintenance of the concrete structure.

Concrete in the structure can be subjected to more than one action, then the combination of exposure classes is assumed, and the most stringent requirements regarding composition and properties are adopted as binding.

Table.1. Description of exposure classes and recommended limits for concrete composition

Mark	Description of the environment Examples of occurrence of classes	Limit values for concrete		
		Max w/c	Min. cement content[kg]	Min compressive strength class
No risk of corrosion or no impact X0				
X0	**Any type of environment except for classes XF, XA and XM (applies to unreinforced concrete)** **Very dry (applies to reinforced concrete)** Concrete inside buildings with very low humidity	-	-	C8/10
Corrosion caused by carbonation XC				
XC1	**Dry** Concrete inside buildings with low humidity or permanently immersed in water	0,70	260	C16/20
XC2	**Constantly wet** Concrete surfaces subject to prolonged contact with water (e.g. foundations)	0,65	280	C16/20
XC3	**Moderately moist** Concrete inside buildings with moderate humidity or outside protected from rain	0,60	280	C20/25
XC4	**Cyclically wet and dry** Concrete surfaces exposed to water, but not like in class XC2	0,55	300	C20/25
Corrosion caused by chlorides (other than from seawater) XD				
XD1	**Moderately moist** Concrete surfaces exposed to chloride air	0,55	300	C30/37
XD2	**Wet, occasionally dry** Pools, concretes exposed to industrial water containing chlorides	0,50	320	C30/37
XD3	**Cyclically wet and dry** Bridge components exposed to sprayed chloride-containing liquids, road surfaces, and parking lots	0,45	320	C35/45
Corrosion caused by chlorides from seawater XS				
XS1	**The action of salts contained in the air** Structures located on the coast	0,50	300	C30/37
XS2	**Constant immersion in water** Elements of maritime buildings	0,45	320	C35/45
XS3	**Tidal zone, splashes and aerosols** Elements of maritime buildings	0,45	340	C35/45
Freeze/thaw corrosion XF				
XF1	**Moderate water saturation** Vertical concrete surfaces exposed for rain and freezing	0,55	300	C30/37
XF2	**Moderate water saturation with de-icing agents** Vertical concrete surfaces of road and bridge structures exposed to freezing and the operation of de-icing agents	0,55	300	C25/30
XF3	**Strong water saturation without de-icing agents** Horizontal concrete surfaces exposed to rain and freezing	0,50	320	C30/37
XF4	**Strong water saturation with de-icing agents** Roads and bridges exposed to deicing agents Splash zones in marine constructions exposed to freezing	0,45	340	C30/37

Table.1. Description of exposure classes and recommended limits for concrete composition - continuation

Chemical aggression XA				
XA1	**Weak chemical aggression** Foundations exposed to the influence of groundwater Bridge supports in river currents	0,55	300	C30/37
XA2	**Moderate chemical aggression** Sewer pipes and wells, petrol station surfaces	0,50	320	C30/37
XA3	**Strong chemical aggression** Collectors for the sewage network, tanks in sewage treatment plants	0,45	360	C35/45
Corrosion caused by friction XM				
XM1	**Moderate hazard** Floors and surfaces operated by pneumatic tires	0,55	300	C30/37
XM2	**Strong hazard** Floors and surfaces operated by solid tires and forklifts with elastomer tires or steel rollers	0,55	300	C30/37
XM3	**Extremely strong wear hazard** Floors and surfaces often invaded by tracked vehicles Bridge pillars, overflow surfaces, drain walls and hydro-technical structures, drop-off basins	0,45	320	C35/45

2.2.3. Preliminary assumptions: concrete compressive strength class

Concrete class – classification of concrete in terms of level of compressive strength, which is the basic functional feature of concrete. Strength classes are marked with a letter and number in which the letters indicate the type of concrete (C – ordinary or heavy concrete, LC - lightweight concrete), and two numbers indicate the minimum characteristic compressive strength determined successively on cubic ($f_{ck,cube}$) and cylindrical ($f_{ck,cyl}$) specimens (see Fig. 1, Table 2, Table 3).

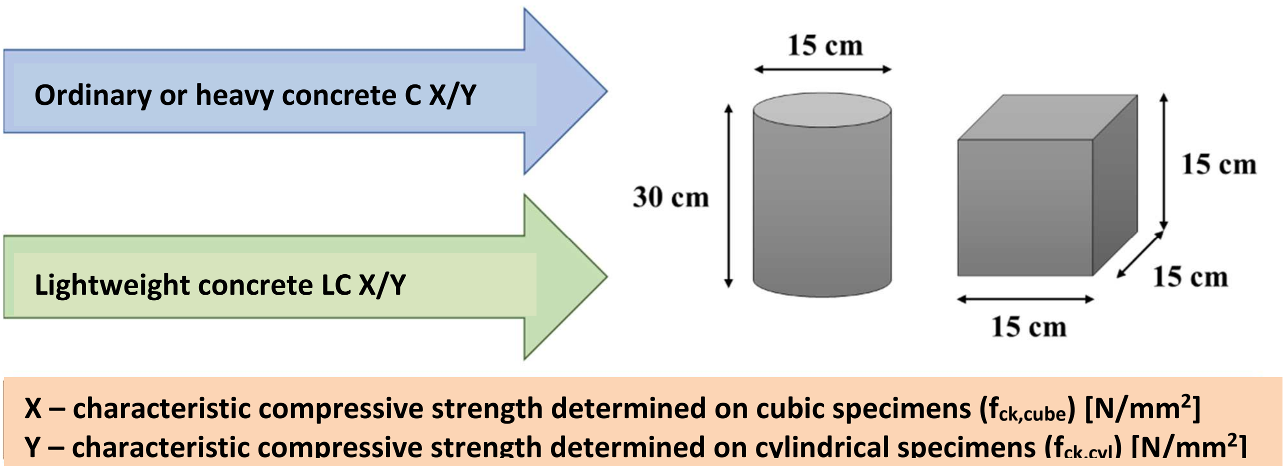


Fig.1. Scheme and dimensions of samples for testing concrete compressive strength

Preparation of specimens for the compressive strength test begins with the application of a thin layer of an anti-adhesion agent to the inner surface of the mold to avoid sticking to the concrete mix. In the prepared molds, a concrete mix is laid in two layers, each layer compacted mechanically (with a vibrating vibrator, on a vibrating table) or manually (with a steel bar 25 times). Finally, remove excess concrete mix and level its surface to the upper edge of the mold, as well as permanently and clearly mark the specimen. Prepared specimens are stored for at least 16 hours, but no more than 3 days, at a temperature of 20°C + 5°C (25°C + 5°C in a hot climate), while protecting against shocks, vibration and water loss. Then specimens are molded and stored until maturity (28 days of ripening) in water at 20°C + 2°C or in a climate chamber at 20°C + 2°C and relative humidity RH > 95%.

Table 2. Compressive strength classes of ordinary and heavy concrete according to PN-EN 206

Ordinary or heavy concrete		
Class	$f_{ck,cyl}$	$f_{ck,cube}$
	[N/mm^2]	
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

Table 3. Compressive strength classes of lightweight concrete according to PN-EN 206

Lightweight concrete		
Class	$f_{ck,cyl}$	$f_{ck,cube}$
	[N/mm^2]	
LC8/9	8	9
LC12/13	12	13
LC16/18	16	18
LC20/22	20	22
LC25/28	25	28
LC30/33	30	33
LC35/38	35	38
LC45/50	45	50
LC50/55	50	55
LC55/60	55	60
LC60/66	60	66
LC70/77	70	77
LC80/88	80	88

2.2.4. Preliminary assumptions: consistence of concrete

Consistence class – classification of concrete mix in terms of liquidity. The consistence classes are identified by a letter and number symbol in which the letters indicate the type of method used to determine the consistence, while the numbers within each class indicate the degree of liquidity of the mix – the higher the number, the greater the degree of liquidity of the concrete mix (Table 4).

When determining the consistence of a concrete mix, the following should be considered: the way the mix is transported and its compaction, the shape of the concreted element and the distribution of reinforcement. The consistency of the concrete mix depending on its degree of liquidity according to PN-EN 12350 can be tested by the method of flow (SF), flow table (F), slump (S), Vebe (V) or the degree of compactness (C). The consistence of concrete mixes with special properties can be tested by special methods agreed between the specifier and a concrete producer. These concrete mix consistence testing methods cannot be used interchangeably, and consistence classes determined by different methods are not directly related to each other.

Table 4. Consistence class according to PN-EN 12350

Method (standard)	Class	Limit values	
Flow (PN-EN 12350-8)	SF1	550 – 650	[mm]
	SF2	660 – 750	
	SF3	760 – 850	
Flow table (PN-EN 12350-5)	F1	≤ 340	[mm]
	F2	350 – 410	
	F3	420 – 480	
	F4	490 – 550	
	F5	560 – 620	
	F6	≥ 630	
Slump test (PN-EN 12350-2)	S1	10 – 40	[mm]
	S2	50 – 90	
	S3	100 – 150	
	S4	160 – 210	
	S5	≥ 220	
Vebe test (PN-EN 12350-3)	V0	≥ 31	[s]
	V1	30 – 21	
	V2	20 – 11	
	V3	10 – 6	
	V4	5 – 3	
Degree of compactness (PN-EN 12350-4)	C0	≥ 1,46	[-]
	C1	1,45 – 1,26	
	C2	1,25 – 1,11	
	C3	1,10 – 1,04	
	C4	< 1,04	

Description of concrete mix consistence test methods:

- **Flow method** – the concrete mix is placed in the form of a truncated cone in one layer, without compaction; then the mold rises and measures the flow diameter in two perpendicular directions, and the average is given as the result.

- **Flow table method** – a refined cone-shaped mold is placed on the reflow table, which is then filled with a concrete mixture in two layers using a spatula, and each layer is compacted with a rod 10 times; the last layer is aligned to the upper edge of the mold; lift the mold vertically and perform 15 lifting cycles and free fall of the upper part of the flow table; the measure of consistency is the average diameter of the flow measured in two perpendicular directions that are simultaneously parallel to the edge of the table.

- **Slump test method** – the concrete mix is laid in the form of a truncated cone in three layers, each layer is compacted 25 times with a rod, and after leveling the last layer, the mold is raised and placed next to it; the measure of consistency is the taper drop in [mm], i.e. the difference between the height of the mold and the height of the highest point of the demolded specimen; the fallout of the deformed mixture must be even.

- **Vebe method** – the concrete mix is laid in the form of a truncated cone in three layers, each layer is compacted 25 times with a rod, and after leveling the last layer, the mold is raised, and then a transparent disk is moved over the upper surface of the molded sample and leaves it until it comes into contact with the mixture; the measure of consistency is the time from the start of the vibrating table to the complete contact of the bottom surface of the transparent disc with the concrete mix.

- **Compaction degree method** – the concrete mix is laid in the container with a metal trowel, avoiding the compaction of the mixture when filling the container; after filling the container, the upper surface of the mix is leveled by cutting, and then the concrete mix is compacted by vibration; the measure of consistency is the distance between the surface of the compacted concrete mix and the upper edge of the container.

2.2.5. Preliminary assumptions: maximal size of aggregate

Class of aggregate maximal size – classifies concrete mixtures due to the maximum size of aggregate grains D_{max} - the upper grain size of the thickest aggregate fraction. The maximum dimension of the aggregate grains used to prepare the designed concrete mix is calculated taking into account the distance between the reinforcement bars (the maximum dimension of the aggregate grains cannot be greater than 3/4 of the distance between the bars), the minimum dimension of the element or structure (the maximum size of the aggregate grains 1/3 of the smallest cross-sectional dimension).

2.2.6. Determination of preliminary assumptions: density class

Density class (only for lightweight concrete) – classifies lightweight concretes in terms of apparent density in the dry state. It is defined by a letter and number symbol, in which the letter is D, and the digit indicates the upper value of the apparent density of one of the ranges in [t/m^3] (Table 5).

Table 5. Density classes of lightweight concrete

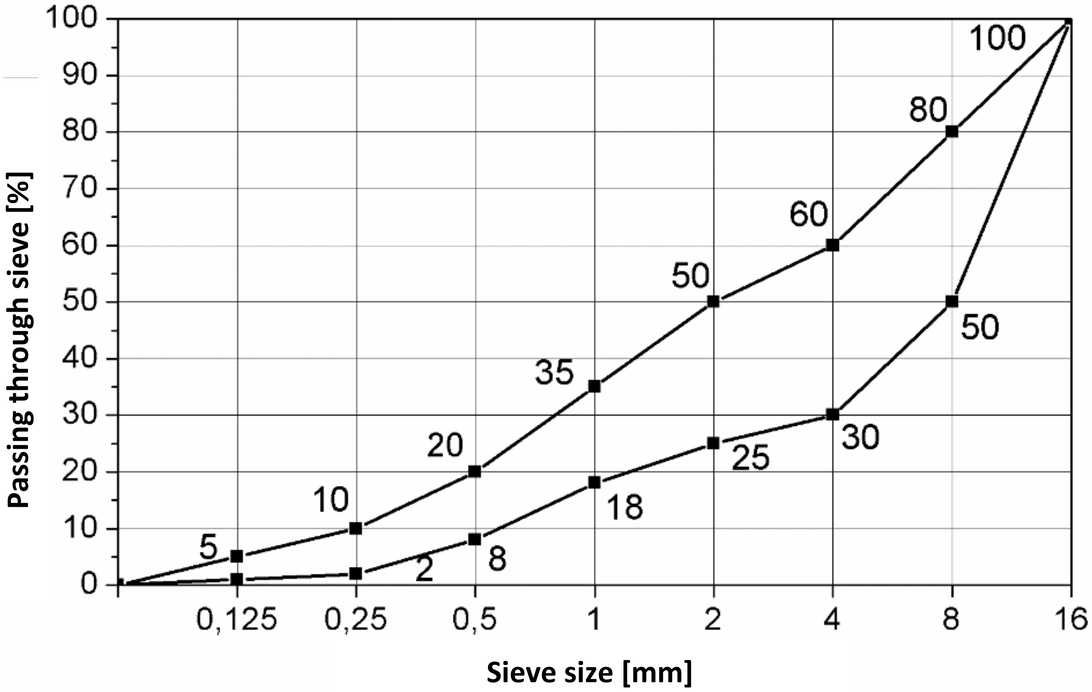
Class	Density [t/m^3]
D1.0	≥ 0,8 i ≤ 1,0
D1.2	> 1,0 i ≤ 1,2
D1.4	> 1,2 i ≤ 1,4
D1.6	> 1,4 i ≤ 1,6
D1.8	> 1,6 i ≤ 1,8
D2.0	> 1,8 i ≤ 2,0

2.3. Qualitative selection, control and testing of concrete mix components

The qualitative and quantitative composition of the designed concrete mix should be selected so that the requirements specified for both the concrete mix are met, as well as concrete (i.e. consistence, density, strength, durability, corrosion protection of steel), taking into account the production process and the planned method of carrying out construction works.

When choosing the type and class of cement, compressive strength level, the conditions for the implementation of works should be taken into account, i.e. ambient temperature, maturation conditions, concrete curing conditions, speed of demolding of the elements, length of transport of the concrete mix, volume of the concreted element, as well as the required concrete properties, i.e. strength class, tightness , frost resistance, potential reactivity of aggregate with alkali, and the purpose of concrete and environmental conditions in which the structure will be located.

The type of aggregate, its grain size and properties should be selected taking into account: execution of works, purpose of concrete, environmental conditions and all requirements for exposed aggregate. The maximum aggregate dimension is selected taking into account the reinforcement cover thickness, reinforcing bar spacing and minimum cross-sectional dimension. The grain size of the properly selected aggregate mix should be within the area defined by the recommended grading curves according to standard PN-B 06265 (Fig. 2). In addition, it should ensure a tight concrete mix with the required consistence, with the lowest possible consumption of cement and water.



Fig, 2. Limiting curves of aggregate for concrete with an upper grain size of 16 mm recommended in the standard PN-B 06250

Mixing water used to make the concrete mix must not affect the setting time, increase of compressive strength and protection of reinforcement against corrosion. Tap water is considered useful for the production of concrete without the need for testing.

There are two types of concrete additives - Type I (almost neutral) and Type II (with pozzolanic or latent hydraulic properties). Type II additives can be included in the composition of concrete within the cement content and thus the value of the w / c coefficient. The suitability and amount of additions to the concrete mix should be assessed and selected in preliminary tests. To determine the amount of additive, which is to be added to concrete, it is recommended to use the so-called concept of the coefficient k.

When using chemical admixtures, the following rules should apply:

- the total amount of admixtures should be less than the permissible amount recommended by the manufacturer and should not be more than 50 g/kg of cement (5% by weight of cement), unless the effect of a larger amount on the properties and durability of concrete is known;
- the use of admixtures in quantities less than 2 g/kg of cement is allowed only if they are mixed earlier with part of the mixing water;
- if the total amount of liquid admixtures exceeds 3 l/m^3 of concrete, the water contained in them should be taken into account when calculating the w/c ratio;
- when using more than one admixture, check compatibility (interoperability).

3. Quantitative composition of concrete mix (3 equations)

A preliminary determination of the amount of components in the concrete mix is made, and then the correctness of the designed composition is checked in an experimental and computational manner, the possible correction of the composition is made and the working recipe is finally developed.

The amount of components in 1 m^3 of concrete mix can be determined by calculation, experimental, calculation and experimental methods. The laboratory exercises will use computational and experimental methods in which the desired properties of concrete mix and hardened concrete are sought, based on three basic technological conditions, as following.

3.1.Equation of compressive strength (Bolomey equation)

Equation of compressive strength (Bolomey equation) - used to calculate the predicted average compressive strength; the strength condition (1) together with the equation combining average and characteristic strength (2) is used to calculate the value of the w / c coefficient based on the assumed concrete strength class:

$$f_{cm} = A_{1,2}\left(\frac{C}{W} \mp 0{,}5\right) \text{ ważny dla } 1{,}2 \leq \frac{c}{w} \leq 2{,}8 \quad (1)$$

$$f_{cm} = f_{ck} + 2\sigma \quad (2)$$

where: f_{cm} – mean compressive strength [MPa], A_1 i A_2 – coefficients depending on the type of cement and aggregate (Table 6), C – cement mass, W – water mass, f_{ck} – characteristic compressive strength [MPa], 2σ – reserve of compressive strength (is assumed to be equal to the standard deviation if known, and when it is not known according to the standard, a value of 2σ = 3 ÷ 6 MPa is assumed).

Table 6. Values of coefficients A_1 and A_2

Aggregate origin	Coefficient	Cement class		
		32,5	**42,5**	**52,5**
Natural	A_1	18,0	21,5	23,0
	A_2	12,0	14,5	15,0
Crushed	A_1	20,0	24,0	26,0
	A_2	13,5	16,0	17,5

3.2.Equation of tightness

Equation of tightness – this condition is used in the design of ordinary concretes when checking the correctness of specific quantities of components in 1 m^3 of concrete mix; this equation represents the sum of the absolute volumes of components contained in 1 m3 of concrete mix:

$$\frac{C}{\rho_C} + \frac{A}{\rho_A} + W = 1000 \pm 2\%$$

where: C – cement mass per 1 m^3 of concrete mix [kg], ρ_C – cement density [kg/dm^3], A – aggregate mass per 1 m^3 of concrete mix [kg], ρ_A – aggregate density [kg/dm^3], W – water mass per 1 m^3 of concrete mix [kg].

It is assumed that the volume of free spaces in the concrete mix after exact compaction is equal to zero. In fact, obtaining such a concentrated mixture is impossible, but for practical purposes this formula is sufficient.

3.3.Equation of consistence

Equation of consistence (water demand equation) – equation for the total amount of water needed to provide the right concrete mix consistence and proper cement hydration:

$$W = C * w_C + A * w_A$$

where: W – water mass per 1 m^3 of concrete mix [kg], C – cement mass per 1 m^3 of concrete mix [kg], w_C – cement water demand [dm^3/kg], A – aggregate mass per 1 m^3 of concrete mix [kg], w_A – aggregate water demand [dm^3/kg].