Materials for Reinforced Concrete

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Introduction — Concrete

Concrete, the most widely used human-made material, is an artificial building material, made of *aggregates* bonded together with a fluid *cement* that hardens to form a hard matrix that binds the materials together into a durable stone-like material.

The essential components of concrete are

- cement
- agregates
- water.

Roman used concrete made with natural (pozzolana) and easy to produce (quicklime) cements. Concrete technology was mostly forgotten for a 1000 years until the invention of Portland cement.

Today, concrete is typically made with Portland cement, that reacts with water to form the hard matrix.

> *Different cements can be used to produce concrete, e.g., also asphalt is a concrete in which the role of cement is taken by bitumen.*

Introduction — Steel

Concrete has a very good strength with respect to compressive stresses, but not so much w/r to tensile stresses.
Romans used concrete in their construction, but used it to build walls, arches and domes in which the resistance to loadings was possible by developing mostly compressive stresses.
The reinforced concrete, where concrete works in compression and reinforcement steel works in tension, was developed starting mid XIX century, initially in France and later in every industrial country that could produce steel and cement as it made possible economical constructions.
The reinforcement steel currently used in Italy is a low-carbon alloy that is not particularly strong but exhibits a good ductility, useful in earthquake resistant designs.

Cement

- Cement, a *hydraulic binder* (that needs water to react), is a fine powder that, mixed with water, produces a slurry that in a few hours hardens due to a chemical reaction of *hydratation*.

  The hydratation process continues as long as there is available water in concrete, leading to an increase in the strength of it.

Cement

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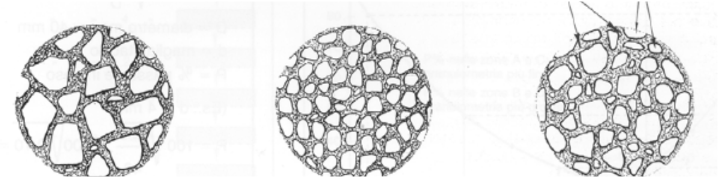
- The most common cement is Portland cement, obtained finely grinding *clinker*, that in turn is produced by sintering (fusing together without melting) limestone and clay into a special oven (the cement kiln). Cement today contains also different components to improve its characteristics.

Aggregates

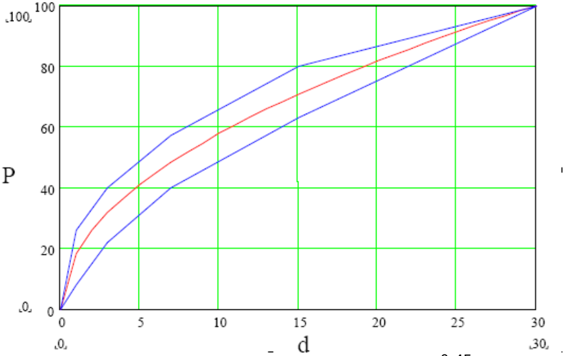
Aggregates are the solid skeleton of concrete and constitute the main part, in weight, of concrete. Their quality is important for a good concrete. Aggregates are made by gravel and sand, mixed in different sizes to get a suitable *granulometry* — the percentage of voids in the aggregate should be as low as possible to have a good concrete using the least possible amount of cement.



Large, large voids — small, small voids but small strength — optimal.

Granulometric curve

The weight percent p of aggregates that are finer than a given diameter d, $p(d)$ is usually described by the Fuller curve,



$$p(d) = 100\sqrt{\frac{d}{d_{\max}}}$$

Another formulation has $p(d) = 100\left(\frac{d}{d_{\max}}\right)^{0.45}$

Aggregate characteristics

Large grains should be from high strength rock, small grains should be from siliceous sands rather than calcareous ones.

Aggregates should be clean, without clay or organic materials that influence bonding between aggregates and cement.

Aggregates influence

- concrete cost,
- strength,
- elastic modulus.

Water

Water in concrete serves two purposes

- reacts with cement, turning the slurry in a solid mass and
- acts as a fluidificant, permitting to cast the slurry in forms.

One one side, any excess of water w/r to the amount required to react with cemente leads to a weaker concrete, on the other not enough water leads to problems when casting the concrete — in general more water than the chemically required amount is used.
It is recommended to use best quality water, free of residuals of organic or chemical nature — impurities interfere with the hydratation reaction, leading to weaker concrete.
In particular the presence of sulphates leads to undesirable phenomena of concrete degradation.

Typical concrete mix

	mass [kg]	volume [dm^3]
air	—	20
water	180	180
cement	300	100
sand	580	223
gravel	1240	477

Typical composition of a cubic metre of concrete

Strength

Concrete strength is measured using compression tests on cylinders or cubes of standard dimensions, computing the stress corresponding to the specimen collapse.

Strength classification

- low strength, $f_c \leq 20\,\mathrm{MPa}$,
- medium strength, $20\,\mathrm{MPa} \leq f_c \leq 40\,\mathrm{MPa}$,
- low strength, $40\,\mathrm{MPa} \leq f_c$.

Density classification

- Regular concrete, approx. $2400\,\mathrm{kg\,m^{-3}}$,
- light concrete, lighter than $1800\,\mathrm{kg\,m^{-3}}$,
- Regular concrete, heavier than $3200\,\mathrm{kg\,m^{-3}}$.

Strength depends on...

Cement

Strength increases almost linearly with cement quantity up to values of 500 kg per cubic metre.

Aggregates

Granulometry and quality of aggregates are both important.

Water/Cement ratio

The chemically required amount of water is 30 kg every 100 kg of cement, but such a cement paste is impossible to work with, w/o addictives at least 60/100 is required.

Addictives

Commonly used addictives are plasticizers that permit to use lower water/cement ratio, increasing the workability of concrete.

Other addictives

Other than plasticizers (or fluidificants)

Accelerators speed up the hydration (hardening) of the concrete, useful to mature concrete in cold weather.

Retarders slow the hydration of concrete, used in large pours where partial setting is undesirable.

Air entraining agents add tiny air bubbles, which reduces damage during freeze-thaw cycles, increasing durability (at the price of a strength decrement)

Pigments can be used for aesthetics.

Corrosion inhibitors to minimize the corrosion of steel.

Environmental conditions

Hardening speed increases with temperature, but a dry hot climate and direct sunligth are nefarious, because lead to evaporation of water near the surface, lower strength and cracking.
In Summer concrete casting must be kept wet and covered to reduce evaporation.
On the other hand, a cold climate slows down the hydratation process and hardening. Further, if water freezes, hydratation stops and bonds between cement and cement and aggregates are ruined by water-ice expansion.

Cover can be attained using mats, towels, sand or waterproof film.

Hardening

In presence of free water hardening can last for years, with always increasing strengths.
Humidity influences the final strength of concrete.
A fast hardening can be obtained using hot steam.

Workability

If a concrete is workable, the pourings are compact, free of cavities and other defects.
Workability is measured using Abrams' cone.

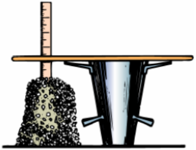
1. Stand on the two foot pieces of cone to hold in firmly in the place during Steps 1 though 4. Fill cone mold 1/3 full by volume [2-5/8" (67 mm) high] with the concrete sample and rod it with 25 strokes using a round, straight steel rod of 5/8" (16 mm) diameter x 24" (600 mm) long with a hemispherical tip end. Uniformly distribute strokes over the cross section of each layer. For the botton layer. this will necessitate inclining the rod slightly and making approximately half the strokes near the perimeter (out edge), then progressing with vertical strokes spirally toward the center.

2. Fill cone 2/3 full by volume (half the height) and again rod 25 times with rod just penetrating into, but not througth, the first layer. Distribute strokes evenly as described in Step 1.

3 Fill cone to overflowing and again rod 25 times with rod just penetrating into, but not through, the second layer. Again distribute strokes evenly.

4 Strikes off excess concrete form top of cone with the steel rod so the cone is exactly level full. Clean the overflow away from the base of the cone mold.

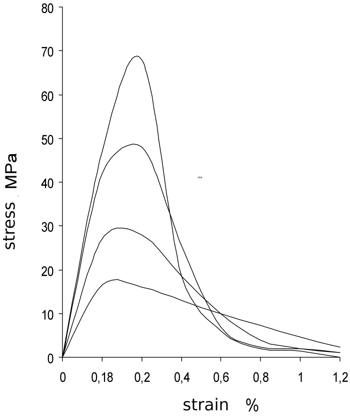
5 Immediately after completion of Step 4, the operation of raising the mold shall be performed in 5±2 sec. by a steady upward lift with no lateral or torsional motion being imparted to the concrete. The entire operation from the start of the filling through removal of the mold shall be carried out without interruption and shall be completed within an elasped time of 2-1/2 minutes



6 Place the steel rod horizontally across the inverted mold so the rod extends over the slumped concrete. Immediately measure the distance from botton of the steel rod to the displaced original center of the specimen. This distance, to the nearest 1/4 inch (6 mm), is the slump of the concrete. If a decided falling away or shearing off concrete from one side or portion of the mass occurs, disregard the test and make a new test on another portion of the sample.

Mechanical Characteristics

Compression tests are performed on 15x15x15 cm cubes or on cylinders 15 cm wide and 30 cm high,



Strain-stress curves are different for different concrete types.

Characteristic Strength

We have hence two different rupture stress measures and two different characteristic values of the strength, the characteristic stress f_c and the cubic characteristic stress, $f_{c,\text{cubic}}$, where $f_c < f_{c,\text{cubic}}$, in any case the strength of 95% of the specimens is greater than the characteristic value.

Strength class

In design, we specify a class for the concrete, implying that the manufacturer has to demonstrate that the characteristic strength of the cast concrete is no less than a design value.
Specifyng a concrete class we specify not only a characteristic value of the compressive strength but also a number of other design parameters.

Strength classes for concrete															Analytical relation / Explanation
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90	
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105	
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98	$f_{cm} = f_{ck}+8$ (MPa)
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0	$f_{ctm}=0,30\times f_{ck}^{(2/3)}$ ≤C50/60 $f_{ctm}=2,12\cdot\ln(1+(f_{cm}/10))$ > C50/60
$f_{ctk,0,05}$ (MPa)	1,1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5	$f_{ctk,0,05} = 0,7\times f_{ctm}$ 5% fractile
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6	$f_{ctk,0,95} = 1,3\times f_{ctm}$ 95% fractile
E_{cm} (GPa)	27	29	30	31	32	34	35	36	37	38	39	41	42	44	$E_{cm} = 22[(f_{cm})/10]^{0,3}$ (f_{cm} in MPa)
ε_{c1} (‰)	1,8	1,9	2,0	-2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8	see Figure 3.2 ε_{c1} (‰) = $0,7\ f_{cm}^{0,31}$ < 2.8
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8	see Figure 3.2 for $f_{ck} \geq 50$ Mpa ε_{cu1}(‰)$=2,8+27[(98-f_{cm})/100]^4$
ε_{c2} (‰)	2,0									2,2	2,3	2,4	2, 5	2,6	see Figure 3.3 for $f_{ck} \geq 50$ Mpa ε_{c2}(‰)$=2,0+0,085(f_{ck}-50)^{0,53}$
ε_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	see Figure 3.3 for $f_{ck} \geq 50$ Mpa ε_{cu2}(‰)$=2,6+35[(90-f_{ck})/100]^4$
n	2,0									1,75	1,6	1,45	1,4	1,4	for $f_{ck} \geq 50$ Mpa $n=1,4+23,4[(90-f_{ck})/100]^4$
ε_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3	see Figure 3.4 for $f_{ck} \geq 50$ Mpa ε_{c3}(‰)$=1,75+0,55[(f_{ck}-50)/40]$
ε_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	see Figure 3.4 for $f_{ck} \geq 50$ Mpa ε_{cu3}(‰)$=2,6+35[(90-f_{ck})/100]^4$

	f_{ck}	R_{ck}	E_c	f_{ctm}	f_{cfm}	f_{ctk}	f_{cfk}	$\min(f_{bk})$	$\max(f_{bk})$
C16/20	16	20	28600	1.90	2.29	1.33	1.60	2.10	3.00
C20/25	20	25	29900	2.21	2.65	1.55	1.86	2.44	3.48
C25/30	25	30	31400	2.56	3.08	1.80	2.15	2.83	4.04
C28/35	28	35	32300	2.77	3.32	1.94	2.32	3.05	4.36
C32/40	32	40	33300	3.02	3.63	2.12	2.54	3.33	4.76
C35/45	35	45	34000	3.21	3.85	2.25	2.70	3.54	5.06
C40/50	40	50	35200	3.51	4.21	2.46	2.95	3.87	5.53
C45/55	45	55	36200	3.80	4.55	2.66	3.19	4.18	5.98
C50/60	50	60	37200	4.07	4.89	2.85	3.42	4.49	6.41

Design strength

Design strength is deduced from f_{ck} using a reduction factor $\alpha_{cc} = 0.85$ to take into account all long-term effects (α_{cc} is not applied when you take into account instantaneous effects) and a material safety factor, specifically for concrete, $\gamma_c = 1.50$

$$f_{cd} = \alpha_{cc} \frac{f_{ck}}{\gamma_c}$$

$$f_{cd} = 0.5667 f_{ck} = \frac{17}{30} f_{ck} = \left(\frac{1}{2} + \frac{1}{15} \right) f_{ck}$$

Young modulus

Concrete has not a clearly defined linear elastic behaviour, conventionally for a tested specimen the elastic modulus is the secant modulus for a stress $f = 0.4 f_c$.
At any rate E is correlated to the strength of concrete, the relationship postulated by the Italian code being

$$E_c = 22\,000\,\mathrm{MPa} \left(\frac{f_{ck} + 8\,\mathrm{MPa}}{10\,\mathrm{MPa}} \right)^{0.3}$$

For medium strength concrete, 30 to 35 GPa.

Poisson modulus

The Poisson modulus is $\nu = 0.20$ for uncracked concrete and $\nu = 0$ for cracked concrete.

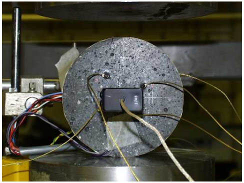
Thermal expansion coefficient

It is $\alpha_T = 10^{-5}\,\mathrm{K}^{-1}$

Tensile strength

Concrete has a brittle failure in tension.

The tensile strength, that is correlated to commpressive strength, is often measured using indirect tests.

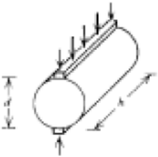


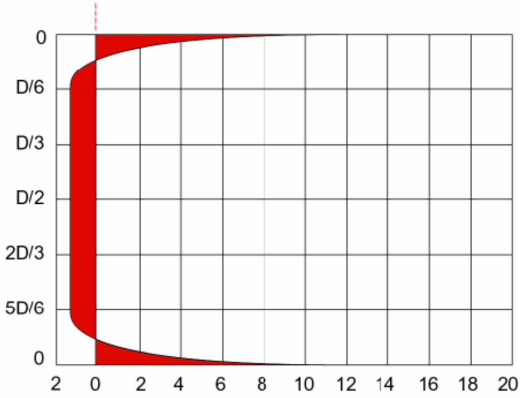
Mean tensile strength can be expressed in terms of f_{ck}, $f_{ctm} = 0.30 f_{ck}^{0.67}$ (beware that 0.30 holds for f_{ck} in MPa), characteristics values are obtained multiplying f_{ctm} by 0.70 or 1.30 respectively.

Tensile strenght for flexure is larger than for a centered axial force,

$$f_{ctm,\text{flex}} = \max(1.6 - h/1000\,\text{mm}, 1) f_{ctm}$$

Brazilian test



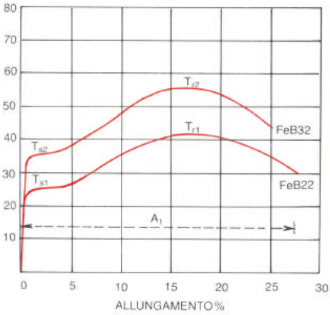


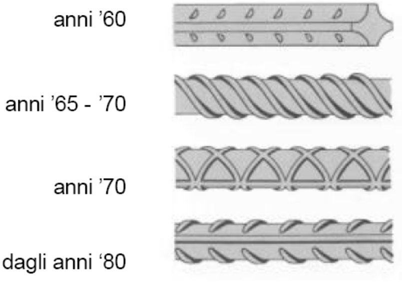
Steel for reinforced concrete

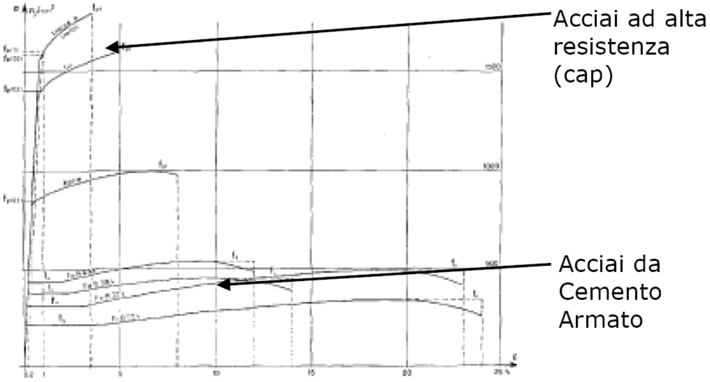
The reinforcement is of two different types of steel, `B450C` and `B450A`. For both classes the characteristic yield and tear strengths are the same

$$f_{yk} = 450\,\mathrm{MPa}, \quad f_{tk} = 540\,\mathrm{MPa}.$$

Steel `B450C` ensures a tear strain not less than 7.5%, `B450A` not less than 2.5%.






Acciai ad alta resistenza (cap)
Acciai da Cemento Armato

Steel-concrete bonding

The steel bars are bond to the surrounding concrete by means of a chemical bond and a mechanical bond (ribbed bars).
Bond is necessary to transfer stresses between the two materials.
The stresses are exchanged in terms of tangential stresses, leading to a diagonal tension field and rupture of concrete in tension, the bonding strength is hence associate to concrete's tensile strength.

$$f_{bk} = 2.25\, \eta_1\, \eta_2\, f_{tck}$$

$\eta_1 = (1.0,\ 0.7)$ describes *bonding conditions*,

$\eta_2 = (1,\ (132\,\mathrm{mm} - \Phi)/100\,\mathrm{mm})$ depends on bar diameter Φ.

Development length

The development length is the minimum lenght of anchorage between steel and concrete that permits yelding of a reinforcement bar.

$$N_d = \frac{\pi \Phi^2}{4} f_{yd} = l_{b,\mathrm{rqrd}} \pi \Phi f_{bd} \quad \rightarrow \quad l_{b,\mathrm{rqrd}} = \frac{\Phi}{4} \frac{f_{yd}}{f_{cd}}$$

The development length can be reduced anchoring the bar mechanically using curved ends, hooks, welded plates.

Durability

Durability is the ability of a material to resist to environmental actions, chemical attacks, abrasion, any process leading to a loss of performances.

Concrete degradation

mechanical abrasion, erosion, collision, explosion

pysical frost-thaw cycles, fire

structural overloads, fatigue, cyclic loads, adaptation

chemical alkaline aggregates, acid attack, sulphate/sulphide attack, clear water attack.

Reinforcement degradation

corrosion *carbonation*, chlorides, stray electric currents.

Durability

- Expected environmental conditions
- Use of the structure
- Required performances
- Material properties
- Members shape and construction details
- Quality assurance for the whole process, workmanship
- Maintenance

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1. Determine the level of environmental aggressivity.
2. Choice of materials, design of members and details to resist environmental hazards during the working life of the construction.

Reinforcement corrosion

Reinforcement corrosion

Concrete, on its own, protects the reinforcement from corrosion.
Concrete is alkaline, iron oxide is formed, iron is *passivated*.
When the alkalinity of concrete decreases, iron hydroxide is formed and (a) strength is reduced to zero in the corroded part and (b) there is a strong volume increase of the corroded part, that swells and expels the concrete cover.

Carbonation calcium reacts with CO2 in air, pH diminishes and rebars are exposed to corrosion.
The process is slow, faster if concrete has more pores hence faster for high values of w/c ratio.
The carbonated depth in mm is $d_c = k\sqrt{y}$, where k depends on w/c ratio and y is time in years. E.g, $k(0.6) = 10.1$, $k(0.5) = 7.0$ and $k(0.4) = 3.8$.

Chlorides when ion Cl is present in significant quantities the protective action of concrete weakens because of increased porosity, water and hoxygen can reach and corrode rebars.

- exogen: sea water
- exogen: anti thaw salts
  The Cl ion enters the concrete by (a) suction in dry concrete and (b) diffusion in pore water in wet concrete.
- endogen: contaminated aggregates, sea sand!

Freeze-taw cycles

Degradation depends on

- saturation levels of pores, if pore is almost full of water the increase of volume of ice exerts an internal pressure that damges concrete
- wetness of concrete, external layers are saturated and subject to ice expansion, leading to the opening of cracks,
- presence of cracks, that drives water to inner layers of concrete.

The problem is mitigated using low w/c ratios and/or entraining air into concrete (using specific addictives) forming microscopic bubbles that act as chambers of compensation when ice forms (note that these bubbles reduce concrete strength).

Prescriptions in favor of Durability

- Structural conception
- Choice of maerials
- Details of constructions
- Execution
- Quality controls
- Surveillance and maintenance
- Special measures (inox steel, coatings, cathodic protection, etc)

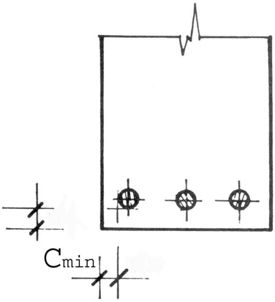
Concrete cover

The single most important action to favor durability is the specification of an appropriate concrete cover c over the reinforcement.

$$c_{\text{nom}} = c_{\text{min}} + \Delta c_{\text{dev}}$$

$$c_{\text{min}} = \max\{c_{\text{min},b}, c_{\text{min,dur}} + \Delta c_{\text{dur},\gamma} - \Delta c_{\text{dur,st}} - \Delta c_{\text{dur,add}}, 10\,\text{mm}\}$$

$c_{\text{min},b}$	minimum cover for bonding
$c_{\text{min,dur}}$	m.c. for environmental hazards
$\Delta c_{\text{dur},\gamma}$	icrement as safety factor
$\Delta c_{\text{dur,st}}$	reduction for use of inox steel
$\Delta c_{\text{dur,add}}$	reduction for use of protective additives.



Minimum cover for bonding

Single bar $c_{\min,b} = \Phi$

Bar bundles $c_{\min,b} = \Phi\sqrt{n_b} \leq 55\,\mathrm{mm}$
where $n_b \leq (3, 4)$ is the nominal number of bars, 4 for vertical, compressed bars and 3 in all other cases.

If aggregate max diameter is larger than $32\,\mathrm{mm}$ $c_{\min,b}$ must be incremented by $5\,\mathrm{mm}$.

Environmental hazard classes

Class	Cause of degradation	# of subclasses
X0	No hazard	1
XC	Carbonation	4
XD	Chlorides (no sea water)	3
XS	Chlorides (in sea salt)	3
XF	Frost thaw cycles	4
XA	Different chemical hazard	3

	Environment desc.	Examples
XC1	Dry or permanently wet	Inside building with low moisture content or permanently immersed in water
XC2	Wet, rarely dry	Surfaces exposed to water, foundations
XC3	Moderately wet	Inside, moderate or high moisture, exterior protected from rain
XC4	Cyclically wet and dry	Surfaces exposed to water not in XC2

	Environment desc.	Examples
XD1	Moderate moisture	Surfaces in contact with saline atmosphere
XD2	Wet, rarely dry	Pools, concrete exposed to industrial waters containing chlorides
XD3	Cyclically wet and dry	Bridge parts exposed to splashes, parking floors

	Environment desc.	Examples
XF1	Moderate water saturation, no antifrost agents	Vertical surfaces exposed to rain and frost
XF2	... with antifrost agents	Vertical surfaces of road structures
XF3	Elevate saturation, no agents	... as XF1
XF4	... with a/f agents or sea water	Roads, bridge decks, marine structures...

Minimum strength class

Carbonation	**XC1, XC2**	C25/30
	XC3, XC4	C30/37
Chlorides	**XD1, XD2, XS1**	C30/37
	XD3, XS2, XS3	C35/45
Frost+Thaw	**XF1, XF2, XF3**	C30/37
Chemical hazard	**XA1, XA2**	C30/37
	XA3	C35/45

$c_{min,dur}$

The reference *structural class* for a working life of 50 years is 4, this class has to be corrected according to the following table

Structural Class							
Criterion	Exposure Class according to Table 4.1						
	X0	XC1	XC2 / XC3	XC4	XD1	XD2 / XS1	XD3 / XS2 / XS3
Service Life of 100 years	increase class by 2	increase class by 2	increase class by 2	increase class by 2	increase class by 2	increase class by 2	increase class by 2
Strength Class 1) 2)	≥ C30/37 reduce class by 1	≥ C30/37 reduce class by 1	≥ C35/45 reduce class by 1	≥ C40/50 reduce class by 1	≥ C40/50 reduce class by 1	≥ C40/50 reduce class by 1	≥ C45/55 reduce class by 1
Member with slab geometry (position of reinforcement not affected by construction process)	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1
Special Quality Control ensured	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1

$c_{\text{min,dur}}$

Environmental Requirement for c_{min} (mm)							
Structural Class	Exposure Class according to Table 4.1						
	X0	XC1	XC2 / XC3	XC4	XD1 / XS1	XD2 / XS2	XD3 / XS3
1	10	10	10	15	20	25	30
2	10	10	15	20	25	30	35
3	10	10	20	25	30	35	40
4	10	15	25	30	35	40	45
5	15	20	30	35	40	45	50
6	20	25	35	40	45	50	55

In lack of prescription from the national annexes (no Italian prescriptions) the recommended values are:

$\Delta c_{\text{dur},\gamma} = 0\,\text{mm}$,

$\Delta c_{\text{dur,st}} = 0\,\text{mm}$,

$\Delta c_{\text{dur,add}} = 0\,\text{mm}$.

$\Delta c_{\mathbf{dev}}$

Recommended value: $\Delta c_{\text{dev}} = 10\,\text{mm}$.
Production subjected to quality control: $5\,\text{mm} \leq \Delta c_{\text{dev}} \leq 10\,\text{mm}$.
Production subjected to quality control and rejection of non conformal items: $0\,\text{mm} \leq \Delta c_{\text{dev}} \leq 10\,\text{mm}$.

In case of pours on irregular surfaces the recommended values, the minimum values are 40 mm (regularized surface) or 75 mm (direct puor on soil).

Example

A building with a planned working life of 50 years has external parts in concrete, indirectly exposed to rain, in class XC3 for the carbonation hazard.
For the external parts a concrete class C30/37 is required, while for the internal parts a class 25/30 is permitted.
A sensible design choice is to choose the same class, C30/37, for both the internal and the external parts (the cost difference is minimal).

Example

What about the concrete cover? The starting class is S4, no reductions are applicable for the external parts and for exposure class XC3 the minimum cover is 25 mm.
For the internal parts, because the class used is better than the class strictly necessary we are in class S3, hence the minimum cover is of 10 mm.
Again a minimum cover of 25 mm should be chosen. A deeper cover is requested in case of $\Phi > 25$ mm to fullfill the requirements in term of bond.
The cover must be measured from the external parts of stirrups.

Example

What about slabs?
No external parts, so XC1 — the structural class is S2 because there is slab behaviour and better concrete: the minimum cover for protection is hence 10 mm, less to the cover required for bonding.
Hypothesizing $\Phi \leq 14\,\mathrm{mm}$ with 5 mm for safety we have
$c_{\mathrm{min}} = 19\,\mathrm{mm} = 20\,\mathrm{mm}$ for the vover of slabs rebars.