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EC 2: Serviceability and Durability

EC 2: Aptitude au service et durabilité

EC 2: Gebrauchstauglichkeit und Dauerhaftigkeit

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SUMMARY

The prescriptions of Eurocode 2 are intended to ensure the required long-term performance. However, the user must apply the relevant prescriptions together with an understanding of engineering models combining the effects of environmental aggressivity, structural form, materials composition, workmanship, and maintenance. Gross error problems cause most premature damage, and improvements at this level will require intensified information and education of persons involved, and specific quality assurance procedures must be enforced.

RESUME

Cette partie de l'Eurocode 2 a été écrite en fonction du comportement à long terme souhaité. Toutefois, l'utilisateur doit non seulement appliquer les prescriptions appropriées du code, il doit aussi tenir compte de l'environnement, de la structure, des matériaux, de la main d'œuvre et de la maintenance. Des erreurs flagrantes à ce niveau sont à la base de la plupart des dommages prématurés. Il faut, pour améliorer la situation, un meilleur réseau d'information, une formation appropriée des utilisateurs et des procédures plus strictes sur le contrôle de la qualité.

ZUSAMMENFASSUNG

Die Vorschriften in EC 2 sollen die erforderliche Lebensdauer gewährleisten. Allerdings muss sie der Benützer mit Verständnis für ingenieurmässige Modellbildung anwenden, das aggressive Umwelteinwirkungen, Formgebung, Ausführungsqualität und Unterhaltung umfasst. Vorzeitige Schäden sind zumeist auf grobe Fehler zurückzuführen, deren Vermeidung intensive Information und Weiterbildung der Beteiligten, aber auch die Durchsetzung spezieller Qualitätssicherungsverfahren verlangen wird.

Background

Concrete has for many years been believed unconditionally to be a very strong and robust material and in its own right to "be strong and durable as rock". Based on today's knowledge of the material characteristics of concrete and with the past two decades of experience with the performance of concrete structures in aggressive environments, a much more differentiated judgement must be made.

It has become painfully clear that concrete is not a foolproof material although its fundamental ingredients are available in abundance and its manufacture requires no special skills,-apparently. The simplicity of old times concrete, and its low cost compared to other available building materials, has made concrete and reinforced concrete the most used building material in the world, appart maybe from sun-dried clay. The availability of such a low cost material has been a very large asset to society, but unfortunately a growing discreppancy has developed over the years between the application of concrete in practice and the refinement of materials research and development of modern days concrete. In combination with more and more advanced applications and more and more aggressive environments not fully identified, concrete has in many cases deteriorated at an unacceptable rate.

Recent years strong efforts to take in the lost land has greatly improved our knowledge of how to design, construct and maintain our concrete structures so their original good reputation can be regained.

For the industrialized community this manifests itself through many different channels spanning from awareness of the need to maintain concrete structures regularly, via concious design and construction procedures, to improved education and training of engineers as well as of concrete workers. Governing major parts of this industry is the national and regional codes, standards and specifications. They form a combined technical and legal basis for the building and construction industry, and have thus a tremendous impact on the final outcome from the building industry, thus determining the future performance of our structures.

On the European level the future Eurocodes will govern the construction industry, and Eurocode 2, EC 2, will cover **"Concrete, Reinforced Concrete and Prestressed Concrete Structures"**. Until the end of 1994 this document will be available as a Prestandard open for discussion until the end of 1993. Then the fate of this EC 2 will be determined by the 18 CEN member Countries. Special provisions ensuring durability and long term performance are covered by the European Standard EN 206 on **"Concrete. Performance, production, placing and compliance criteria"**. Currently this standard is available as a Prestandard, ENV 206, also open for discussion, and changes in the current text may be expected before the final version is obtained.

Objectives of EC 2 and ENV 206

Within the topics of Serviceability and Durability EC 2 together with ENV 206 shall ensure that concrete structures are designed and constructed so they maintain their required durability and performance for a sufficiently long period of time, which is expected to be in excess of 50 years. ENV 206 itself gives technical requirements for the constituent materials of structural concrete, the concrete composition, the properties of fresh and hardened concrete and their verification. It also covers the production of concrete, its transport, delivery, placing and curing, and the quality control procedures. The standard also ensures that the concretes can be used with the relevant Eurocodes.

Limitations

EC 2 and ENV 206 cover all ordinary type structures with foreseeable environmental conditions and expected normal service lives. However, there are a number of situations where additional, or sometimes even different, requirements may be necessary. This could be for:

- complex structures such as special viaducts, large dams, pressure vessels for nuclear power stations, offshore structures, and for roads

- using new constituent materials, special technologies (e.g. manufacturing processes) or innovating technologies in the building process.

In all such cases the measures chosen shall be suitable and shall not conflict with the requirements for safety and durability of the structure.

Multidisciplinary Problems

Codes and Standards are not foolproof, and following then blindfolded will not necessarily result in satisfactory structures. One of the most important realizations from recent years experience gained with structures in service is, that only by a coordinated effort by all parties involved in all phases of the planning, construction and use of structures can durability problems be avoided throughout the expected lifetime, regardless of how strictly the code or the standard is followed.

This requires cooperation between the following four parties:

- The owner, by defining his present and foreseen future demands and wishes, if any.

- The designers (engineers and architects); by preparing design specifications (including proposed quality control schemes) and conditions.

- The contractor who should follow these intentions in his construction works. Most commonly also subcontractors are involved.

- The user, when he is responsible for the maintenance of the structure during the period of use.

Any of these four parties may - by their actions or lack of actions - contribute to an unsatisfactory state of durability of the structure and thus cause a reduction of the service life. Also interactions between two parties may cause faults which can have an adverse effect on durability and service life.

Modern Durability Technology

Consistent engineering models describing the deterioration mechanisms threatening concrete structures incorporate knowledge from a very wide range of technical disciplines, such as

- statics (structural behaviour)
- materials technology (materials composition)
- design (codes, structural form, design traditions)
- execution (workmanship, local traditions)
- statistics
- economy.

Experience from inspection, maintenance and repair of existing structures must be used to identify and calibrate the critical parameters governing these engineering models.

Based on these models, durability performance can be developed to include the whole range of structural engineering problems from operation, maintenance, inspection, assessment, repair and re-design of existing structures to design and execution of new structures.

Deterioration Mechanisms and Governing Parameters

The number of really significant deterioration mechanisms are few, i.e. only the following four are really important:

- Reinforcement corrosion
- Alkali-aggregate reactions
- Chemical attacks (e.g. sulphate)
- Freeze-thaw bursting

Corrosion destroys primarily the reinforcement and subsequently cracks and spalls the concrete. The three others destroy primarily the concrete.

The presence of water and salt are the two most decisive parameters governing these mechanisms.

Water

All the major deterioration mechanisms require the presence of water in sufficient amounts. Only temperature conditioned cracking, shrinkage cracking, and mechanical wear can take place without water, and such crack formations do not necessarily represent deterioration as such, but can open the concrete for ingress of harmful materials.

Any kind of dry-keeping of the concrete will reduce the rate of development of damage. Indoor concrete is normally sufficiently dry for damage not to develop under normal usages, even if all other conditions for the development of damage are present.

Salt

Chloride based salts are some of the most harmful materials to which concrete can be exposed, either when accidentally mixed into the fresh concrete or when coming on to the concrete surface. The harmful effect is fourfold:

- Chloride based salts provide serious risks for local pit corrosion of the bars when the chlorides reach the reinforcement. This is the most serious threat to concrete structures in the nineties,- as it was in the eighties!

- If the salt contains alkali-metal ions (Na^+, K^+), they also enter the concrete with added risk of alkali-aggregate reactions in case the concrete at the same time contains reactive particles.

- As de-icing agent, salting causes a freeze chock of the concrete surfaces when ice is forced to melt. This can result in thermo-cracks which open the concrete for subsequent ingress of water, salts or other materials. Lamination, spalling and crumbling of the concrete can occur due to combined salting and frost-thaw impacts.

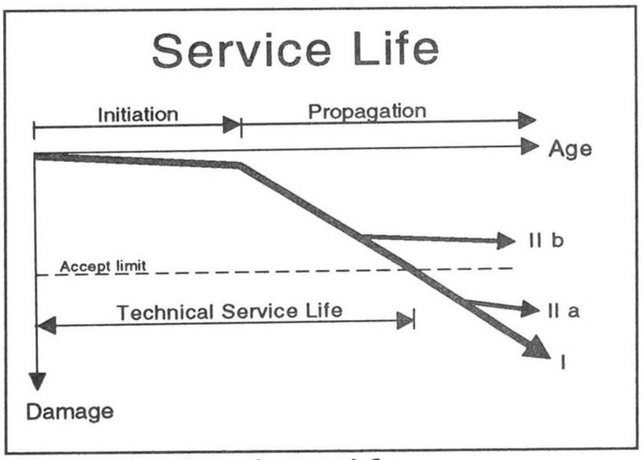
- Salt is hygroscopic since it is retaining water. With salt in the concrete drying out is more difficult and so is stopping possible development of deterioration.

Time Development

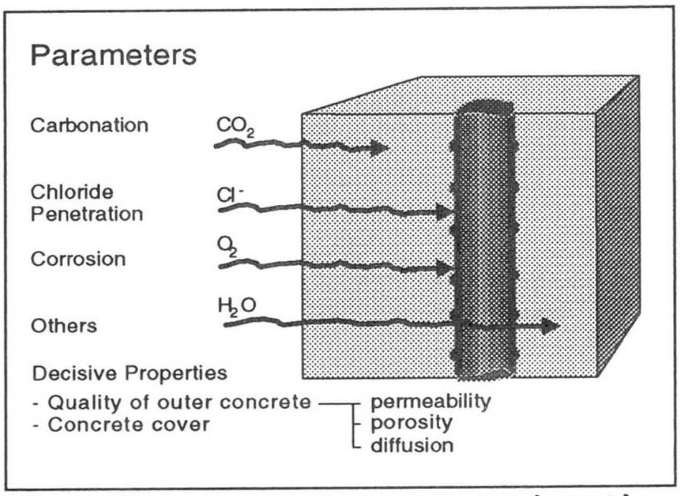
In overall terms nearly all deterioration mechanisms develop in time following a two-phase broken curve as illustrated on Fig.1. The two phases represent:

- An ***initiation phase***, during which no noticeable weakening of the material or of the function of the structure occurs, but some protective barrier is broken down or overcome by the aggressive media. Carbonation, chloride penetration and sulphate accumulation, the latter two accelerated by cyclic wetting and drying, are examples of such mechanisms determining the duration of the initiation period.

- A ***propagation phase***, during which active deterioration normally proceeds rapidly and in a number of cases at accelerating pace. Reinforcement corrosion is one such important example of propagating deterioration.



Figur 1: Service Life



Figur 2: Parametres governing the rate of deterioration

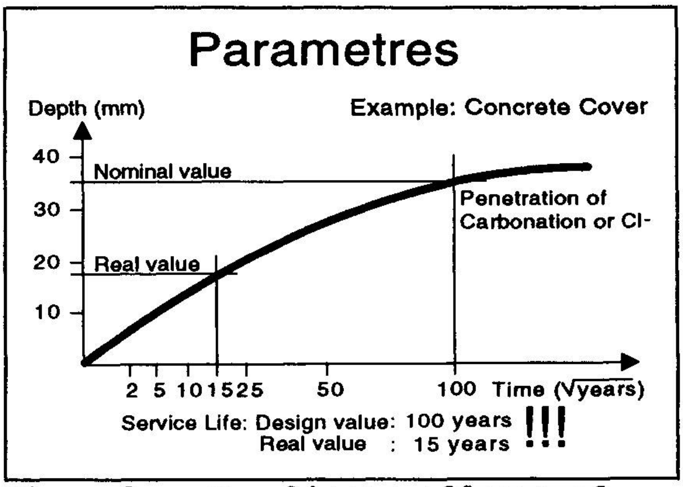
Transport Phenomena

When understanding the mechanisms in both the initiation phase and the propagation phase one very decisive fact comes clear, as illustrated on Fig.2:

All important deterioration mechanisms depend on some substance penetrating from the outside into the bulk of the concrete through the surface.

This observation is important as it highlights which zones are critical for the future performance, when designing and executing structures. Cyclic wetting and drying effects will strongly accelerate the rate at which dissolved aggressive substance enters the concrete and concentrates near the surface of evaporation.

All these transport mechanisms are non-linear by nature. This must be considered when evaluating the consequences of a given aggressive environment acting on a structure. For example, the penetration rate of a carbonation front into concrete is nearly proportional to the square-root of the exposure time. Chloride and sulphate diffusion will have a similar non-linear rate of penetration. This fact has serious practical implications, as smaller covers than anticipated in the design may lead to severely shortening of the service life, as exemplified on Fig.3.



Figur 3: Non-linear effects of governing parametres

Design

It is the prime concern during the design process to consider the transport phenomena mentioned above and ensure that they are kept under control. This is the key to designing for long service life.

Consequently, much effort shall be made to ensure an appropriate quality of the concrete in the outer layer of the concrete structures, i.e. a well compacted strong concrete "skin" is needed with low permeability, low diffusivity and without map cracking. Besides, an adequate thickness of concrete cover to the reinforcement shall be provided. These requirements emphasize the need for careful and controlled moisture curing of the structure, as well as avoiding thermo cracking by controlling the temperature profile caused by heat of hydration.

Service life depends equally on the behaviour of structural and non-structural elements. Both shall be considered during design, construction and use of the structure.

Non-structural elements such as drainage, joints, bearings, installations etc. may require specialist attention other than that of structural engineering. Particular structural components such as anchorages, couplers and deviators for prestressing tendons and their location in the structure may require special attention.

Such equipment in structures usually have a shorter service life than the structure itself, and adequate provisions for inspection, maintenance and replacement of such elements should be provided in the design.

Structures should Grow Old Gracefully

The design should consider detailing which increases self-protection and robustness of the structure against aggressive environment. This includes provisions to ensure satisfactory weathering and ageing of exposed surfaces thus allowing buildings to grow old gracefully without expensive maintenance. An appropriate selection of structural form should be ensured at an early, conceptual stage of the project.

This is a problem very much overlooked by engineers as it "does not influence safety and serviceability" in technical sence. However, it has a great influence on the public opinion and on the user of structures. The confidence in structures is much influenced by the visual appearance. The reputation of our building material suffers much from dirty and shabby looking structures, see e.g. Fig.4, and in this sence engineers should cooperate intensively with the architects who should be much more concerned with this aspect than they have been in the past. In this respect valuable works have been done in Belgium and in England.

Figur 4: Miscoloured facade due to dirt and soot

Environmental Actions

Actions on structures influencing durability and performance are chemical and physical elements of the environment which result in effects that are not considered as loads in structural design.

Environmental conditions specified in EC 2 and in ENV 206 are presented in **Table 1.**

Table 1: Exposure classes related to environmental conditions

Exposure class		Examples of environmental conditions
1 dry environment		interior of dwellings or offices[1]
2 humid environment	a without frost	- interior of buildings where humidity is high (e.g. laundries) - exterior components - components in non-aggressive soil and/or water
	b with frost	- exterior components exposed to frost - components in non-aggressive soil and/or water and exposed to frost - interior components where the humidity is high and exposed to frost
3 humid environment with frost and de-icing agents		- interior and exterior components exposed to frost and de-icing agenst
4 seawater environment	a without frost	- components completely or partially submerged in seawater, or in the splash zone - components in saturated salt air (coastal area)
	b with frost	- components partially submerged in seawater or in the splash zone and exposed to frost - components in saturated salt air and exposed to frost
The following classes may occur alone or in combination with the above classes:		
5 aggressive chemical environment[2]	a	- slightly aggressive chemical environment (gas, liquid or solid) - aggressive industrial atmosphere
	b	moderately aggressive chemical environment (gas, liquid or solid)
	c	highly aggressive chemical environment (gas, liquid or solid)

1) This exposure class is valid only as long as during construction the structure or some of its components is not exposed to more severe conditions over a prolonged period of time

2) Chemically aggressive environments are classified in ISO 9690. The following equivalent exposure conditions may be used:

Exposure class 5 a: ISO classification A1G, A1L, A1S
Exposure class 5 b: ISO classification A2G, A2L, A2S
Exposure class 5 c: ISO classification A3G, A3L, A3S

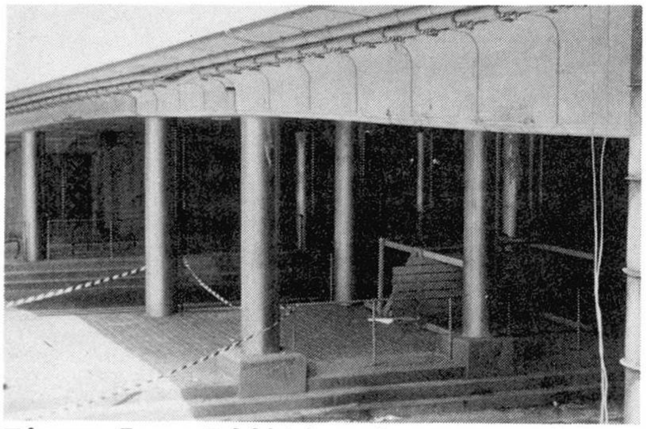
This classification covers most of the ordinary structures to be designed according to EC 2. However, some additional remarks can be valuable.

Class 1 should cover the large majority of interior concrete used in practice, but footnote 1 may cause uncertainty in some areas. This class is valid only as long as during construction the structure or some of its components is not exposed to more severe conditions over a prolonged period of time. In normal construction the exterior exposure will be more severe than the permanent interior condition, in some cases, e.g. with winter construction, this difference will be very pronounced. Thus the open question is "how long is a prolonged period of time"? It seems reasonable that only if there are risks of critical amounts of aggressive substance, like chlorides, to accumulate in the concrete during this exposure, or experience shows that frost damage may occur, then a more severe classification shall be used.

Class 2 covers a large number of interior and particularly exterior structures or structural components with the main limitation that there is no exposure to salt.

Class 3 covers salt exposed land based structures, whereby the majority of bridges, bridge columns, and balkonies exposed to de-icing salts, belong to this exposure class. This class may require some carefull consideration of the micro-environment, because very local concentrations of moisture, cyclic wetting and drying with salty water, salt laiden fog etc., may locally create very aggressive conditions that would require additional protection. The general or overall classification does not suffice in such cases, and the future performance will depend strongly on the competence and experience of the design engineer.

Class 4 covers all marine structures. In this respect the difference between class 3 and class 4b is small. Again the cyclic wetting and drying condition represents the most severe situation. Experience has shown that normal design provisions usually cannot ensure very long service life in these zones. Due to the especially aggressive effects of chlorides with respect to corrosion of reinforcement, and the difficulty to ensure long term reliable repairs due to the catalytic effect of chlorides, such zones should be identified in the design and be considered specially. In such situations additional protection may become necessary, see e.g. Fig.5.



Figur 5: Additional protection. Stainless steel lined reinforced concrete columns frequently exposed to de-icing salt

Class 5 covers chemical attacks from gaseous, liquid or solid substance defined by special ISO classifications. It is important to realize, that this class only covers chemical aggressivity towards concrete, and not substance that only is aggressive when reaching the reinforcement or other steel items embedded in or partially cast into concrete, but is non-aggressive to concrete.

Resistance through Design and Execution

To cope with the identified environmental actions, the following approach has been adopted.

The concrete shall be able to protect the reinforcing steel against corrosion and withstand satisfactorily the environmental and working conditions to which it is exposed during the intended lifetime. Thus the following factors have to be taken into account by the designer:

a) choice of suitable constituents
b) choice of concrete composition
c) mechanical attacks
d) mixing, placing and compaction of the fresh concrete
e) curing of the concrete

The curing shall particularly ensure that the surface zone of the structure, i.e. the cover to the reinforcement, achieves the potential properties to be expected from the chosen mix. All these factors considered shall be controlled and verified by production control by the contractor, the subcontractor or the supplier, each within his specific task, as specified in more detail in ENV 206.

Concrete

The durability requirements in ENV 206 for the fresh and hardened concrete related to the environmental exposure are presented in **Table 2.**

Table 2: Durability requirements related to environmental exposure

Requirements	Exposure class according to table 1								
	1	2a	2b	3	3a	4b	5a	5b	5c
max w/c ratio for[2] - plain concrete - reinforced concrete - prestressed concrete	- 0.65 0.60	0.70 0.60 0.60	0.55	0.50	0.55	0.50	0.55	0.50	0.45
min cement content[2] in kg/m^3 for - plain concrete - reinforced concrete - prestressed concrete	150 260 300	200 280 300	200 280 300	300	300	300	200 280 300	300	300
min air content of fresh concrete in % for nominal max aggregate size of[3] - 32 mm - 16 mm - 8 mm	- - -	- - -	4) 4 5 6	4) 4 5 6	- - -	4) 4 5 6	- - -	- - -	- - -
frost resistant aggregates[6]	-	-	yes	yes	-	yes	-	-	-
impermeable concrete according to clause 7.3.1.5	-	-	yes	yes	yes	yes	yes	yes	yes

Requirements	Exposure class according to table 1	
types of cement for plain and reinforced concrete according to EN 197		sulphate resisting cement[5] for sulphate contents > 500 mg/kg in water > 3000 mg/kg in soil
	These values of w/c ratio and cement content are based on cement where there is long experience in many countries. However, at the time of drafting this pre-standard experience with some of the cements standardized in EN 197 is limited to local climatic conditions in some countries. Therefore during the life of this pre-standard, particularly for exposure classes 2b, 3, 4b the choice of the type of cement and its composition should follow the national standards or regulations valid in the place of use of the concrete. Alternatively the suitability for use of the cements may be proved by testing the concrete under the intended conditions of use. Additionally cement CEI may be used generally for prestressed concrete. Other types of cement may be used if experience with these types is available and the apælication is allowed by the national standards or regulations valid in the place of use of the concrete.	

1) In addition, the concrete shall be protected against direct contact with the aggressive media by coatings unless for particular cases such protection is considered unnecessary.
2) For minimum cement content and maximum water/cement ratio laid down in this standard only cement listed in clause 4.1 shall be taken into account. When pozzolanic or latent hydraulic additions are added to the mix, national standards or regulations, valid in the place of use of the concrete may state if and how the minimum or maximum values respectively are allowed to be modified.
3) With a spacing factor of the entrained air void system < 0.20 mm measured on the hardened concrete
4) in cases where the degree of saturation is high for prlonged periods of time.
Other values or measures may apply if the concrete is tested and documented to have adequate frost resistance according to the national standards or regulations valid in the place of use of the concrete.
5) The sulphate resistance of the cement shall be judged on the basis of national standards or regulations valid in the place of use of the concrete.
6) Assessed against the national standards or regulations valid in the place of use of the concrete.

The cements accepted according to EN 197 have been the subject of much discussion, and the individual cement compositions adopted for the different environmental classes should be carefully considered. In particular some cements contain very large contents of pozzolanic additions making them less suited to resist some external conditions, e.g. frost and de-icing salts. Such cements are only frost resistant with the appropriate amount and distribution of entrained air. In the cements covered by EN 197 all powders in the mix are considered to have the same efficiency as cementitious material. Some countries have been used to consider e.g. microsilica more efficient than flyash (factor on strength of 2 to 0.5 respectively, when compared to Ordinary Portland Cement).

Water/cement ratio has deliberately been keept low, knowing the very strong influence this parameter has on the diffusivity of concrete. In particular the maximum value of 0.65 in exposure class 1 could be considered severe, but this will undoubtedly become advantagous in practice, as the concern about interior components exposed during construction, as mentioned above, becomes less of a worry. The maximum values specified will lead to target values being about 0.03 lower. For locally very exposed zones outside the general classification, lower values should be used, e.g. max. values of 0.35 to 0.40 would be relevant for chloride attacks.

Referring to Table 20 of ENV 206, a correlation between w/c ratio and strength class has been attempted. In practical terms this can be very convenient, and works apparently well in some cases. This is the case when considering frost resistance and resistance against carbonation which correlates well with strength classes, but this is certainly not the case when considering penetration of chlorides. Special requirements to ensure low diffusion coefficients in such cases should be provided.

Minimum cement content ensures a minimum amount of binder in the concrete in spite of the fact that strength requirements in several cases could be satisfied with much lower cement contents. This is valuable for durability, but has the drawback that it weakens the motivation to ensure good control with low variations in control parameters; strength requirements are satisfied even with sloppy control. One alternative could be to specify rather high minimum strength classes for the different exposure classes, this could keep up motivation for good quality control as this has a direct beneficial effect on the economy of the producer.

The requirements in Table 2 for minimum air content, frost resistant aggregates, impermeable concretes and types of cement seem self explanatory.

The reqirements of Table 1 in ENV 206 specifies the maximum chloride content of concrete. They are:

plain concrete: 1.0%
reinforced concrete: 0.4%
prestressed concrete: 0.2%

It is interesting to note that the value for reinforced concrete is the same as the corrosion threshold value often presented in the literature, so the ENV 206 allows no future penetration of chlorides.

Concrete cover

The concrete covers specified in EC 2 are presented in **Table 3.**

Table 3: Minimum cover requirements for normal weight concrete[1]

		Exposure class, according to table 1								
		1	2a	2b	3	4a	4b	5a	5b	(3) 5c
(2) Minimum cover (mm)	Reinforcement	15	20	25	40	40	40	25	30	40
	Prestressing steel	25	30	35	50	50	50	35	40	50

Notes:

1) In order to protect the reinforcement against corrosion, these minimum values for cover should be associated with particular concrete qualities, to be determined from Table 2 above.

2) For slab elements, a reduction of 5 mm may be made for exposure classes 2-5.

3) A reduction of 5 mm may be made where concrete of strength class C40/50 and above is used for reinforced concrete in exposure classes 2a-5b, and for prestressed concrete in exposure classes 1-5b. However, the minimum cover should never be less than that for Exposure Class 1 in Table 3 above.

4) For exposure class 5c, the use of a protective barrier, to prevent direct contact with the aggressive media, should be provided, see e.g. Fig.5.

Special care shall be taken to ensure a high quality impermeable concrete in the outer layer - or "skin" - of the structure. Casting and curing conditions have a decisive influence on the permeability of this "skin"-concrete. Experience has shown that some individual judgement of cover is needed in especially aggressive environments.

The nominal values, c_{nom}, are equal to the minimum values plus tolerance according to the following rule:

$$c_{nom} = c_{min} + \text{tolerance}$$

Tolerances are in the range of 5 to 10 mm for insitu cast formset concrete, and in the range of 0 to 5 mm for precast elements, if production conctrol can guarantee these latter values and if they are verified by appropriate quality control.

Spacers shall be designed according to c_{nom}. This fact is often overlooked! When controlling concrete cover after placing and hardening of concrete the measured values may not be less than c_{min}.

The values of cover above, quoted from EC 2, refer only to corrosion protection of the reinforcement. Other reasons may warrant larger covers such as:

- ensuring bond strength
- ensuring fire protection
- use of large aggregate sizes
- prevent spalling

In aggressive environments spacer material should preferably have good adhesion to the concrete. Requirements to concrete quality in the outer layer - or "skin" - of the structure shall also be satisfied for concrete spacers.

Curing

In order to obtain the potential properties to be expected from the concrete, especially in the surface zone, thorough curing and protection for an adequate period is necessary. Such curing and protection should start as soon as possible after the compaction of the concrete.

Guidance as to curing methods and curing times are given in ENV 206, but for more complicated cases it is recommended to perform a more detailed analysis of the curing needed, as this is very different depending on, among others, the type of cement chosen. Concretes with pozzolanic additions are very sensitive to early drying out.

In practice protection against thermal cracking of the surface is performed at the same time as the moisture curing is performed. The provisions to satisfy both requirements are thus often combined. The maximum temperature difference between the center and the surface of the hardening concrete shall be less than

20 °C. However, thermo cracking due to temperature differences across construction joints often cause more severe problems than the temperature difference between the center and the surface. Based on extensive analysis and practical experience it can be recommended for the ordinary cases to ensure a maximum temperature of 15 °C across construction joints.

Special Protective Measures

In case of especially aggressive environments where the normal provisions to ensure the required service life cannot suffice, and in cases where insufficient durability have resulted in damage to an existing structure, special protective measures may be applied to obtain the required service life.

The special protective measures are of the following type:

- Provide smooth surfaces and minimize the area exposed to the environmental aggressivity

- Provide structural protection such as:
  * roof, eaves or similar to protect concrete surfaces against rain,
  * surface protection
  * increased concrete cover. Provide special skin reinforcement if $c_{nom} \geq$ 70 mm.
  * reduce environmental aggressivity by e.g. surface insulation thus controlling heat and moisture conditions in the concrete (in buildings and housing).

- Provide special protection of the reinforcement, such as:
  * place prestressed reinforcement in sheathings (metallic or plastic) with special corrosion protective grout or void filler
  * coating of reinforcement
  * cathodic protection
  * select non-corroding reinforcement (specific stainless steel).

- Provide special monitoring systems (e.g. a warning system) to follow the condition of the structure.

- Provide intensified inspection and maintenance routines to cope with early deterioration. Implement a Management System.

With respect to epoxy coated reinforcement, this technology has only recently been introduced in Europe. The usual procedure has been to coat straight bars individually. Then cut them to length and bend them to form. This required patch repairs of the coating at cut ends and at damaged bends. When reinforcing bars are coated individually, they will not be in electric contact in the structure. This will prevent a later installation of cathodic protection, should the need arise.

The first large scale European application of epoxy coated reinforcement was for the 62,000 precast tunnel segments for the lining of the Eastern Tunnel of the Great Belt Link in Denmark. The cages were fully welded together prior to cleaning and coating, where the fluidized bed dipping technique was applied to coat the finished cages. This minimized the need for repairs and allows for cathodic protection to be applied some time in the future, should the need arise.

Gross-Error Problems, a Challenge to Education, Information and Quality Assurance

Analysing numerous cases of serious premature deterioration reveals that in the majority of cases the cause of damage is not due to normally anticipated (accepted) insitu variations in material properties, concrete covers etc. but is due to gross deviations from anticipated values. Examples are:

- 5 mm covers instead of 50 mm
- large honeycombing/bad compaction
- 150 kg cement/m^3 instead of say 350 kg
- w/c ratio = 0.75 instead of 0.45
- Design faults threatening safety (e.g. insufficient reinforcement)
- Errors in specified types of cement (e.g. high sulphate resistant cement in heavily chloride contaminated environments).

Such gross-error problems cannot be solved by stricter Eurocodes or tighter European Standards, nor by more refined design procedures, nor by the use of advanced theories of reliability. Only by enforceing relevant information and education routines and by carefully planned and strictly enforced quality assurance procedures can the frequency of such gross errors be minimized,- and our profession maintain respectability.