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Teach-In 2

Durability in Design, Detailing and Construction

Durabilité des constructions: dimensionnement, projet et détails constructifs

Dauerhaftigkeit von Bauwerken: Projektierung, Konstruktion und Herstellung

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Durability in Design, Detailing and Construction

Chemical and physical effects on the durability of concrete structures

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1 General

Today, the main criteria for durability are well understood, agreed upon, and reflected in most specifications and codes [1],[2]. Improved durability of stauctures requires both, knowledge of materials and experience in execution. The fields which have to be mastered are improved materials characteristics, architectural and structural design, process of execution, inspection techniques and maintenance procedures.

Planning and execution must meet quality assurance requirements. Quality assurance covers technology as well asorganization: The construction company, the local branch,the building site, the client and the architect need to be involved in every total project. Schematised approaches to service life design are not considered reliable in practice.

Concerning these specific items, the Teach-In is subdivided into the following main sections: 1.Theoretical Background (Hillemeier), 2. Design (Pakvor), 3. Execution (Limsuwan), 4. Curing (Müller), 5. Examples (Dillman).

2 Influences on durability

Durability of concrete structures is mainly controlled by transportation processes of heat, moisture and chemical substances and by physical, chemical and biological corrosion as type and rate of degradation processes of concrete and steel.

Dominant factors for durability of structures are water and the transport mechanisms of water and gases within pores and cracks. Planning and design must aim to minimize negative effects of water attack.

3 Necessity of dense and durable concrete

Concrete consists of two major phases: cement paste and aggregate. The mechanical as well as the durability properties of concrete are determined above all by the cement paste.

Cement and water react with each other to form the fibrous and very finely interlocking cement gel. The cement needs only a portion of the mixing water for its hydratation. Water that is not used by the cement evaporates, leaving capillary pores behind that runs through the cement paste like veins. It is obvious that a high water content and insufficient curing increases the evaporation and thus the number of capillary pores breaking through to the surface of the concrete. Acidic gases invade the concrete through these pores and react with the alkaline elements of the hydrated cement.

3.1 Concrete attack mechanisms

Carbonization. Carbon dioxide (CO_2) in the air changes alkaline calcium hydroxide into neutral limestone and thus prevents the rust protection of the steel reinforcement:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

$Ca(OH)_2$	CO_2	$CaCO_3$
high alcalinity, pH ~ 12,6, corrosion protection of steel	gas, 0,03 V-% in the air	lime-stone, pH ~ 8 , no corrosion protection of steel

Chloride attack. The permeability of concrete facilitates the entry of chlorides. This, in turn, makes the destructive chloride corrosion possible. It is well known that the presence of significant levels of free chloride ions (0,4 M-% of cement Cl combined with Friedel-salt $C_3A \cdot CaCl_2 \cdot 10H_2O$) causes disruption of the protective passivating, thin film of gamma ferric oxide which forms on steel embedded in concrete by virtue of the high alkalinity of the concrete pore water.

The objective is therefore to limit chloride levels in the concrete mix constituents to as low a level as possible and to provide a dense concrete of low permeability to reduce the intrusion of chloride ions from external sources.

Sulphate attack. High concentrations of sulphate ions, particularly of magnesium sulphate, attack concrete. This attack involves the formation of calcium sulphate ($CaSO_4$ - gypsum) and calcium trisulphoaluminate within the cement matrix by reaction of the sulphate ions with the cement constituents, calcium hydroxide and tricalcium aluminate (C_3A) respectively. These reactions are expansive, which can weaken the concrete and cause cracking and breakdown of the concrete core.

Acid attack involves, initially, the softening of the cement matrix by the removal of calcium oxide leaving only hydrated silica and alumina. Strong acids may even dissolve silica and alumina hydrates.
The mechanism and kinetics of dissolution of the cement matrix and soluble aggregates in concrete subject to carbonic acid attack are complex. In the first instance, it is necessary to establish whether a water is undersaturated with carbonate, contains free carbon dioxide and is aggressive to concrete, or is oversaturated with carbonate acid and can deposit calcium carbonate.

From the point of view of a permanent contact of water with a concrete surface the state of undersaturation of water with respect to calcium carbonate is important. A simple technique exists to establish the undersaturation state of a water, commonly called the marble test, which is used by hydrochemists. The test is specified in DIN 4030. [3]

To summarize, the key elements determining the durability of concrete are:

1. low water/cement ratio and sufficient cement content so that the cement particles are densely packed.
2. intensive curing in order to keep the water required for the chemical reaction from evaporating. Both are prerequisites for a
3. good quality concrete cover for the steel reinforcement.

The well-known relationship concerning Power's theory according to which the percentage volume of capillary pores decreases by reducing the water/cement ratio leads to the major requirement for durable concrete:

Limitation of the volume of pores in hydrated cement

$$\boxed{V_K = c / \gamma_W \cdot (w/c - 0{,}36 \cdot m)}$$

where

V_K Capillary pores in the cement paste [dm^3]

c cement content [kg]

w/c water cement ratio

γ_W density of water [kg/dm^3]

m maturity of cement paste, degree of hydration $m \sim 0{,}17 \ln(d)+0{,}18$ (for Portland cement, at 20 °C)

d age of cement paste in days

An intensive curing must make sure that the cement has enough water available for the hydratation process which will serve to minimize the capillary pores. During the planning and design phase quality assurance (QA) measures have to be involved to actually realize the specific requirements for a dense concrete. ISO standards 29000 to 29004 represent the relevant quality assurance measures.

3.2 Concrete resistance properties

Permeability is influenced by the pore structure of the cement paste. For a characterization of the relevant pore structure with regard to the transport of substances into and within porous building materials, two parameters are of importance:

- relevant porosity, and
- pore size distribution.

Relevant porosity means pores which are interconnected so far that a transport of liquids or gases and/or the exchange of dissolved substances is possible. At the same time, the relevant porosity corresponds to the maximum reversible water content and, in the case of cement paste, lies in the region of between 20 and 30 per cent.

The pore size distribution influences particularly the type and the rate of transport mechanisms and binding mechanisms in respect of water. The size of pores in the cement paste covers a range of several orders of magnitude. According to origin and characteristics, the pores are described as:

- compaction pores
- air pores
- capillary pores
- gelpores.

Expressed in more general terms, the following classification appears to be convenient:

- micropores (10^{-10} to 10^{-7} m in diameter), gel pores
- capillary pores (10^{-7} to 10^{-4} m)
- macropores (10^{-4} to 10^{-2} m), compaction pores + air pores

Free surfaces of solids exhibit a surplus of energy due to a lack of binding components to the adjacent molecules. This energy is called surface energy. In the pores of the cement paste surface energy causes the water vapour molecules within the pores to adsorb to the pore surface (adsorption), the thickness of the water film thereby depending on the degree of humidity within the pores.
Due to the fact that the ratio between the surface area and the volume of the pores increases with decreasing pore radius, the rate of the water quantity adsorbed relatively to the pore volume will also increase until, at a certain limit value of the pore radius, the pore is completely filled with water. This process is called capillary condensation. The limit value of the pore diameter primarily depends on the water content of the air within the pore which, in the case of constant conditions, is proportional to the humidity of the air surrounding the concrete. (Fig. 1)

Any transport processes of gases, water, or substances dissolved in water are diffusion processes in respect to the ambient conditions.

Diffusion processes are induced by the tendency of equilibrating differences in concentrations. The driving forces for diffusion are therefore differences in concentrations.

Carbon dioxide diffuses into concrete due to a chemical reaction with CO_2 developing at the pore walls in the concrete, which causes the concentration within the pores to be reduced. This applies equally to oxygen when it is consumed during corrosion of the reinforcement.[1]

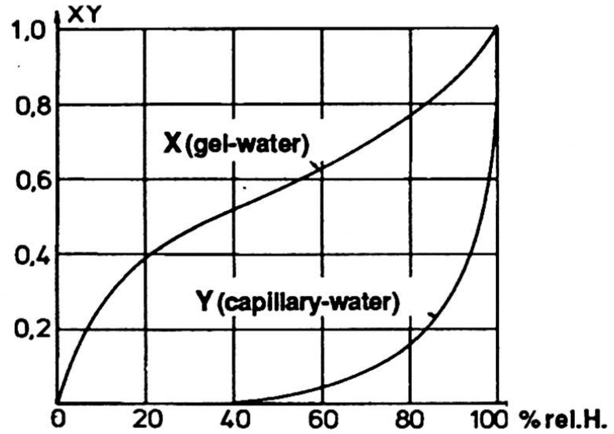

Fig. 1 Sorption-isothermes (Powers)

In the case of continuously immersed structures, large quantities of water may, under unfavourable conditions, be transported. A continuous transport of water will develop when water is allowed to evaporate at the concrete surfaces exposed to the air. The intensity of this water transport depends on the following three variables:

- evaporation
- capillary suction
- hydraulic pressure.

With the water, dissolved agents (carbonate, chloride, sulphate, etc.) will be transported. However, these agents are left behind in the concrete in the region of evaporation where they are likely to arrive at considerable concentrations. Efflorescence phenomena may also be due to this effect: the agents first dissolved are caused to crystallize at the concrete surfaces.

In concrete the expansive forces due to salt crystallization near the surface only cause minor problems, of importance is the chemical effect of the increased concentration of aggressive substance. However, in other porous materials such as sandstone, marble, masonry, etc., bursting and scaling due to salt crystallization is a serious cause of deterioration. This mechanism results in rapid deterioration of sculptures, monuments, etc. exposed to aggressive environments.

3.3 Cracking of Concrete

Cracking of concrete will occur whenever the tensile strain to which concrete is subjected exceeds the tensile strain capacity.

The tensile strain capacity of concrete reaches a nearly constant limit value of about 0,15 ‰ approximately after the 7 th day of age. This ultimate value is nearly the same for all types of concrete. The minimum ultimate tensile strain of about 0,05 ‰ is found in the concrete age between 6 hours and one day.

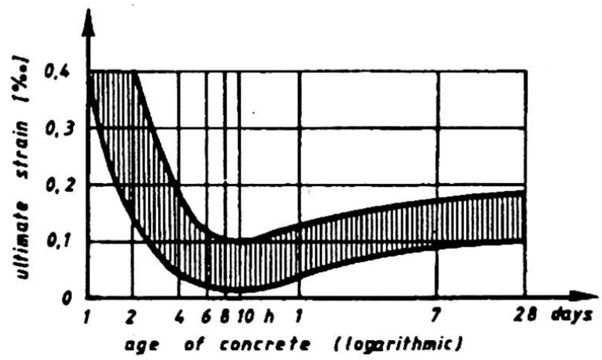

Fig. 2 Ultimate tensile strain of concrete depending upon age. [1]

As Fig. 2 shows young concrete is especially prone to cracking. Within the transition phase leading from fresh ("green") to hardened ("young") concrete, a critical period with very low tensile strength and a very low deformability is observed.

To consider whether a concrete may get cracked the different types of local deformations have to be added and compared to the ultimate tensile strain rate. Influences causing lokal strains which lead to tensile stresses if the movements are restrained are:

- drying shrinkage
- contraction due to temperature change
- externally imposed loading and/or deformation conditions
- expansion of material embedded within the concrete, (corrosion of reinforcement, alkali aggregate reaction,...)

Shrinkage can be assessed analogous to temperature change ΔT. The applicable range tends from 10 to 45 degrees Celsius, depending on the environmental conditions. Cracking occurs if

$\varepsilon \sim 0{,}5 \cdot 10^{-5} \cdot (\Delta T_{Temp.} + \Delta T_{Shrink.})$

exceeds the ultimate tensile strain.

The temperature distribution in the cross section of a structural element has generally to be analysed with the equation for non-stationary heat conductivity:

$$\boxed{dT/dt = \lambda/\rho c * d^2T/dx^2}$$

In most cases it will be possible to transform the model of consideration to a one dimensional problem.

4 Corrosion of reinforcement

The corrosion process can be separated into two single processes, the cathodic and the anodic process.

The anodic process is the real dissolution of iron. Positively charged iron ions pass into solution:

Anodic process: $Fe \longrightarrow Fe^{++} + 2e^-$

The surplus electrons in the steel will combine at the cathode with water and oxygen to form hydroxyl ions.

Cathodic process: $2e^- + 1/2\ O_2 + H_2O \longrightarrow 2(OH)^-$

After some intermediate stages, the iron and hydroxide ions will combine to form rust which, at least theoretically, can be written as Fe_2O_3. Water is only necessary to enable the electrolytic process to take place.

The highest corrosion rate will occur in concrete surface layers, subjected to highly changing wetting and drying conditions.

At the steel surface, anodically and cathodically acting areas may be situated either close together (micro-cell corrosion) or at locally separated places (macro-cell corrosion) even over relatively great distances. Consequently, corrosion may occur in areas of the structure where the direct access of oxygen to the surface of the reinforcement is impeded.

5 10 rules for durable concrete [4]

1. Select high quality materials

- Cement: Select high strength, moderate C_3A (5-8 %), moderate alkali content, uniform quality.
- Aggregates: Check soundness and impurities, control content of fines < 0,30 mm to ensure stability at high slump, uniform grading.
- Admixtures: Select efficient water reducers (superplasticizers), air entrainers at high slump benefit by modified batching process, check air spacing factor (<0,2 mm) and specific surface for frost resistance.

2. Get mix proportions right

- w/c ratio < 0,50 is imperative.
- Cement content > 380 kg/m^3 gives high "self healing" ability in cracks and joints.
- Stable mix at high slump requires selected grading of sand and efficient superplasticizers.
- Small dosage (< 5%) of CSF (condensed silica fume) benefits strength and stability, large dosage impairs constructability.
- Full scale site trials are essential before mix is chosen.

3. Employ modern automatic batching plants

- Batcher type and batching procedure affects obtained properties.
- Select optimum batching procedure.
- Print-out of each batch (100% control).

4. Develop sound work procedures beforehand

- Think concreting before steelfixing. Ensure back up of plant and materials.
- Do trials or mock-ups if in doubt.

5. Compact the concrete generously

- Revibrate top layer for increased strength and elimination of voids under embedded items. (Revibration is an added bonus in slipforming).
- Make sure the concrete cover to the rebars is fully compacted

6. Ensure adequate cover to rebars

- Min. 50 mm cover to main reinforcement.
- Quality of cover is as important as thickness.
- Deficient cover is made up by cement-based coating (for 30-50 mm cover) or epoxy coating ((30 mm cover).

7. Pay attention to construction joints

- Remove laitance (surface retarder and water jet are efficient on large areas).
- Apply rich mix against joint. Vibrate thoroughly.

8. Make allowances for temperature

- Avoid excessive temperature differences across sections. Temperature rise in thick sections can generally be expected as 12°C/100 kg cement.
- Initial temperature can be efficiently reduced by ice flakes as part replacement of mixing water (8 kg/m^3 ice gives 1°C Temp. reduction).

9. Keep design simple

- Genereous sections are easier to pour.
- Roundea and smooth surfaces discourage surface decay.
- Avoid sudden changes in geometry.
- Larger rebars take less space.

10. Use trained and skilled operators

- Only the operators performing the work can efficiently and continuously affect the quality of what is being produced.

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REPAIR AND MAINTENANCE

by

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1. INTRODUCTION

Durability becomes one of the most important factors in planning, design, construction and maintenance of structures. It is established that construction materials, load levels, and environmental conditions govern the service life of structures. The most common construction materials such as concrete and steel may be considered inherently durable ones, if properly designed for the enviroment and carefully produced or fabricated with good quality. However, concrete is potentially vulnerable to be attacked under different exposures unless certain precautions are taken. Deterioration of concrete structures at manifest condition is more inducive to further damage, which may render its unsuitable for futher use. Even economic and political consideration may be important in decision on maintenance and repair, preventive maintenance will play the major role in controlling durability of structures.

In general, early attention to seal the cracks and restoration of water-proof joints may eliminate the need for costly repairs. The durability performance and service life relationship as shown in Fig.1, can be extended by periodic inspection, proper maintenance and repairs. In the case where more extensive deterioration has already occured, or earlier measures have not controlled a potential problem, an investigation should be made to determine the cause and steps taken to counteract the situation during the repair operations.

This paper has introduced inspection procedure, testing and monitoring methods, repair materials and techniques. Examples of repair cases for a chimney, bridge and building have been presented in accordance with their deterioration, structural evaluation and repair techniques.

2. INSPECTION WORK

Durability problems with part of the existing structures have emphasized the need to follow a rational operation and maintenance strategy in the upkeep of structures. If the problems have grown to levels where the traditional approach of repairing damaged structures, attempting them back to initial quaility will be exorbitantly expensive. New ways of handling such problems on both structural level and safety and reliability level have been sought. In the intermediate with unclear maintenance and repair strategies, size of the problems has been getting worse, especially problems concerning concrete structures, because major parts of concrete problems are rather new and the number of concrete structures is rather large.

Regular and systematic inspection shall be performed in order to identify and quantify possible ongoing deteriorations. Inspection constitutes an integral part of structural safety and serviceability by providing a link between the environmental condition to which the structure is subjected and the manner in which it performs with time. In an advanced form the general strategy toward durability should incorporate systematic inspection routines for structures in services, including automatic data recording and handling dicision models based on forcasting rate of degradations, and economic consequences of either short-term or long-term remedial measures. To arrive at comparable figures of alternative solutions, present-day value of the future costs for maintenance, repair and eventually demolition and rebuilding, must be sought.

Rational decision models applying modern probabilistic methods including safety policy and economics, are indispensable elements of an in-depth going appraisal. The element of investigation may in general contain the following items:

- Perform visual inspection.
- Check of original design : drawings, calculations.
- Check execution data : technical, non-technical, quality statement, inspection record.
- Perform in-situ testing : non-destructive, destructive, sampling.
- Perform laboratory testing : mechanical, physical, chemical.
- Perform recalculation.

Based hereon dicisions regarding safety precaution, repair, strengthening/upgrading, demolition and prevention of occurrance, must be made. Check list as provided in Table 1 has been established by RILEM and recommended by CEB (1) for investigation of deteriorated concrete.

3. TESTS AND MONITORING

The traditional testing of concrete at 28 days is a simple and operation means of verifying the strength requirements. With the growing concern for durability characteristics of concrete, much more involved testing is required in order to clarify if a concrete will be durable in a structure exposed to certain aggressive environments.

The tests and monitoring must concentrate on enviromental aggressivity, concrete quality, structural detailing, loading condition, crack sizes and surface condition. Test methods as shown in Tables 2 to 5 are for strength evalution, void location, water penetration, and chemical analyses as part of concrete and Table 6 is for evaluation of reinforcement condition and location as part of reinforcing steel.

In-situ load testing may be required to determine the performance of a structural element under loading greater than the working loads. A load test may be undertaken either to overcome the doubt concerning the quality of construction or design or to establish the behavior of a complete structures after services. Sophisticated analysis techniques can be calibrated using load tests. Where the test is undertaken to demonstrate that the structure behaves satisfactorily under load, it will be generally sufficient to measure the deflection. These must be shown to remain within acceptable limits, correlate with predicted values and recover substantially on unloading.

Long-term monitoring of a structures over a period of time can be used both to check on the safe working of the structures and also to provide information on its response to load or under service condition. When a structure is progressively deteriorating, long-term monitoring can be used to indicate when replacement or repair become necessary. Unlike load testing, this form of evaluation relies on loads occurring during the normal use of the structure. The loads that are imposed must be quantified to enable the structural adequacy to be determined. Due to the duration over which measurements are taken, the instrumentation must have good long-term stability. Movements in particular may need to be related to a reliable fixed datum and possibly also to second independent measuring system. Allowance must be made for the effects of daily or seasonal changes in temperature or humidity, and these must be separated from the permanent movements such as increases in crack widths.

4. REPAIR TECHNIQUES AND MATERIALS

Materials

Modern technology has made available many kinds of materials for repair and maintenance of concrete. These range from low-viscosity polymers for the sealing of very fine cracks, very rapid setting cements for repairs in the presence of flowing or seeping water, special concrete for overlays, to portland cement motar and concrete itself. As summerized in Table 7, it can be a guide for selecting repair materials to suit crack sizes and application techniques. The engineer will be faced with an array of potential materials to choose from, requiring a special knowledge for proper evaluation. A final selection will depend on many factors, such as properties during repair, mechanical reponse, long-term durability, cost index and prior field experience.

In repair, all damaged materials must be removed until a sound surface is reached, then cavity should be prepared to ensure good bonding between the concrete and the repair materials and to ensure proper consolidation. Measures should be taken to remove aggressive materials or to prevent their re-entry. It should be emphazied that all major causes of damages or deterioration must be properly taken care of for satisfactory condition prior to the execution of repair work.

Repair materials must be adjusted to conformed the properties as required for specific strength or durability as structural performance. Material testing must be conducted to satisfy the condition before usage.

Techniques

Injection - This technique has been successfully applied to very fine cracks as small as 0.05 mm with low viscosity polymeric grout. Such materials should be capable of forming a solid polymer in situ after injection. Epoxies are a popular choice, and many proprietary formulations are commercially available. The epoxy is injected under pressure in order to penetrate the very fine and to tortuous crack pattern that may exist. The success of pressure grouting depends on proper application to ensure that all cracks are sealed. The grouting can restore structural integrity as well as seal cracks against seepage.

Grouting - The grouting method is normally applied for larger cracks or joints. Cementetious mortars and caulking materials are general used. For durable and successful seal, the crack should be cleaned out and cut back to form a V-shaped groove into which the sealant can be well compacted. For deeper cracks and narrow cavities, pressure grout many be required. A good-quality portland cement mortar is satisfactory for larger cracks. In the presence of moisture, quick-setting admixtures should be used. For finer openings under dry conditions, caulks and putties based on organic polymers can be used. Sealants are of many types and properties; the selection should depend on considerations of anticipated service conditions, such as applied loads, condition of exposure, and the like. Once cracks and joints are repaired, a general protective coating is both beneficial and aesthetic.

Patching - This may involve filling of tie holes, bolt holes, prestressing ducts spaled holes, and so on. The simplest approach is to use dry-pack mortar for shallow hole and conventional replacement mortar for deeper cavities or for filling around rebars. If the area is so large, then shotcrete techniques may be used for some applications. Mortar should be as dry as possible, consistent with good compaction and pumpability. The use of admixtures to improve flow characteristic and to avoid shrinkage on subsequent drying may be advisable where the creation and maintenance of a good bond is important. All unsound, unbonded concrete should be removed, since a good bond is required between the old concrete and patching material. A mechanical bond by roughening the surface and shaping the hole to provide a mechanical key. Priming with cement mortar or a polymer bonding agent will develop additional chemical bond between the old and the new concrete.

Placing - For large cavities, replacement concrete may be used for economy. The use of admixture to improve fresh concrete properties and to avoid shrinkage are essential to develop good bond to the existing one. In difficult situations, the use of prepacked aggregate may be advisable with the mortar grouted in subsequently as for good quality, controlled gradation and satisfy flowability. The use of replacement mortar and concrete or equivalent materials such as polymer concrete, or high performance concrete, is common practice in localized repair of concrete structure. If reinforcement is corroded, the surface rust should be removed and where possible it is advisable to completely expose the outer layer of reinforcement to provide additional interlocking. Mechanical bond or chemical bond may also be provided to develop additional bond between the old and the new concretes. Alternatively, use of materials such as polymer concrete or latex modified concrete can be used to provide good bond by itself.

Overlaying - Overlaid techniques generally be applied to the surfaces where extensive deterioration does not warrant localized patching or placing. Normally the applied resurface is rather thin as for pavements, bridge decks, or slabs. The overlays are to be bonded directly to the underlying sound concrete and strong bond should be developed. The overlay should match the underlying concrete in thermal properties, or have good crack resistant properties. On vertical surface, pneumatic application may be used. In some cases, additional reinforcement is required, especially where considerable structural damage has occured, or when a thicker layer of new concrete is used. Conventional portland cement concrete using special quick setting admixtures is most commonly used, but the use of modified concretes, such as fiber-reinforced, regulated-set cement, or latex additions has been advocated (Fig.2).

Coating - Coating can be advantageous in preventing structural surface from direct contact to enviromental condition and in preventing water from entering structural elements. The thin layer of coating can be done by spraying, painting, or hand application. Various forms of manufacturing produce film, felt, paint and so on. Polymer materials such as epoxies, mastic, poly-eurethane ; poly-vinyl chloride, are commonly used. Some modification by adding filler or reinforcement is also available for more strength and more durable. The thermal properties, elongation and permeability have been advocated for some applications.

5. CASE STUDY OF STRUCTURAL REPAIR

Three examples of case study for structural repair have been introduced. Each cases represent different causes of deterioration and of structural damage. After structural evaluation have been made, then repair materials and techniques must be carefully chosen to suit the behavior, field expereinces and estimated durable performance. Figures 3 has shown an examples of material testing for repair work as shear-compression test. Another tests may involve shrinkage, compression, and flexural tests.

Case A : Concrete Chimney

A concrete chimney had been subjected to long-term deterioration from carbonation, especially on the top portion of the structure. The damage at top-most portion of the chimney where exposed to gas effluence, was so great that reinforcing bars were completely corroded; concrete was loosing and falling apart. Larger cracks had been observed at lower levels with large carbonation depth. The reinforcing bar had been corroded to the amount 20-25%. At lower zones, only small cracks have been observed with the maximum width of 0.04 mm and no corrosion on reinforcing bars have been measured.

The repair work involved almost every technique available. Epoxy injection was introduced for small cracks where there was no corrosion of rebars. Polymer modified mortar have been used for pressure grouting of larger cracks where the cavities have been washed out with high presure water jet and the corroded rebars have been inhibited by chemical injection. Topmost portions of the chimney where concrete was unsound and rebars were completely corroded, had been hacked down and then be replaced by a special type of nonshrink concrete with new reinforcement. Localized pathing mortar have been use in several places where small holes or spalling surfaces were inspected. Coating materials were also applied on the outside surface of the chimney in order to protect the concrete from direct contact with carbon dioxide.

Case B : Bridge Deck

An example of bridge deck where concrete was subjected to freeze-thaw deterioration. Concrete slab became loosen and several large cracks longitudinally and laterally had been observed. Slight corrosion on reinforcing bars has been measured and inspected. Unsound concrete can be examined to demonstrate deeper deterioration than mid depth of the concrete deck.

Repair method has been carried out by removing all unsound concretes. Rust has also been removed by sand-blasting. Formwork soffit has been erected by hanging from precast beams, and the polymer concrete has been placed to accommodate service traffic within 3 hrs of repair (Fig.4). This method can minimize traffic blockage and reduce traffic congestion during the repair.

Case C : Building

Small cracks and large deformation as a result of to large cavities in the beam as caused by of heavy reinforcement and improper consolidation. Ultrasonic pulse velocity was used to detect void size and location. Repair mathod has been introduced the epoxy injection to fill the void and to seal the cracks. (Fig.5)

6. CONCLUSION

In accordance with durability problems of structural concrete, the service life can be extended by routine inspection, proper repair and maintanance. Inspection work must be carried out to evaluate the repair work and for decision model of maintenance, repair, demolition or replacement. Tests methods and monitoring system have demonstated the information on decision to satisfy the structural level, safety level, reliability level and cost index. Repair materials and techniques would be essential to warant the durability performance based on properties, proper evaluation, mechanical response and field experience. Excellent repairs can be achieved, only when adequate information, sufficient tests, effective investigation, and reliable operation, have been carried out.

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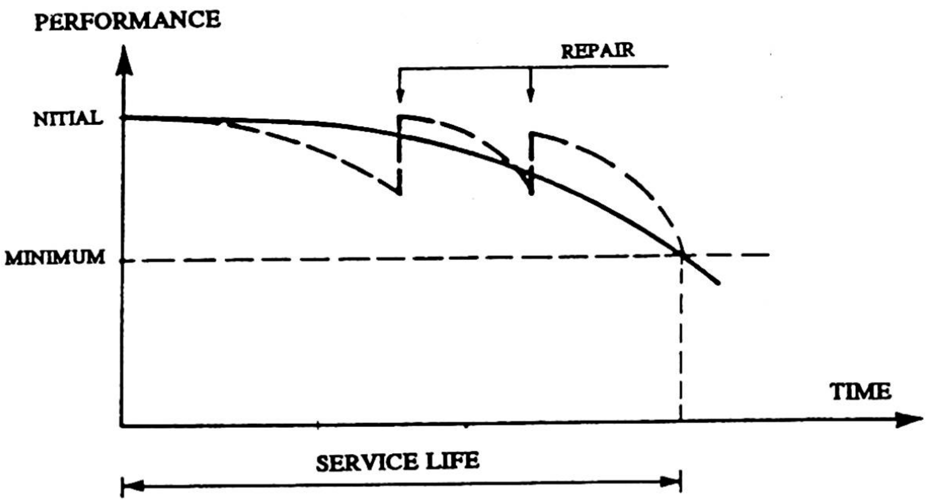

Fig. 1 Durability performance and service life of structures.

Table 1 Checklist for investigation of deteriorated concrete

Item	Description	Investigation check lists
1.	Concrete under inspection	- Concrete structures - Sample from a structures - Lab specimen stored on site - Lab specimen stored on lab - Sampling procedure - Sample storage and treatment
2.	Initial data on Concrete	- Concrete structures (design, load, dimensions) - Concrete specification - Mix design - Tests on materials - Quality control of fresh concrete - Quality in placing - Duration and method of curing - Age at time of attack
3.	Influence from the environment	- Temperature - Humidity - Pressure - Permeability of surrounding media - Sea-Water - Other aggressive substances - Type of contact - Concentration of aggressive substance - Frequency of exposure - Special environmented influences
4.	Visual sign of deterioration	- Erosion - Spalling - Exfoliation - Dusting - Crumbling - Softening - Staining - Pop-outs - Cracks - Liquid gel exudation - Crystallization - Corrosion of reinforcement - Mis-alignment
5.	Laboratory examination and tests	- Visual examination - Chemical analysis - Mechanical test - Physical test - Void location - Rebar location and condition - Water penetration test - Others

Table 2 Strength Testing

Test Method	Principle and Main Application	Test Standard
Core Testing	Determine in-situ strength of concrete. Compressive strength, tensile strength and modulus of elasticity can be obtained. It can be used with N.D.T. for calibration value of lowest strength.	ASTM C 42 ACI-318-89 BS 1881 Part 120
Rebound Hammer	Measures surface hardness by spring driven hammer striking concrete surface and rebound distance is given in R. values. It can be applied for estimation of compressive strength uniformity and quality of concrete.	ASTM C-805-79 BS 1881 Part 202
Pull-out Test	Measures the force required to pull out a steel rod with enlarged heal cast in concrete. It is for estimation of compressive and tensile strength of concrete.	ASTM C-900-82 BS 1881 Part 207
Break-off Test	Measures the force required at the top and at right angle to the axis to break-off the core at the bottom. The flextural strength can be estimated.	BS 1881 Part 207
Penetration Test (Windsor Probe)	Measures the depth of penetration into the concrete. Surface and sub-surface hardness are used to estimate compressive strength, uniformity and quality of concrete.	ASTM C-803-79 BS 1881 Part 207
Ultrasonic Pulse Velocity	Measures the transit time of an induces pulse compressional wave propagating thru the concrete. It is useful to estimate the quality and uniformity of concrete. It can also locate voids in concrete.	ASTM C-597-83 BS 1881 Part 203

Fig.2 Overlaying

Table 3 Test for Void Location

Test Method	Principle and Main Application	Test Standard
Endoscope	Lens and illuminating system which is inserted into a small diameter hole to inspect the interior cavities.. The main application for checking void along grouted prestressed tandons.	
Radiography	Gamma radiation attenuated when passing thru the concrete. Extent of attenuation controlled by density and thickness of concrete. The location of cracks, voids and internal part (rebars) can be obtained.	BS 1881 Part 205
Radar	High frequency electromagnatic pulse are set into concrete and the reflected pulse are processed graphically Voids as well as reinforcement can be located.	ACI-581-62
Thermography	Measure infra-red radiation and is used to determine the surface temperature differential of concrete member during heating and cooling. It is advantaged in locating delamination and voids.	Ref: Manning D.G. &Holt F.B., 1980
Tomography	Gamma-ray source is collimated to form flat fan of ray that are attenuated as they pass thru the structure to detectors. It is used to locate void and reinforcement.	

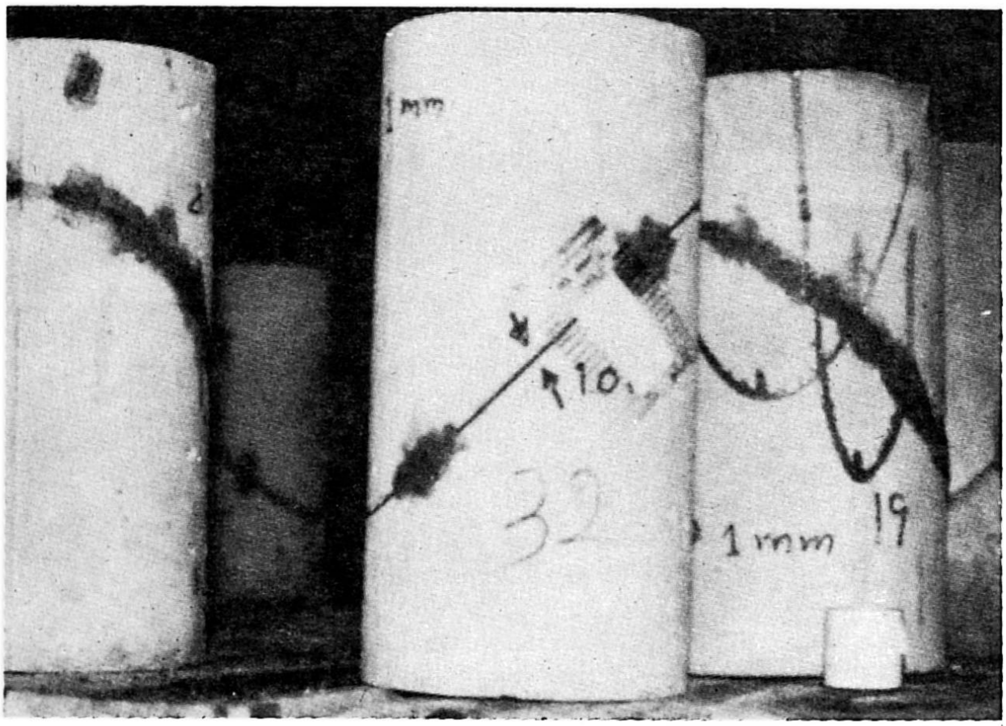

Fig.3 Shear-compression tests

Table 4 Water Penetration Tests

Test Method	Principle and Main Application	Test Standard
Absorption	An over dried specimen of known dimensions is cooled and immersed in water for 30 minutes. The quality and particular the obsorption of concrete in relation to durability can be obtained.	ASTM C 462-82 BS 1881 Part 122
Permeability	Measures the flow rate of water thru the concrete. It will indicate the degree of protection to reinforcement offered by the cover.	NBN 748.18 ISO/DIS 7032
Air Entrainment	By examining a concrete sample impregnate with a dye under the stereo microscope. Effective protection of cement paste from freezing and thawing cycles.	ASTM C 457-82
Initial Surface Absorption	Measures the flow rate of water into the surface concrete. The quality of concrete can be indicated.	BS 1881 Part 211

Table 5 Chemical Tests

Test Method	Principle and Main Application	Test Standard
Cement Content and Aggregate / Cement Ratio	Chemical analysis of the crushed concrete to determine cement content and aggregate to cement ratio.	BS 1881 Part 6 ASTM C 85-620
Water / Cement / Ratio	Measure the combined water present as cement hydrates and the capillary water. The water content can be determined from the sum of combined and capillary water to give the water to cement ratio.	BS 1881 Part 6
Cement Type	Chemical analysis of the crushed concrete sample based upon the dermination of Al_2O_3 and Fe_2O_3 atomic spectrophotometry. If the ratio of Al_2O_3 : Fe_2O_3 is less than 0.9 is SRPC and if the ratio is greater than 1.5 the cement is OPC.	BS 1881 Part 6
Carbonation Depth	Determined by spraying a solution of Phenolphtalene in alcohol and water onto a freshly cut face. An assessment of the time before the carbonation first reaches the level of the reinforcement can be made.	RILEM CPC-18
Choloride Content	Determination of chloride content of hardened concrete enables the corrosion risk to embeded reinforcement to be assessed.	BS 1881 Part 211

Table 6 Tests for Reinforcement Location and Condition

Test Method	Principle and Main Application	Test Standard
Electromagnatic Covermeter	Locates and measures the depth of reinforcement by utilizing an alternating current induced in a secondary coil caused by the proximity and active size of the reinforcement.	BS 1881 Part 204
Eddy Current Techniques	The equipment based on Eddy current techniques, is capable of indicating bar diameter and detecting bar at a greater depth. This is known as the Fe-depth meter.	
Reinforcement Potential	Electrical potential between the surface of the concrete and reinforcement measured. It is applied to determine the condition of rein-forcement in the concrete.	ASTM C876-80
Resistivity	A row of four electrodes are held and a current passed between the outer and the potential drop measured between the inner., It provides a inner. It provides a measure of the maximum rate of corrosion affter the reinforcement becomes active.	Ref: Browne and Geoghegan (1978)

Fig.4 Bridge deck repaired by polymer concrete

Table 7 Repair Materials and Techniques

Repair Techniques	Material	Application
Injection	Epoxy resins Polymer modified	Fine Cracks
Pressure Grouting	Portland cement mortar Polymer mortar Putties and caulks Cement paste with filler	Large cracks Small holes/cavition Joints
Normal Grouting	Portland cement mortar Latex modified mortar Polymer mortar	Large Holes/cavition
Patching	Rapid setting mortar Polymer rasins Portland cement mortar (set control)	Localized area shallow
Placing	Portland cement concrete Polymer concrete Expansive cement concrete Latex concrete Epoxy concrete	Replacement
Overlaying	Asphaltic concrete Polymer concrete Expansive cement concrete Latex concrete Epoxy concrete	Thin layer surface
Coating	Polymer modifier Paints Mastic fult	Surface coating

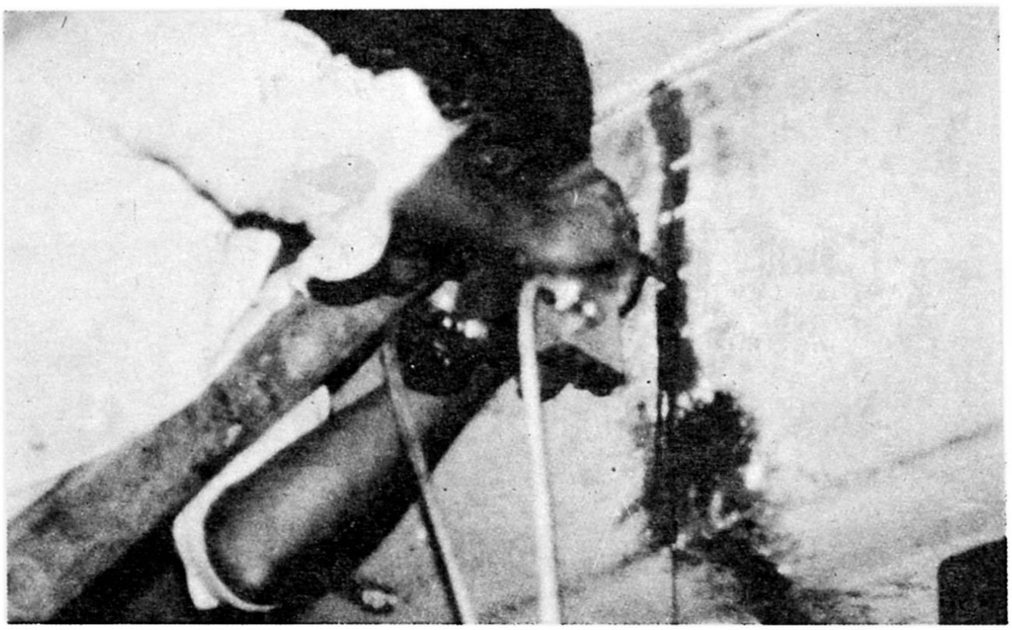

Fig.5 Building frame repaired by epoxy injection

DESIGN FOR DURABILITY

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SUMMARY

Durability of concrete structures, from both *technical* and *economic* aspects has become one of the basic civil engineering tasks. In order to achieve durable concrete structures, *measures* should be taken for *prevention, decrease* or *slow-down* of their *deterioration* processes. The *measures* should be taken in *all phases* of *creation* and *life* of the structure. A *long service life* of the structure could be achieved by high level of *design* and *construction*, by adequate *operation*, regular *maintenance* and due *repairs* and *rehabilitations*. The basic *factors* of concrete structure *deterioration* are: presence of *water* and *moisture, environmental aggressivity, compactness* and *thickness* of the *concrete cover, compactness* of *grouting* for the protection of prestressing wires and the *width* of *cracks*. The analysis of these factors leads to the *measures* that should be taken during the *design, construction, operation* and *maintenance* of concrete structures.

GENERAL

Following the current principles, *concrete structures* , either reinforced or prestressed, should have the corresponding *reliability* at every moment of their operation. It means that the concrete structures should have the sufficient *safety*, the required *serviceability* and the necessary *durability*.

From the historical point of view the analysis of concrete structures *durability* is the youngest one. The reasons not to sufficiently seriously consider the durability of concrete structures since the time they have first appeared can surely be found in the fact that they are very *durable*. At the beginning, many people have wrongly taken them for eternal thus considering their maintenance not necessary.

Nowadays, however, when numerous concrete structures are of considerable age or at the end of their service life, durability problems are paid great attention to. Unfortunately, in the near past sudden unexpected catastrophic failures of poorly maintained structures took place. *Durability, maintenance, rehabilitation* and *strengthening* of the existing concrete structures, especially of bridges, of numerous structures subjected to aggressive effects, has become one of the basic civil engineering tasks. Scientists and experts all over the world are engaged in studying those problems from both *technical* and *economic* aspects.

SERVICE LIFE

The *service life* of a concrete structure is a period of time during which it has the sufficient *safety* and the required *serviceability*.

The *designed service life* can be achieved with different scope of rehabilitations, Figure 1.

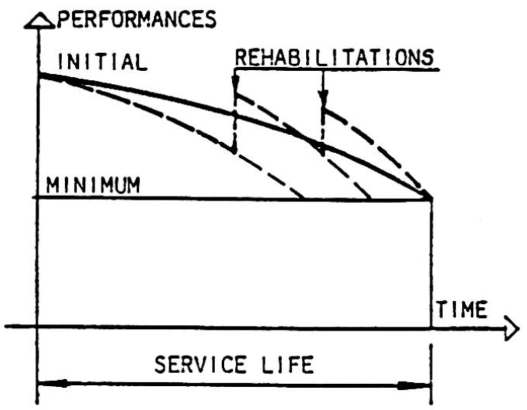

Fig. 1 - SERVICE LIFE

The better the quality of structure which is subjected to regular maintenance, the lower the decrease of its performances from the initial to the minimum required values at the end of the service life.

In order to achieve the same service life for a lower quality structure which is not regularly maintained as for the higher quality, regularly maintained, more frequent rehabilitations are necessary. That, certainly, requires *higher* total *expences*.

A *long service life* of the structure could be achieved by high level of design and construction, by adequate operation, regular maintenance and due repairs and rehabilitations.

During the *design*, it is difficult to establish the *service life* of a structure because the requirements that it has to meet during the operation period are increased with time. It is not easy to rightly assess the future development of the technology many years in advance.

The service life of a concrete structure is much longer in comparison with the service life of the equipment and vehicles transmitting their effects onto it. It is realistic to expect the structure to last a number of generations of the equipment and vehicles with possible adaptations and strengthenings of the structure.

A structure reaches its *real service life*, which due to numerous unpredictable factors does not equal the design service life, when the expenses of its further maintenance in the condition of sufficient safety and the required serviceability exceed the expenses of maintenance which, during the operation period, have been considered acceptable.

It is absolutely clear that the concrete structure, when it *reaches* its *service life* should *not be immediately replaced*. That is, however, the moment when it should be analyzed in detail and estimated if the indispensable rehabilitation including the future maintenance is technically justified and economically more favourable then the construction of a new structure. That is the time when the *decision* should be made on *future destiny* of the existing structure.

DURABILITY

Although they are very durable, concrete structures, sooner or later, start showing the signs of *deterioration*. The appearance and the development of the deterioration process come as a consequence of very *different causes*.

The most dangerous form of concrete structures deterioration is the *deterioration of steel*. Full attention must be paid to the *permanent corrosion protection* of the reinforcement and prestressing wires. In the highly-alkaline mass of concrete, they are fully protected by *passivation*.

Deterioration of concrete, physical, chemical or biological, is less dangerous. However, it can significantly influence the increase of the deterioration of steel.

The required *durability* of concrete structures should be achieved by taking a series of *measures*. They refer to *prevention*, *decrease* or *slow-down* of the *deterioration process*, as well as to due *repairs* and *rehabilitations* of the damages.

In order to achieve the purpose, in the best way possible, but from engineering and economical points of view, a series of measures should be taken in *all phases* of *creation* and *life* of each structure:

- During the *design* (gathering of the detailed relevant data on the location, the selection of an adequate structural conception, the selection of the corresponding structural materials, the application of the appropriate computation models, dimensioning according to all limit states, correct solving of the structural details);

- During the *construction* (selection of adequate construction methods, realization of the structure in accordance with the design, realization of the required preciseness of the structural geometry and the position of reinforcement and tendons, the application of the designed quality of the materials, the selection of adequate composition of concrete, correct mixing, transportation, placement and curing of concrete in order to obtain the required quality, realization of the concrete cover of the required thickness and compactness, good grouting of tendons, correct continuations of concrete placement);

- During the *operation* (provision of the design use of the structure, protection from overloading and undesigned actions);

- During the *maintenance* (regular follow up of the condition and behaviour of the structure, due repair and rehabilitation).

The *designer*, the *contractor*, the *owner* and the *user* should take care of the execution of those measures.

WATER AND MOISTURE

The presence of *water* and *moisture* make the most dangerous cause for the appearance and development of the deterioration process of concrete structures. Practically, in all deterioration processes, water can be found and it plays a very important role.

In order to provide *durability*, measures should be taken to prevent or to decrease retaining of water on the surface and its penetration into the concrete. Water should be drained off as soon as possible.

During the *design*, a secure *waterproofing* and efficient *draining system* should be planned.

The *shapes* of concrete surfaces exposed to atmospheric waters should be selected so as to prevent retaining of water and to enable its quickest possible draining, Figure 2.

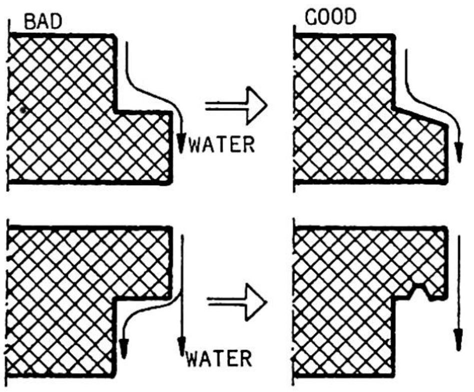

Fig. 2 - SHAPE OF CONCRETE SURFACES

Smooth surfaces are much better than the rough ones.

If possible, concrete should be *protected* from direct *splashing* by water due to passing vehicles, Figure 3.

During the winter, such water can even contain defreezing salt. Easy *replacement* should be designed for the members which are difficult to protect.

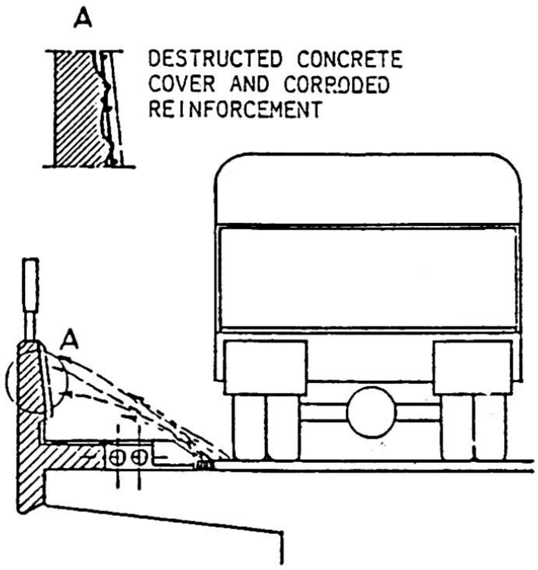

Fig.3 - SPLASHING DUE VEHICLES

Asphalt pavement on concrete bridges is not, as it has been thought earlier, sufficient to prevent the penetration of water, containing defreezing salt during the winter, to the deck, and, if it is cracked through it, too, Figure 4.

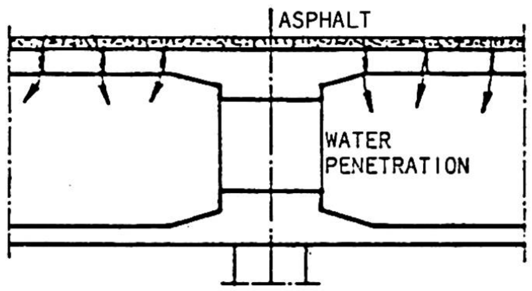

Fig.4 - BRIDGE DECK WITHOUT WATERPROOFING

It is indispensable to make *waterproofing* between the pavement and the deck.

The *draining system* should be so designed as to safely and quickly drain the water and to be easily accessable for maintenance. The draining tubes should not be embedded into the concrete mass, Figure 5.

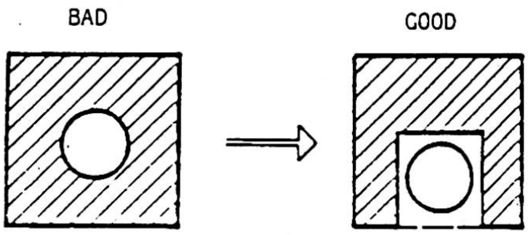

Fig. 5 - DRAINING TUBES

Beside good *construction* and correct *operation*, regular control of waterproofing and draining system functioning should be undertaken during the *maintenance*.

Possible *damages* or *cloggings* should be immediately removed. The penetration of water from damaged gullies and draining tubes to the box girder was one of main causes of damages, for a concrete bridge, Figure 6.

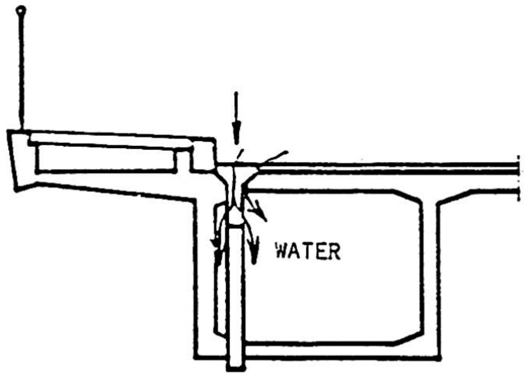

Fig. 6 - DAMAGED DRAINING SYSTEM

In the box girders, *openings* for quick draining of possibly penetrated water, as well as for aeration should be designed.

AGGRESSIVE ENVIRONMENT

The deterioration process of concrete structures is highly influenced by *aggressive environment*.

The most frequent is *chloride aggressivity* . It is caused by the presence of *defreezing salt* on bridges during the winter, or due to presence of *sea salt* on the structures in coastal regions. Chloride ions decrease alkalinity of concrete so depassivation takes place together with the corrosion of steel.

In industrial structures, concrete can get into contact with very aggressive *inorganic acids* (hydrochloric, sulphuric, nitric) or with *organic acids* (lactic, acetic). During the production of fertilizers, concrete is endangered by *ammonium salts*. Such aggressive substancess as well as *magnesium salts* from the sea and ground waters including *soft water* chemically react with *all calcium components* of the hardened cement creating expansion comound which are washed out from the surface of the concrete causing its deterioration.

Sulphate aggressivity on the concrete causes chemical reaction of sulphate ions with *aluminate component* of the hardened cement, creating expansion compound resulting in the appearance of cracks.

Alkalies in contact with concrete *silicates* and *carbonates* from aggregates. *Alkali-silica* and *alkali-carbonate* reactions lead to expansion, resulting in appearance of cracks.

In the box girder of a concrete bridge, into which the entrance of birds through the openings without doors or wire networks was not prevented, thick layers of birds excrement, eggs and similar impurities were found, Figure 7.

The lower chord of that box girder especially in the vicinity of incorrect draining tubes, was so damaged that it was inevitable to replace it, Figure 8.

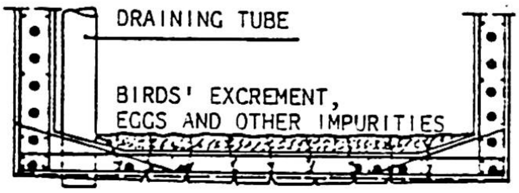

Fig. 7 - PRESENCE OF BIRDS IN THE BOX GIRDER

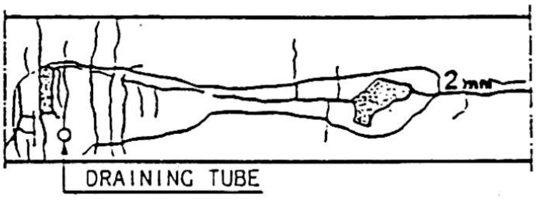

Fig. 8 - VERY DAMAGED LOWER CHORD

The prestressing wires taken from that lower chord were very much corroded and even completely broken, Figure 9.

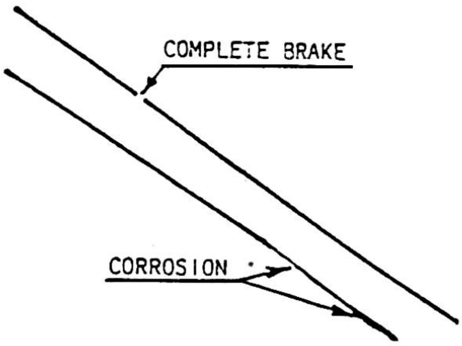

Fig. 9 - VERY CORRODED PRESTRESSING WIRES

Very much corroded reinforcement and an outstanding taking off of concrete on poorly made ceiling in very wet aggressive surroundings of a swimming pool in a spa are shown in Figure 10.

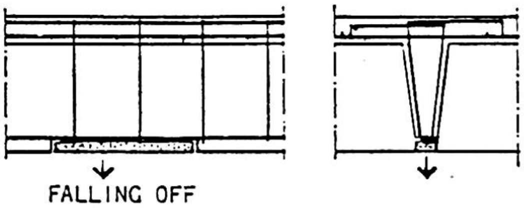

Fig. 10 - VERY MUCH DAMAGED CEILING

During the *design* and *construction*, it is necessary to take measures to permanently *protect* the concrete structures from aggressive environment. Depending on the kind of aggressive environment, the corresponding kinds of *cement* and *aggregates* should be selected - their deterioration resistance should be higher.

During the *operation*, measures should be taken to *decrease* the aggressivity, and during the *maintenance*, measures should be taken to *control* the structures together with the measures to *remove* the deposited aggressive substances.

CONCRETE COVER

An essential influence on the concrete structures deterioration has the state of the *concrete cover*, as well as the state of *grouting* for prestressing wire protection.

Porous, thin, poorly made and *damaged concrete cover* directly influences the *corrosion* of the reinforcement.

Moisture containing aggressive substances penetrated through porous and thin concrete cover causes reinforcement corrosion visible by the appearance of rust spots on the concrete surface. The corroded reinforcement swells causing longitudinal cracks and falling off of the concrete cover. The process is a progressive one as longitudinal cracks and separation of concrete intensify the penetration of moisture containing aggressive substances to the reinforcement.

Porous and *poorly* made *concrete cover* enables *physical deterioration* of concrete structures, due to *frost, erosion* or *cavities*.

Porous, poorly made and partly *not placed grouting* for the protection of prestressing wires directly influences their *corrosion*.

Poorly grouted and partly not grouted tendons of the box girder of a bridge were the causes of intensive corrosion of prestressing wires, Figure 11.

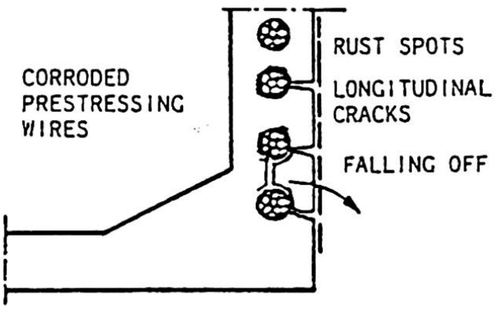

Fig. 11 - POORLY GROUTED TENDONS

In the past, prestressing wires were frequently conducted through the inside of the box girder, with a good concrete protection along its length. However, it was difficult to achieve a good protection at its entrance to the deck. Poorly made concrete protection, beside lack of waterproofing and the cracked deck of a concret bridge, has caused the penetration of water containing defreezing salt, intensive corrosion and the complete brake of all prestressing wires of one of four existing groups, Figure 12.

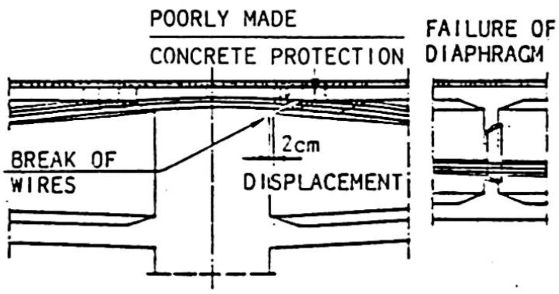

Fig. 12 - POORLY MADE CONCRETE PROTECTION

That had caused a serious rehabilitation of the bridge.

Poorly sealed grouting control tubes of the prestressed hangers of a concrete bridge have enabled the penetration of water along the tendons, Figure 13.

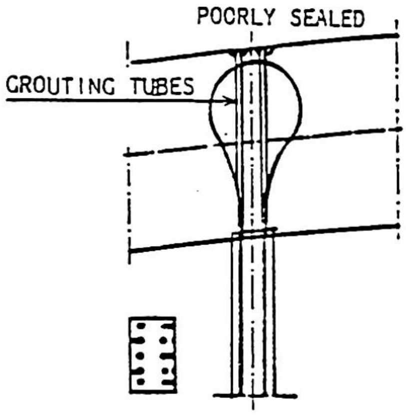

Fig. 13 - POORLY SEALED GROUTING TUBES

Very aggressive corrosion of prestressing wires took place together with the longitudinal cracks in the hangers. This later led to the rehabilitation of the bridge hangers.

It is essential for *durability* of concrete structures to realize, during their *design* and *construction*, the best possible *compactness* and the necessary *thickness* of the *concrete cover*. *Grouting* for the protection of prestressing wires should be *compact* and *well made* during the *whole length* of the tendons.

Achievement of the necessary *compactness* of the concrete cover depends on a series of factors regarding the *technology* of concrete as are kind, quality and quantity of cement, kind and grain size distribution of the aggregates, water cement ratio, kinds and quantities of possible admixtures, methods of mixing, transportation placement and curing of concrete.

During the *maintenance*, it is very important to *control* the concrete cover and the grout for the protection of prestressing wires.

The appearance of *rust, lime* or *water spots* on the concrete surface, as well as the appearance of *blistering, separation* and *falling off* of the concrete cover, require urgent establishment of the *causes* and *degrees* of *damages* and their *removal*.

Carbonation of concrete cover is also one of the causes of deterioration. By diffusion of *carbon dioxide* from the air to the surface layers of concrete, the alkalinity is decreased causing *depassivation* and the reinforcement *corrosion*. However, the process penetrates into the depth of concrete very slowly, and its progress can be easily established by measuring pH values.

CRACKS

The state of *cracks* is also an essential cause of concrete structures deterioration. In the cracked areas, the penetration of aggressive substances into the concrete is much easier.

It is indispensable to keep the real *width* of the cracks within the coded values. Cracks of lower width, frequently full of deposits of lime, dirt and rust, have significantly lower influence on the deterioration process.

During the *design*, it is necessary to analyze, as precisely as possible, the expected values of the crack widths. Through structural measures, concentration of stresses and the appearance of unexpected cracks should be avoided.

Unforseen cracks arising during anchoring the prestressing tendons without necessary overlapping are shown in Figure 14.

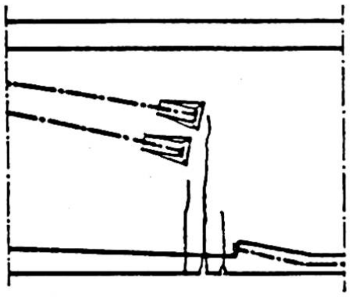

Fig. 14 - TENDONS ANCHORING WITHOUT OVERLAPPING

During the *construction* it is necessary to achieve the designed structure, with regards to the system, geometry, quality of the materials and of the executed works.

During the *operation*, the structure should be protected from overloading.

During the *maintenance* , it is necessary to regularly control the crack widths. If they are not within the design limits, the causes should be immediately established and removed, as well as the cracks of excessive widths sealed or injected.

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Curing of Concrete Surfaces

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Abstract

Curing of concrete is mainly understood to be measures to maintain a satisfactory moisture content in concrete during its early stages so that desired properties may develop. This paper gives an overview on basic aspects and principles of curing. The effects of curing on the structure of concrete are summarized on the basis of a literature review. Various commonly accepted methods of curing are listed and their effectiveness is delt with. Furthermore, relevant recommendations and codes on curing and in particular on the estimate of the duration of curing are concisely presented and compared with each other. Finally, some comments are given on test methods to be applied on the construction site to determine the effectiveness and required duration of curing.

1 General considerations

After placing and compaction of the concrete, adequate measures have to be taken in order to obtain the expected properties from hardened concrete, in particular strength, impermeability and durability. In that context curing of concrete is understood to be measures to avoid premature drying of the concrete and to provide the cement paste in the concrete with a sufficient amount of water over a sufficiently long period of time to achieve a high degree of hydration within its mass and particularly in its surface layers. In addition, curing includes measures against environmental effects such as direct sunshine or wind and comprises also measures to prevent cracking due to early shrinkage.

In contrast to curing protection is understood to be a measure against other external effects which may harm the young concrete such as leaching due to rain or flowing water, rapid cooling or freezing, thermal stresses due to heat of hydration, vibration or impact [1].

Carefully curing is an important contribution to obtain a high quality concrete and durable concrete structures. This results from the fact that the durability of concrete members is primarily controlled by the properties of the surface layers. If concrete is adequately composed, sufficiently curing results in an impermeable and strong surface layer with a high resistance to the ingress of aggressive media which may exert an attack to the concrete and/or to the embedded steel. While insufficient curing strongly impairs the surface layers,

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it often has only a minor effect on the strength development of the concrete in the structure with the exception of thin sections because the core of a thicker concrete section maintains a sufficiently high moisture content for a prolonged period of time even without curing. It is essential that curing and protection start immediately after compaction of the fresh concrete.

2 Effect of curing on the structure of concrete

The hardening of the concrete is the consequence of the hydration of the cement, i.e. the reaction between the cement and the mixing water forming solid hydration products. To achieve a complete hydration of the cement and an impermeable structure of the concrete a certain amount of mixing water is necessary but the water-cement ratio has to be sufficiently low. An early loss of water from a young concrete may prevent further hydration. This may occur, e.g. in the surface region of a structural member if early drying is possible due to insufficient curing. As a consequence this region obtains a low strength and a high permeability. This results from the pronounced effect of the prevented hydration on the pore structure of concrete. The relations between the pore structure of concrete surfaces and the duration of moist curing have been investigated in [2]. Some of the test results of this study are shown in Fig. 1.

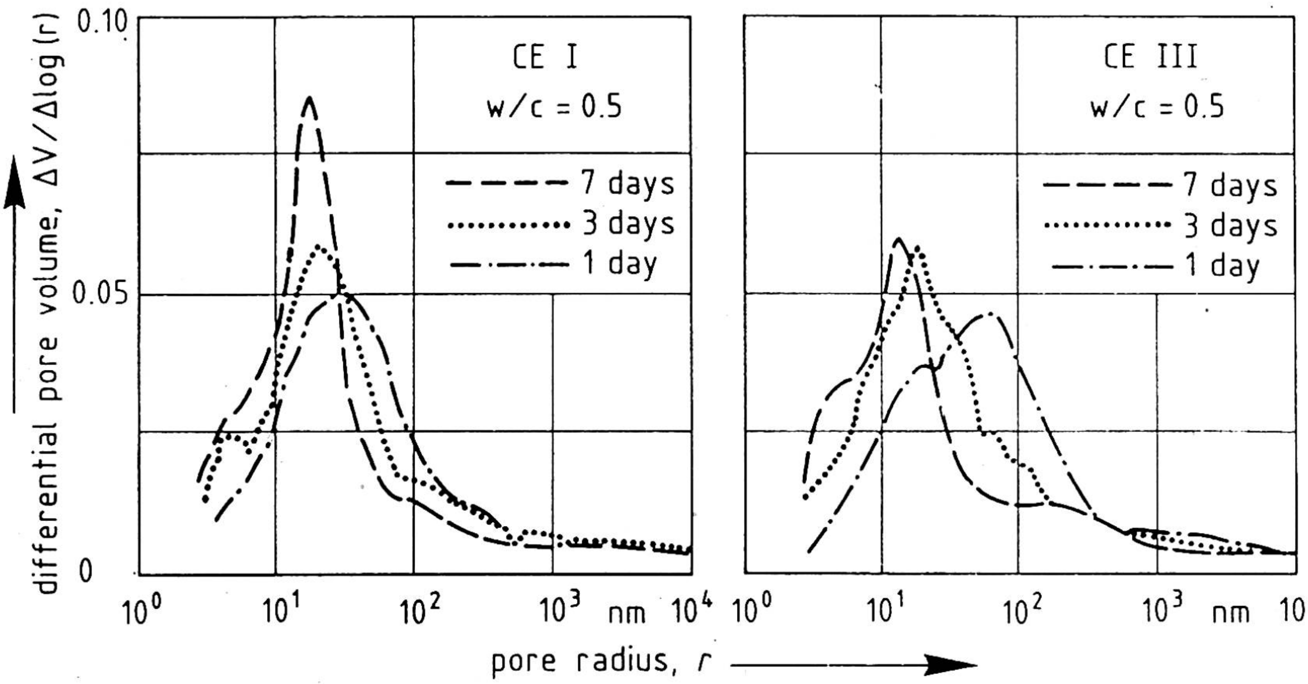

Fig. 1: Effect of the duration of curing on the pore size distribution of concretes made with Portland cement (CE I) and blast furnace slag cement (CE III) [2]

The diagrams represent pore size distributions which were obtained by differentiating the curves of the cumulative pore volume measured by mercury intrusion porosimetry. The investigated concretes have been made with an ordinary Portland cement (CE I) and a blast furnace slag cement (CE III), respectively. Both concretes have a water-cement ratio of w/c = 0.5. The specimens have been moist cured for 1, 3 and 7 days and afterwards stored at 20°C and 65% relative humidity. The tests have been carried out at the concrete age of 28 days. It is apparent from Fig. 1 that for both concretes the pore size distribution is shifted to smaller pore radii if the duration of curing increases. The pore volume measured by the mercury intrusion porosimetry is only little affect by the duration of curing for both concretes (mean value: 0.070 cm^3/g). From the diagrams it is also evident, that the concrete made with the cement type CE III is more sensitive to curing. The peak of the pore size distribution for 1 day of curing is found to be at a significantly larger pore radius for a concrete made with a CE III cement than for a concrete made with a CE I cement. However, after 7 days of curing the structure is found to be slightly more dense for the concrete made with the CE III cement.

These findings agree very well with the results of permeability tests (Fig. 2) conducted in [3]. The storage of the investigated concrete specimens corresponds to that reported above for the experiments of [2]. The air permeability tests have been carried out at the concrete age of 56 days. It is apparent from Fig. 2 that the air permeability decreases with decreasing water-cement ratio and increasing duration of curing. Also in these tests the curing sensitivity of a concrete made with a CE III cement is very pronounced compared to a concrete made with a CE I cement both having a water-cement ratio of 0.45. The results found for the air permeability can easily be understood in view of the pore size distributions obtained for different durations of curing shown in Fig. 1.

Furthermore, the strength class of the cement and in particular its hardening behavior have a significant effect on the development of the pore structure and therefore on the curing sensitivity of corresponding concretes. Fig. 2 shows that the air permeability of concretes after a duration of curing of 1 day is considerably lower if the concrete is made with a rapid hardening cement of a high strength class (CE I, 42.5 R) compared to a concrete having also a w/c ratio of 0.45 but made with a cement of a lower strength class (CE I, 32.5 R). This difference vanishes if the duration of curing increases. These test results are confirmed by a similar investigation in [4]. In summing up, Figs. 1 and 2 clearly indicate the pronounced effect of the duration of curing on the porosity and permeability of surface regions of concretes.

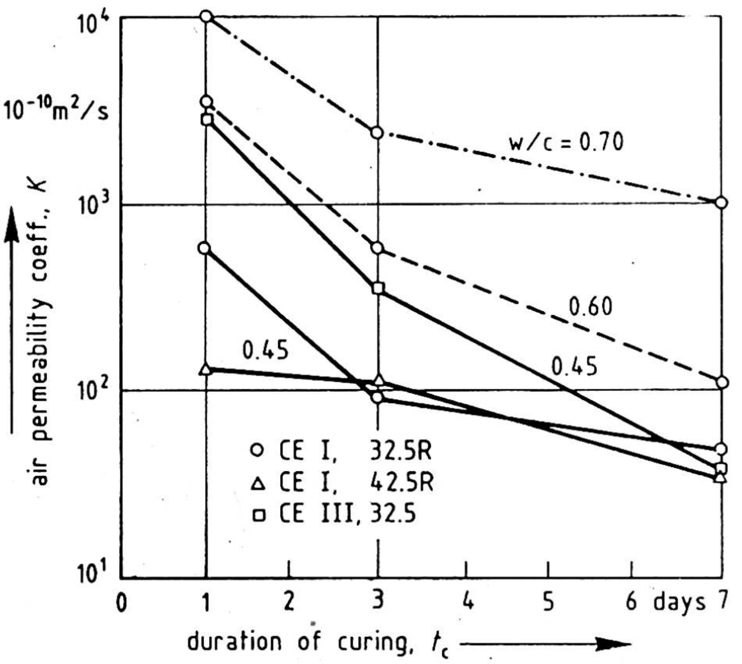

Fig. 2: Effect of the duration of curing on the air permeability coefficient of various concretes [3]

3 Parameters affecting the duration of curing

The required duration of curing of concrete depends on various parameters. First of all, the *composition of concrete* itself is of major importance in that context. As has been shown in the preceding section, the water-cement ratio and the type and strength class of the cement exert a tremendous effect on the hydration rate, i.e. the pore structure and its development, respectively, and thus on required curing durations of concretes. Furthermore, additions such as e.g. fly ash may lead to prolonged curing periods if a sufficient impermeable surface of concrete shall be achieved. Another parameter affecting the duration of curing is the *concrete temperature*. The heat of hydration increases the concrete temperature and thus accelerates hydration. Hence, thin concrete sections exposed to low ambient temperatures during curing where the concrete is made of cements with a low heat of hydration need a very careful curing. The *ambient conditions during and after curing* have a relevant effect on the required duration of curing. Under the conditions of low relative humidity of the ambient air, sunshine and high wind velocity prolonged curing is required. Finally the *exposure conditions of the finished structure in service* have to be taken into consideration. The more severe the exposure conditions are, e.g. chemical aggressive environment, the longer is the required duration of curing. Some of the mentioned parameters are interrelated particular with regard to the concrete temperature. This interrelation also contributes to the complexity of the problem of estimating required durations of curing. Some detailed guidelines on the estimation of the duration of curing will be presented in section 5.

4 Methods of curing and their effectiveness

The various methods of curing may be subdivided into two principal groups. The first group includes those methods of curing which decelerate drying of the concrete, such as:

- keeping the formwork in place
- covering the concrete surfaces with plastic films
- application of curing compounds which form protective membranes.

In contrast, the second group of curing methods includes those procedures where the concrete surface is kept moist by the application of water:

- placing of wet coverings on the free concrete surface
- storage of the concrete under water
- sprinkling the concrete surface with water.

The individual curing methods can be applied either separately or in combination. They are not equally effective; in particular the methods where water is applied are more effective than other methods provided that thermal shocks, e. g. by using cold water on a concrete surface which is warm due to the heat of hydration, are avoided. However, the effectiveness of curing methods is significantly affected by the composition of the concrete, see e. g. [4], [5].

Besides the test methods mentioned in section 2, the effectiveness of curing methods has also been evaluated on the basis of strength tests and from testing the rate of carbonation. However, it has been repeatedly observed that the standard compressive strength is not a suitable measure of curing effects, whereas the rate of carbonation has proved to be more sensitive.

Fig. 3 shows the influence of various curing methods on the depth of carbonation observed at an age of concrete of 6 months. The investigation has been carried out on structural concretes, having a water-cement ratio w/c = 0.55 and made of different types of cement. After demoulding at the age of 1 day, some of the specimens have been water or wet cured for 6 days before being stored in the air at 23 °C and 50 % relative humidity. Comparing the effects of the curing methods "wet covering" and "air", there is only a minor difference between the measured depths of carbonation if concretes made with rapid hardening cements (CE I, 32.5 and CE I, 52.5) are under consideration. This is not observed for the concrete made with a CE III cement. Obviously the curing compound No. 4 strongly reduced the diffusion of CO_2 by sealing the concrete surface. The experimental results indicate that the effectiveness of curing methods, i.e. the progress of carbonation clearly depends on the composition of concrete.

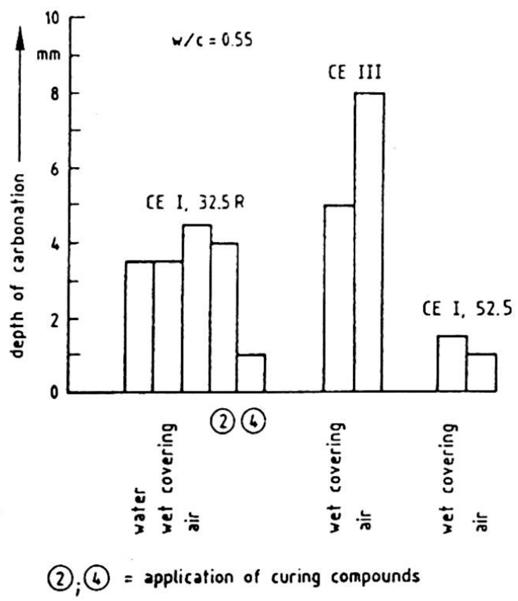

Fig. 3: Effect of various curing methods on the depth of carbonation at a concrete age of 6 months [5]

In practice the choice of a particular curing method often depends on the facilities given on the site. With respect to the effectiveness and practical aspects the following general guidelines on curing methods are given [7]:

The storage under water may be regarded as the most effective curing method. It has mainly a positive effect on concretes with a low water-cement ratio as well as on concretes made with a rapid hardening cement. However, on the construction site this method is hardly feasable for practical reasons.

Covering the concrete surface with wet burlap in combination with plastic films is considered to be as effective as curing under water. This curing method may often be applied on the construction site. For architectural concrete surfaces attention has to be paid to the fact that efflorescences may occur.

Keeping the formwork in place is a favourable method of curing because it starts working just after compaction of the concrete. A wooden formwork which may suck water has to be kept moist.

The covering with plastic films is a simple, practicable and in many cases sufficient curing method; however, they should be so placed, weighted or fastened that the wind is prevented from getting under the film and removing it.

The application of membrane-forming curing compounds has been proved for curing of horizontal concrete surfaces; in addition, they may be of advantage for structural components which can be cured only for a short time period, e.g. due to the construction process [6].
The curing compounds may have an adverse effect on the bond behavior of a coating which is applied on the concrete surface; hence the chemical compatibility of curing compound and coating material has to be checked. At temperatures below the freezing point it is recommended to apply dissolved curing agents instead of emulsions.

Curing by sprinkling with water may result in cracking of the concrete surface due to differences in temperature between the concrete and the water. Generally, temperature differences of more than 15 K between the concrete core and the surface have to be avoided.

It is essential that curing commences not later than the time the concrete surface looses its sheen. Any delay or interruption of the curing can hardly be compensated by an extension of the duration of curing. Additional information on commonly accepted curing methods and materials may be found in [11].

5 Estimates of the duration of curing

The required duration of curing depends on the time needed of the surface zone to reach a sufficient resistance to the penetration of gases or liquids into the hardened concrete.

According to [8] the duration of curing shall be determined from the following criteria:

- parameters which determine the maturity of concrete
- local requirements
- minimum standard curing periods.

The standard curing times as required by various recommendations or building codes are based on the following parameters which influence the rate of hydration essentially:

- concrete composition, in particular the strength class of cement and the water-cement ratio
- ambient conditions during and after curing
- temperature of concrete.

Table 1: Minimum duration of curing in days for T > 10 °C according to [1]

Rate of development of impermeability of concrete		Very rapid	Rapid	Medium	Slow
Expected ambient conditions during and after curing	I No direct sunshine, rel. humidity of surrounding air RH > 80 %	1	2	3	4
	II Exposed to medium sunshine or medium wind velocity or rel. humidity RH: 50 % < RH < 80 %	2	3	4	5
	III Exposed to strong sunshine or high wind velocity or rel. humidity RH < 50 %	3	4	6	8

Table 2: Rate of development of impermeability according to [1]

Rate of development of impermeability	w / c	Class of cement
Very rapid	0.5 - 0.6 < 0.5	RS RS; R
Rapid	0.5 - 0.6 < 0.5	R N
Medium	0.5 - 0.6 < 0.5	N SL
Slow	All other cases	

Table 1 gives in combination with Table 2 the minimum durations of curing for concrete temperatures T > 10 °C as proposed in the CEB-FIP Model Code 1990 [1]. The values are valid for concretes made with Portland cements (CE I), where the cements are subdivided into the classes RS = rapid hardening high strength cement, R = rapid hardening cement, N = normally hardening cement, and SL = slowly hardening cement. In ENV 206 [8] a very similar approach to estimate the duration of curing is chosen. However, with respect to the concrete temperature there is a more detailed classification into three different temperature ranges.

The recommended standard curing times have to be extended in certain cases. According to [8], the curing times should be substantially increased if the concrete is exposed to severe abrasion or to severe environmental conditions. It is also mentioned that longer curing times may be appropriate for other types of cement than CE I. More detailed information is given in [1] and [9]. For example, the curing time has to be extended in the following cases:

for concretes made of cements containing high amounts of constituents other than Portland cement clinker and concretes containing latent hydraulic and pozzolana additions in high amounts, for 1 to 2 days beyond the values given in Table 1 if concrete is exposed to conditions II and III [1];

where concrete is exposed to severe abrasion or to severe environmental conditions, for 3 to 5 days [1];

- when the temperature of the concrete surface drops below 0 °C, for at least by the number of days with $T < 0$ °C [9];

- for concretes containing set retarding admixtures, for the time of retardation [9];

- for concretes containing fly ash in combination with reduced cement contents, for 2 days [9].

With respect to the concrete temperature, the duration of curing may be determined more accurately on the basis of the maturity concept given in the CEB Model Code 1990 [1]. The temperature adjusted concrete age may be calculated from eq. 1:

$$t_T = \sum_{i=1}^{n} \Delta t_i \cdot \exp\left[13.65 - \frac{4000}{273 + T(\Delta t_i)/T_0}\right] \tag{1}$$

where: t_T = temperature adjusted concrete age [days] if the concrete temperature deviates from $T = 20$ °C;

$T(\Delta t_i)$ = concrete temperature [°C] during the time period Δt_i;

T_0 = 1 °C;

Δt_i = number of days where a concrete temperature T prevails.

Eq. 1 is valid for temperatures $T > 0$ °C. If the required duration of curing is calculated from eq. 1, then t_T has to be considered as the duration of curing at $T = 20$ °C and $\Sigma \Delta t_i$ is the required duration of curing if the temperature T deviates from 20 °C.

Presently, a working group within CEN TC 104 is preparing a revised approach to estimate the duration of curing [12]. According to this approach the following relations have to be used to estimate the duration of curing:

$$t_c = \Sigma \Delta t_i \tag{2}$$

$$\Sigma \Delta t_i \cdot T_i = k \cdot 20 \cdot MH \tag{3}$$

where: t_c = actual curing time for an applied curing method;

Δt_i = time interval [hours] during which a temperature T_i [°C] prevails;

T_i = concrete temperature [°C];

k = coefficient which depends on the method of curing;

MH = required maturity hours [hours · °C].

The required maturity hours MH are defined as the required curing time for a constant concrete temperature of 20 °C. Values of MH are given in a table for the exposure conditions indoor, outdoor and severe abrasion and for various curing sensitivity classes of the concrete. The curing sensitivity of the concrete depends on the type of cement, the strength class of cement, the water-cement ratio of the mix and the type of additions. This approach [12] which is still under discussion allows a considerably more precise and comprehensive estimation of a required duration of curing than [8]. In particular, the effects of curing methods, types of cement and additions as well as variable concrete temperatures are taken into consideration.

6 Test methods for the application on the construction site

Generally the estimation of the effectiveness of a curing method is possible only indirectly, i.e. through testing such concrete properties which are affected by curing.

In various studies the compressive strength of companion specimens has been used as a parameter to evaluate the effectiveness of curing methods. The experimental investigations showed that the compressive strength often undergoes only a little reduction when curing is deficient. Sufficient curing results in an impermeable and strong surface zone of the concrete which contributes only minor to the compressive strength of concrete measured on standard specimens. However, the porosity and thus the permeability of the surface zone of concrete is significantly affect by the curing procedure (see section 2). Hence, test methods which determine the resistance to the penetration of gases or liquids into the surface zone of the concrete in view of the evaluating the efficiency of curing but also with respect to durability considerations became an important subject of the recent research.

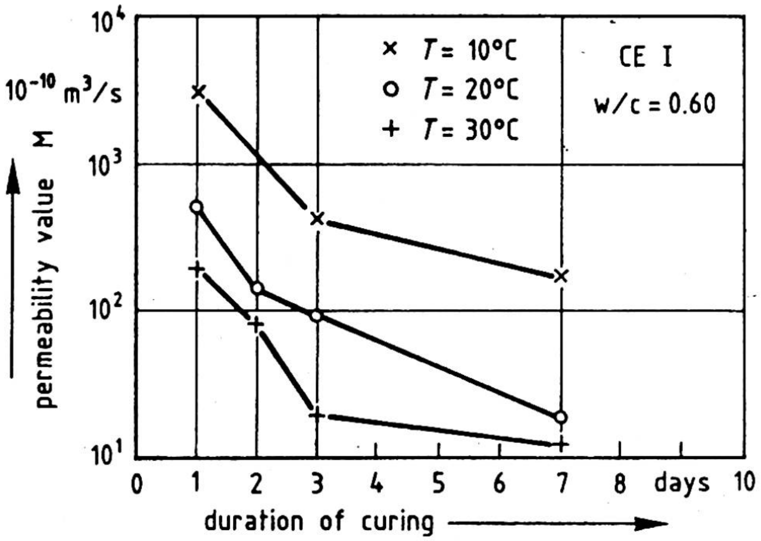

Fig. 4: Effect of the duration of curing on the permeability value at various concrete temperatures [3]

Suitable test methods to be used in the laboratory for a characterization of the structure and permeability of concrete are the mercury porosimetry and the methods of measuring the gas permeability and the water penetration. In contrast, for the time being there are no generally accepted methods for a rapid determination of concrete porosity and permeability which may be used on the construction site. In particular, the aim of the research in this area is to develop a non-destructive test method in order to assess the effectiveness of curing and to determine the end of curing time on the construction site. A promising test procedure has been developed e.g. by Schönlin [3].

He uses a suction device which is placed directly on the concrete surface. This instrument allows to exert an underpressure generated by a connected vacuum pump on a circular surface area of 50 mm in diameter. After the pump is removed, the air pressure inside the vacuum chamber of the suction device will rise to a certain amount within a fixed time period depending on the porosity and air permeability of the concrete, respectively. As the penetrated area and the path of the penetrating air cannot be determined exactly a permeability value M is defined and obtained from corresponding tests. However, this permeability value M may be correlated to the permeability coefficient K. As it is apparent from Fig. 4 the permeability value M of concrete surfaces depends pronouncedly on the duration of curing and concrete temperature. However, also the moisture content and the moisture history of surface regions tremendously affect the measured values. Hence it is difficult to obtain reliable test values on site. For further details and test methods see [10].

Further research work is mendatory to arrive at a test procedure being reliable and operational for application on the construction site. In summing up it has to be stated that presently there is no commonly accepted rapid test method to determine the effectiveness and duration of curing on the construction site.

7 Concluding remarks

The significance of curing on the impermeability of concrete surfaces and thus on the durability of concrete structures has been demonstrated in numerous experimental investigations. As a consequence, nowadays many efforts are undertaken to give more detailed and more substantiated proposals for curing requirements in recommendations and codes on the basis of these findings. In view of the connection between curing and durability the measures for curing and protection should be a separate item of the construction contract to be agreed upon prior to the commencement of the construction work.

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Controlling Durability during Construction
- Examples, Case Studies

Dr. Rolf Dillmann

1. Introduction

One substantial problem of the durability of reinforced concrete structures is the protection of reinforcement against corrosion, This protection is normally ensured by the basic (that is: hydroxyl ion concentration) nature of the concrete. However, this basic environment surrounding the reinforcement bar can be destroyed by carbonation, i. e. the reaction of atmospheric carbon dioxide with the calcium hydroxide of the concrete.

In the face of this fact two outstanding factors have emerged as protection against corrosion:

- the thickness of the concrete covering and
- the density of the concrete covering.

The concrete covering is the concrete layer between the surface of the reinforcement bar and the outer surface of the concrete. In addition to securing a sufficient protection against corrosion of the reinforcement the covering also serves in

- taking up bond strength
- providing an effective fire protection.

2. Measures for increasing the durability of the concrete structure by increased protection against corrosion during construction

2.1 Thickness of concrete covering

The thickness of concrete covering is, generally speaking, influenced by the following factors:

- measurements of the bent and suspended reinforcement
- clearing width of the form work
- amount of dislocation of the reinforcement cage during concreting.
- height/thickness of spacers

On the basis of a research projekt it became evident that, provided the influencing factors are independently and normally distributed, a standard deviation of concrete covering of approx. 8 mm is to be expected.

Consequently, on construction sites the following checks are carried out routinely or at least randomly:

- inspection of the measurements of bent and suspended reinforcement and rejection of those reinforcement bars that deviate in their lengths from the values of table 1.

- inspection of form work struts and rechecking of the clearing width of the form work immediately prior to concreting.

In order to avoid dislocation of the reinforcement cage during concreting a sufficient number of spacers must be used. The spacers must have sufficient bearing strength and be resistant against deformation and tilting. Their height/thickness must correspond to the minimum concrete covering and include an allowance that takes into account all inevitable deviations.

2.2 Density of the covering

The density of the concrete covering is largely influenced by the following two factors:

- the water/cement ratio of the concrete
- the degree of hydration, i. e. the curing of the concrete

By using concrete plasticizers it is nowadays no problem to produce and use a concrete with a sufficiently low water/cement ratio.

Because of the greater human factor involved it is definitely more difficult to achieve sufficient curing under site conditions. However, when using a minimum of discipline there are enough curing methods on hand today to suit every specific site and purpose.

The effectivness of curing can be checked under site conditions. This may be done either by testing the permeability towards air by means of a vacuum or by the rate of water absorption of the concrete near to the surface.

3. Summary

The two parameters, thickness and density of the concrete covering, are the determining factors for durability of concrete structures as far as corrosion of reinforcement is concerned. Defect preventing methods are recommended that explain how the two parameters can be controlled during construction.

In the long run so-called "Trade-off-methods" may become feasable. These methods pre-suppose that quality is a constant while the two factors concrete thickness and concrete density can have variable values.

Stablänge l (m)	≦ 5,0	> 5,0
Abmaß Δ l (cm)	± 1,5	± 2,0
bei Paßlängen Δ l (cm)	± 0,5	± 1,0

Biegeform			 [1]			
Stab Ø (mm)	bis 14	über 14	bis 14	über 14	bis 10	über 10
Abmaß Δ l (cm)	+ 0	+ 0	+ 0	+ 0	+ 0	+ 0
	− 1,5	− 2,5	− 1,0	− 2,0	− 1,0	− 1,5
bei Paßlängen Δ l (cm)	+ 0	+ 0	+ 0	+ 0	+ 0	+ 0
	− 1,0	− 1,5	− 1,0	− 2,0	− 0,5	− 1,0

[1] Bei Festlegung dieses Maßes Abmaß der zugehörigen Bügel beachten (Passung)