AFGC

Groupe de travail

"Réhabilitation du béton armé dégradé par la corrosion"

CEFRACOR

Unformal translation of "Documents scientifiques et techniques:
"Réhabilitation du béton armé dégradé par la corrosion"

"Rehabilitation of reinforced concrete damaged by corrosion"

November 2003

The French association of civil engineering (AFGC formerly: AFREM-AFPC), in partnership with CEFRACOR (French centre on anti-corrosion), created a working group on the **rehabilitation of reinforced concrete damaged by corrosion**

The objective of this group has been to establish recommendations for choosing the best method of rehabilitation, which is convenient for a structure subject to corrosion, according to criteria such as the concerned damage process, the properties of the reinforced concrete, of the environment, of the constraints and subjections met, etc.

This document presents the results of this task. It is addressed to structures managers and owners, to project designers, to architects facing the problems of structure corrosion, as well as to repair companies, control laboratories, applicators and suppliers of products concerned with the implementation of methods or rehabilitation products.

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OUTLINES

The French version includes Annexes referring to structures located in France. So, these Annexes have not been translated.

1. DATA CONCERNING THE STRUCTURE

1.1: INTRODUCTION

This document deals with damages due to corrosion of reinforced concrete structures, which are in service, as well as with techniques for preventing or repairing these disorders.

The structures and elements concerned by reinforcement corrosion are as follows:

- Buildings acroteria and balconies, in all atmospheres, vertical elements and terraces, in industrial and maritime sites. They are of course the most sensitive buildings elements, because of either their thinness, or of the difficulty of maintaining sufficient covers.

Photo 1.1: Spalls on a facade

- Industrial buildings posts and slabs. These elements are rather often exposed to chemical agents. Beams are also particularly sensitive elements of industrial structures, because they often support floor slabs. They are sometimes in an enough surprising condition.

Photo 1.2: Corroded beam supporting a reservoir

- Car parks beams and slabs, in maritime or mountain sites. This is related in both cases to the presence of chlorides (coming respectively from sea water and deicing salts).

Photo 1.3: Piling under a garage   Photo 1.4: Pole for an electrical line

- Components of prefabricated structures it does not seem that significant problems are to be faced here, because concrete is likely better cured, and better placed. However, the posts of electrical lines, for example, seem to be an issue. There is also a significant pathology concerning various structural components, due to the use of concrete setting accelerators containing calcium chlorides, in years 1960s-80s. This is the case of exterior wall panels, acroteria, flowers stand, etc

- Bridges and structures for these structures, it appears that the most significant zones are decks, supports in superstructures, and deck equipment, where the influence of deicing salts is significant.

Photo 1.5: Bridge piling

- Tanks (buried, on ground, in air). The main problem of these structures is related to water leakages, which are due to cracks (of various origins: thermal, mechanical, etc.) or to poor reinforcement cover, in particular if the environment contains aggressive salts (mostly chlorides).

On existing structures with cracks, or leakages, repairs consist in sealing off the defects or in water-tightening.

- Silos the silos for storing granular or powder materials (cereals, cements, etc.) are subjected to high stresses, in particular during loading and unloading. These stresses induce horizontal or vertical cracks, which can result in water penetration, initiating reinforcement corrosion.

- Industrial air coolers of nuclear power plant these structures are subjected to a severe environment (water droplet or spray vapour inside the structure, sun, rain or freezing outside), which induces stress resulting in cracks. In addition, the high moisture results in a water vapour transfer, which can be the origin of concrete damage.

Photo 1.6: Wall of an aircooler tower

- Chimneys, chimneys (industrial ones, in particular) are subjected to a very severe, mostly acid environment (sulphuric acid and hydrochloric acid).

- Harbour Structures located on sea shore suffer from aggressions due to chlorides. The corrosion intensity is related to the environment aggressiveness (tide, splashes, spray zones). Some lack of concrete cover or of concrete quality are then immediately highlighted.

Photo 1.7: Bridge piling in a tidal zone

Photo 1.8: Beam under a bridge deck

Photo 1.9: Dock in a tidal zone

- Reinforced and prestressed concrete pipes, most of them are buried, and failures occur when the concrete protection is no more sufficient (carbonation, presence of chlorides).

Photo 1.10: Reinforced concrete pipe

It is also necessary to take into account historical buildings (churches and other structures by architects A. Perret or Le Corbusier), or more and more classified buildings made of reinforced concrete, which have their own constraints, in particular in terms of repair.

Photo 1.11: Façade of a historical monastery

Some structures are in contact with the atmosphere, such as, for example, bridge piles and decks, silos or tanks. Other structures are in contact with ground and possibly with water: such as, for example, foundation drains or piles. Finally, some structures are in contact with both ground and water or with atmosphere and water. It deals, for example, with bridge abutments, with quays (near river or sea), with tunnels or with retaining walls.
The natural environments, which are atmosphere, ground or water, can also contain products , such as, for example, fertilizers or deicing salts, which are aggressive to reinforced concrete.
It is as advisable to add that concrete itself can be damaged in various ways. But, in fact, the corrosion process of reinforcement little depends on its origin.
The various reinforced concrete structures are different, not only by their function, but also by their monitoring and their maintenance. Some of them are well followed, whereas others have a poor maintenance.

1.2 TYPES OF DAMAGE OF CONCRETE PARTS

1.2.1- STAGES OF DAMAGE

The damaging of reinforced concrete comprises two successive stages:
- an incubation or latent stage (sometimes named initiation), which corresponds to the slow concrete damage, without any visible effects yet,
- a development stage (sometimes named growth or propagation) of the material damages.

The initiation stage ends when
- the products formed by internal cement reactions of reach a " critical volume " resulting in a harmful swelling of concrete (for example, by sulphatic reaction),
- the concrete cover does not protect anymore steel against corrosion (for example, if the concrete cover is carbonated).
During the development stage, damages are visible. Then, repairs become more heavy and expensive.

1.2.2- DAMAGES DUE TO REINFORCEMENT CORROSION

The bodies dissolved in the environment around the structure, can progressively penetrate into concrete. Some of them are aggressive, for example carbon dioxide (CO_2), acids (fertilizer, etc.) and chlorides.

A steel in contact with a concrete, which has a high alkalinity (pH of about 12) and which is not polluted by chlorides, is covered with protective oxides. If this thin cover is chemically changed, then steel is covered with " intermediate " products, which are not stable in the presence of the oxygen dissolved in concrete. They change into " final " products, which do not protect, and lead to steel dissolution and continuous rusting.
This is the reason why, damages due to reinforcement corrosion result in defects, which become visible only after a certain time. The invisible defects are chemical and sometimes physical changes (related to the microstructure) of concrete cover. It also deals with the beginning of a bursting (delamination) of this cover or a formation of a thin layer of rust on steel. In some cases, reinforcement dissolution occurs, without any visible trace on concrete surface.

The visible deteriorations are bursting, spalling and cracking of concrete cover. Other mechanisms can also induce this type of deteriorations. When corrosion is very advanced, some traces of rust are visible, reinforcements can be exposed to atmosphere, and dissolved (loss of cross section).

1.3 ORIGIN AND MECHANISM OF DISORDERS DUE TO CORROSION

1.3.1- CORROSIVE AGENTS IN THE ENVIRONMENT IN CONTACT WITH CONCRETE

A reinforced concrete structure is in contact with a natural environment, atmosphere, water or grounds. These environments often contain some products, which are aggressive against concrete (or its reinforcement). So, sulphates contained for example in seawater and waters with gypsum, can induce concrete expansion, if they are in a sufficient amount. But agents, which are at the origin of reinforcement corrosion, are mainly carbon dioxide and chlorides.
Carbon dioxide CO_2 penetrates in a gaseous form in concrete. It causes a reaction, named carbonation, with cement pore water. The carbonation front advances progressively, starting from concrete surface. It changes hydroxides [mainly, lime $Ca(OH)_2$] into some carbonates ($CaCO_3$) and decreases the pH of pore solution from approximately 13 to approximately 9. This process deteriorates the passivation of reinforcement.

Chlorides dissolved in water (sea water, deicing salts on roads, etc.) penetrate starting from concrete surface. Thus, the chloride content in concrete has a certain profile. This profile is a curve "content-depth", which is strictly decreasing, if the humidification-drying cycles are negligible. In the contrary case, this profile is decreasing only starting from a depth where concrete is permanently saturated of water (pore water is not evaporating).

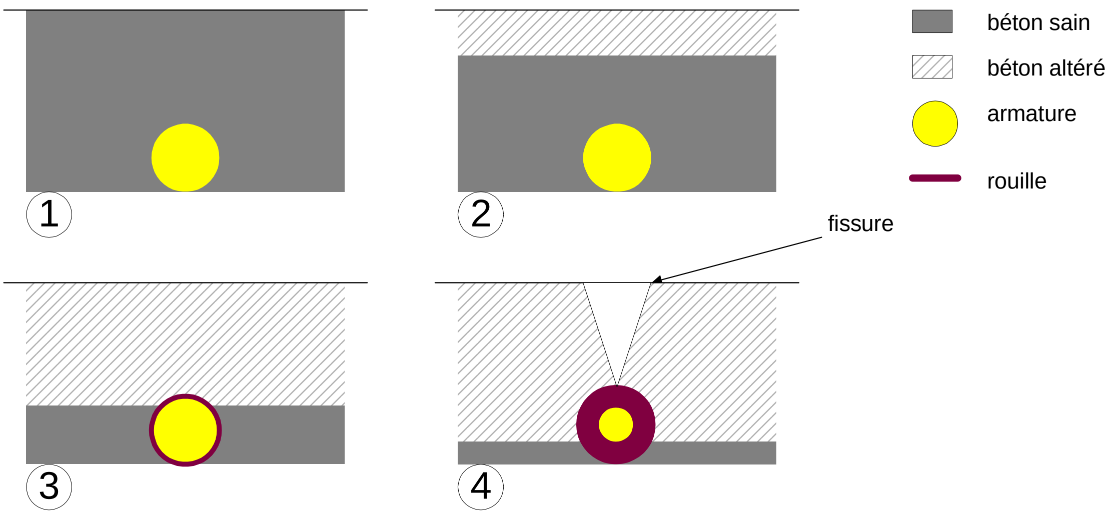
1.3.2- STAGES (STEPS) OF CORROSION

The initiation stage of corrosion corresponds to the duration during which aggressive agents (carbon dioxide, chlorides) penetrate in concrete cover, without corroding reinforcement. It ends when, at the reinforcement level, the content of aggressive agent reaches a threshold. Figure 1 illustrates these stages of damages by corrosion due to aggressive agents coming from the environment.

In the case of carbonation, this threshold corresponds to the fact that reinforcement is in a carbonated and sufficiently wet concrete.

In the case of chlorides, concrete is then usually wet and oxygenated, the threshold corresponds to roughly 0,4% against cement weight. This value corresponds to a content ratio $[Cl^-]/[OH^-]$ ranging between 0,6 and 1, depending on cement types.
During the stage of rust growth, the dissolution (corrosion) rate of steel is significant. The formed rust is generally expanding and causes a cover disintegration , with spalling, bursting or cracking.

The appearance of cracks strongly depends on the properties of cover: thickness, mechanical ultimate strength, etc. More precisely, once that reinforcement started to corrode, cracks appear very early even in a concrete with a good mechanical ultimate strength. The corrosion products diffuse easily in a porous concrete and stain its surface.



Damage due to corrosion.
This damage proceeds by stages: in sound concrete (1), an aggressive agent penetrates progressively (2), when its content is rather high, the reinforcement begins to corrode (3) and rust can make cover spall (4)

1.4 CONSEQUENCES OF DISORDERS

1.4.1- STRUCTURE APPEARANCE

The white and rust stains due to the penetration of aggressive agents in concrete cover, deteriorate the structure aspect. Sometimes, this point is considered as being of a little importance, by structure managers. On the other hand, in fact concrete cracking and fracturing make the managers worry, because concrete can spall.

1.4.2- SAFETY FOR USERS

The concrete spalling shows a risk for people, who circulate close to the structure. So, its prevention and elimination must be treated carefully.

1.4.3- STRUCTURE STABILITY

Tests carried out on specimens make it possible to estimate the values of bonding forces for concrete elements with corroded reinforcement. It appeared that neither the concrete quality, or the cover/diameter ratio of reinforcement influence the residual bonding force, even if cover is cracked by reinforcement corrosion, without being totally spalled off.

For bending moments and transverse shears, an experimental research related to the effect of corrosion on these mechanical parameters is carried out. It usually shows that to forecast conservatively the behaviour of reinforced concrete elements, it is enough to apply the traditional calculation models, with considering the reduced section of reinforcement as well as the reduced concrete section. Thus, as long as the reductions of reinforcement section remain low, and when cover remains cohesive, a reinforcement corrosion does not significantly change the performance of bending moments or transverse shears.

But when corrosion reached an advanced stage, more precise calculations must be made to evaluate the residual performance of the structure. This document treats only materials and not the problems of structures.

1.5 CASES OF PRESTRESSED CONCRETE STRUCTURES

Prestressing steels (tendons) are either directly placed in concrete (prestressing by pre-tensioning), or placed in ducts, which are then filled with a grout, or with wax (prestressing by post-tensioning). The tensioned tendons, which are directly in contact with concrete, show a risk of corrosion with dissolution and rusting, like traditional reinforcing bars.

Moreover, all tensioned prestressing tendons are also subjected to the risk of stress corrosion, without a systematic formation of rust. The structure failure is then difficult to forecast.

The specific case of prestressed concrete structures is not detailed in this document.

2. CHARACTERISATION, DIAGNOSIS

2.1 OBJECTIVES OF DIAGNOSIS (MONITORING)

2.1.1- DATE OF DIAGNOSIS

The French technical guide " Choice and application of repair and protection products for concrete structures " defines six stages in the procedure leading to a repair action. The diagnosis intervenes in the two first stages of this procedure.

The first stage, named " stage of pointing out damage ", can be triggered by an operation of survey (case of civil engineering structures), by an operation of maintenance, or after an accidental event (falls of concrete pieces, for example). It leads to transfer information towards the responsible, who are thus sensitized on the problem observed.

The second stage is the " diagnosis " itself, or search of a pathology starting from the symptoms. It is asked within the framework of:
- a single study,
- structure strengthening, restoration or renovation,
- a regular inspection highlighting disorders,
- an expertise,
- or a preventive step.

It should be noted that this text does not replace the French "Technical instructions for the survey and the maintenance of structures", which are a reference document for road structures, and which describes the methods of monitoring.

2.1.2- PARTICULAR CASE OF REINFORCEMENT CORROSION

The reinforcement corrosion often results in visible symptoms on concrete surface, such as cracks, spalls, spots of rust. In some circumstances, however, a delamination can occur at the reinforcement mat, without apparent signs of corrosion.

The form of disorders, their extent, and their intensity depend both on the position of reinforcement (cover thickness, spacing), on the quality of concrete cover (compactness and homogeneity), on the environment (type of the aggressive agent: carbonation, chlorides). Thus, when a corrosion appears, it is reasonable to expect that the damage process extends beyond visible deteriorated areas.

So, the majority of investigation methods are directed towards the determination of properties related to these parameters.

2.1.3: OBJECTIVES OF CORROSION DIAGNOSIS

The objectives of a corrosion diagnosis are to:
- identify the origin (carbonation, chlorides external or interns, others) of damage,
- evaluate the space extension (location),
- predict the probable evolution, in term of time or space,
- estimate the effects on the safety concerning the structure or people,
- define the action to be taken and the principle of repair solutions.

Considerations on cosmetics (appearance) are also to be taken into account in many cases: buildings, historic structures, because of the nature of basic materials, of their texture, of their colour and of the cement type. This is to be taken into account when writing the investigations program.

2.1.4- PROCEDURE TO BE FOLLOWED

The procedure to be followed for a diagnosis, is integrated in a whole phase, which can lead to structure repair.

The discovery of disorders on a structure, generally involves:
- the implementation of safeguard measures, if necessary (chiselling off concrete, protecting it with a net, etc.),
- the realization of a preliminary visit and some other operations for establishing a pre-diagnosis,
- the development of an investigation program,
- the launching of operations related to the diagnosis...

The engineer in charge of diagnosis operations must be competent on physical chemistry of materials, on instrumentation, on methods of repair and treatment. In delicate cases, he will have to join with an engineer specialist in structures (for mechanical problems), or a chemical engineer in laboratory (for problems involved in concrete expansions, etc).

2.2 PRELIMINARY VISIT

The object of preliminary visit is to improve the understanding of the structure condition and functioning, to describe environmental conditions, visible disorders and the accessibility to damaged areas. This inspection leads to a pre-diagnosis and a program of investigations. It includes:
- the collection of information needed to understand the structure: history, documents, files, reports, location, orientation, date of construction, plans of structure and reinforcement, environment (nature, chemical properties, main winds), materials (cement, aggregates, concrete design, etc.).
- a brief examination of the whole structure (or building), and the description of all the symptoms with shooting photographs. The most adapted access means will be used: it is necessary to closely watch damaged surfaces. Some simple tests (carbonation depth, presence of chlorides, alkali-aggregate reaction) could be considered at this stage, for orienting the future program of analyses.

After this visit, the engineer must be able:
- to emit a pre-diagnosis on the likely causes of disorders,
- to carry out the development of an investigation program. This program will take account all subjections relating to the access, to the environment, to the presence of electrical supply etc,
- to evaluate if it is necessary to write specifications on responsibilities and guarantees,
- and to improve safeguard measures (traffic restraint, higher monitoring...).

He must also consider the probable costs and duration of the investigations, and compare them with the value of the structure.

2.3 DETAILED INSPECTION

The visual inspection of the whole the structure is implemented for detecting all signs of damage, and identifying all likely sources of disorders. It includes the two following items:

a) Preparation of the inspection

It mainly deals with checking and supplementing the information collected during the preliminary visit, and seeking already existing documents, such as former expert reports,

The access means will be listed and previously determined, as well as measures to be taken (safety, access, cleaning, etc).

b) Inspection

The inspection itself includes the description, possibly on maps, of all visible disorders, and any useful information about concrete surface appearance:
- presence of old coatings, or sealing products,
- appearance of concrete surface, stalactites, white stains, traces of rust,
- presence of cracks, (opening, network),
- deterioration of concrete skin,
- exposed reinforcements and spalling,
- structural deformation,
- presence of hollow zones determined by hammering,
- the traces of moisture.

This report will refer to a guide on defects.

2.4 IN-SITU INVESTIGATIONS

The program of on-site investigations is established while taking account the following constraints and requirements:
- importance of the structure (adapt investigations to the nature and the importance of the structure),
- nature, severity and intensity of the phenomena, safety of people,
- deadlines and costs,
- accessibility,
- environment, etc.

2.4.1: MEASUREMENTS CONCERNING REINFORCEMENT

2.4.1.1: Measuring cover thickness on reinforcement

The cover thickness on reinforcement is a relevant parameter in corrosion processes. The measurement technique of cover thickness is carried out with many apparatuses available on the market, based on magnetic and reflectometry principles (geophysical radar). However, precise details and accuracy strongly vary from one technique to another, in particular according to the reinforcement density. These techniques, whose performances are related to their guiding principle, give the following information:
- cover thickness,
- estimated diameter of reinforcement,
- presence of adjacent reinforcements,
- approximate steel profile.

Photo 2.1: Locating reinforcements with a radar

The objective of these measurements is to locate any thinly covered reinforcement (in relation to regulations, as well as to particular requirements), to consider the concerned surfaces, and finally to bring quantitative elements for modelling the possible change of the phenomena (in relation to carbonation depth or to chlorides penetration). These methods have not been standardized yet.

2.4.1.2: Estimating corroded surfaces and evaluating the risks of corrosion: measurements of half-cell potential

Among the electrochemical methods, which can be applied for detecting the risk of reinforcement corrosion in concrete, the measurements of half-cell potential are used and are the best known, because they are simple and non-destructive. This method makes it possible to evaluate the risks of reinforcement depassivation.

As soon as reinforcement is in contact with concrete, a potential difference is established at steel-concrete interface, depending both on the reactions known as anodic (oxidations: change of metal into oxides) and the reactions known as cathodic (reduction of oxygen). This half-cell potential is complex and its value depends on the corrosion condition of steel (potential tends towards negative values, as soon as corrosion is initiated), but also on the water content in concrete, the content of aggressive elements, the carbonation depth, the concrete compactness, etc... Half-cell potential cannot be connected to these parameters by any law, or mathematical relationship. So, its absolute value has only little significance. Nevertheless, the measurements taken on representative surfaces make it possible to establish a map of corrosion probabilities and to locate the areas having a maximum risk.

Measurements of half-cell potential are especially used during *diagnosis stage* (they make it possible to locate material sampling or complementary tests), but also during *repair operations* (precise location of zones to be repaired). *In continuous* monitoring, they also make it possible to detect a phenomenon, far before a disorder becomes visible at concrete surface, and thus to draw better plans of repair (preventive measures). They do not make it possible neither to determine reinforcement location (instead, use magnetic methods or reflectometry radar), nor steel corrosion (cross-section loss) rate.

Photo 2.2: Measuring half-cell potential

Photo 2.3: Wheel with reference electrode

They do not apply to:
- buried or immersed elements, unless adapting methodology to these particular cases (for example, remove ground, by undermining, around the structure element, then depolarization can take several days),
- concrete coated of an electrically insulator product: this one must be removed at the measurement points,
- concrete prestressed by post-tensioning, because the presence of plastic or metal duct, does not make it possible to send the electrical signal to the cables.

The method requires to expose a reinforcement, which is connected to a terminal of a millivoltmeter, the other terminal of which is connected to a reference electrode placed on the concrete surface.

The junction between concrete and reference electrode must be wet, and if not, this moisture must be assured (spraying pure or slightly alkaline water, soaked cotton, etc...).

The reference electrode is an electrode with constant potential, and is defined by a succession of electrochemical equilibriums.

The layout of potential maps, and the study of half-cell potential gradients associated with the development of numerical data-processing methods (data logging) give now reliable and precise interpretations, and they lead to the development of this type of measurements. The material can include one or more reference electrodes, or wheels electrodes.

Foot-note About the measurement methodology, there is no real standard, but RILEM published a recommendation (see bibliography)

Photo 2.4: Measuring corrosion rate

2.4.1.3: Estimate corrosion rate

Another electrochemical method makes it possible to estimate the instantaneous corrosion rate of reinforcement, in a given zone.

This method is based on the linearity of the current-potential curves in the vicinity of the free corrosion potential. The slope of the straight line ΔE / ΔI expresses the polarization resistance, R_p , which is connected to corrosion current by $I_{corr} = B/(A.Rp)$, where B is a constant, and A the area concerned by polarization. In spite of several restrictions, of theoretical type, measuring R_p periodically, makes it possible to control the change of corrosion process, to identify the zones with highly corrosive activity, and to predict a residual lifespan for the structure considered.

The apparatuses allowing this type of measurement have their own system of measurement.

Foot-note A RILEM method defines the methodology of measurement and interpretation.

2.4.2: MEASUREMENTS RELATED TO CONCRETE QUALITY OR TO ITS AGEING

2.4.2.1: Determination of carbonation depth

This is a determination of the degree of natural ageing of concrete (but especially its depth of neutralization by carbon dioxide).

Among the methods for determining carbonation depth, the simplest one is the test with phenolphthalein. This consists in measuring the depth of coloured front by using this pH sensitive indicator, which is sprayed on a fresh concrete cut. A European standard is under development for this test, and there are some test procedures (AFREM-AFPC, RILEM CPC 18, etc.). Other indicators, with different ranges of colour changes (blue of bromothymol, for example), can be used. However, the differences between the results obtained with these indicators and those with phenolphthalein are low and their use is seldom justified. This test was checked and validated by examining concrete samples with scan electron microscope.

However, some precautions are necessary to make sure that a reading of carbonation depth is representative: it is necessary to make a sufficient number of determinations, taking into account the local exposure conditions, and the possible inhomogeneity of concrete.

Today, no non-destructive method for determining carbonation depth exists.

2.4.2.2: Measurements of resistivity

Corrosion is an electrochemical phenomenon, and concrete is electrically conductive, so concrete electrical resistance is a significant parameter for the intensity of exchanges. However, this effect depends on some parameters: water content in concrete, chemical composition of pore solution (presence of salts, etc.).

Measurements of resistivity on site are used in parallel with measurements of half-cell potential, to refine corrosion diagnosis. Indeed, corrosion rate is controlled by the facility for the ions dissolved in pore solution, to move in concrete, both at anodic zone and at cathodic zone. Thus, high potential gradients associated with low resistivity values are characteristic of high corrosion rate.

Resistivity measurements can be influenced by the presence of reinforcements near the measuring point, by a scale effect, or by the presence of a surface concrete layer having a resistivity different from that of the (bulk) concrete heart. In addition, the principle of measurement (four-point method to 4 electrodes) has its limits. A new method using a small counter-electrode was described, and this makes it possible to establish a grade of risk after the obtained resistivity value.

2.4.2.3: Measurements of permeability

Among the physical properties of concrete, permeability influences the duration of the period for initiating corrosion. A measurement of permeability from concrete surface is particularly interesting. However, this on-site measurement is influenced by water content in concrete, which limits its application.

Permeability to air its determination consists with increasing gas pressure in a vessel, and measuring the decrease of pressure.

Permeability to water the pressure of water in a vessel is first increased , then the water flow is measured.

The zones for measuring permeability must be perfectly located, to avoid defects on concrete surface (rock pockets, cracks, etc).

In the absence of standards or specifications, these measurements remain comparative.

2.4.2.4: Surface cohesion

This determination is interesting, for example, when defining the nature of the coating to be placed, particularly in the case of brittle or other coatings.

This parameter is determined by tensioning patches glued on concrete surface (square section 5x5 cm^2, or circular with a diameter 5 cm), and by measuring the ultimate bonding load. Tensioning is carried out, by using a specific apparatus. Several measurements are necessary in one zone (not less than 3). The values are read in MPa. As an information, the application of a coating on a concrete substrate requires a minimum of 0,5 MPa.

2.5 LABORATORY ANALYSES AND TESTS

2.5.1- METHODS FOR TAKING SAMPLES

Concrete samples are taken out, if necessary, in zones representative of the damage condition, by coring or drilling. An AFREM procedure gives indications on this point.

Drilling is used, for example to estimate chloride penetration, In this case, samples are taken at successive depths, in the order of a centimetre.

Photo 2.5: Taking samples by drilling

2.5.2- CHEMICAL ANALYSES

The chemical properties of a concrete cover are determined, on samples:
- *total chemical composition:* the operation includes the analysis of concrete soluble part, and of insoluble residue. Its aim is to determine concrete properties, such as cement content and the absence of any anomaly,
- *total chlorides and free chlorides (water soluble) contents*. The methods for these analyses are described in AFREM (or RILEM) procedures. Chlorides contents are expressed against cement or concrete weight. Cement content in concrete can be known or evaluated after in laboratory analysis of soluble silica in cement, which is previously identified (in the

construction file or by microscopic examination). The interpretation of results must consider not only measured single values, but also the shape of content profiles,
- *sulphates content*
- *other particular determinations* (for example, sulphides).

2.5.3- MINERALOGICAL PROPERTIES

The mineralogical properties of concrete are determined by:
- optical microscopy (transmitted or reflected light) for determining cement type, and scan electron microscopy SEM for microanalysis of elements,
- x-rays diffraction for detecting crystals and their properties.

An AFREM-AFPC document ("Application of microscopic methods to characterize the microstructure of concrete") gives indications on this point.

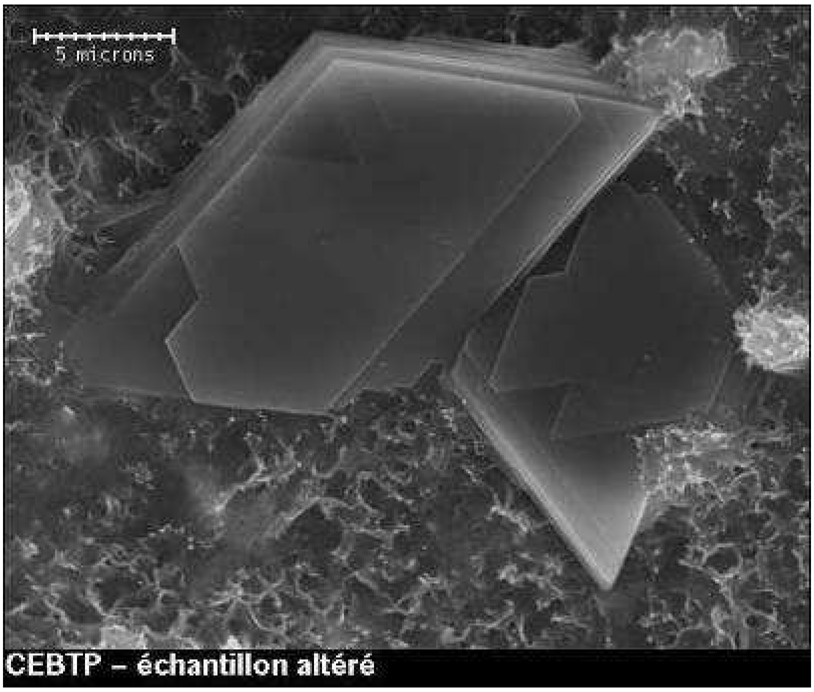


Photo 2.6 Chloro-aluminate crystal

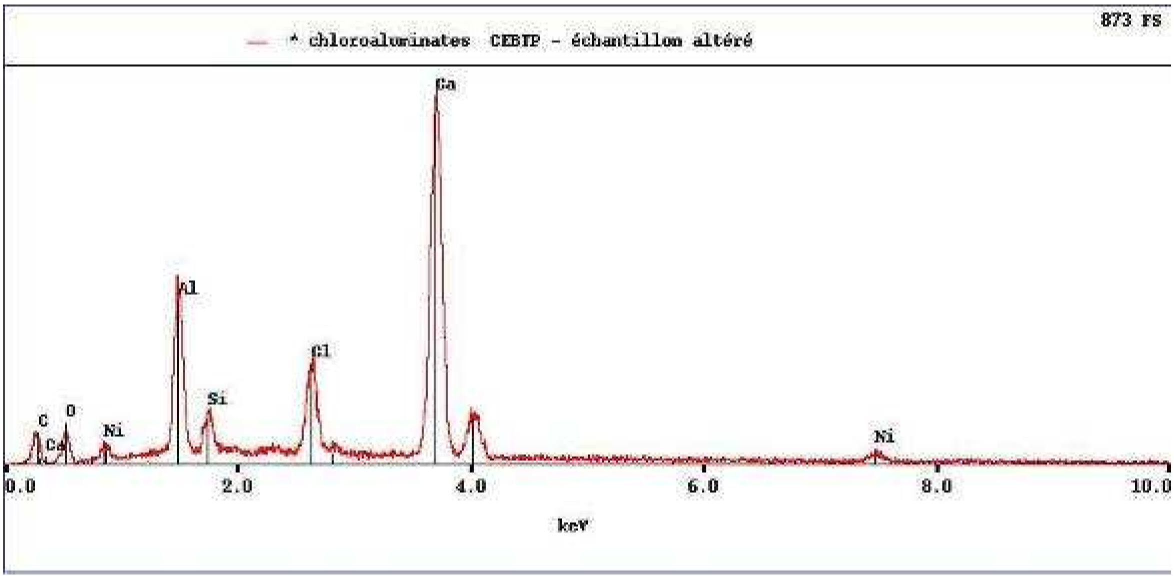


Photo 2.7:Corresponding EDS spectrum

2.5.4- PHYSICAL PROPERTIES

The physical properties of a concrete cover are mainly related to their penetration resistance (transfer) against fluids:
- porosity measured with water (possibly with mercury),
- permeability,
- diffusivity of elements, such as chlorides,
- capillary absorption,
- mechanical strength and possibly other properties.

Foot-note. A concrete can also be affected by other pathologies, such as alkali-aggregate reaction, sulphatic reactions, or freezing. In case of doubt, additional investigations are necessary to identify the pathology origin.

2.6 DIAGNOSIS REPORT

A diagnosis report presents all the results and their interpretation, but it must be understood by a not specialist person.
It includes:
- structure identification, name of the applicant,
- identification of the laboratory (or engineer) in charge of the study, date of the report,
- a short description of the structure,
- reminding study aims,
- list of the consulted documents,
- results of the detailed inspection,
- results of in-situ and in laboratory tests,
- discussion on the origin of the disorders, their extent, their probable evolution, and their incidence on safety,

- clear conclusions on the observed disorders and possibly on proposals for a complementary study,
- list of priorities of repairs and works to be carried out,
- recommendations on the most convenient methods of repair.

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3. CONSTRAINTS AND REQUIREMENTS

This chapter gives a non-exhaustive list of criteria for guiding an engineer, who has to recommend a rehabilitation of reinforced concrete damaged by corrosion. Indeed, the choice of repair method or products is subjected to constraints and requirements, which are related to the rehabilitation type, the type and the environment of the structure to be repaired

3.1 STRUCTURAL CONSTRAINTS

One of the consequences of steel corrosion in reinforced concrete is a weakening of the structure. The engineer in charge of studying repair must always keep in mind the respect of the safety of the structure in service, therefore of its stability. Before considering solutions for treating this corrosion, he must estimate the general condition of the structure and understand its mechanical functioning.

He must take into account, as for a new project, the constraints about service operations, about loadings and about the structure environment.

A thorough visit of the structure, makes it possible to detect relevant indices of resistance loss of the structure, such as concrete crack, chipping and local crushing, etc. Sometimes this inspection reveals that corrosion is initially due to a structural dysfunction. So, corrosion is in fact only a worsening factor.

The visited structures are in general in service and subjected to loadings, their age and their general condition make it possible for an engineer to assess the quality of the initial design and the structural functioning. It is not advisable to systematically change structures, when their performance is satisfactory. But the treatment of corrosion, which is considered, shall respect the project in general, by giving again the structure its original properties.

3.1.1-RESPECTING THE STRUCTURE FUNCTIONING AND PRESENT CONDITION

A reinforcement corrosion in reinforced concrete can result in a loss of the load bearing capacity of the structure. This resistance loss appears after materials deteriorations, as follows.

3.1.1.1: Losses of concrete section

The expansion of iron oxides induces stresses, which can damage concrete, up to its bursting. So, the resistant concrete sections decrease, stresses are redistributed, and forwarded to adjacent zones. The simple rebuilding of these sections with a patching material, is not always sufficient to obtain the initial structure functioning. It can be necessary to use jacking technique for relieving the structure, before rebuilding the weakened section. This can be the case in compressed zones, the nature of patching products must take into account the composition of concrete in place and its Young’s modulus. The shape of the part removed for cleaning damaged zones, has to take into account the angle of concreting joints in the new zone, so that stresses are correctly distributed during new loading.

3.1.1.2: Reinforcement cross-section loss

Metal corrosion is a dissolution, so it gives a loss of reinforcement cross section. The safety factor taken into account in design calculations, is somewhat reduced. The engineer in charge of rehabilitating a structure has to estimate these losses. This task is not easy, the estimate is generally made in a statistical way after a series of residual diameters measurements, carried out during surveys. For evaluation visits, access means are seldom those used for operations on site. The evaluation surveys are generally carried out at easy access points, where the sections not always are the most loaded. So, it is necessary to keep some funding left for possibly carry out new surveys in the most loaded sections, and forecast a possible reinforcement strengthening.

If the section loss is higher than 10%, it is advisable to strengthen reinforcements. But the in-service loadings should have changed, and in-place reinforcements correspond to the required loadings. The introduction of new reinforcements can then be done inside concrete, after demolition of some zones and concrete patching, either by an external introduction embedded in a sprayed concrete connected to the structure, or by additional reinforcements glued as sheets or carbon fabrics.

3.1.1.3: Anchoring and reinforcement bonding

The iron oxides form around reinforcement a sheath, which, when it reaches some importance, can decrease their bonding to concrete. Then, this bond loss of bars results in a general resistance loss of the structure. The force transmission by tensioned bars can be changed by a relative slip of the anchoring during loading, the force transmission is obtained with greater strains.

Sometimes, for taking off damaged concrete cover then patching, bar anchors must be totally exposed. When they are not accompanied by a proper support of the structure before chiselling off, these concrete removals deeply change their functioning, and can present a real danger during operations.

3.1.2- RESPECTING ALL IN-PLACE MATERIALS

3.1.2.1: Respect of in-place materials

The treatments of reinforcement corrosion in reinforced concrete are carried out either by placing material on concrete surface, or by patching after concrete removal, or by processes acting in-depth. The choice of techniques must be made, by considering the materials constitutive of the structure, as well on physical level as on chemical one. Thus, treatment of reinforcement corrosion should not result in the deterioration of in-place concrete, which would be due to the incompatibility of two involved products. The action of protective products on reinforcement should not induce, for concrete, secondary effects harmful to a correct structure functioning.

Before recommending a treatment, the engineer has to make sure that the selected solution is in adequacy with the functioning conditions and with the environment of the structure.

The effects of a treatment can be of three types.

a) Irreversible actions on the nature of materials

The application of repairing products can change in an irreversible way the internal or surface structure of treated materials. Some surface products completely fill concrete porosity, “trap” moisture inside the structures, and they make them more sensitive to freezing-thaw cycles. Sealants, which create new minerals, can change the chemical equilibriums in concrete in-place or Young’s modulus of highly impregnated zones on concrete surface. Other products can prevent forever further installation of coatings, etc.

b) Side effects after treatment

Some treatments can have side effects, after their application on some concrete types. For example, electrochemical treatments, which increase the pH of concrete cover, can enhance alkali-aggregate reactions In the same way, the use of product with an expanding effect (at long term) can create significant stresses, able to induce cracking or bursting.

c) Consequence of the choice of replacing materials

So, the choice of replacing or substitutive materials on damaged zones must take into account the ageing condition of materials in place. If some parts must be partially rebuilt, one has to be sure that materials have a good compatibility. Some products, used in patching, easy to use, fast, and compatible with reinforcement, are not always compatible with the adjacent concrete. This can be the case of products with binder containing aluminous cement put in contact with concrete containing Portland cement CEM I.

3.2 CONSTRAINTS OF SITE AND EXPLOITATION

The choice of repair products and processes to be recommended strongly influences the durability of a repair. It must also take into account exploitation constraints, and the respect of the environment during operations.

To meet the requirements related to the site, the person in charge of a study has to consider at least the structure location, its properties and its environment.

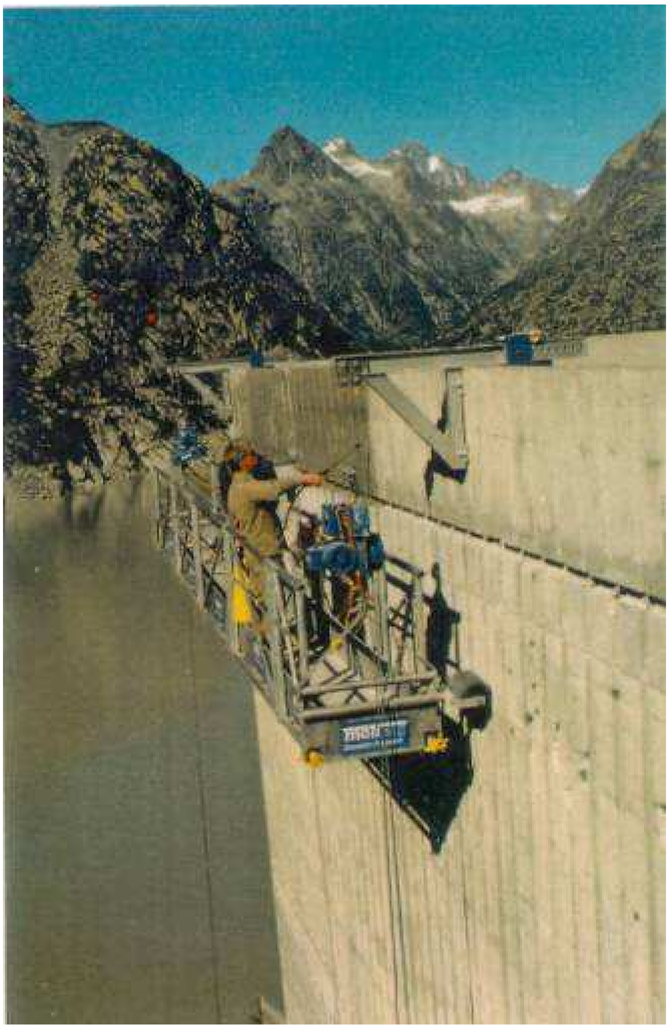


Photo 3.1: Scaffolds needed for works on a site

3.2.1- SITE (AGGRESSIVENESS OF THE ENVIRONMENT, LOCATION)

3.2.1.1: River and maritime sites

The maritime and river sites are characterized by the presence of more or less salted water, and by a wet atmosphere, with spray on seashore. The chemical composition of these mediums makes them aggressive against reinforced concrete, especially in the presence of wind.

In addition, the works for repair or rehabilitation, must be designed so that water is not polluted.

3.2.1.2: Industrial site

On an industrial site, it is difficult to settle the list of pollutants and their interactions.

The choice of a technical solution compatible with the products present on site shall be considered, as well as the phase sequence of works, with the constraints impressed by the owner. As the economical losses due to works on industrial plants are significant, it is often preferable to envisage short and partial operations, carried out when the factory stops, rather than complete treatments, which would block the production plant.

3.2.1.3: Urban site

The urban atmosphere contains pollutants, which are mainly of industrial origin or exhaust fumes. Rainwater is also aggressive.

In addition, deicing salts, which are spread on roadways, are carried away by vehicles into underground car parks, or penetrate in grounds and can attack underground pipes.

The achievements of works in urban sites have more constraints: they take into account the traffic constraints, the safety of users in public areas, etc.

3.2.1.4: In open country

Environment in open country is relatively little aggressive. It is advisable to consider the difficulties of provisioning uninterrupted for certain " fluids ", such as electricity.

3.2.2- EXISTING STRUCTURES (ON SERVICE)

The treatment of on-service structures has to take into account temporary nuisances, that the y can induce during their realizations such as:
- vibrations,
- noise,
- odours,
- dust.

3.2.3- ENVIRONMENT (LOCAL CONDITIONS, DURING REPAIR APPLICATION)

The quality of a rehabilitation depends not only on treatment product or process, but also on their implementation conditions. Powerful products or processes, which require delicate implementation conditions, likely lead to a failure, if every specification is not met. Every process or product has its application limit, in given ambient conditions. The technical notes and recommendations for implementation must thoroughly be studied as a preliminary.

It is advisable to check in particular, for a given site:
- the hygroscopy (atmosphere moisture),
- the dew point,
- the temperature,
- whether space is closed or open (gas, ventilation, solvent product, etc).

For this last point, the risks of explosion and those for applicators' health, must be taken into account.

Photo 3.2: Spraying concrete under hard conditions

3.3 REQUIREMENTS FOR REPAIR

The main object of a rehabilitation is to stop or avoid reinforcement corrosion in reinforced concrete. But a selected treatment must also answer customer's expectations, which can be of a functional or aesthetic nature, respecting the initial or historical properties of the structure.

These requirements are treated individually. In general, a document on particular technical requirements shall fix the realization criteria. It is recommended to ask the contractor in charge of the works, to make some tests for validating treatments to be implemented. He can also be asked to realize in situ, a part of works, which will be used as suitability test. This last procedure offers the advantage of making it possible to validate jointly the equipment, the materials and the implementation of the suitability " area ". These validations can relate to requirements on:
- shape,
- colour,
- appearance,
- respect of the environment.

3.4 DURABILITY

The durability of a repair (or a rehabilitation) corresponds to the fact that it should not be renewed before a certain time, which is specified in a guarantee. This durability depends on how relevant is the choice of the technique retained, its implementation and the loadings after treatment.

The durability of a structure corresponds to its aptitude to meet the forecasted functions (mechanical, aesthetic, etc). It can be increased, after a rehabilitation treatment, when the concrete surface is covered with a complementary protective shield against aggressive agents.

The concept of guarantee is a contractual one, where the duration is related to the treatment chosen, for a structure under given operating conditions. The guarantee takes effect after the works acceptance. A works acceptance is a document about the end of works, and it attests that the realization has been in conformity with the contract. Before this acceptance, treatment effectiveness must be checked.

3.4.1- CONTROLS OF TREATMENT RESULTS

Some treatment checks are simple, such as for example colours, shapes, roughness, etc. Other controls require much finer analyses, which are described in chapter 2. It is often necessary to ask specialized laboratories to carry out these controls.

3.4.2- CONTROL OF PROTECTIVE COATINGS ON CONCRETE

The protective products on concrete are not always required, although they constitute a barrier against aggressive agents, which are contained in the environment.

The checking of coatings is generally limited to the controls of their bond to substrate, their appearance and their thickness.

4. METHODS OF REHABILITATION

4.1: PATCHING

Several methods are available to permanently repair a concrete cover, to stop the damage progression and to avoid new disorders. They assume that their implementation is careful, results are controlled and monitoring is adapted.

4.1.1- PRINCIPLES AND DEFINITIONS

The patching, reconstitution of concrete cover, aims to restore concrete appearance, while stopping corrosion process, and giving back its integrity to the structure. It deals with repairs with discontinuous, specific and surface repair, for which several cares must be taken:
- if the damaged zones are visually identifiable (delaminated concrete, cracks, spalls, etc), the condition of adjacent areas is usually known only after a general diagnosis. Thus, areas to be removed are in general underestimated during their first assessment;
- if some zones present a risk of corrosion (concrete carbonated, or polluted by chlorides), damage can appear after few years, near the repaired area, due to a galvanic cell between repaired area and adjacent areas (see paragraph 4.1.6).

A careful attention is to be paid to the following points:
- including material with extra thickness can change the section of structure elements. So, it is necessary to take into account the resulting loads;
- removing the damaged or polluted concrete, risks to weaken or unbalance the structure. The contractor must implement a precise timetable, and a temporary stay can be necessary.

- replacing reinforcements is to be considered, according to decision criteria (residual diameter, length), which are described further. The objective is to restore the initial section.

Surface preparation onto substrate is one of the essential stages of patching repair.

Foot-note in the case of a general treatment with inhibitor, the methodology of concrete removal and support preparation can be different (see part 4.3).

4.1.2- REMOVING DAMAGED ZONES

Before repairing damaged areas (exposed reinforcement, concrete expansion, traces of rust, etc), the coating in place must be withdrawn, on all its surface, by mechanical or chemical means. The products of demolition must be put in waste disposal or recycled, in conformity with the regulatory texts about environmental protection.

To treat corroded reinforcement, it is advisable to expose them by chiselling, hammering, water jetting or sandblasting. This operation must be carried out until sound steel appears, and its length must be free on its whole periphery, according to the French standard NF P 95.101 (a free space of a minimum of 2 cm behind the reinforcement, is recommended). When a reinforcement, which is not parallel to concrete surface, corrodes at its ends, the surrounding concrete must be removed and these ends must shortened by 2 cm, to restore a sufficient cover.

The elimination of corroding areas is one of the most delicate tasks to realize. A good long-term performance of repairs on concrete cover, directly depends on the quality of works realization. So, it is imperative that damaged areas should be totally eliminated, whether they are in depth or on surface, and this is done on the whole steel periphery, with scouring, with careful brushing or with mechanical means (sandblasting, water-jetting, etc). This operation must be more particularly careful in marine environment, because rust includes acid chlorides. Concrete surfaces are then cleaned, in order to make them free from any dust or any stain, remaining after damaged concrete is taken off. This cleaning can be carried out with wet or dry (brushing and blowing) processes, but in the case of washing, water must be eliminated by blowing or aspiration.

4.1.3- REPLACEMENT OF HIGHLY CORRODING REINFORCEMENT

At this stage of works, a control of residual diameter of most strongly attacked reinforcement, is carried out (with using callipers).

The additional reinforcement of a comparable type is installed, by sealing or welding, in order to restore the initial steel cross section, with a tolerance of 5%, while taking into account anchoring and covering lengths, and seaming steel. Welding operations are to be carried out, according to standards requirements, after steel weldability is checked.

4.1.4- PROTECTION OF REINFORCEMENT.

The protection of reinforcement consists in applying to all visible surfaces (total periphery), a product ensuring a protection against corrosion. This treatment is actually necessary only if, for technical or aesthetic reasons, final concrete cover thickness cannot have the value required in regulations (BAEL 91, for example), for a given environment. It also depends on the nature of patching product on concrete, and their compatibility must be respected.

This application must immediately follow scouring, because reinforcement oxidation likely starts, and the good performance of repair is impaired.

Photo 4.1: Protecting in-place reinforcement

4.1.5- STAGE OF CONCRETE REPAIR

A concrete repair consists in restoring the cover on reinforcement by placing a mortar. This mortar must meet the criteria on:

- vertical behaviour in the absence of formwork,
- faster resistance rise and mechanical resistance higher than that of concrete substrate,
- bonding not lower than that of the substrate,
- tightness to water and aggressive agents,
- thermal expansion coefficient and dynamic Young's modulus are equivalent to that of concrete substrate,
- good protection of steel.

The protective products are preferably selected in the family of products containing hydraulic binders with additives or modified (French Technical Guide: " *Choice and application of the products of repair and protection of concrete works* " LCPC SETRA). They must be either in agreement with French standard NF P 18-840 or allowed by the mark *" NF Special products for hydraulic concrete structures "*. This mark defines in particular for surface repair products, the guaranteed standardized properties (bonding class, behaviour against shocks, etc).

When for aesthetic reasons, any formulated pre-products cannot be applied, it will be advisable to design a specific mortar, of the same texture, surface colour and aspect similar to that of concrete in place. The mortars must be not too sensitive to shrinkage, be resistant against freezing and be durable. Another approach consists in applying a first layer of product, which is certified NF or equivalent, in order to ensure a fixing to concrete substrate, then a top coat for the aspect.

Photo 4.2: Replacing concrete cover

Lastly, it should be noted that it is difficult to completely hide areas, which are locally repaired. Sometimes, these areas reappear like ghosts, because concrete substrate and its repair product have different behaviours. A solution can consist in applying a protective product on the whole surface.

4.1.6- PARTICULAR PRECAUTIONS TO TAKE

As a rule, a repaired structure is again exposed in an environment, which has already enhanced corrosion. So, it should be made sure that treated surfaces will not generate new disorders, in particular on adjacent areas.

Unfortunately, it is often noted that local repairs are responsible for new pathologies:
- repaired area bursts, and reinforcement corrodes again;
- adjacent areas crack, and not repaired reinforcement corrodes.

Thus near a local repair, corrosion is characterized by the possible appearance of anodic zones (dissolution) with lower potential and of cathodic zones (protected steel). The coupling between these surfaces results in a flow of corrosion current, starting from anodic points. The surface preparation and patching make a change in the electrochemical conditions of reinforcement. As a rule, repaired zones are protected from a future corrosion.

However:
- their half-cell potential increases (reinforcement is gradually again passivated),
- new anodes are created around this zone.

Corrosion currents are created. The current density, which corresponds to corrosion rate, is the more significant, when
- the potential difference is higher,
- anodic areas are smaller,
- electrical resistance is lower (highly depending on concrete moisture and of salts contents),
- polarizations of both anodic and cathodic areas are lower. These polarizations depend primarily on the electrochemical conditions at steel-concrete interface. In an anodic area, the

more the medium is polluted by chlorides or the less basic is concrete due to carbonation, the lower is this polarization, and the larger is corrosion current.

The extent of areas concerned by these corrosion currents depends mainly on the moisture of the polluted concrete. In general, the area of this zone does not exceed a few square centimetres. Beyond that area, " natural " corrosion is the principal damaging mechanism.

In fact, several cases are to be considered:
a- repair has been correctly carried out, and the adjacent zones are passivated (no carbonation, no chlorides). The risks of initiation and growth of localised corrosion are weak. In this case, corrosion is due to a local defect (thin cover or poor concrete)

b- repair has been correctly carried out, and the adjacent areas are protected (no carbonation or low chloride content), but aggressive agents will reach reinforcement within a few year.

c- *repair has been correctly carried out*, reinforcing bars are free from corrosion product, and they are protected by the alkalinity of the repair product (if it contains cement), or by a resin (which is an insulator), *but surfaces adjacent are corroding* (i.e. concrete is carbonated or polluted by chlorides, there).

d-*repair has not been correctly carried out*, i.e. reinforcement was not exposed, then coated with a repair product.

In cases b, c and d, the risks are significant, corrosion can be initiated within a duration difficult to determine, but possibly lower than ten years, after repair (see part 4.3: inhibitors).

e- *repair has been carried out using a resin mortar,* which is theoretically an insulator. The process anode-cathode cannot apply. However, a void can appear at the inter-phase resin mortar-reinforcement-old concrete. There, corrosion is initiated by differential aeration, then chemical changes are created, in the absence of alkalinity (carbonated concrete), or in the presence of chlorides. In this void, the medium quickly becomes acid because of the hydrolysis of corrosion products, and the attack progresses quickly.

Thus, several essential points should not be neglected in the stages of repair:
- the diagnosis, which determines *the origin of corrosion* (carbonation, chlorides, etc), *its extent* (local or general corrosions), and *its probable evolution* (will the areas adjacent to a forecasted repair be depassivated, too?)
- surface preparation of reinforcement, which, if any traces of corrosion products remain, risks to enhance corrosion initiation;
- the connection between repair product and old concrete, which is likely to generate voids responsible of initiating localised corrosion.

4.1.7- STANDARDS

The main French standards concerning repair products are as follows:

Special products for hydraulic concrete structures			
Standard No	**Title**	**Binder type**	**Year**
NF P 18-800	Classifying, conditioning, marking, acceptance requirements	H – R	1989
NF P 18-802	Controls on construction site	H – R	1992
Products or systems of products for repair of hardened concrete surface			
NF P 18-840	Standardized properties – Standardized tests – Standards		1993
NF P 18-852	Bond test on sawn surfaces	H – R	1993
NF P 18-853	Bond test after thermal cycles, on sawn surfaces	H – R	1993

NF P 18-854	Resistance to repeated impacts on sawn surfaces	H – R	1993
NF P 18-855	Test of permeability to liquids, on sawn surfaces	H – R	1992
NF P 18-856	Resistance to UV rays	R	1993
NF P 18-857	Resistance to impacts on sawn surfaces, after cycles	H – R	1993
NF P 18-858	Bond test on rough surfaces	H	1993
NF P 18-859	Bond test after thermal cycles, on rough surfaces	H	1993
NF P 18-860	Resistance to repeated impacts on rough surfaces	H	1993
NF P 18-861	Resistance to repeated impacts after freeze-thaw cycles, on rough surfaces	H	1993
NF P 18-862	Test of permeability to liquids, on rough surfaces	H	1993

H : hydraulic binder R : résins

Civil engineering structures, Standard on repair technique		Year
NF P 95-101	Repair and strengthening of concrete and masonry structures - Repair of damaged concrete - Requirements on technique and on materials used	1990

4.1.8- TESTS, CONTROLS AND ACCEPTANCE

4.8.1.1-Suitability tests

A test of suitability is necessary, its procedure must be defined: surface, the length, or the type of element needed.

4.1.8.2- Patching mortars

If the mortars may be used according French mark NF, no preliminary test is to be carried out. In the contrary case, it is necessary to carry out one or more tests required in the standard (suitability tests), which is thus to be planned, before the works start on site.

4.1.8.3- Controls and acceptance of the products.

The purpose of these controls is to check that the delivered products are in conformity with the indications of the CCTP (French document on Particular requirements) or in conformity with standards, if they exist, with qualification certificates, and with advices on suitability for use.

4.1.8.4- Controls of the application

The purpose of these controls is to check that at any moment of the works, the execution is in conformity with the CCTP. The most significant stages are as follows:

a. acceptance of the substrate after surface preparation

In this stage, it should be made sure that the properties of the substrate prepared (4.1.2 and 4.1.3) are in conformity with the assumptions considered for repair or strengthening.
The acceptance is first based on *visual examination* of treated surface, on *a sonic control* (survey with hammer), and finally on *a control of residual steel diameter.*
This control aims to check that:

- all forecasted surfaces have been prepared;
- starters of delamination or cracking are absent;
- surface texture is compatible with the application of the repair product;
- traces of rust on reinforcement are absent;
- the substrate is not polluted by agents aggressive against reinforcement (chlorides);
- strengthening is needed.

A surface bond test, by direct tension, is also desirable. It can be necessary, in the case of a high substrate pollution by sulphates and chlorides (risk of reaction with cement in repair product).

b acceptance and control of reinforcements for replacement;

c controls acceptance after application of patching mortar;
This control is done by visual examination and surface bond test by direct tension. The significant parameters of this test are: failure mode (in repair product, in inter-phase, or in substrate), the value of ultimate tensile strength. The test conditions and interpretation are contractual.

d. acceptance of substrate before implementing coatings:
It deals with a visual examination.

4.1.8.5 Final acceptance of works

The acceptance tests for works are forecasted in the technical requirements, which take into account standards or recommendations.

Their objective is to validate at the end of the works, the contractor engagements: geometrical or mechanical features, etc.

4.1.9 FRENCH LITERATURE on Part 4.1

“ Exécution des ouvrages en béton armé ou en béton précontraint par post-tension ”, Fascicule N°65 A, 1992

“ Choix et application des produits de réparation et de protection des ouvrages en béton ” Guide Technique LCPC SETRA, Août 1996.

4.2: SEALING

4.2.1- PRINCIPLES AND DEFINITIONS

As a rule, the products applied by impregnation (sealing) are consolidators or water repellents. They are characterized by their principal function:

- a *consolidator product* gives back to a damaged zone, which is not too thick, a cohesion identical to that of same initial material. So, it does not deal with a structural consolidation of a structure.

- *a water repellent* is an internal barrier inside the material, against the penetration of liquid water, without too much affecting its permeability to water vapour. A water repellent is known as of surface water repellent, when it is applied on hardened concrete.

By its principal function, a damp-proof product is neither waterproofing, nor protecting against graffiti. Some products have secondary functions (antifouling, etc). Consolidators and water repellents do not have a direct action on protection against reinforcement corrosion. But they can be used as complementary treatments.

Thereafter, only surface water repellents are treated in this document. It should be noted that some points are given only as indications.

The implementation of these products is specified in documents such as the “Guide for the protection of reinforced concrete by application with surface products onto concrete surface” (LCPC).

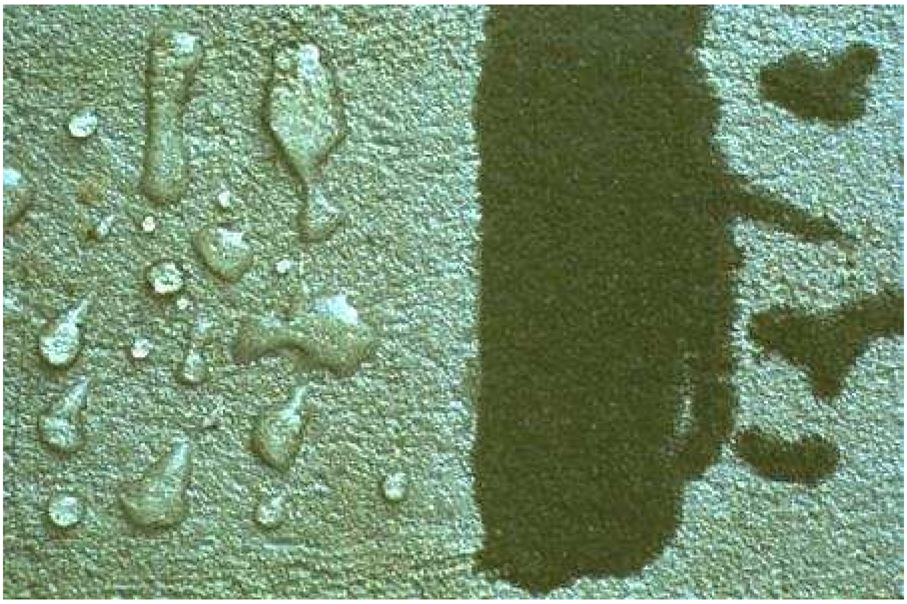


Photo 4.3: Action of a sealant

4.2.2- FIELD AND LIMITS OF USE

Applying a water repellent is justified, when concrete is subjected to a damage, due to a contact with liquid water, which comes from the atmosphere (and not from ground or a water leakage). This treatment is applied as a purely preventive or curative measure.

As a rule, a concrete deterioration affects only the areas subjected to hard rains, to streaming or splashing. So, it is useless to waterproof areas, which are, for example, inside a building.

Damages related to soluble salts are more intense after a water repellent application. To make a treatment well durable, it is important to limit the risks of salt and water penetration from the back of treated surface.

Surfaces on which water stagnates, cannot be treated effectively.

Lastly, the application of a water repellent is one part of a total repair procedure. The compatibility between the various repair techniques must be checked and especially the long term objectives must be clearly defined (possibilities of " re-treatment ", in particular for the impregnations with corrosion inhibitors; or for posterior application of any other product, which has to migrate in liquid phase, etc).

4.2.3- STATE OF THE ART, STANDARDS

4.2.3.1. Standards

According to the French standard P 84-403, a water repellent of class D1 makes it possible to maintain the initial aspect of concrete surface of a façade or to give it a not very different aspect. This standard does not define any criterion or specification.

According to the European draft standard Pr EN 1504-2, a hydrophobic impregnation of concrete "is intended to produce a damp-proof surface, characterized by the fact that cement pores are not filled but not only covered. No film is formed on the surface and its aspect is practically not changed". This standard defines testing methods with the requirements, which water repellents have to meet.

4.2.3.2. Water repellent products

The water repellent products can be classified according to the chemical nature of their basic component. The most common products are silicones and their derivatives (siliconates, silanes, siloxanes). But there are also acrylic water repellents, fluorinated resins and others.

The classification of water repellents takes into account the molecules size. For a given application, it is advisable to choose the product, which is adapted to the porosity of the concrete to be treated.

It should be noted that many water repellent products are in "solvent phase", which means that, as European legislation is changing, some of these products will disappear, and be replaced by those in "waterborne".

4.2.4- PROCEDURE FOR CHOOSING AND APPLYING

The choice of a product, and its application procedure can be carried out, only after a diagnosis and preliminary tests.

4.2.4.1. Diagnosis

Before treating a concrete with a water repellent, it is essential to determine whether this operation is useful and compatible with material to be treated and with its environment, as well. The first stage of a treatment consists in specifying in the diagnosis:

- the nature and extent of damage which affect material,
- the absence of crack or delamination of concrete,
- the origin of damages,
- main properties of the concrete to be treated (in particular its porosity),
- and finally if no counter-indication is opposed to the treatment.

4.2.4.2. Choices of product and preliminary tests

The choice of a family of water repellents is carried out

- only after a preliminary characterization of the substrate,
- but also after having clearly determined the implementation conditions on construction site (season, previous treatments considered, posterior painting...).

The effectiveness and the durability of a treatment with water repellent are optimized, by selecting a product particularly adapted to the substrate and to its physical properties (sizes of pores, colour, etc). This optimization is made after suitability tests. It deals with the product content and with its consumption, by taking into account the application procedure.

4.2.4.3. Application procedure

The durability of a treatment is determined by its penetration depth.

The main application equipments are brush, roller, sprayer for silicones and "airless" sprayer or hose

As a rule, the product has to be well distributed in the substrate, this is the reason why using a sprayer (or " airless") is often privileged.

The climatic conditions are particularly important for polymerization processes. This is the reason why, it is advisable to respect the technical notes, for avoiding a too fast polymerization when the weather is warm, or too slow polymerization when the weather in too cool and wet (generally, the advised limiting temperatures are between 5 and 30°C).

Lastly, the substrate must be repaired and cleaned. But moreover, the requirements of the product chart, concerning substrate moisture, must be met.

4.2.5- CONTROL OF TREATMENT

The control of a treatment aims to check that:
- the products and their implementation conditions, which are defined in the application procedure, are correct,
- and the treatment is effective.

In addition, some tests are proposed to characterize a water repellent treatment, and they are carried out either on site or on concrete cores. But it is also important to check that this treatment does not change too much, other concrete properties, such as:

- structural properties (porosity, etc),
- properties of transfer (permeability to water vapour, etc),
- or aesthetic properties (colour, brightness).

Examples of suitability tests
to characterize a treatment by impregnation with water repellent

Test on site	*Penetration depth*	*Water-repellent effect*
Beading effect	yes	yes
Permeability test	no	yes

Tests on cores	*Penetration depth*	*Water proof effect*
Soaking fringe	yes	no
Wetting or microdrop	yes	yes
Acid attack	yes	no
Contact angle	yes	yes
Capillary soaking test	no	yes

4.2.6- ACCEPTANCE TESTS

The acceptance tests of works are described in the Conditions of contract.

The only non-destructive test, which can be carried out for the acceptance of a sealing (impregnation), is to measure the permeability of treated concrete. It deals with the permeability either to water, or to air.

4.2.7- DURATION AND EFFECTIVENESS OF TREATMENT

The effectiveness of an impregnation treatment (sealing) generally lasts two years. It concerns both the penetration behaviour against aggressive agents into concrete and the concrete surface aspect.

4.2.8- FRENCH LITERATURE REFERENCE on part 4.2

“ Guide technique LCPC sur la protection du béton armé par application de produit à la surface du parement ”

4.3: CORROSION INHIBITORS

4.3.1- PRINCIPLES AND DEFINITIONS

A corrosion inhibitor is defined as a chemical compound, which is added in low dosage to a corrosive medium, and slows down or stops the corrosion process of a metal placed in this medium.

Its fundamental functions are as follows:
- to enter concrete, which is always very inhomogeneous (particularly, changes of compactness),
- to lower metal corrosion rate, without affecting metal properties (nor those of the surrounding medium),
- to be stable in the medium considered, and compatible with it, at the temperature of use,
- to be effective at the recommended dosage,
- not to be toxic.

In addition, the inhibitor content of must be controlled, by taking into account various parameters, such as geometrical factors or materials shape and surface quality, etc.

As corrosion is an electrochemical process, the action of an inhibitor occurs at the level of one elementary reaction of the corrosion process, and more particularly in the immediate vicinity of metal surface: transfers of reactive species, formation of intermediary compounds, adsorption, etc.

The action process of an inhibitor can be of various types. An inhibitor covers (adsorption) metal surface, and reduces elementary surfaces of reactions. It can also form compounds with metal and the surrounding liquid, and change reactions occurring at interface. In both cases, corrosion rate can be decreased and even be nil.

Photo 4.4: Application of inhibitor

Photo 4.5: Application of inhibitor

The corrosion inhibitors are classified according to their mode of action

a- Anodic inhibitors have an action of decreasing the current on the anodic part of metal surface. If this action is only partial, a local increase of current density can occur on these areas. This can lead to a process of local corrosion, more intense than in the absence of inhibitor, so the content of active element close to steel is important.

b- Cathodic inhibitors induce an increase of cathodic potential, and thus they decrease corrosion current. If these inhibitors never completely stop the corrosion reaction, they do not present any danger of local corrosion. These inhibitors often precipitate as salts or hydroxides, because of accumulation of OH^- ions on cathodes.

c-Mixed inhibitors have at the same time the properties of the anodic and cathodic inhibitors.

4.3.2- STATE OF THE ART

Several inhibitors with chemical, organic and inorganic bases, have been used for ten years, for rehabilitating various reinforced concrete structures.

The effectiveness control system of a treatment is specific to each basic chemical component.

For an use on reinforced concrete, an inhibitor applied to surface has to:
- have a fast and verifiable action;
- be efficient during many years;
- be effective in a medium, which can be basic, neutral (carbonation), even acid (in the presence of chlorides, metal surface, in a corrosion process with occluded cells, is in contact with hydrochloric acid).

4.3.3- FIELD AND LIMITS OF USE

The precise frontier of the field of application depends on the inhibitor considered.

The parameters of effectiveness to be taken into account for a study are as follows:
a- *influence of steel surface quality* (absence of discontinuity between steel and concrete). The use of corrosion inhibitors makes it possible to protect a set of corroding steel without having to remove contaminated or carbonated concrete, provided that no spalling or delamination between steel and concrete has started;
b- *penetration of product* inhibitor penetration into concrete depends on many parameters: concrete porosity, moisture, degree of carbonation, type of cement used, chloride content, previous treatments, etc. Thus, this penetration cannot, at this stage of knowledge, be the subject of a precise modelling. Subsequently, it is always necessary to check inhibitor penetration with validation tests on site;
c- *effective minimum content* near reinforcement. This critical content must be specified by the manufacturer, on the basis of representative test result, by taking into account, in particular, chloride content in concrete close to reinforcement (limit of effectiveness).

The use of inhibitors makes it possible to best preserve the initial aspect of a structure, and to reduce zones to be dismantled.

4.3.4- APPLICATION PROCEDURE

Before applying an inhibitor, concrete surface must be prepared. It deals with eliminating painting or another coating by sandblasting or water jetting. It should be noted that a treatment with inhibitor is not possible, if concrete surface was previously treated with a water repellent.

An inhibitor, which is in liquid form, is applied directly to concrete surface. In order to respect the consumption prescribed by the applicator, or the procedures defined after validation phase, the application is carried out on several passes.

The solution in a gel is applied in one step.

Several application methods can be tested, for validating the most adapted implementation.

4.3.5- CONTROL OF IMPLEMENTATION

4.3.5.1- Implementation

The quality system of the applicator must allow, during the treatment implementation, to control the respect of:
- consumption,

- application procedure determined during validation tests.

In the present state of knowledge, it appears essential to evaluate the amount of product in concrete and to determine its content at the level of reinforcement, at times determined in the contract, on the basis of suitability test (procedure validation). This content must be in conformity with the manufacturer's specifications, concerning the minimum effective content (see 4.3.3 c).

4.3.5.2- Acceptance tests

The application is considered as acceptable, when the minimal amount of inhibitor is reached at the level of reinforcement to be treated, and shown by analyzing samples representative of the structure.

Moreover, the documents for following up the implementation quality of the treatment must be given progressively, as works progress.

4.3.6- DURATION AND EFFECTIVENESS. STANDARD

In 2003, the experience feedback on works treated by penetrating inhibitor is now more than ten years old. The treatment durability can be checked by:
- measuring inhibitor content at steel level after a few years
- monitoring versus time, half-cell potential (mapping) or corrosion currents (polarization resistance).

No standard defines inhibitor classes, making it possible to assess their intrinsic effectiveness. There does not exist now any procedure for qualifying products.

4.4: SURFACE COATINGS

4.4.1- COATINGS FOR CIVIL ENGINEERING STRUCTURES

The painting operation of civil engineering structures, made of concrete, has usually these main objectives:
- to improve structure aesthetics, by colouring or by creating decorative items, in order to give the structure a particular aspect, or by homogenizing, when needed, its surface colour
- to increase the comfort and the safety of users, while facilitating cleaning (example: coating of tunnels)
- to take part in structure safety (example: beaconing of posts)
- to contribute to concrete protection: the installation of a paint system in thin layer, improves substrate water-tightness, and it can make it possible to slow down the penetration of external moisture, thus to improve concrete durability.

Thus, the structures concerned are primarily tunnels, retaining walls, screens against noise and, in some cases, bridges.

Photo 4.6: Application of inhibitor

There is a qualification procedure concerning paint systems for concrete of civil engineering structures. It concerns bonding criteria, aspect and more generally aesthetic considerations, and not on criteria for appreciating how effective are the systems to fulfil a function of protection. The whole procedure is described in the French guide "Painting operations on concrete of civil engineering structures" (LCPC, June 1999) which brings also all useful information on the implementation of paints systems of and the quality control of their application "

When protection function (protection against chloride penetration, or against the penetration of carbon dioxide, which results in a progressive carbonation of concrete cover, etc.) is the most required function, other types of coatings can be considered. They will be named hereafter “thin coatings”. However, it is advisable to specify that there is now no technical reference frame, which could make it possible to qualify these products and to direct the choice of a product adapted to the problem. The development of such a reference frame is pending, as well as the drafting of a guide on the protection of reinforced concrete by applying products on concrete surface.

4.4.1.1- Principles. Definitions. State of the art

A: Paints

A "paint" indicates a protection by a system of paints or Lasures, with dry thicknesses ranging between 20 and 600 µm.

The paints systems are applied in total wet quantities ranging between 300 and 1500g/m², depending on their density and dry extract, They are applied in quantities lower than 300 g/m², but this can change depending on the substrate absorption.

A paint system consists of a succession of layers, each of them has a specific function, in order to obtain a final coating showing the required properties.
A paint is made with:
- a binder (also called resin or polymer): its chemical nature makes it possible to name a paint; it deals, for example, with epoxydic, polyurethane, vinyl, acrylic or hydraulic paint modified by resins
- fillers: they confer to paint particular physical properties (rheology, aspect...)
- pigments: they bring colour, opacity...
- additives: they can be wetting, thixotropic, fungicidal agents...

- a vehicle: water (paint called "waterborne"), or solvent (paint in solvent phase). There are also paints with very little, even without any vehicle.

Generally, a standard system of paints has 3 layers:
- a primer, which ensures the bonding of the system on substrate
- a transition layer, which ensures compatibility between the primer and the top coat and gives the system a sufficient thickness
- a top coat, which brings the aesthetic function and ensures the resistance of the system against external aggressions.

The performance of a paint system depends on the thickness of each layer and on the respect these thicknesses. It is to be noticed that the change of regulations on environmental protection supports now the development of waterborne paints.

Paints can have one or two components; in the latter case, paint is obtained from a mixture of a base and a hardener or of cement and latex.

B: Lasures

Lasures, are composed of a very fluid binder and of highly diluted pigments. They are used to preserve or emphasize the surface texture of concrete. They are with or without colour and contrary to paint, they are not opacifying.

A Lasure is made of:
- a binder (generally of acrylic type or polyurethane),
- a vehicle (water, solvent),
- pigments or dyes,
- possibly fillers,

A Lasure is generally applied in two layers, the first being diluted.

C: "Thin coatings"

A "thin coating" can be:
- thick plastic coating generally containing coarse powders and acrylic resins or polyurethanes,
- coating for water-proofing, containing acrylic resin,
- any coating containing polyurethane or modified hydraulic binder.

Depending on their nature, these products are applied with using spatulas or special devices.

4.4.1.2 Application procedure - actors of implementation and material

A: Procedure

Various conditions are to be met for obtaining a good fixing of products and a sufficient durability of coatings.
- quality of substrate preparation,
- choice of coating nature and components,
- application carried out under good conditions,
- total dry thickness in-place and regularity,
- age of concrete substrate (minimum: 2 months).

Part 65A of the CCTG (French General technical requirements) requires that the systems used must be qualified systems. The contractor must define the products used, in its quality assurance plan (PAQ).

B: Materials

The materials used for preparing substrate must be identical to those used at the suitability test. Depending on the substrate condition and type, and on the final aim, the preparation modes of a substrate are:
- brushing, blowing off dust,
- sandblasting,
- washing,
- projection of abrasives: recovering and treating abrasives before their disposal must be planned,
- projection of pressurized water: it is fundamental to respect the pressure value determined after suitability tests.

The materials used for products implementation are in conformity with those of the suitability test and with the items indicated in the technical description of product. These documents specify, if necessary, for each means of possible implementation, a dilution ratio and an amount of placed product

For the applications with a sprayer, a careful attention is paid to the injector channels.

4.4.1.3- Execution procedure and controls

A: Preliminary test

In the particular case of a concrete with visible surface defects and for which the application of a paint system is likely insufficient to hide all the defects, a preliminary test must be realized before drafting the bid to tender. This preliminary test makes it possible to check, before the launching of the tender documents, that the technical choice considered well corresponds to the required results.

B: Implementation

The implementation of a coating is carried out according to an execution procedure, to which various stages of controls are attached. These are stages as follows:

a) preliminary operations at construction site

Before the works start, a meeting must be organized gathering all the actors concerned, namely: the project manager, the head of the works, the exterior control of the contractor and the organizer in charge of exterior controls.
This meeting has these main objectives:
- to jointly examine the consistency of works, their procedure and controls planned,
- to examine the solutions about particular difficulties (areas to be patched, zones with difficult access, etc),
- to organize the suitability tests,
- to define the program of works concerning in particular the scaffold displacement and the application conditions and drying of the layers, as well as the program of controls.

b) suitability test

A suitability test is not a preliminary test, and Part 65A of the CCTG made it compulsory. It makes it possible to check, after the market is signed, that under the construction site conditions, and on a surface representative of the structure, the selected methods well meet the objectives. This test is carried out with the means, the personnel and the products on the construction site, it concerns both the substrate preparation and the application. It makes it possible to check that the means used by the contractor are well adapted to realize the planned work and to assess the aspect of the coating applied onto the concrete of the structure.

c) control of substrate preparation

It deals with:
- the list of products used (abrasives for example),
- the conformity of materials,
- the acceptance of surfaces,
- the adequacy of coating with the required function,
- the surface bond with substrate (not less than 0.5 MPa),
- the conformity of abrasives.

d) control of products

The principal points to be checked concern:
- the identity of products used on the construction site, it deals with checking by sampling (according to standard NF EN 21512) the conformity of products. These tests are based on "Characterizing by fast identification of product" (CIR data),
- the labels of containers, which must include the product name, the number of manufacturing batch, the denominations base or hardener, the weight, the deadline for use, the label on safety, etc,
- the storage conditions (suitable temperature and moisture),
- the follow-up of the delivered quantities.

e) controls before application

It is necessary, before carrying out the application, to check:
- concrete moisture,
- air temperature and moisture (adequacy of these criteria concerning the products to be applied),
- substrate temperature (it must be 3°C higher than the dew-point) .

For the products, control before application concerns:
- products identification and labelling,
- components content and mixtures,
- nature and quantity of thinner used,
- homogenisation,
- respect of mixing duration, ageing and practical duration for use of the mixture.

It is also necessary to check:
- the conformity of techniques and materials used with the adopted solutions,
- for new layers, the respect of minimum period of drying and of waiting times between layers applications.

f) controls during application

These controls primarily consist in measuring product consumption for each layer of the system. These measurements can be carried out, by:
- weighing the quantity of in-can product before and after its application on a known and determined surface,
- counting containers, which contain the products and which are previously marked and used for a definite area of the structure,
- measuring wet thickness.

4.4.1.4. - Applicability and limits of use

For a research on aesthetic improvement, the concrete substrate aspect before coating is essential for the quality of the final result: a coating between 20 and 600 µm thick cannot hide all surface defects.

A coating by painting makes it possible to hide differences in colour, even texture difference, if these defects remain limited.

If the defects are more important (air bubbles, rock pockets or glares), it is necessary to use surface repair products, which make it possible to hide these irregularities, then painting has to homogenize again the colour of the whole concrete surface.

4.4.1.5 Acceptance tests

Acceptance controls concern:
- the thickness of dry film. It can be estimated by using the wet thickness measured during applications and the value of dry extract in paint. It can be also measured using a microscope (cutting at 45 °, whose width is measured according to French standard NF T 30 123) or by examining with a micrometric magnifying glass a surface core,
- aspect: it deals with detecting defects, such as significant drips, extra thickness, crazing, blistering,
- bonding: the bonding control on construction site is carried out by a pull-off test, in accordance with standard NF T 30 062. This test is delicate, and must be repeated at a sufficient number of representative points,
- colour: the colour control is carried out, according to standard NF T 34 554-2. The colorimetric properties, measured at the acceptance, are used to check that their possible future change remains in conformity with the market requirements.

4.4.1.6 Duration and effectiveness of process

The painting operation carried out according to codes of practice, makes it possible to obtain, for most of structures (bridges, tunnels),a coating durability of about 15 years.

This durability is variable depending on the coating dry thicknesses, the nature of paints (one or two components) and their aptitude (or not) for being washed (case of tunnels).

It is recommended to distinguish various types of guarantees, which are related to:
- the main functions required in terms of concrete protection,
- the coating detachment or blistering,
- the colour,
- cracking, if this characteristic is specified. The attention is drawn to the fact that in practice, this last complementary requirement cannot generally be met with systems, which are more than 600 µm thick.

The here below table specifies the contractual warranty durations to be mentioned in a market, for the various functions aimed, depending on the range of coating thickness:

Thickness of dry film	Main functions	Crazing and blistering	Cracking	Uniformity and constancy of colour

50 µm to 300 µm	2 years	2 years (*)	-	2 years
300 µm to 3 mm	10 years	10 years (**)	10 years	2 years

(*) *In the case of protection systems by painting, this 2 years value, which is less than the values appearing in the additive Part 65A of the CCTG – August 2000 (respectively 4 years for paints with one component and 5 years for paints with two components), is significant of a good performance of a system, without disbonding, nor blistering – a basic requirement for the main protection function to be provided in addition to aesthetic aspect.*

(* *) *The 10 years guarantee for the main protection function implies a good performance of the system, without disbonding nor blistering during 10 year, is higher than the minimum of 6 years required by the additive with Part 65A of the CCTG –August 2000 for the protection systems containing paints with one component, and the minimum of 8 years, if they contain paints with two components.*

4.4.2- COATINGS FOR BUILDINGS

4.4.2.1 - Principles and definitions

The functions of a coating on a building are significantly different from those of a coating for civil engineering structures. It concerns:
- *the aesthetic function* on bare or old surfaces (colour, brightness aspect, etc.)
- *the correction of defects* on surface (porosity, cracks);
- *the technical function* by protecting the substrate against the environment. The products for coating on concrete must indeed prevent aggressive water and its elements to penetrate into concrete and they must ensure function of tightness against water vapour or carbon dioxide.

There is no qualification procedure, but a Technical Document (DTU, now standardized), defines the contents of the works to be carried out, in Books of Technical requirements.

The products must be in conformity with standards, which relate to them.

4.4.2.2 Classification of coatings

These coatings are intended to increase the protection of repairs and of not repaired areas. It can consist of several products, classified according to their expected performances, in the Building industry:
a- Coatings with mainly decorative function, this category includes three classes D1, D2, D3 of coatings;
a- Coatings for water-tightness, applied as a purely curative mean to mitigate disorders, which can affect closed structures (infiltrating cracks), classified I1, I2, I3, I4 according to their capacity for resisting to substrate:.

A: Coatings for decoration

a- Coatings of class D1 are mostly colourless products, which maintain the initial aspect of façades, but they improve their performance against water and substrate stains. They are water repellents and Lasures.

b- Coatings of class D2 are paints, which consist of a binder (film forming component), of pigments (both protective and covering functions), of powders (darkening agents), and of a

solvent (or vehicle). Several classes of paints exist, depending on their chemical nature or that of solvent:
- solvent phase: consists in general of hydrocarbons, chlorinated derivatives, alcohols, esters, ketones, aldehydes;
- waterborne: the solvent is water, which is friendly to environments, but these paints dry with difficulty in cold weather. Siloxanes paints, which have a tight character and a high permeability to vapour, are waterborne paints.
- mineral paints: they contain silicates or lime, and dyes. They are interesting when considering the final decorative aspect obtained, and their high permeability to vapour water, they are more vulnerable to rainwater.

Micro-porous paints for façades must comply with French standard NF T 30-804. Their application must comply with the DTU 59.1 (standard NF P 74-102-1).

French standard NF T 36-005 gives the classification of varnishes, paints and similar materials.

c- Coatings of class D3

The "thick flexible coatings" (RPE) are of this type. They have a function of correcting surface quality, either by improving flatness, or by creating a structured aspect, and an additional function of proofing. They consist of a copolymer vinyl or acrylic resin in an aqueous dispersion, powders of pigments and additives. They are applied in high thickness (2 to 3 kg/m^2). However, they do not have sufficient elasticity to resist against substrate cracking. Their specifications are given in standard NF T 30-700, and their application must comply with the DTU 59.2.

The "half-thick" coatings (700 g/m^2), intended to mask crazing, are described in French standard NF T 34-720.

B: Coating for waterproofing

They are multi layers systems (except the class I1), applied on a purely curative basis, to mitigate disorders affecting closed structures. They have a real technical function of waterproofing against liquid water. They consist of a bonding layer, and one or more layers of paints (copolymers in aqueous dispersion), having a sufficient elasticity to resist against existing substrate cracking (I1 and I2) or future cracking (I3 and I4). Moreover, system I4 includes a reinforcement embedded in the top coat.

The DTU 42.1 (standard NF P 84-404-1) defines the work completion for these coatings, the products are selected depending on the surface defects observed, according to standard NF P 84-401-3. The products must meet standard NF 84-403 about their characteristics (maintenance of aspect, waterproofing, thermal insulation). A preliminary study of recognition is necessary to select the type of preliminary works to be carried out (scouring or conservation of old coatings).

C: Render on façade

The renders for façade contain hydraulic binders, and/or lime. They belong to two categories:
- traditional renders, placed in three distinct layers (DTU 26.1);
- renders for one layer, ready for use. They are under a MERUC classification, providing indications on their mechanical properties

4.4.2.3- Guarantees

Contractual guarantees can be proposed by the manufacturer (for a given construction site with particular conditions), but the legal guarantees are:
- biennial guarantee, called “of correct operation”, which applies to class D coatings (D1, D2, D3). A good performance (standard NF T 36-001) is the absence of blistering, cracking, chipping, disbonding higher than 5% of the area of a reference element.
- the decennial guarantee, which applies to class I coatings. It deals only with waterproofing function (blistering, fouling, chalking are not taken into account, because they do not damage closed structures).

Lastly, the decorative function is appreciated by a comparison with *a reference area*, which shall be included in all the operations previously described.

4.4.3 FRENCH LITERATURE REFERENCES on part 4.4

“ Mise en peinture des bétons de génie civil ” Guide technique LCPC, Juin 1999

“ Les systèmes de peinture pour les bétons de génie civil ” Guide LCPC, 1999

“ Protection des bétons armés ” Guide Technique LCPC (*to be published*)

“ Exécution des ouvrages en béton armé ou en béton précontraint ” Fascicule 65A du Cahier des clauses techniques générales (CCTG)

4.5: SPRAYED CONCRETE

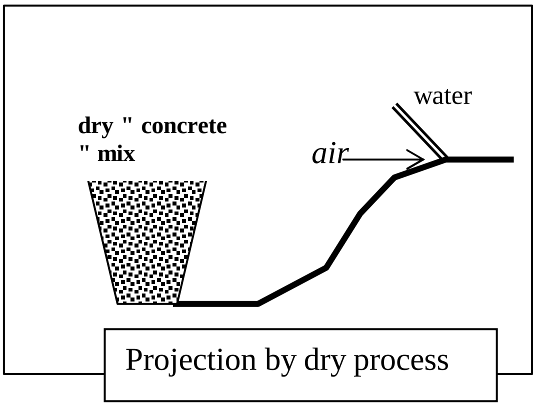
4.5.1- PRINCIPLES AND DEFINITIONS

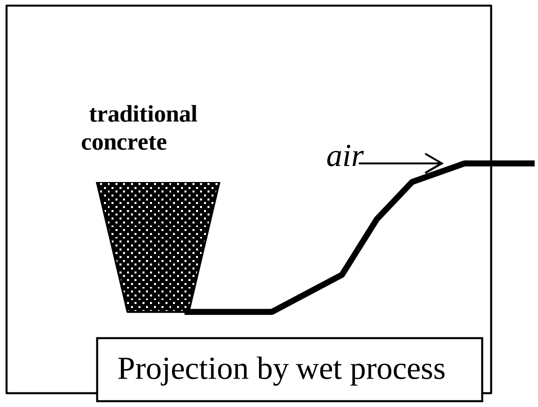
4.5.1.1- Definition

A sprayed concrete consists of a mix of aggregates, cement and water, with sometimes additives, which is projected with compressed air, onto a wall.

Photo 4.7: Projection of concrete

It is necessary to distinguish two projection techniques, depending on when water is put into the process:
- by dry process with or without pre-damping: water is introduced at the hose,
- by wet process: water is introduced into the concrete mix.





4.5.1.2- Roles of additives, fibres and silica fume

A sprayed concrete can also contain additives, fibres or silica fume.
a- The use of additives confers concrete some specific properties during its implementation:
- obtaining and maintaining fluidity, by using setting stabilizers, which are introduced at the exit of the plant, for optimizing the transport conditions,
- obtaining initial consistency, by using activators introduced a few meters before the hose,
- effective implementation by using setting accelerators, which are introduced in end of the hose. But sometimes they induce a decrease of long-term mechanical resistances.

b- The fibre addition confers sprayed concrete complementary properties, which depend on fibres amount and type:
- cohesion improved for freshly-mixed concrete,
- limitation of shrinkage effects,
- possible improvement of mechanical properties (increased resistance to shearing and to bending).
The post-cracking performance confers the material a ductility (recommendations AFTES on Reinforced Fibre Sprayed concrete – BPRF, conclusions of French national project BEFIM).

c- The use of silica fumes makes projection more easy (concrete more easily sticking), and it improves material durability (denser concrete).

- *Foot-note: Adding steel bars allows the strengthening or repair of a structure.*

4.5.2- STATE OF THE ART. STANDARDS

Sprayed concrete works must be realized in accordance with French standards (NF P 95 102, NF EN 934-2) and with recommendations, such as the Booklet n°3 of STRRES (Union of contractors specialists in repair and reinforcement works on structures) and the recommendation of ASQUAPRO (Association for the quality of mortars and concretes projection) concerning prevention, hygiene and safety during concrete projections.

4.5.3 – APPLICATION PROCEDURE OF SPRAYED CONCRETE.

The application procedure must justify materials and means chosen for the implementation.

4.5.3.1- Preparation of works on site: studies

The studies relate concern concrete design about requirements of the tender documents (D.C.E.), with in particular the projection technique and the choice of components, as well as the required properties.

a- for structural strengthening, the dry process or possibly the wet process with diluted flow, is preferable, and cement content must be minimum.

b- Studies take into account, as soon as possible, constraints related to the job site
- the environment (noise – pollution),
- the access (adjustment and sufficient platform for works, so that the hose holder can suitably carry out his works (distance between hose and surface ranges between 0,50 m and 1.50 m approximately),
- signing (safety), traffic (vibration of the substrate).

The Assurance quality plan (PAQ) of the contractor must detail the provisions, which are referred to it.

The studies specify
- design of works (timetable, type of scaffold, equipment for projection, means of transport and maximum distance, etc),
- properties of sprayed concrete (practical duration for use, thickness to be projected, a number of passes, time between master passes),
- the quality of the substrate for projection (cleanliness degree, moisture, etc),
- the curing of sprayed concrete,
- the time necessary for works without traffic.

4.5.3.2- Execution of the works

The ordering of concrete takes into account the results of the study and suitability tests, by integrating constraints on transport and implementation (phases, programs). The additives used must be allowed by mark NF when it exists or equivalent.

The provisioning is a function of the selected projection mode. In the case of a Ready for Use Concrete (BPE), the Quality assurance Plan (PAQ) of BPE plants applies. In the case of a construction on job site, the delivery of raw materials is made either in bulk, or with bags (dry mixture ready for use). The identification and quality control are carried out within the framework of an internal control, while proceeding by batches (generally related to the construction phases of the works).

Storage must make it possible to have a sufficient amount of materials, to avoid a break in concreting, and to preserve raw materials without deteriorating their quality (pollution...).

In dry process, the control of materials moisture is a major point to control.

The quality of a repair by sprayed concrete is highly related on the implementation conditions and in particular on the qualification of the hose holder. The suitability test realized, in accordance with standard NFP 95102, makes it possible to ensure that all conditions (personnel, means, choice of materials) are met for a good completion of the works.

4.5.3.3 – Choice of materials

The equipments are identified: they must correspond to the required use - capacity, power, flow (air, water), resistance -. Their characteristics are defined in the PAQ, as compared to the objectives written in the Conditions of contract, with a detailed attention for the choice of equipment and in particular on the adaptations, which condition good projection.

All the weighing equipments needed to gravimetric measuring must be calibrated. The additives measuring pots must be controlled by the output of the projection machine and be approved by a suitability test.

Some materials must be envisaged to be stored, in order to avoid any break in the works, which would likely harm the final quality of the works.

4.5.3.4 – Qualification of personnel

The staff (hose holder, hose holder assistant and machinist) must be qualified, i.e. they have certified references for similar works or they have followed a training resulting in a qualification certificate, obtained after checking of theoretical or practical knowledge. The number of personnel is adapted to the importance of the works.

The PAQ of the contractor specifies the functions and the responsibilities for each member of the staff, as well as their references.

4.5.3.5 – Operational procedure

The operation of concreting respects the following chronology:
- preparation of the substrate,
- possible sealing of connectors,
- possible installation of reinforcement and of (non-oxidable) rods for thickness control,
- projection of concrete by respecting the timetable (from bottom and upwards on strips of a given width),
- successive passes (respect of the number and time between passes),
- stop of concreting at the end of either a batch or a day, according to the code of practice,
- possible top coat (always distinct from the structural layer).
- protection by curing, if necessary,

4.5.4 – CONTROL OF IMPLEMENTATION

4.5.4.1- Interior control

It deals with:
- study and suitability tests,
- checking the conformity of any delivery to the concrete order (case of BPE), concerning materials (cement/aggregates previously mixed, additive/admixtures/water or bags, in the case of concrete manufactured on site), reinforcement, curing agents,
- sampling materials, for possible further analyses,
- checking substrate condition and surfaces between layers,
- checking reinforcement installation,
- control of execution and of sprayed concrete quality,
- control of sprayed concrete thickness,
- control of curing,
- control of bonding to substrate.

4.5.4.2- Exterior control

It deals with following stop points:

- validation of the test of study,
- validation of suitability test,
- checking of substrate condition, of reinforcement installation and of rods for measuring thickness,
- control of bonding to the substrate,
- checking the quality of sprayed concrete (thickness, texture, resistance).

4.5.5- FIELD AND LIMITS OF USE

4.5.5.1 – Sprayed concrete by dry process

a- Advantages

The advantages of the sprayed concrete by dry process are as follows:

- a great flexibility in use: it is easy to stop work and to start again without having to do tiresome cleanings,
- a transport on long distance: it is possible to install the projection equipment a few hundred meters of the job site. In precise cases - for example, repair of railway tunnels - carefully studied installations allow a transport on more than one kilometre, without disruption,
- a possibility of projecting high thicknesses in only one layer, even without any accelerator,
- high resistances: because the compaction effect by gravels projected at high speed and the weak water-cement tend to improve resistances,
- easy obtaining of high performance sprayed concrete,
- a possible automation to increase rates and working conditions.

b- Privileged fields of application

They are as follows:

- repair and strengthening of structures,
- making of thin shells with reinforcement,
- immediate projection with discontinuous activity and restricted volume,
- projection on cliff,
- restoration of underground structures, etc

c- Limits of use and disadvantages

It deals with:

- a limited output,
- a release of dust, due to the equipment and the hose (this can be reduced by wetting aggregates)
- a visual appreciation of water content by the hose holder,
- a significant loss by rebound,
- in the case of fibre concrete, fibre content is lessened in the sprayed concrete placed,
- a risk of damaging brittle substrate, etc

4.5.5.2 Sprayed concrete by wet process

a- Advantages

The advantages of the sprayed concrete by wet process are as follows:

- improved output, reaching the double or triple of that of the dry process,
- reduction of dust, improving the working conditions,
- reduction of losses by rebound,
- better quality control of concrete,
- concrete in place has a homogeneous composition in the whole layer thickness,
- in the case of fibre concrete, fibre content in sprayed concrete placed is close to initial content,
- robotization (automation) improves the working conditions.

b- Privileged fields of application

They are as follows:
- work in confined space,
- tunnel sustaining walls, requiring of high projection rates,
- projection on brittle substrate, etc,

c- Limits of use and disadvantages
It deals with:
- a less flexibility; the design requires a rigorous development (fluidity, stabilization, etc) and a regularity of consistency,
- a transfer at long distances is difficult,
- tightening or accelerating additives are needed for compensating sprayed concrete fluidity and stabilization,
- a stabilizer is recommended to allow a sufficient time of use of concrete mix, and to minimize cleanings when the projection equipment possibly stops,
- lower compaction and bonding,
- need of an initial high cement content (minimum 400kg/m^3), which can result in an important shrinkage.

4.5.6 – ACCEPTANCE TESTS

The acceptance tests are defined in standards, recommendations, or contradictory procedures.

Their objective is to validate at the end of the works, the engagements of the contractor, who agreed to meet the requirements written in the market: geometrical properties (shape, completion, etc), aesthetic characters (colours, texture, etc), mechanical properties (compressive strength, bonding, etc), physico-chemical properties, etc.

4.5.7 – DURATION AND EFFECTIVENESS OF PROCESS

The projection of material on a substrate confers it mechanical and physico-chemical properties, which are interesting, especially by dry process, because of its very high speed:
- cement content in the projected mix is higher, in the vicinity of receiving surface, due to the rebounds of the coarsest aggregates,
- the whole layer thickness is compacted

The expected properties are as follows:
- bonding with the substrate,
- higher early mechanical resistances,
- elastic modulus close to that of the substrate,
- controlled cracking: adding fibre still improves this property,
- protection of substrate against aggressive agents and against freezing-thawing actions when particular cares are taken: (concrete design, implementation),
- possibility of projecting thick layers in only one pass.

4.5.8 – FRENCH STANDARDS, REFERENCES AND BOOKS on Part 4.5

Standards :
- NF P 95.102 “ Réparation et renforcement des ouvrages en béton et en maçonnerie – béton projeté ”
- NF EN 934-2 “ Adjuvants pour bétons. Définitions, exigences ”

Recommendations :

- Fascicule n° 3 " Béton projeté "du STRRES (Syndicat national des entrepreneurs spécialistes des travaux de réparation et de renforcement de structures), 1987
- " Recommandations pour la prévention, l'hygiène et la sécurité lors des projections des mortiers et bétons " de l'ASQUAPRO.
- " Marché pour la réparation et les modifications d'Ouvrages d'Art " Recommandation du SETRA

Books :

- Resse (C.), Venuat (P.) " Projection des mortiers, bétons et plâtres " Techniques et applications Bâtiment et T.P 1981
- Calgaro (J. A.), Lacroix (R.) " Maintenance et réparation des ponts ", chapitre 6 - Presses de l'E.N.P.C., 1997

Pending documents (2003) :

- Guide technologique ASQUAPRO pour l'exécution des travaux de projection des mortiers et bétons
- Groupe de travail AFTES n° 6 - Recommandations relatives à la technologie et à la mise en œuvre du béton projeté renforcé de fibres.

4.6: ELECTROCHEMICAL TREATMENTS

4.6.1-ELECTROCHEMICAL TREATMENTS: RE-ALCALINISATION AND CHLORIDE EXTRACTION

4.6.1.1- Principle

The principle of these treatments consists in polarizing the reinforcement nearest to the concrete surface, using an anode placed on this surface and embedded in a paste saturated with a suitably selected liquid (electrolyte). The polarization current flows from the anode towards reinforcement (cathode). The deeper steel bars must be electrically connected to a reinforcement, which is directly polarized.

These electrochemical treatments are known as temporary, because they generally last between one and six weeks.
Two techniques of temporary treatments are to be distinguished:
- a technique for which an electric power supply (impressed current technique) is placed between anode and reinforcement,
- a technique for which the anode, made of an alloy judiciously chosen, is directly connected to reinforcement (galvanic current).

Their objective is to give again concrete cover, its capacity to protect reinforcement. It deals with increasing the pH of carbonated concrete (re-alkalisation), or with extracting chlorides ions, which entered this cover (chloride extraction). The aspect of treated concrete is respected.

4.6.1.2. - Expertises and works before application

A: Expertises

Before implementing these treatments, it is necessary to carry out *a complete diagnosis* of disorders (see chapter 2 *Diagnosis)* for:
- determining the causes of disorders,
- determining possible sensitivity to alkali-aggregate reaction, related to alkaline content (equivalent of Na_2O) of concrete containing of reactive aggregates,

- carrying out a quantitative analysis of the parameters needed for controlling treatment effectiveness.

B: Works before treatment

It deals with:

- checking *the electric continuity* of steel bars. If need be, electrically to connect any insulated reinforcement.
- patching (rebuilding concrete cover) *if required* by using a mortar containing cement, which is as close as possible to the original cement, without passivating steels: passivation treatments are a source of heterogeneity, and they electrically insulate reinforcement.

4.6.1.3: Design

The preliminary expertises make it possible to locate the areas to be treated. The sets of steel bars, which are not connected electrically, are regarded as being distinct zones.

Dimensions of anodes and the capacity of DC power supply are determined according to the reinforcement dimensions (diameters, lengths) and to the areas to be treated.

4.6.1.4- Application procedure

A treatment is applied in several stages.

A: System with impressed current:

- projection of a first paste layer (cellulose or rockwool) with an adapted electrolytic solution (alkaline carbonate for re-alkalisation or lime water for chloride extraction),
- installation of the metal anodic mesh (steel or titanium) on insulating rods, fixed on concrete surface,
- connecting anode wire on the mesh,
- projection of a second paste layer,
- electric connections to the power supply: D.C. current, voltage ranging between 10 and 48 volts,
- periodic wetting of the paste with electrolyte, or water,
- monitoring voltages and currents, sampling of concrete during treatment for analyses (alkalinity, chloride content),
- dismantling the whole system,
- rinsing with water under low pressure.

B: System with galvanic current:

- projection or extrusion of a paste layer saturated with an electrolyte and placed on concrete,
- installation of an anode (grid) metal fixed on a rod and in contact with the paste,
- connecting of anode to the electric circuit, since this moment the treatment is active,
- periodic wetting of the paste with water,
- monitoring voltages and currents, sampling of concrete during treatment for analyses (alkalinity, chloride content),
- dismantling the whole system,
- rinsing with water under low pressure.

In this case, the selected electrolyte makes it possible to carry out both chloride extraction and re-alkalisation.

Photo 4.8

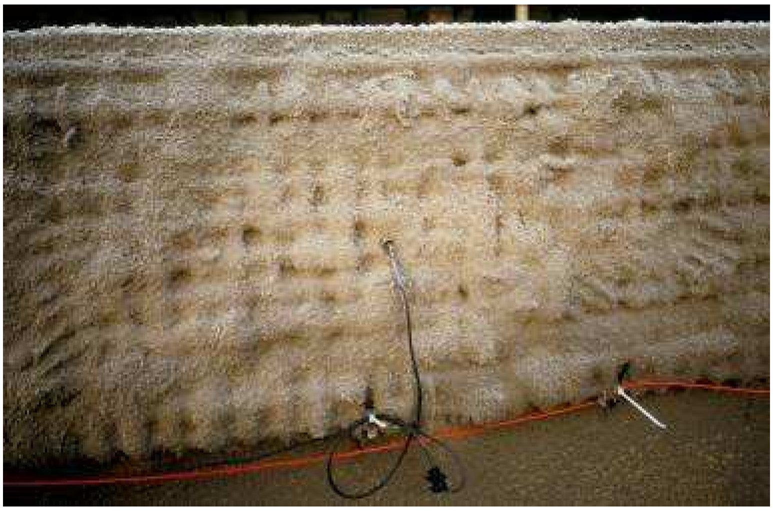


Photo 4.9

4.6.1.5.- Implementation control

The applicators of treatments are fully responsible for the implementation and the result.

4.6.1.6.-Limits of use and fields

The processes of temporary electrochemical treatments apply only to reinforced concrete, which is damaged

- by carbonation with a maximum depth not higher than cover thickness,
- or by chlorination of external origin, with a depth not higher than the first mat of reinforcement.

They are not adapted for other pathologies, such as sulfatic attacks, alkali-aggregate reaction, etc. In the case of a concrete potentially reactive to this last deterioration, preliminary tests must be carried out.

4.6.1.7.- Acceptance tests

The results of the temporary electrochemical treatments are evaluated quantitatively.

For re-alkalisation, the application of a colour indicator (generally, phenolphthalein) makes it possible to determine the concrete areas of rather high pH.

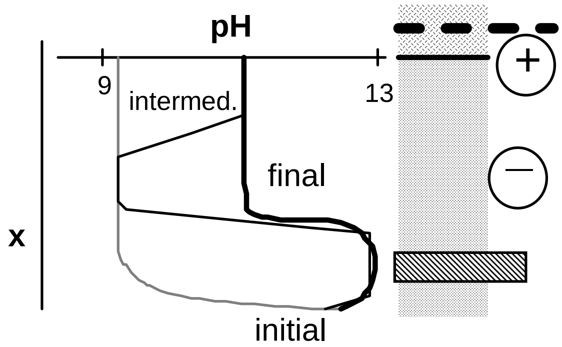
For the chloride extraction, measuring chloride contents, before and after treatment, makes it possible to quantify the results.

4.6.1.8. - *Duration and effectiveness of the process*

A: Re-alkalisation

The effects of re-alkalisation persist after 10 years, if the thickness of re-alkalized concrete around reinforcement is higher than 10 mm.

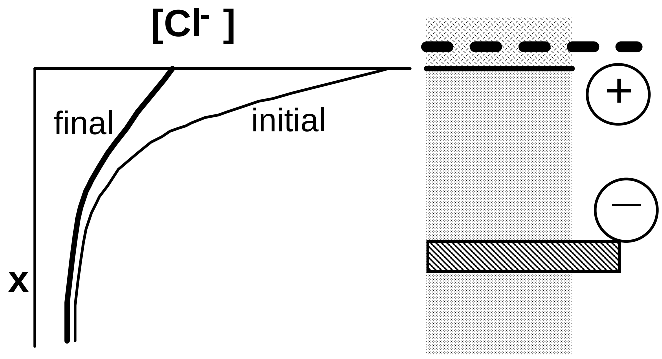
It is possible to apply after this treatment, a film coating, onto concrete surface.



Zones where concrete is re-alkalized after treatment. Polarization makes it possible to re-alkalize concrete, which is in contact with reinforcement.

B: Chloride extraction

An extraction is effective, if chloride content in the vicinity of a reinforcement, is lower than the usually allowed threshold to avoid metal corrosion. This often corresponds to an extraction of 80 to 90 % for the extraction of chloride ions.



Chloride content profiles before and after extraction treatment

It is recommended to protect concrete surface to avoid a new arrival of these ions. Any traditional protection system is applicable.

4.6.2 CATHODIC PROTECTION

4.6.2.1 Principle of cathodic protection

The cathodic protection of metal reinforcement in concrete is a treatment permanently applied, which makes it possible to slow down, to even stop metal corrosion. It consists in lowering the electrochemical potential of reinforcement down to a threshold value called protection potential, which is so that steel corrosion rate becomes negligible.

The principle of cathodic protection consists in polarizing reinforcement in concrete, using an anode placed permanently on concrete surface or sometimes inside concrete cover. The polarization current, which flows from anode towards reinforcement, ranges between 2 and 50 mA by square-meter of reinforcement side area.

There are two techniques of cathodic protection:
- by impressed current: an electric generator is placed between the anode and reinforcement,
- by sacrificial anode (galvanic current): the anode, made of correctly selected alloy, is directly connected to reinforcement.

Photo 4.10

Photo 4.11

The cathodic protection of steel in concrete is the subject of the European standard EN 12 696 " Cathodic protection of steel in the concrete ". It must be studied, implemented and applied by qualified personnel.

4.6.2.2. – Expertises and works before application

Cathodic protection is necessary, when steel in reinforced concrete corrodes or is about to corrode. A diagnosis of concrete conditions and of structure soundness makes it possible to specify the need for a strengthening or a repair, before installing a cathodic protection system. The structure condition, its structural integrity and the need of some repairs, are the object of an assessment by a specialist.

All information available, must be exploited and supplemented by an examination on site and possibly by tests, to determine the nature and the extent of disorders and the repair to be carried out:
- visual examination and research of delaminations,
- cover thickness and locating of reinforcement,
- analyses of chlorides (profile of chloride contents),
- carbonation depth,
- electrical continuity of reinforcement,
- half-cell potential of reinforcement,

- electrical resistance of concrete.

Complementary analyses are useful, like measuring surface resistivity and checking concrete sensitivity to alkali-aggregate reaction.

Preliminary works can be necessary, before applying cathodic protection:
- removal of damaged concrete, as well as concrete of former repairs, having a resistivity significantly different,
- preparation of reinforcement: to remove loose rust and to restore electrical continuity (if needed),
- patching (reconstitution of cover) to have a minimum thickness of 20 mm between reinforcement and concrete surface.
- patching with a material containing cement

4.6.2.3 - Design

The preliminary expertises make it possible to determine the areas to be treated. The sets of steel bars, which are not connected electrically, are considered as being in distinct zones.

Dimensions of anodes and the capacity of DC power supply are determined depending on the dimensions (diameter, length) of reinforcement to be treated.

The aim of a calculation design is to determine the characteristics of the installed system (type and quantity of anodes to be installed, total current needed and corresponding voltage, number of control areas and subsequently, number of reference electrodes, connecting cathodes on reinforcement, making wiring).

The detailed study of a cathodic protection system leads to writing a quality plan including:

A detailed note of design indicating in particular:
- the number and the locations of anodic areas,
- the consumed current [mA/m²(steel)] for each area,
- the type of anode chosen,
- the number and the locations of sensors for monitoring and control.

Detailed installation drawings related to:
- the locations of anodes and anodic connections,
- the wiring (junction boxes, positive and negative cables)
- the location of the transformer-rectifier (for impressed current),
- the details of connections (to anodes, sensors, etc),
- the locations and wiring of sensors.

Detailed specifications related to the system *materials*

Relative declarations or detailed specifications about:
- the method of installation,
- the tests,
- the energizing,
- the starting
- the exploitation.

4.6.2.4: Application procedure

A system of cathodic protection is installed in several steps.

A: Installation of anodes

Holes are drilled in concrete surface to expose reinforcement and to connect it to the electrical circuit. These holes are then filled.

The anodes are generally placed on concrete surface, but they can also be embedded in concrete. Each type of anode has its particular mode of installation, as indicates it the European standard NF EN 12.696.

All concrete areas intended to receive the surface anodes must be prepared.

These anodes are generally of titanium (activated), of zinc, of conducting paintings, etc. After their installation, titanium anodes are covered with mortar (more than 20 mm thick). The surface zinc anodes can be painted. The anodes in the form of paints can be covered with another layer (top coat) for aesthetic reasons and for improving their performance in atmosphere.

The anodes placed inside concrete are embedded in a material containing cement.

B: Placing of sensors

Sensors are to be placed in concrete for monitoring the system. They are installed in the areas, which are the most strongly subjected to corrosion. They are reference electrodes or temperature sensor. But of other types of sensors can be installed (to characterize polarization current, etc.)

C: Before energizing

a- Visual inspection of
- electrical circuits (polarization and measurements) to confirm that all components and cables are correctly installed, labelled and if necessary, protected from possible damage due to the environment, to man or to animals.
- cover on anodes with a survey with hammer, to check that bonding is correct at any point.

b- Checking
- polarity of all circuits,
- continuity of all circuits,
- insulation of all electric circuits,
- equipment for centralized electronic measurement and/or transmission of data on the monitoring of the system.

c-Measurement of the following parameters:
- steel potential against reference electrodes permanently installed and to potential decay,
- steel potential measured with to portable reference electrodes,
- voltage between reinforcement and anode,
- all data from other sensors belonging to the monitoring system,

D: Initial energizing

a- The first energizing preferably includes the following stages:
- a polarization applied progressively and step by step, for each individual area (impressed current),
- recording at each step, the applied intensity I and the structure half-cell potential E_c to determine the protection current I_0
- maintenance of protection current I_0 for a sufficient duration, which can be up to 28 days or more.

b- The initial performance is evaluated by measuring:
- output voltage,
- current intensity in each area, with calculation of the circuit resistance,
- instantaneous potentials at current cut-off with all reference electrodes permanently installed,
- potential decay after permanent cut-off,
- parameters of all other sensors installed as elements for monitoring.

E: Final adjustment

The final adjustment of polarization current I_0 is carried out after a period of about 28 days or more.

F: Application and maintenance

The operation of a cathodic protection system is monitored, especially by measuring the polarization current for each anode area. The data of other sensors are recorded according to a periodicity, which is indicated in the quality plan.

The operation control of this system is reported in an official document, for the following actions:
- routine inspections (with reporting) which makes it possible to check the correct operation of cathodic protection, to assess the performance of all elements, and to analyze results,
- the monitoring of the system, which takes again all the data of the previous routine inspections and includes a visual examination of the system, a new routine inspection.
It should be noted that if the system has an equipment of remote management, coming to the site is necessary only for the follow-up of the system, except if abnormal events were detected,
- the control of effectiveness after 5 years by visual observation of reinforcement, which is exposed for this purpose, as well as a test of cutting-off current.

4.6.2.5 Control implementation

The interior control by the contractor, which is defined in the quality assurance plan, relates to all the phases described here above.

4.6.2.6 Limits and fields of use

Cathodic protection applies to reinforced concrete structures, exposed to the atmosphere, whose reinforcement corrodes or is likely to corrode. It applies to the steel bars, which are uncoated and the steel bars with an organic coating.

It can be applied to tendons of prestressed concrete, if steel potential is not more negative than -1100 $mV_{Ag\text{-}AgCl}$, a threshold below which hydrogen can embrittle high-strength steels. In this case, the prestressing tendons must be connected to the passive reinforcement net.

A cathodic protection should not be applied when concrete risks any damage by alkali-aggregate reaction, mainly when reinforcement is highly polarized.

4.6.2.7 Acceptance tests

The acceptance tests are done at the system installation and at its first energizing.

Every test carried out, in accordance with the plan quality, is reported in a document (test report), which is inserted into the file of the works.

4.6.2.8 Duration and effectiveness of the process

A system of cathodic protection is effective, as long as the criteria (potential under cut-off current, etc.) are checked and met. Among all the electrical circuit components, the least durable components are reference electrodes, which are easily replaceable, and anodes. A titanium anode is given for a minimum duration of 20 years. Some complements make it possible to prolong anodes lifespan.

4.6.2 *FRENCH LITERATURE REFERENCES on Part 4.6*

"Corrosion and protection of metals in contact with concrete" Final report COST 509, European Commission report EUR 17608 EN, Part 3, 1997

A. RAHARINAIVO, G. ARLIGIE, Th. CHAUSSADENT, G. GRIMALDI, V. POLLET, G. TACHE " La corrosion et la protection des aciers dans le béton ". Presse Ecole Nationale Ponts et Chaussées - 1998

A. RAHARINAIVO, J. C. LENGLET, C. TOURNEUR, H. MAHOUCHE, V. POLLET, "Chloride extraction and re-alkalisation of concrete by using sacrificial anodes". In: "Controlling Concrete Degradation", Ed. R. K. Dhir, M. D. Newlands. Proc. of International Congress. University of Dundee, UK, September 1999, pp. 189 - 197

Technical recommendation (French version) FD CEN/TS 14038-1 " Réalcalinisation électrochimique et traitements d'extraction des chlorures applicables au béton armé – Partie 1 : Réalcalinisation ".

European standard NF EN 12696 (French index A 05-668) " Protection cathodique de l'acier dans le béton " Juillet 2000

4.7: SUMMARY ABOUT REHABILITATION METHODS

Several processes exist to rehabilitate reinforced concrete damaged by corrosion. None them is applicable in any case. Their characteristics are summarized in the tables here below.

It is reminded that each process or treatment must include the following stages:
- Assessment of the structure
- Nature and possible causes of damages
- Choice of the possible solutions on technical level
- Compatibility between the processes and the various requirements. Indeed, most of the time, several different options are possible: the adopted solution must be compatible with the various requirements, the technical choices and the acceptable cost.

Patching

Field of action	Restoring the appearance of concrete surface
Implementation	Removing damaged concrete. Brushing, replacing reinforcement. Possible protection. Application of NF or similar product
Limits and precautions for use	Precise timetable of the operations (risks of structure equilibrium loss)
Effectiveness. Control and duration	Acceptance of reinforcing steel Control of reinforcement, Acceptance of substrates
Side effects. Incidences on the structure. Comments	Risks of continuation if corroded parts are not perfectly removed, Take care to the adjacent cathodic effects

Sprayed concrete

Field of action	Structural repairs, strengthening
Implementation	Projection on wall, using compressed air, according to two techniques: dry and wet processes
Limits and precautions for use	To meet standard NF 95102 for the design and for the

	thickness
Effectiveness. Control and duration	Acceptance of reinforcement, Controls of bonding, Making boxes for suitability tests, with core sampling for controlling properties
Side effects. Incidences on the structure. Comments	Overloads

Protective products. Surface water repellents (sealants)

Field of action	Waterproofing effect on concrete surface
Implementation	Implementation on surface with roller or sprayer. The preparation of the substrate is fundamental
Limits and precautions for use	Application when damage is due to a contact with liquid water coming from the atmosphere Not to apply on horizontal surfaces
Effectiveness. Control and duration	Control of effectiveness with beading test (qualitative)
Side effects. Incidences on the work. Comments	Poor compatibility of the water repellents with soluble salts and with some treatment products

Protective products: Corrosion inhibitors

Field of action	Slowing down the rate of reinforcement corrosion process
Application	Implementation by spraying on several passes (liquid form) on concrete surface or direct application on surface (gel form) or on steel
Limits and precautions for use	Incompatibility with the elements already treated with water repellents. Limits related to too high chloride contents
Effectiveness. Control and duration	Effectiveness depending on the type of product and on its amount available at steel level (inhibitor content) Control by measuring half-cell potential and corrosion current
Side effects. Incidences on the structure; Comments	Some mineral inhibitors interact with concrete Risk of white stains, which must be cleaned

Surface coatings : Paints, Lasures and other coatings

Field of action	Improvement of concrete surface: aesthetic action, reduction of sooting, protective action for concrete.
Implementation	Application in several layers on a substrate not showing too significant imperfections
Limits and precautions for use	Surface, non-curative protection The substrate condition during application has a decisive role
Effectiveness. Control and lasted	The effectiveness is related to the bonding between substrate and coating, Risks of blistering, cracking, chipping. Control of surface permeability
Side effects. Incidences on the work. Comments	Take care to the performance under UV rays for the choice of products. Incompatibility risk with some concrete treatments

Surface coatings : Renders for buildings

Field of action	Improvement of concrete surface: aesthetics, correction of

	surface irregularities, protection against the environment
Implementation	Depending on the nature of the product
Limits and precautions for use	Surface, non-curative protection
Effectiveness. Control and duration	The effectiveness is related to the bonding between substrate and coating, Risks of blistering, cracking, chipping.
Side effects. Incidences on the work.	

Electrochemical treatments: Re-alkalisation of concrete, chloride extraction

Field of action	Re-alkalisation for carbonated concrete Chlorides extraction for concrete polluted with chlorides
Implementation	Polarization of reinforcement using an electrode placed on concrete surface and embedded in a paste saturated with an electrolyte Duration: a few weeks
Limits and precautions for use	Electrical continuity of steel bars Concrete non-sensitive to alkali-aggregate reaction Incompatibility with coated reinforcement Incompatibility with concrete coatings
Effectiveness. Control and lasted	Checking with pH indicators (re-alkalisation) or determination of chloride content (chloride extraction). Treatment possibly to be renewed, in the long term.
Side effects. Incidences on the work. Comments	Unbalance pore solution in concrete Possible formation of white stains, which are to be cleaned

Electrochemical treatments: Cathodic protection

Field of action	Protection of steel by lowering of its half-cell potential
Implementation	Polarization of steel using an electrode permanently placed on concrete surface or in concrete cover
Limits and precautions for use	Electrical continuity of steel bars Possible repair of surface, Concrete non-sensitive to alkali-silica reaction Incompatibility with coated reinforcement Incompatibility with watertight coatings.
Effectiveness. Control and lasted	Effective if steel half-cell potential is kept at the required value Replacement of reference electrodes
Side effects. Incidences on the work. Comments	Risk of embrittling tensioned prestressing steel. Change of concrete surface appearance

5. CONTROLS OF IMPLEMENTATION

This part of the document applies in France.

The rehabilitation of reinforced concrete damaged by reinforcement corrosion calls for various techniques, whose methods or controls are not all codified yet.

The object of this chapter is to specify the actions (i.e. to make appear in contractual parts and contractor requirements), for interior control, and to specify the nature of exterior control, which remains a prerogative of the Project manager.

It is recommended to point out the following definitions:

- Sensitive point: it is a point during execution, which must draw particular attention.

- Critical point: it is a point during execution, which requires reporting interior control on a document for follow-up, as well as preliminary information of exterior control, so that this latter can be done, if needed. The intervention of exterior control is not necessary for continuing of the works.

- Stop point: it is a critical point, for which a formal agreement of the Project manager or of an institution selected by him, is necessary for the execution to continue. The lengths of notices and the deadlines for reply to the Project manager are fixed in the CCAP, which must specify the actions to be taken by the contractor, at the end of the deadline for reply, if the Project manager does not react.

5.1 PREPARATION OF STRUCTURES

5.1.1- TENDER DOCUMENTS FOR COMPANIES

When *writing* the tender documents for contractors (*DCE)* it is necessary:
- to indicate that the contractor, who proposes an alternative will have to determine the corresponding interior controls,
- to include a clause in the CCTP concerning Quality assurance.
One is reminded that " the contractor establishes the quality assurance plan (PAQ), in which he describes the general organization of the construction site, the principal means, which he intends to assign to it and the actions of interior control associated with these means ". The PAQ is submitted to the visa of the Project manager, as well as the framework of the follow-up documents,
- to indicate, in the CCTP, subjections implied by the exterior control, concerning the contractor; in particular, this part of the market shall contain the list of Stop points, as well as the deadlines for cancelling stops.

The contractor carries out tests and controls, as interior control and he has to pay them.

The Project manager carries out tests and controls as exterior control and he pays them on the funding from the Owner, whether they were included or not in the market.

5.1.2: DEVELOPMENT OF PROCEDURE

During the development of the market it is necessary to:
- change CCTP on points concerning interior controls, according to alternative proposals (to supplement, if needed, the list of interior controls envisaged by the contractor),
- develop the framework of the PAQ, which will includes the main provisions of the document about the general organization and the list of execution procedures, and to annex it to the CCTP.

5.1.3: QUALITY ASSURANCE PLAN (PAQ)

During the period of the preparation and during the execution of works, the contractor establishes a PAQ, which deals with:
- *factors* contributing to obtaining quality:
: assignment of the works, means and personnel
: materials and supplies
: methods and significant points of the execution
- *internal control*

During the examination of the PAQ, the Project manager shall make sure that the contractor will not improvise anything on the construction site.

5.2 INTERIOR CONTROL BY THE CONTRACTOR

The interior control of the contractor relates to tests, acceptances and control of finished works.

5.2.1: TESTS

5.2.1.1- Trial for study

The trial for study is *a critical point.*

When the product is a composite material, with an explicit formulation (e.g. case of sprayed concrete), the contractor provides a study file. This document includes the results of a trial for study.

5.2.2.2- Suitability test

The suitability test is *a stop point.*

The purpose of it is to test, under the conditions of job site, the aptitude of the contractor to fulfil works with the materials, the equipments and the human means indicated in the PAQ. On this occasion, the particular points are examined. For every technique, a close attention is paid to substrate preparation, so that it is compatible with the technique suggested.

The place for suitability test is generally a zone (in the order of a square-meter) of the structure to rehabilitate. It must be representative of the whole rehabilitation, on technical levels, difficulty of access, safety etc.

The materials, the equipments and the staff skill are assessed, during suitability test. For some techniques, the qualification of the staff (e.g. hose holder, assistant of hose holder and machinist for sprayed concrete, or electrician for electrical components of cathodic protection) will be required.

5.2.2- ACCEPTANCES

5.2.2.1: Acceptance of materials

The acceptance of materials is *a critical point*

The conformity of the delivery to the order is checked for
- concrete (case of the ready-mixed concrete),
- materials (cement/aggregate, admixtures/additives/water or bags pre-proportioned in the case of concrete manufactured on site),
- products of patching and other products of protection,
- reinforcements and curing agents,
- anodes, other electrical supplies and sensors for monitoring the systems for electrical treatments.

Double core samplings of materials are carried out for possible further analyses.

5.2.2.2- Acceptance of substrate

The acceptance of the substrate includes:
a- the checking of determined zones to rehabilitate
b- the checking of substrate condition and surfaces between layers (sprayed concrete) *(stop point)*

c- the checking of reinforcement installation *(not critical)* **,**
d- the checking of the installation of electrical system for treatment *(not critical)*

5.2.2.3: Acceptance of products

The acceptance of products includes:
- the checking of the respect of compositions *(not critical)*
- the characterization of product workability.

5.2.3 CONTROL OF IMPLEMENTATION

The control of implementation includes the following points:
- control of the respect of rehabilitation timetable (number of layers, waiting time between layers applications, total thickness) *(critical point)*
- follow-up of products consumption,
- quality control of execution and of products implemented *(critical point)*
- thickness control of sprayed concrete, of surface coatings *(critical point)*
- control of top coat (aspect, flatness) *(critical point)*
- control of curing *(critical point)*
- control of bonding to substrate *(stop point)*
- control of energizing (electrical treatments) *(stop point)*

5.2.4- CONTROL OF ACHIEVED WORKS

The control of achieved work is *a stop point.* It deals with checking necessary characteristics and the effectiveness of protection and/or repair.

5.3 EXTERIOR CONTROL FOR THE STRUTURE OWNER

"Exterior control" of the Project manager is a control of conformity to the requirements in the CCTP (particular technical requirements), about
- the equipment for making materials,
- acceptance, transport and implementations of equipments and materials,
- staff for executing and supporting the implementation of rehabilitation methods .

The concept "Exterior controls", which is defined in DCE, in SDQ, in PAQ and in the procedures of the various contributors, includes the following tasks
a- *to examine* and *formulate an opinion* on the contractor's proposals concerning:
: staff means and qualification, means in equipment for manufacturing and implementation,
: contents of the studies,
: materials,
: contents of interior control.

b- *to propose* to the Project manager an exterior control, according to interior control.

c- *to carry out* exterior control on:.
: checking the PAQ of Contractor and subcontractors and/or suppliers,
: validating the trial of study *(stop point)*
: validating the suitability test *(stop point)*
: checking the application of the Contractor's PAQ concerning the internal control related to the execution of the works,

: the acceptance control of substrate *(stop point)*
: the quality control of equipments and materials implemented,
: the control of bonding to substrate *(stop point)*
: the acceptance control of the structure (or of structure element) *(stop point)*